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Medición de secciones eficaces de fusión entre isótopos de carbono utilizando un blanco activo ^(*)

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Resumen

La fusión de núcleos de carbono ha llamado la atención tanto a físicos como astrónomos en por lo menos los últimos 50 años. Desde los fundamentos de la estructura nuclear hasta descubrimientos de nuevos fenómenos estelares, todavía hay temas abiertos. Uno de ellos es la fusión en el sistema $^{12}\text{C}+^{12}\text{C}$, la cual muestra oscilaciones que no se presentan en sistemas vecinos y que aún no son totalmente entendidas. Por otra parte, fueron observadas discrepancias significativas en las secciones eficaces de fusión en los sistemas $^{14}\text{N}+^{12}\text{C}$ y $^{15}\text{N}+^{12}\text{C}$, los cuales difieren únicamente en un neutrón. Sin embargo, hasta hoy no fue posible estudiar el mismo efecto para otros sistemas similares con carbono. En astrofísica nuclear, la fusión de isótopos radiactivos de carbono tendría un rol fundamental al abrir nuevos caminos para la nucleosíntesis en ambientes astrofísicos tales como estrellas binarias emisoras de rayos X, en las que se descubrieron nuevos fenómenos explosivos llamados *súperllamaradas*.

Con estas motivaciones, en este trabajo se midieron secciones eficaces de fusión con los haces $^{10,12,13,14,15}\text{C}$ sobre un blanco de ^{12}C . Los haces usados fueron de unos 3.5 MeV/nucleón, obteniendo funciones excitación de fusión en el rango de energías de centro de masa entre 9 y 18 MeV. Para lograr esto, se desarrolló una nueva técnica de medición, la cual está basada en una *cámara de ionización de muestreo múltiple* (*MUSIC*, por sus siglas en inglés), operada como blanco activo, con gas metano actuando como medio de detección y blanco al mismo tiempo. Este es un método de detección de alta eficiencia que permite obtener una función excitación en un rango de energías determinado por la presión del gas, sin variar la energía del haz incidente. Así, se evitan problemas en la normalización de los datos y se reduce drásticamente el tiempo de medición. Dada su alta eficiencia, el detector MUSIC es ideal para su uso en experimentos donde la intensidad del haz es muy baja, como es el caso en los experimentos con núcleos radiactivos.

Además, con los experimentos realizados se mejoraron las capacidades de la instalación *ATLAS* (del Laboratorio Nacional de Argonne, Estados Unidos), donde se utilizó por primera vez, y con éxito, nuevo equipamiento instalado para la producción *en vuelo* de haces radiactivos.

En el presente trabajo, las funciones excitación obtenidas experimentalmente se presentan y comparan con datos experimentales ya existentes. Incluimos también una comparación con tres aproximaciones teóricas diferentes: canales acoplados, un modelo de penetración basado en el potencial de São Paulo, y cálculos de Hartree-Fock dependientes del tiempo. Hemos encontrado un muy buen acuerdo general, tanto con los datos previos como con los cálculos teóricos, haciendo posible la extrapolación de nuestros resultados hacia energías más bajas. También se incluyen simulaciones, que fueron validadas y pueden resultar útiles para el planeamiento de las mejoras y experimentos que aquí se proponen para el futuro.

Palabras clave: Fusión, Isótopos de Carbono, Blanco Activo, Haces de Iones Radiactivos, Súperllamaradas de Rayos X.

Measurement of fusion cross sections of carbon isotopes using an active target

Abstract

Carbon fusion has called the attention of both physicists and astronomers for at least the last 50 years. From fundamental nuclear structure to recent discoveries in stellar phenomena, there are still open topics. One of them is the presence of oscillations in the $^{12}\text{C}+^{12}\text{C}$ fusion cross sections that are not observed in neighboring systems and are not completely understood yet. Moreover, a significant change was observed between the fusion cross sections of the $^{14}\text{N}+^{12}\text{C}$ and the $^{15}\text{N}+^{12}\text{C}$ systems, which differ only in one neutron. However, the same effect could not be studied for other similar carbon systems, up to today. In nuclear astrophysics, fusion reactions involving neutron-rich carbon isotopes may have a fundamental role opening new paths for nucleosynthesis in stellar environments such as X-ray binaries, where new explosive phenomena called *superbursts* have recently been observed.

With these motivations, in the present work fusion cross sections with $^{10,12,13,14,15}\text{C}$ beams on a ^{12}C target have been measured. Beams of about 3.5 MeV/nucleon were used for obtaining excitation functions in the center of mass energy range between 9 and 18 MeV. For doing this, a new measurement technique was developed, which is based on a *Multi-Sampling Ionization Chamber* (MUSIC), operated as an *active target*, with methane gas acting as both counting gas and reaction target. It constitutes a high-efficiency detection method that allows sampling an excitation function in a range determined by the ionization gas pressure, without changing the beam energy. This avoids data normalization issues and drastically reduces the measuring time. Through its high efficiency, the MUSIC detector is an ideal device for experiments in which the beam intensity is very low, as in the case of radioactive ion beams.

The experiments presented here also pushed the capabilities of the *ATLAS* facility (at the Argonne National Laboratory), where newly developed equipment for the *in-flight* production of radioactive ion beams was employed, successfully, for the first time.

In this work, the experimental excitation functions are presented and compared with previous available data. We include also a comparison with three theoretical approaches: coupled-channels, a penetration model based on the São Paulo Potential, and time-dependent Hartree-Fock calculations. We obtained an overall good agreement, both with previous experiments and theory, making it possible to extrapolate our results to lower energies. We also include validated simulations of the MUSIC detector, which may be helpful in planning future improvements and experiments that are here proposed.

Keywords: Fusion, Carbon Isotopes, Active Target, Radioactive Ion Beams, X-Ray Superbursts.

Lista de publicaciones relacionadas con la Tesis

- [PRL14] *Measurements of Fusion Cross Sections in the Systems $^{10,14,15}\text{C}+^{12}\text{C}$ with a Multi-sampling Ionization Chamber.*
P. F. F. Carnelli, S. Almaraz-Calderon, K. E. Rehm, M. Albers, M. Alcorta, A. Arazi, P. F. Bertone, B. Digiovine, H. Esbensen, J. O. Fernández Niello, D. Henderson, C. L. Jiang, J. Lai, S. T. Marley, O. Nusair, T. Palchan-Hazan, R. C. Pardo, M. Paul, y C. Ugalde.
Phys. Rev. Lett., en proceso de evaluación (2014).
- [NIM14] *A Multi-sampling Ionization Chamber for Fusion reaction measurements.*
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Nucl. Inst. Meth. A, en preparación (2014).
- [DNP12] *Measurement of the $^{12}\text{C}+^{12}\text{C}$ Fusion Reaction with MUSIC.*
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Nota preliminar

El presente documento es fruto de mi trabajo de tesis doctoral. Para el mismo, comencé una colaboración con el grupo de Física de Iones Pesados del Laboratorio Nacional de Argonne (Estados Unidos). Tuve la oportunidad de viajar y conducir cuatro experimentos en dos estancias durante 2012 y 2013.

Dado que una cantidad importante de mis colaboradores necesita leer este informe para continuar con el trabajo motivado por nuestra colaboración, el presente documento se encuentra escrito en idioma inglés.

No obstante lo cual, el resumen y las conclusiones de esta tesis se incluyen también en idioma castellano.

Lic. Patricio F. F. Carnelli

San Martín

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A mi madre y mis abuelos.

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CHAPTER 1

INTRODUCTION

Nuclear fusion reactions have many consequences in the Universe: starting from the building of the light elements in the Big Bang, up to the development of heavier elements in the stars' quiescent burning or in stellar explosions. These processes also produce the energy that created and maintains life as we know it.

Given its significance in nature, there has been a great effort to understand the fusion mechanism, and how nuclear structure affects it, through almost the last century. Fusion reactions are of main interest in the field of *nuclear astrophysics* and are central in our attempts to produce and study *exotic nuclei*.

Despite being investigated for so long and with such an enthusiasm, nowadays the experimental research on fusion reactions is still a challenge. This is especially the case for radioactive isotopes and for very low energies. Both situations are at the frontier of our current knowledge and need sophisticated experimental techniques, as the ones that will be presented in this work.

For fusion to occur, two (or more) nuclei need energies which are sufficient to overcome the *Coulomb repulsion*. Then the *strong nuclear interaction* can lead to the formation of a highly excited *compound nucleus*. Depending on the excitation energy, the compound nucleus may live long enough to share that energy almost uniformly between the nucleons, and then decay via particle emission (dominantly neutrons, but also protons or α -particles) to produce the so-called *evaporation residues*.

Because of the delay between formation and decay, and the many complicated nucleon motions that take place during that period, the compound nucleus is said to have "lost memory" of the particular nuclei by which it was

formed, so the probabilities of the various decay modes will be independent of each other and of the specific formation means. This is called the *independence hypothesis*. As a consequence, the decay products are emitted in random directions and so their distribution is symmetric in the center of mass reference system (c.m.). The evaporation residues will then release their remaining energy, via β - or γ -radiation.

Another characteristic of fusion, predicted by classical models, is that it has a smooth energy dependence, except at low energies where discrete *quasi-stable states* of the compound nucleus can produce *resonances*. As a consequence, the *excitation function* (cross section as a function of energy) will show sharp peaks located at the energy values of the discrete states.

This qualitative behavior is common to a large number of systems, but studies performed in the last three decades have revealed something different. The underlying reaction dynamics was found to be more complex than expected by simply assuming the formation of a compound nucleus starting from a bi-nuclear configuration at the *interaction barrier*. It was found that deformations and/or intrinsic excitations of the target or projectile can critically affect the fusion process. This led to the development of *coupled-channels* descriptions including *inelastic* and *transfer* channels [Das98]. These coupled-channel effects can enhance the fusion cross section by several orders of magnitude at sub-barrier energies.

Anyway, the majority of semiempirical models in nuclear physics, developed in the mid-twentieth century, are valid for describing the structure and the reactions of stable (or long-lived) nuclides since they were conceived to fit the experimental data existing at that time. In the last few decades the availability of facilities capable of producing beams of short-lived nuclides changed the field dramatically.

There are about 260 stable nuclei but more than three thousand are radioactive. Nuclei very far from the *line of stability* and close to the *neutron drip line*, the so-called exotic nuclei, present very interesting new features as the “neutron halo” observed in ^{11}Li , ^{11}Be , ^6He and others [Lia05]. The very low binding energy and low angular momentum of the valence neutrons in these nuclei favors the formation of a halo of neutrons which extends over large distances from the stable core and

has densities much lower than the normal nuclear density [Kob88]. It is thought that this may also cause a further enhancement of the sub-barrier fusion cross sections [Lia05].

However, the interest in investigating the structure and reaction mechanisms of these radioactive nuclides is not exclusive to nuclear physics: the temperatures and densities found in astrophysical environments, such as in stellar crusts, are high enough not only to produce massive amounts of these nuclei, but to induce reactions between them. Hence, to thoroughly understand the *stellar evolution* and the *nucleosynthesis* of the elements, and to be able to quantitatively calculate the stellar parameters, fusion reactions involving radioactive nuclei must be known and taken into account. For instance, the existence in massive stars of light neutron-rich nuclei, as ${}^6\text{He}$ and ${}^8\text{Li}$, can play a role in the nucleosynthesis of heavier elements by e.g. helping to bridge the mass gaps at $A = 5$ and $A = 8$ [Gör95].

When nuclei lighter than iron form a compound nucleus, there is an energy release due to the increase in the *nuclear binding*. Nuclei heavier than iron can also fuse, but in an endothermic reaction (although, they can release energy by means of the *fission process*). This behavior is reflected in the variation of the nuclear binding energy with the number of nucleons in a nucleus (the mass number A), which is plotted in Fig. 1.1. From the same figure, it is also evident that the fusion process is more efficient than fission in terms of energy release per nucleon.

In stars, hydrogen and helium are by far the most abundant nuclear species. Thus, fusion of those elements is their main energy source. Instead, here on Earth the fission process is used to obtain energy from a nuclear reaction in a controlled way. The same has not yet been achieved for nuclear fusion.

Fusion plays a combined role in stars: it produces heavier elements and provides part of the energy to fuse, or *burn*, them when the temperature is high enough. By this process, also called *stellar nucleosynthesis*, it is possible to explain the natural abundance of elements from carbon to iron. The production of heavier elements than iron is achieved by the *slow-neutron-capture-process* (*s-process*) and by *explosive nucleosynthesis* in more extreme astrophysical scenarios. Even though

fusion is not always the main process involved, it often provides the energy to trigger those explosions [Tho09].

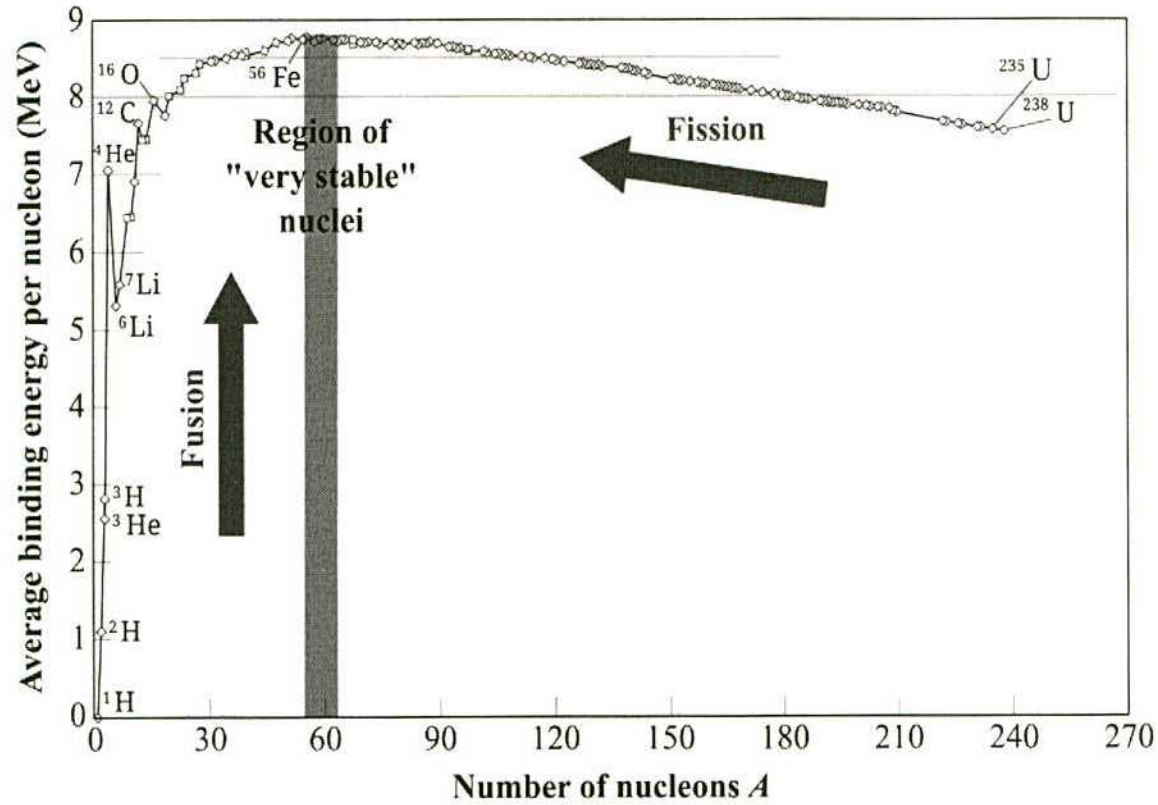


Figure 1.1. Average binding energy per nucleon as a function of mass number A for several abundant nuclei. (Data obtained from Ref. [Aud03]).

Explosive nucleosynthesis in the Universe takes place in very different kinds of astrophysical environments. They involve solitary stars in different stages of their evolution (e.g., stellar outbursts, eruptive supergiants, core-collapse supernovae) or binary systems of stars bound by gravitational attraction (e.g., novae, type Ia supernovae, X-ray bursters and γ -ray bursters).

Although the general mechanisms of most explosive events are thought to be well understood, many important questions remain unanswered, including very recent discoveries on *X-ray bursters*.

As a general description, X-ray bursters are thought to occur on the surface of *neutron stars*, which in a *stellar binary system* accrete matter with rates of up to 40 kg/s/cm² (10^{-8} – $10^{-10}M_{\odot}/y$) from a neighboring *companion star*. The gravitational energy released continuously by the falling material explains the observation of a

high persistent X-ray flux. After a few hours a layer of hydrogen or helium rich material accumulates on the surface of the neutron star that becomes thermonuclear unstable. At temperatures of a few 10^8 K hydrogen or helium ignite as nuclear fusion reactions set in. The energy released from these nuclear reactions leads to a temperature increase in the layer, which in turn dramatically increases the rates of the strongly temperature dependent hydrogen and helium fusion reactions leading to a *thermonuclear runaway*.

The bursting behavior can differ greatly from source to source, and also among bursts from the same source. Observed bursts range from *short bursts* to *superbursts*, depending on the type of nuclear fuel and the associated ignition depth.

Short bursts last from a few seconds to tens of seconds and are thought to be powered by pure helium burning, which does not involve weak interactions and can therefore burn the available fuel quickly. The burst timescale is then set by the thermal timescale for the heat transport from the burning layer to the surface, which is of the order of 10 s. Short bursts can occur on systems with low accretion rates when accreted hydrogen can be burned away in a stable fashion prior to burst ignition [Str03].

On the other extreme, superbursts are very rare but very energetic bursts that last from hours to a significant fraction of a day [Kuu04]. They occur with recurrence times of the order of years in systems that otherwise show frequent regular bursts. It is thought that superbursts are powered by the explosion of a very deep liquid layer of accumulated carbon [Cum01, Str02]. While superburst luminosities are similar to regular X-ray bursts, it is the extended duration that makes them about a factor of 1,000 more energetic. For this reason they are difficult to observe as they must be distinguished from fluctuations in the persistent baseline flux due to accretion rate changes, and because they require continuous long term monitoring of sources. As a consequence, only a dozen or so superbursts have been observed so far [Kuu09].

It is clear that a better knowledge of the nuclear physics of X-ray superbursts is needed, since this will allow to take advantage of recent astrophysical observations and to analyze them quantitatively.

Particularly, fusion of carbon isotopes has several implications in the topics mentioned above. On side of nuclear reactions and structure, a number of questions remain open from previous studies, which could not be answered before the arriving of *radioactive ion beam* (RIB) facilities. So, a great deal of interest is focused on heavy-ion fusion reactions, at energies close to the Coulomb barrier, for target-projectile systems involving $1p$ -shell and $2s1d$ -shell nuclei. This interest was motivated to a large extent by the observation of two unexpected features in the fusion excitation function of systems involving carbon isotopes. The first was the presence of oscillatory structures for some systems (e.g., $^{12}\text{C}+^{12}\text{C}$ and $^{16}\text{O}+^{12}\text{C}$) but not for others [Kov79 and references therein]. The other was the observation of significantly different maximum fusion cross sections for systems differing by only a nucleon in the $^{14,15}\text{N}+^{12}\text{C}$ systems [Kov79]. These features suggest that the detailed structure of these nuclei plays an important role in fusion.

As for the astrophysical interest, we already mentioned that the C+C fusion reactions are an important energy source in stellar explosions such as X-ray superbursts. Studies of these reactions started in the early 1960s in the $^{12}\text{C}+^{12}\text{C}$ system. For at least three energies, $E_{\text{c.m.}} = 5.68, 6.00$ and 6.32 MeV, resonances were observed with characteristic widths of about 100 keV [Alm60]. This measurement triggered several decades of studies in both experimental and theoretical nuclear physics. As measurements were pushed down towards lower energies, the discoveries of such resonances continued as far as the lowest measured energies [Spi07].

However, the resonant behavior observed in $^{12}\text{C}+^{12}\text{C}$ fusion, is not present in other carbon isotopes fusion reactions, such as $^{13}\text{C}+^{12}\text{C}$ and $^{13}\text{C}+^{13}\text{C}$. Only minor resonance features have been observed in these two systems [Day75, Tre88].

For the superburst problem the reactions involving (stable) $^{12,13}\text{C}$ cannot explain the ignition of carbon at the column depth inferred by observations.

Therefore, due to their relatively large abundance in neutron stars crusts the neutron-rich isotopes may be the key to solve this problem [Tan12].

Although details of the superburst process are still being debated, several publications discussing calculations of fusion cross sections between very neutron-rich carbon (up to $^{24}\text{C}+^{24}\text{C}$), oxygen (up to $^{24}\text{O}+^{24}\text{O}$) and neon (up to $^{40}\text{Ne}+^{40}\text{Ne}$) nuclei have recently been published [Hor08, Yak10, Uma12]. Most of the nuclei included in these calculations are outside the range of our current experimental capabilities. A first experimental attempt has been made to study fusion reactions involving neutron-rich nuclei, using a ^{20}O beam from the SPIRAL facility for a measurement of the fusion cross section in the system $^{20}\text{O}+^{12}\text{C}$ [Rud12, Des13]. Due to the detection system, however, only the cross sections associated with charged-particle emission could be extracted in this experiment. This exemplifies the experimental challenges found in fusion measurements involving exotic nuclei.

Motivated by these reasons, in this work a systematic study of carbon isotopes fusion was carried out in order to assess the effect of the neutron number in each system. To obtain high efficiency measurements of this process, particularly with radioactive beams, a new detection system was developed and tested: a *Multi-Sampling Ionization Chamber*, or *MUSIC*.

Five carbon isotopes (three of them radioactive), with masses $A = 10, 12, 13, 14$ and 15 , were used as beams impinging on a ^{12}C gaseous target. The target (methane gas) was also used as counting gas in the detector, operated as an *active target*. The cross sections measurements were done in four different experiments at the ATLAS facility of the Argonne National Laboratory, during a total beam time of 95 hours.

The study of these carbon reactions provides valuable information for both the nuclear reactions/structure topics and for nuclear astrophysics models.

The present thesis is structured in the following way: In Chapter 2, the theoretical background of this work is given, including generalities of nuclear structure, reaction mechanisms, fusion models, and the quantities of interest that were measured. In Chapter 3 we present a brief description of the structure of

carbon isotopes and a summary of our current knowledge on carbon fusion. Then, Chapter 4 focuses on the ATLAS experimental facility, mainly on the available instruments and the radioactive ion beam production methods. In Chapter 5 we provide a detailed explanation of the experimental technique developed for this thesis, with the presentation of the MUSIC detector. After that, Chapter 6 includes the methods developed for the data analysis, incorporating Monte Carlo simulations of the processes occurring in the MUSIC detector. The results of this analysis are presented and discussed in Chapter 7, where we give a comparison with existing experimental data and theoretical calculations. Finally, the conclusions and perspectives are presented in Chapter 8. At the end of this report, the cited bibliography and the appendices are included.

CHAPTER 2

BACKGROUND

In this Chapter, we offer a brief summary of nuclear physics and astrophysics concepts needed for the understanding of this work. To begin with, in Sec. 2.1 we introduce the basics of the nuclear structure *shell model*. Then, Sec. 2.2 describes some parameters used in this work to characterize nuclear reactions with heavy ions. One of those parameters is the *interaction barrier*, in terms of which the nuclear reactions can be classified into two main groups: *direct* and *compound nucleus* reactions. The latter are the subject of Sec. 2.3, where we also present a description of the models that will be used for comparison with the experimental data of this work. Finally, Sec. 2.4 displays the essential aspects of the interaction between the heavy ions and the electrons in a material. This will help in understanding the working principle of the MUSIC detector.

2.1. Nuclear shell model

The nuclear shell model is a description of the structure of the nucleus in terms of energy levels. It is partly analogous to the atomic shell model that describes the arrangement of electrons in an atom. In this respect, it is to a large extent an *independent particle* description. Although, it makes use of the *Pauli exclusion principle* and other types of couplings in more advanced approaches.

This model arose by the need to describe a number of observations, especially the so-called *magic numbers*. When studying, for example, the *neutron separation energy* S_n , we observe several maxima at certain neutron numbers N . The same happens for the *proton separation energy* S_p as a function of the atomic

2. BACKGROUND

number Z . This effect cannot be described by collective models and, as mentioned, resembles the behavior of the *ionization energy* of electrons in an atom.

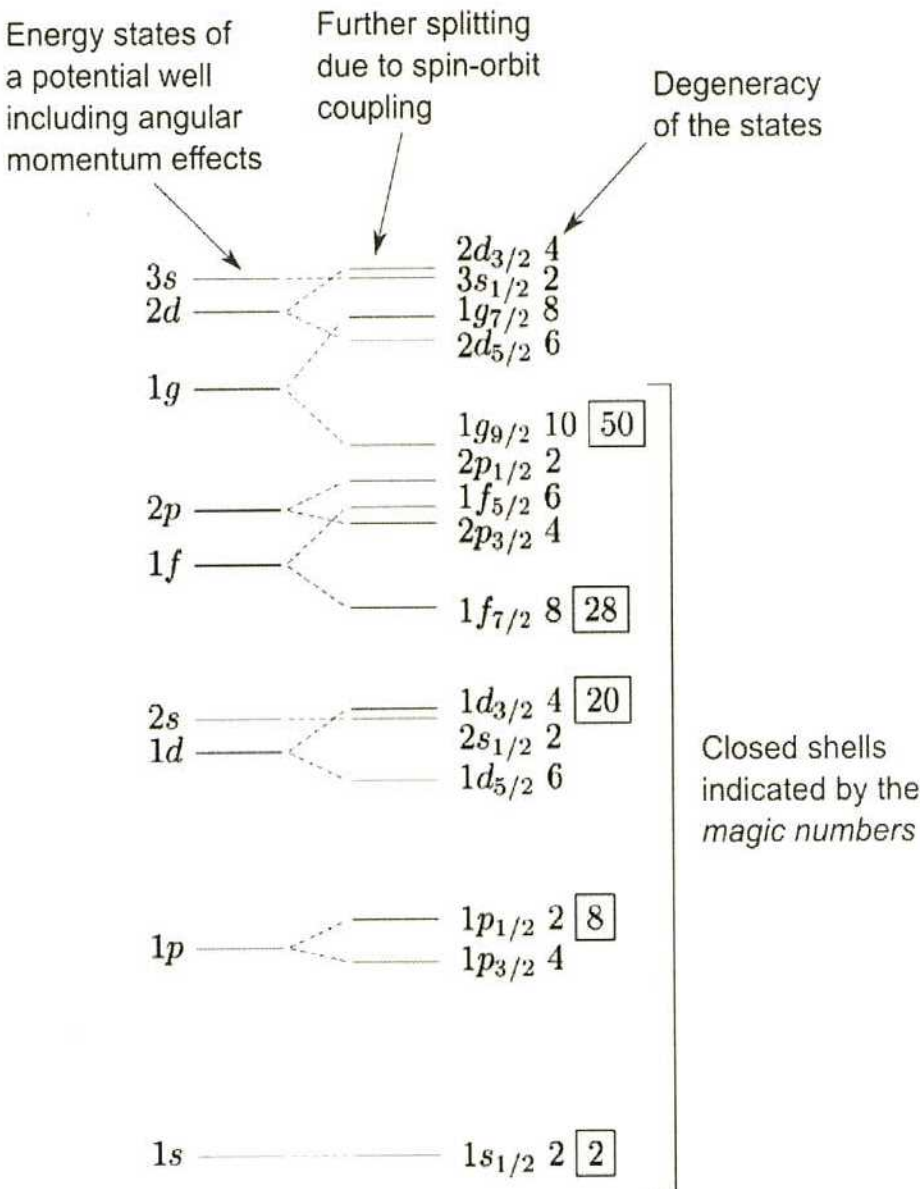


Figure 2.1. Low-lying energy levels in a single-particle shell model with an oscillator potential (and a small negative ℓ^2 term) without spin-orbit (left) and with spin-orbit (right) coupling. The number to the right of a level indicates its degeneracy, $(2j + 1)$. The boxed integers indicate the magic numbers.

The evidence of a kind of shell structure, and also of the limited number of allowed energy states, suggests that a nucleon moves in a type of *effective potential well* created by the forces of all the other nucleons. This leads to energy quantization

in a similar manner for a square well and for the harmonic oscillator potentials. Since the details of the potential determine the energies, its construction demands a great effort for reproducing the observed nuclear energy levels.

As an example, the energy levels derived from rather simple potentials are shown in Fig. 2.1. The labels are somewhat different from the corresponding symbols for their atomic counterparts. The energy levels increase with orbital angular momentum quantum number ℓ , and the s,p,d,f... symbols are used for $\ell = 0,1,2,3 \dots$ just like the atomic case. But there is really no physical analog for the principal quantum number n . So, the numbers associated with a level just start at $n = 1$ for the lowest level associated with a given orbital quantum number. This makes symbols as $1g$ possible, which could not occur in the atomic labeling scheme. Even more, the quantum number for orbital angular momentum is not limited to n as in the atomic case.

In addition to the dependence on the details of the potential well and the orbital quantum number, there is a sizable *spin-orbit interaction* which splits the levels by an amount that increases with orbital quantum number. This leads to the overlapping levels shown in Fig. 2.1. The subscript indicates the value of the total angular momentum j , and the degeneracy of the state is $2j + 1$.

The contribution of a proton to the energy is somewhat different from that of a neutron because of the Coulomb repulsion, but it makes little difference in the sequence of the energy levels.

With this set of identified nuclear states and the magic numbers, we can predict the net nuclear spin of a nucleus. Following this, we can represent its nuclear state with the level of the odd nucleon in the order shown in Fig. 2.1. The parity of the state can also be predicted.

All the more, some nuclear reactions properties can also be explained by shell model considerations, such as the fusion enhancement due to valence neutrons already mentioned in the last Chapter. Therefore, the single particle shell model has shown itself to be of significant benefit in characterizing nuclei.

2.2. Nuclear reactions parameters

We may study (unstable) nuclei passively by observing the radioactive decay products. In other cases, we may study the interaction between a nucleus and its electronic environment, which for example gives rise to the *hyperfine structure* in atomic spectra. However, the most fruitful source of information is obtained by making nuclei interact with each other. Then, the interaction can be characterized by detecting the various generated products and their distribution in angle, energy, etc.

If a nuclear interaction involves only two nuclei it is called a *binary process* or *reaction*. In this case, an incident particle, or *projectile*, **a** interacts with a *target nucleus* **A**. This leads to the emission of an outgoing particle, or *ejectile*, **b** and a *residual* or *recoil nucleus* **B**. A commonly used notation for this type of process is:

$$\mathbf{a} + \mathbf{A} \rightarrow \mathbf{b} + \mathbf{B}, \quad (2.1)$$

or equivalently,

$$\mathbf{A}(\mathbf{a}, \mathbf{b})\mathbf{B}. \quad (2.2)$$

In Eq. (2.1) **a+A** denotes the *entrance channel* and **b+B** is the *exit channel*. Each channel has as main characteristic a particular nucleon arrangement, or *partition*.

In practice, the projectile has an initial kinetic energy (provided by an accelerator) in the laboratory reference system (lab), while the target is at rest (in the same reference system).

As the projectile comes closer to the target, they first interact by the electrostatic force due to their positive charges (the protons). If their distance of maximal approach is not within the range of the strong nuclear force, the electrostatic repulsion is by far the most probable interaction. So, there is an electrostatic *barrier* to be crossed in order to produce a nuclear reaction between the nuclei. This is called the *Coulomb barrier* and can be expressed in terms of the necessary energy V_{CB} to overcome it, which can be written as:

$$V_{\text{CB}} = \frac{Z_a Z_A e^2}{r_0 (A_a^{1/3} + A_A^{1/3})}, \quad (2.3)$$

where r_0 is typically between 1.2 and 1.4 fm, $Z_{a,A}$ are the atomic numbers, and $A_{a,A}$ are the mass numbers of the projectile and target, respectively.

Not only the Coulomb force opposes to the approximation of the projectile, but its angular momentum can also prevent it, which gives rise to the so-called *centrifugal barrier*. It is a component of the kinetic energy when expressed in terms of the conserved orbital angular momentum ℓ , and it only depends on the distance of separation between nuclei. The energy V_{cent} to cross this barrier can be expressed as:

$$V_{\text{cent}}(r) = \frac{\hbar^2}{2\mu} \frac{\ell(\ell+1)}{r^2}, \quad (2.4)$$

where μ is the reduced mass of the system, and r is the distance of separation between projectile and target.

In nuclear and particle physics, a quantitative measure of the probability that a certain reaction $\mathbf{A}(\mathbf{a}, \mathbf{b})\mathbf{B}$ takes place (normalized to the number of atoms per unit of area) is given by means of the *cross section* σ , which is defined by [Sat80]:

$$\sigma_\alpha = \frac{I}{J}, \quad (2.5)$$

where α denotes the entrance channel, I is the number of particles of type $\mathbf{b}$ produced per unit time per nucleus of type $\mathbf{A}$ in the target, and J is the number of incident particles of type $\mathbf{a}$ per unit time per unit area.

The *differential cross section* $(d\sigma/d\Omega)_\alpha(\theta, \phi)$ is defined by the number of reactions per unit time with the particles of type $\mathbf{b}$ emitted within an element of solid angle $d\Omega$ in the direction of polar angles (θ, ϕ) with respect to the incident beam.

For the reactions studied in this work, the spins of the particles are not polarized and therefore the scattering process is symmetrical with respect to the direction of the incident beam, i.e. the differential cross section does not depend on the azimuthal angle ϕ .

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Experimentally, the differential cross section can be measured with a detector placed at the polar angle θ covering a small solid angle Ω_{det} , using the approximation

$$\left(\frac{d\sigma}{d\Omega}\right)_\alpha = \frac{I_{\text{det}}}{J} \frac{1}{\Omega_{\text{det}}}, \quad (2.6)$$

where in this case I_{det} is associated with the number of particles of type **b** emitted in the direction of the detector per unit time per nucleus of type **A** in the target.

In nuclear physics, the unit for cross sections is the *barn* (b), equivalent to 10^{-28} m^2 , with the submultiple millibarn (mb) being the most used unit. While the differential cross section is expressed in units of millibarn per steradian (mb/sr).

The energy dependence of cross sections in charged-particle induced nuclear reactions at center of mass energies $E_{\text{c.m.}}$, less than and close to the Coulomb barrier energy V_{CB} , can be described by two contributions which do not involve the internal nuclear structure. These contributions arise from the fact that at those energies nuclei primarily interact like sub-atomic charged spheres governed by the laws of quantum mechanics.

One of the contributions depends on the effective geometrical area $\tilde{A}$ of the interacting nuclei, the cross section σ being proportional to $\tilde{A}$. Due to wave aspects of quantum mechanical processes this area can be approximated as $\tilde{A} \sim \pi\lambda^2$, where λ stands for the *de Broglie wavelength*. Because for non-relativistic particles $\lambda^2 = h^2/2\mu E_{\text{c.m.}}$ (h is *Planck's constant*), the energy dependence of this geometrical contribution to the cross section becomes

$$\sigma \propto \frac{1}{E_{\text{c.m.}}}. \quad (2.7)$$

The other contribution depends on the tunneling probability for the interacting nuclei to penetrate the Coulomb barrier, which can be approximated by the so-called *Gamow factor* [Gam28]

$$\sigma \propto \exp(-2\pi\eta), \quad (2.8)$$

where

$$\eta = \frac{Z_a Z_A e^2}{\hbar} \sqrt{\frac{\mu}{2E_{\text{c.m.}}}} \quad (2.9)$$

is the *Sommerfeld parameter*. This parameter describes the slope of the fusion cross sections at energies well below the Coulomb barrier, due to the extremely small probability of tunneling.

It is therefore useful to express the cross section as

$$\sigma(E_{\text{c.m.}}) = \frac{1}{E_{\text{c.m.}}} \exp(-2\pi\eta) S(E_{\text{c.m.}}), \quad (2.10)$$

where S is the so-called *astrophysical S-factor*. In this way, all of the strictly nuclear effects on the energy dependence of the cross section are exclusively included in S . For non-resonant reactions (see next Section), the S -factor has a smooth behavior and is much less dependent on the energy than the cross section. For this reason, the S -factor is valuable for extrapolations of experimental cross sections to lower astrophysical energies.

2.3. Fusion models

Two different reaction regimes have been recognized in a binary system collision, and both are important for the understanding of nuclear reaction phenomena.

In one case, the two nuclei may make just slight contact and immediately separate. Their internal states may be unchanged (*elastic scattering*), one (or both) may be excited by the contact (*inelastic scattering*), or one or a few nucleons may be transferred from one nucleus to the other (*transfer reaction*). These cases are depicted in Fig. 2.2. Because these reactions occur on time scales comparable to the time of transit ($\sim 10^{-22}$ s) and proceed directly from initial to final states without forming an intermediate *compound state*, they are called *direct reactions* or *peripheral reactions*. In this kind of reaction the outcome (exit channel) depends intimately on the way it is initiated (entrance channel) and therein lays its importance.

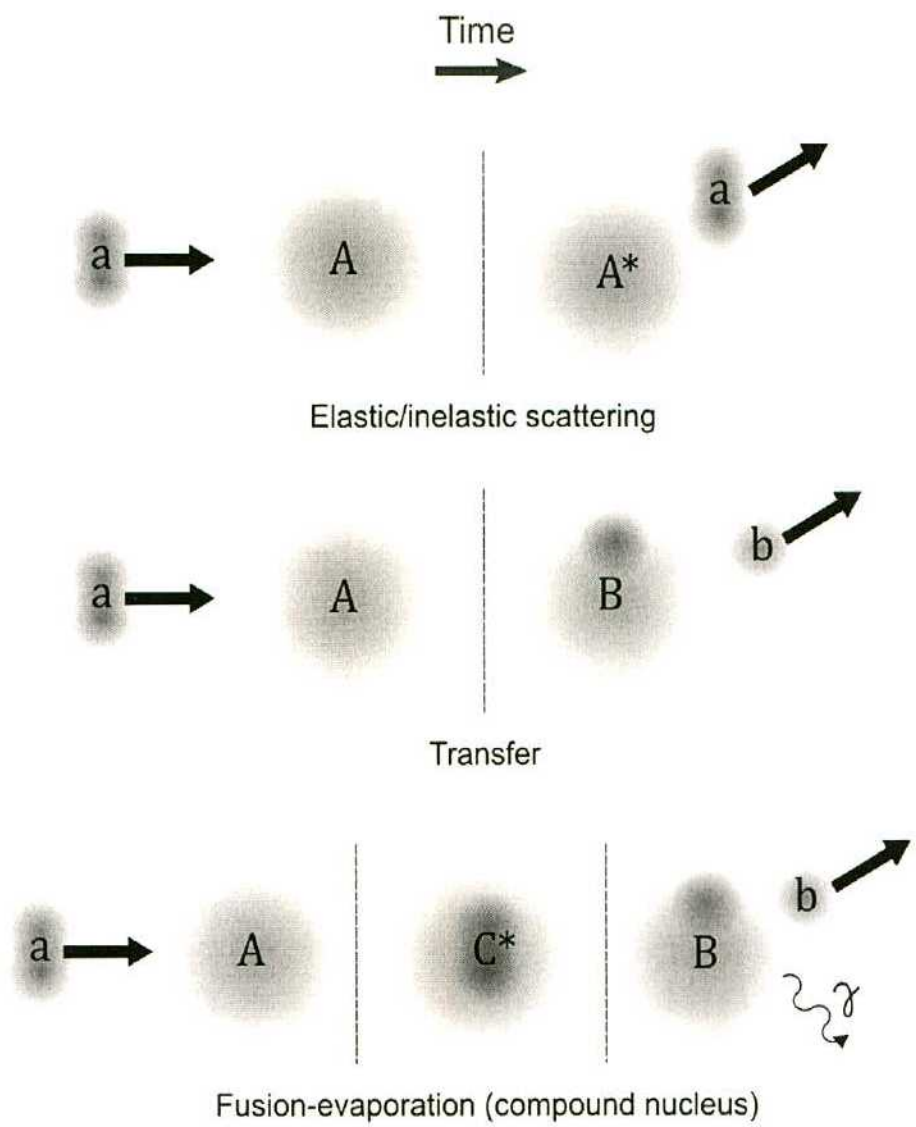


Figure 2.2. Schematic illustration of the three mentioned kinds of nuclear processes, elastic/inelastic scattering, transfer reaction, and fusion-evaporation (via the formation of a compound nucleus).

At the other extreme, the two nuclei may coalesce to form a highly excited compound system. This compound nucleus usually stays together sufficiently long ($\sim 10^{-16}$ s) for its excitation energy (E_x) to be shared more or less uniformly by all its constituent nucleons. Then, by chance, sufficient energy is localized on one nucleon, or one group of nucleons, for it to escape and in this way the compound nucleus decays (see Fig 2.2). Schematically:

$$a+A \rightarrow C^* \rightarrow b+B^*. \tag{2.11}$$

If sufficient excitation energy still remains in $\mathbf{B}^*$, further emissions may occur (γ -decay, or more unusually β -decay).

Because this process is relatively slow, the system $\mathbf{C}^*$ and the following partition $\mathbf{b}+\mathbf{B}$ are independent of the particular entrance channel that formed the compound nucleus (independence hypothesis).

The picture of a nucleus as a “liquid drop” is perhaps helpful in visualizing this process. In the compound nucleus reaction, the two colliding droplets combine to form a single compound drop that, because it is excited, is at a high temperature. The decay, or *cooling*, of this drop can then be thought of in terms of the evaporation of one or more of its constituent particles. This is why it is common to name this reaction as *fusion-evaporation*, and its products *evaporation residues* (ERs).

This liquid drop representation is further improved by the *collective* model. In this case the motions of individual nucleons are highly correlated and do not need to be discussed in detail. As opposite, the other major model of nuclear structure is the shell (or independent-particle) model, already presented in Sec. 2.1. The shell model regards the nucleus as a “cloud” of nucleons moving in more-or-less independent orbits (or shells), like the electrons in an atom.

In the treatment of fusion reactions, the different models try to include the internal structure of the nuclei in more sophisticated ways as they increase in complexity. The models described in what follows exemplify this, and they will be used for comparison with the results from this work (presented in Chap. 7).

2.3.1. The barrier penetration formalism

The different types of nuclear processes can be to some extent sorted according to the energy of the projectile and its relation with the *interaction barrier*. To get in contact, the nuclei have to overcome this barrier, which results from the combination of the Coulomb barrier, the centrifugal barrier, and the nuclear potential (when the separation between nuclei is small enough). Compound

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reactions will be favored for systems with energies above the interaction barrier, thus there is a tunneling probability for this reactions to happen below this barrier.

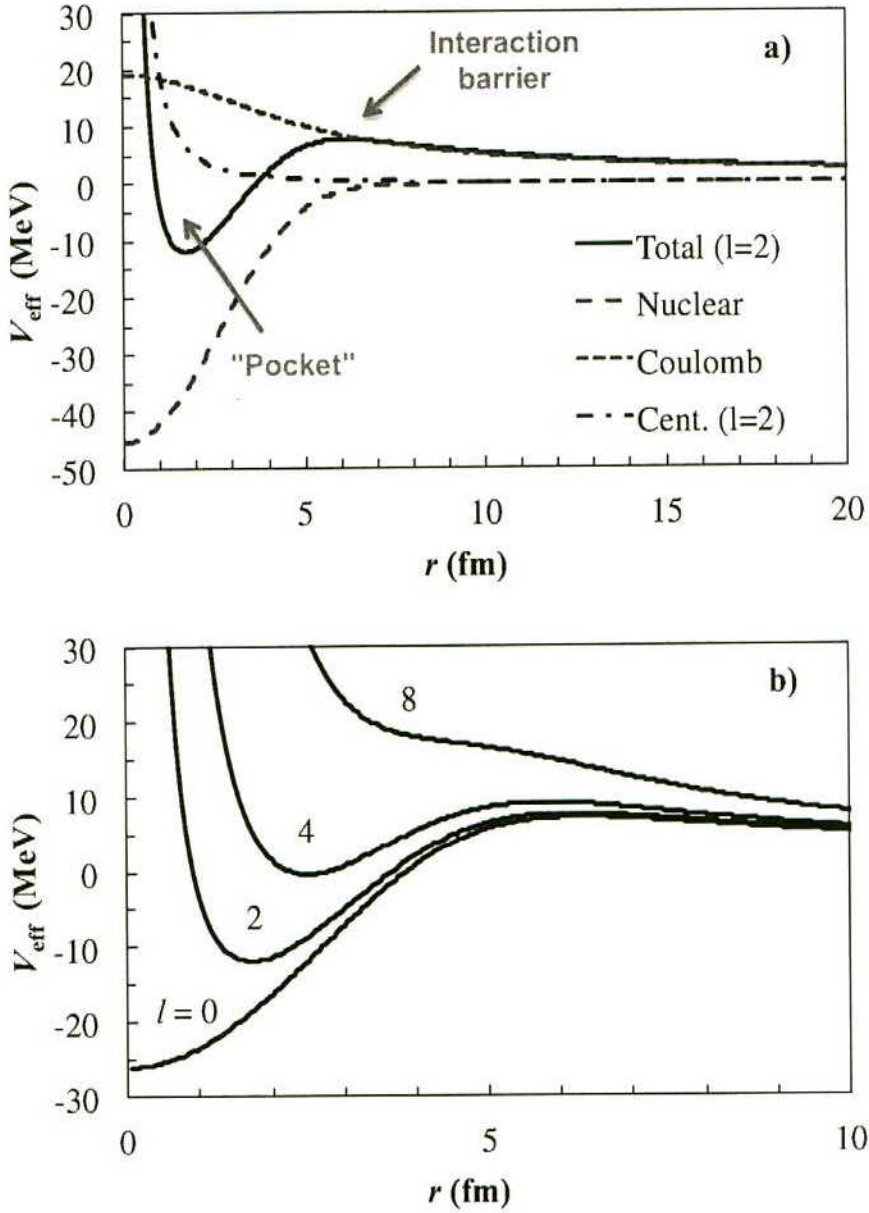


Figure 2.3. Effective interaction potential for $^{12}\text{C}+^{12}\text{C}$. a) The three contributions to the potential and the sum of them for angular momentum $\ell = 2$. b) The total interaction potential for different values of ℓ .

The interaction barrier is a feature of the *effective interaction potential*, i.e. the sum of the long-range Coulomb potential, the short-range strong nuclear potential, and the angular-momentum-dependent centrifugal potential (the latter being an

effective contribution from angular momentum ℓ conservation). As an example, in Fig. 2.3 there is a representation of such an effective potential for various ℓ values. For fusion to occur, the effective potential has to show a minimum (so-called a “pocket”) so the system is trapped in a quasi-steady state for the compound nucleus to form. From Fig 2.3 it is evident that these pockets tend to disappear for large angular momentum values (e.g., high impact parameters). The simplest approach to characterize a fusion reaction is to consider the distance of separation r between nuclei as the most relevant degree of freedom. In this way, the problem is reduced to a one-dimensional motion in a potential such as the described above. We consider that fusion happens when the barrier is surpassed (below the barrier fusion is possible only by quantum tunneling).

Within this approximation, the fusion cross section can be expressed in terms of the *transmission probability* $T_\ell(E_{\text{c.m.}})$ through the barrier (for a given energy $E_{\text{c.m.}}$ and angular momentum ℓ):

$$\sigma_f(E_{\text{c.m.}}) = \sum_{\ell} \frac{\pi \hbar^2}{2\mu E_{\text{c.m.}}} (2\ell + 1) T_\ell(E_{\text{c.m.}}). \quad (2.12)$$

To obtain an analytical expression of T_ℓ , we can approximate the barrier by an inverted parabola of curvature $\hbar\omega_B$ and height B (valid only close to the barrier). This approximation leads to:

$$T_\ell(E_{\text{c.m.}}) = \frac{1}{1 + \exp(2\pi(B - E_{\text{c.m.}})/\hbar\omega_B)}. \quad (2.13)$$

Summing Eq. (2.12) over ℓ we get the *Wong formula* [Won73]:

$$\sigma_f(E_{\text{c.m.}}) = \frac{R_B^2 \hbar\omega_B}{2E_{\text{c.m.}}} \ln \left\{ 1 + \exp \left[\frac{2\pi}{\hbar\omega_B} (E_{\text{c.m.}} - B) \right] \right\}, \quad (2.14)$$

where R_B is the position of the barrier.

This expression is useful to study the behavior of the fusion cross section in the limits of the system energy. For energies well above the barrier, i.e. $E_{\text{c.m.}} \gg B$, we get

$$\sigma_f(E_{\text{c.m.}}) \approx \pi R_B^2 \left(1 - \frac{B}{E_{\text{c.m.}}} \right), \quad (2.15)$$

which has the same energy dependence obtained in classical models. This form is used in phenomenological simple models such as the one proposed by Bass with good success [Bas74, Bas77].

On the other hand, in the energy regime well below the barrier ($E_{\text{c.m.}} \ll B$), the fusion cross section shows an exponential decay with energy:

$$\sigma_f(E_{\text{c.m.}}) \approx \frac{R_B^2 \hbar \omega_B}{2E_{\text{c.m.}}} \exp \left[-\frac{2\pi}{\hbar \omega_B} (B - E_{\text{c.m.}}) \right]. \quad (2.16)$$

In general this model can reproduce experimental results above the barrier, but fails to do so below it. This can be understood by the fact that the nuclei are considered as rigid objects. A more realistic approach needs to contemplate the coupling between the internal degrees of freedom and the relative motion. This coupling is induced by the rearrangement of nucleons, as the nuclei get closer. At a macroscopic level, a better description can be achieved by introducing more complexity to the potentials, such as: deformation, orientation, mass and charge asymmetries, including others.

To accurately explain the enhancement of sub-barrier fusion it is also necessary to include couplings to other processes. This is done by solving a system of Schrödinger equations for the different channels, including: elastic scattering, inelastic excitations, collective modes and transfer reactions. This is the so-called coupled-channels method.

2.3.2. Compound nucleus resonances

Another important characteristic of fusion is the possible appearance of resonances. A resonance occurs when the sum of the masses in the entrance channel plus the kinetic energy of the system is equal to the sum of the masses in the exit channel plus the excitation energy of a compound-nucleus quasi-stable state. If a compound reaction occurs through one of these states, the resonance will interfere with the fusion cross section. If the interference is constructive the cross section will increase abruptly, and so the excitation function will show a sharp peak, at the

resonance energy E_r , with a *width* Γ . The width is given by the uncertainty principle in the form $\Gamma = \hbar/\tau$, where τ is the *mean lifetime* of the excited state. Therefore, long-lived states have narrow resonances (i.e. a well defined energy) and the short-lived ones have wide resonances.

It is possible to show [Sat80] that the cross section for the transition from **a+A** (entrance channel α) to **b+B** (exit channel β), i.e. the reaction **A(a,b)B**, through a compound nucleus resonance is

$$\sigma_{\alpha\beta} = \frac{\pi}{k_\alpha^2} \frac{\Gamma_\alpha \Gamma_\beta}{(E - E_r)^2 + \left(\frac{1}{2}\Gamma\right)^2}. \quad (2.17)$$

where k_α is the entrance channel wave number.

This has the factored form required by the independence hypothesis and is called the *Breit-Wigner single level formula* for a resonant cross section.

The cross section value of a resonance will depend on the partial widths $\Gamma_\alpha, \Gamma_\beta$, etc. It may happen that Γ_α is very small ($\Gamma_\alpha \ll \Gamma$) for a particular resonance and a particular channel α . This could occur because the internal structure of that compound state makes it difficult to form it from the **a+A** pair or because of some angular momentum or parity selection rule acting. If instead it is the width Γ_β for the exit channel that is small, the resonance will not be observable in the cross section for the particular **A(a,b)B** reaction, but may be seen in other **a+A** reactions.

From another point of view, resonances will be distinguishable from each other when their partial widths are small compared to the average spacing D between compound nucleus states, i.e. $\Gamma_\beta/D \ll 1$, meaning the states are isolated and non-overlapping. On the other hand, if there are many overlapping compound nucleus energy levels ($\Gamma_\beta/D \gg 1$), the resonance pattern will wash out giving rise to a smooth shape in the cross section, as represented in Fig. 2.4.

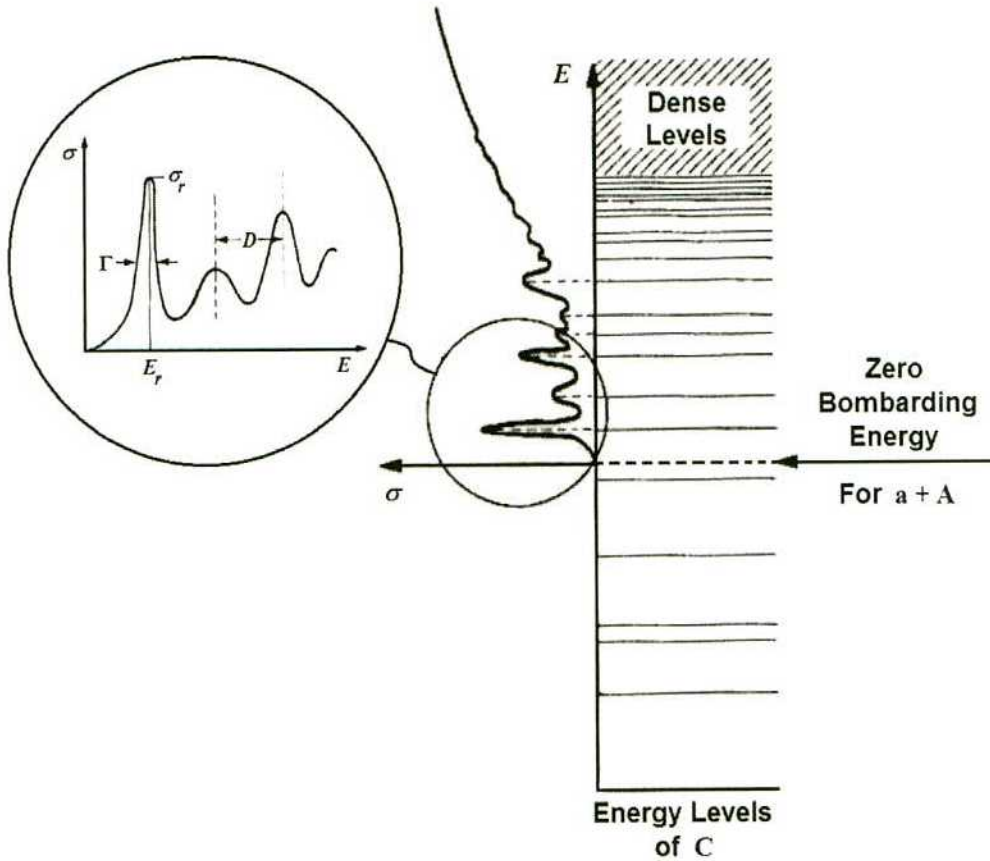


Figure 2.4. Diagram of the levels of a compound nucleus and the excitation function of its formation. At low bombarding energies, the sparse levels are populated and a resonance pattern arises. At higher energies, the states are dense enough for the resonances to merge and the excitation function has a smooth shape. (Adapted from Ref. [Sat80]).

2.3.3. The optical model

It is evident so far that the choice of a potential is essential in a fusion model. In this respect, the options are truly vast but we will cite here only a couple of them.

In the optical model the idea is that in a nuclear process the projectiles can be *scattered* or eliminated of the entrance channel, i.e. *absorbed*. This is in analogy to a beam of light incident on a glass sphere.

This behavior is modeled by a complex nuclear potential. The real part is responsible for describing the elastic scattering. All other processes are taken into account by the imaginary part, considered as “absorption” from the elastic channel.

Usually this absorption is separated into a “volume” term to account for fusion and a “surface” term to explain peripheral non-elastic processes as transfer and inelastic scattering.

The real part of the potential is usually described by an attractive well of *Woods-Saxon shape*:

$$f(r; R, a) = -\frac{1}{1 + \exp[(r - R)/a]} \quad (2.18)$$

where the distance of separation between nuclei is given by r , $R = r_0(A_a^{1/3} + A_A^{1/3})$ is the sum of the nuclei radii, and a is the *diffuseness*.

The Woods-Saxon shape is often used for both the real and the imaginary terms of the potential. As mentioned, a surface-peaked imaginary contribution is frequently included, with a shape like the derivative of Eq. (2.18).

In turn, the nuclear potential of the optical model can be expressed as:

$$V_{\text{nuc}}(r) = Vf(r; R_r, a_r) + i \left[W_{\text{vol}}f(r; R_i, a_i) + W_{\text{sur}} \frac{df}{dr}(r; R_i, a_i) \right]. \quad (2.19)$$

The parameters of the optical model are commonly determined by measuring the elastic scattering, which is habitually the simplest process to study. This is a way for easily obtaining information of other reaction mechanisms without actually measuring them. However, the set of parameters cannot be univocally determined and the results are not really accurate but for elastic scattering itself.

Choosing other shapes instead of Woods-Saxon is a way of using the optical model and avoiding a lot of free parameters. The so-called *double-folding potential* is one of the main options in this respect. It uses a *nucleon-nucleon* potential and the *density distribution* $\rho(\vec{r})$ of each nucleus. The density distribution is a rather simple way of describing a nucleus and accounting for deformations, which are important in explaining the sub-barrier fusion enhancement.

In this case, the nuclear potential is obtained via a convolution integral also called *double-folding integral* (for comprising two density distributions):

$$V_{\text{fol}}(\vec{r}) = \int dr_A \int dr_a \rho_A(\vec{r}_A) \rho_a(\vec{r}_a) v(\vec{r} - \vec{r}_A + \vec{r}_a), \quad (2.20)$$

where v is the mentioned nucleon-nucleon potential.

An example of the application of this method is the well-known *São Paulo Potential* (SPP) [Cha02, Gas04]. The SPP is based on the effects of the *Pauli non-locality*, and takes a *zero-range* approach for v . Through an extensive systematization of nuclear densities, based on experimental charge distributions, the SPP offers a parameter-free interaction model. This makes it ideal for coupled-channel calculations, and so far has been successful in describing elastic scattering and fusion experimental data of many systems, including those with light radioactive beams [Gom12].

2.3.4. The time-dependent Hartree-Fock method

So far we have considered phenomenological or empirical models that include only a few degrees of freedom and no dynamics in the nuclear densities.

On its side, the *time-dependent Hartree-Fock* (TDHF) method [Uma06] treats the bi-nuclear system as a many-body system, with densities evolving in time and no restrictions in the choice of collective variables. Nevertheless, it still is a *mean-field* model that makes use of the *independent-particle* approximation, meaning that each nucleon is considered to move in a potential generated by the rest of the system.

This approach has been tested for fusion in symmetrical systems and compared with experimental data and SPP calculations with a very good agreement. Nevertheless, for neutron-rich systems discrepancies exists between these two models [Uma12]. This will also be discussed later in Sec. 7.3.

2.4. The ionization process in gases

So far we have discussed the principal nuclear processes between two colliding nuclei. In an ionization chamber such as the MUSIC detector, however, the heavy ions (beam, ERs) will mainly interact with the electrons of the ionization gas molecules. This interaction is caused principally by the Coulomb force between the positive charges of the nuclei and the negative charges of the electrons.

When a heavy ion passes through a material it interacts simultaneously with several electrons transferring energy to them. In this way, the particle gradually reduces its velocity and may come to a complete stop. Due to the large difference in masses, the particle does not importantly deviate in a collision with an electron from its original trajectory.

Along its path, the heavy ion will create both *excited* and *ionized* molecules. After a neutral molecule is ionized, the resulting positive ion and the free electrons are, called an *ion pair*, serve as the basic constituent of the electrical signal developed by an ionization chamber.

For ionization to occur, the incident particle must transfer at least the *ionization energy* of the gas molecule. In most gases used for particle detection, this ionization energy is between 10 and 25 eV (14.5 eV for CH₄). However, the incident particle can also lose energy by inelastic excitations of the gas molecules. Therefore, there is actually an average energy value needed for an ion pair to be formed, which is called the *W-value*. Empirical observations show that this is a rather constant value among gases (29.1 eV for CH₄). As a consequence, the number of generated ion pairs is proportional to the energy of the incident particle. For example, a 1 MeV incident particle will generate about 30,000 ion pairs total if it deposits all the energy in the detector.

In an ionization chamber, the ion pairs are collected through an electric field. The electrical current generated by the ion pairs constitutes the signal obtained from the chamber, which is proportional to the energy deposited by a particle in the gas. The electrons have drift times on the order of microseconds, while for the positive ions the drift times are about 1,000 times higher. Hence, in order to limit the measuring time of each event to few microseconds, only the current generated by the electrons is registered.

The interaction between heavy ions and the ionization gas molecules is characterized by the *linear stopping power SP*. This quantity is defined as the energy loss per distance unit, i.e.: $SP = -dE/dx$. The classic model that describes the stopping power is the so-called *Bethe formula*, given by [Kno89]:

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$$SP = -\frac{dE}{dx} = \frac{4\pi e^4 Z^2}{mv^2} nB, \quad (2.21)$$

where v and Ze are the velocity and charge of the incident particle, m is the mass of the electron, and n is the density of the absorber material.

For non-relativistic particles ($v \ll c$), we have that $B \approx z \ln(2mv^2/I)$, with z the atomic number and I the average ionization potential of the absorbing atoms. The expression for B varies slowly with the incident particle energy. Therefore, for a non-relativistic particle the SP goes as the inverse of the energy. On the other side, two particles with the same energy and different atomic number will suffer noticeable different energy losses due to the Z^2 factor in the numerator of Eq. (2.21).

With respect to the absorber, the SP depends principally in the nz product, or the *electronic density* of the material. Absorbers with high atomic numbers and/or highly dense will have a large SP .

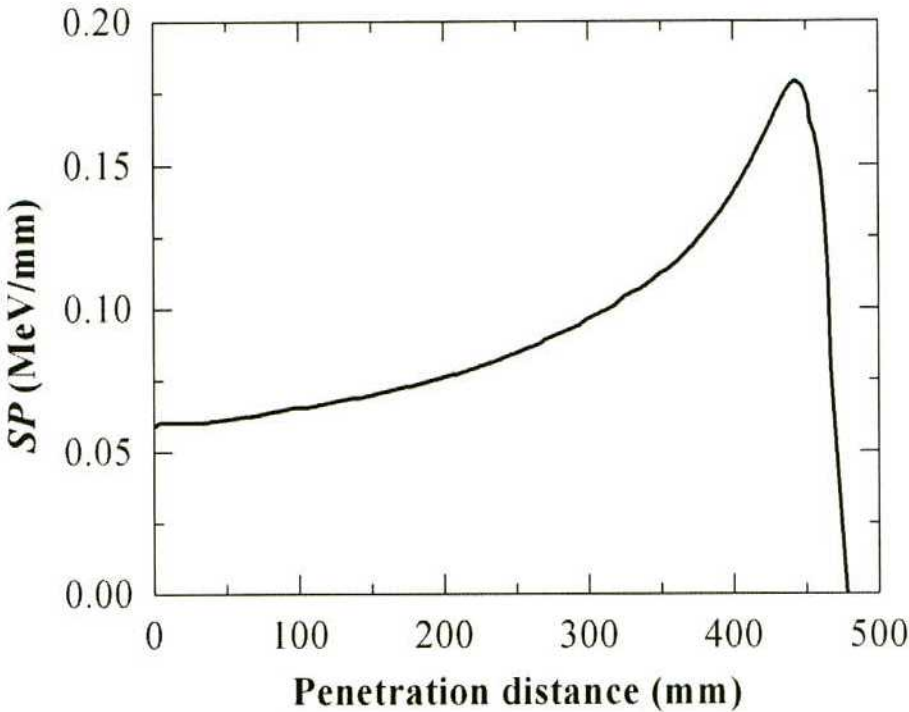


Figure 2.5. Bragg curve for a 42 MeV ^{12}C beam going through methane at 200 mbar.

From the Bethe formula it is possible to obtain the SP as a function of the distance of penetration into the material, known as the *Bragg curve*. An example of

such a curve is presented in Fig 2.5, where we can see that a charged particle incident on a thin foil can go through the material without losing too much energy. For larger thicknesses, as the particle slows down, the SP increases and finally the particle stops.

It is worth to note that the Bethe formula is not accurate when the incident particles have very low energies where the charge exchange effects with the absorber become important. Nevertheless, it is a widely used and simple expression for the SP .

Nowadays, the main sources of stopping power values are data tables and predictions from empirical models. For instance, in this work we will make use of the codes SRIM 2013 [Zie10], LISE++ 9.7 [Tar08], and FLUKA 2011 [Bat07], which complement experimental data with simulations.

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CHAPTER 3

CARBON FUSION

As already mentioned, fusion reactions with carbon isotopes play an important role in the understanding of the fusion mechanism itself and in the production of energy in stellar scenarios such as X-ray binaries. This Chapter discusses the existing information on carbon fusion which is of relevance for this thesis.

In the present work, we explored the properties of carbon isotopes (Sec. 3.1) through fusion studies in carbon-carbon systems which only differ in the number of neutrons in the projectile. We also re-measured the $^{12}\text{C}+^{12}\text{C}$ fusion cross sections in an energy range overlapping with a previous data set that presented unexplained oscillations (Sec. 3.2). In the same work [Kov79], an unexpected behavior was found in the $^{15}\text{N}+^{12}\text{C}$ system fusion, which has remained unconfirmed. Fusion with neutron-rich carbon isotopes studied here is also of interest to nuclear astrophysics (Sec. 3.3).

3.1. Properties of carbon isotopes

Carbon has fifteen known isotopes, from ^8C to ^{22}C . Three of them are naturally occurring on Earth: 99% of the carbon is ^{12}C , 1% is ^{13}C , and ^{14}C occurs in trace amounts (i.e., making up about 1 part per trillion of the total carbon). From the natural isotopes, ^{12}C and ^{13}C are stable, while ^{14}C has a half-life of 5700(30) years (it decays into ^{14}N through β -emission). After ^{14}C , the other long-lived radioisotope is ^{11}C , which has a half-life of 20.334 minutes. The rest of carbon radioisotopes have half-lives less than 20 seconds, most of them less than 200 milliseconds.

3. CARBON FUSION

Averaging over natural abundances, the standard atomic mass for carbon is 12.0107(8) u, while the mass of ^{12}C is 12 u by definition.

The nuclear properties of the carbon isotopes studied in the present work are reviewed in Table 3.1.

Table 3.1. Selected nuclear properties of the carbon isotopes studied in this work. Stable isotopes are marked in bold.

Isotope	N	Half-life	Decay mode	Daughter	Spin & parity
^{10}C	4	19.290(12) s	β^+	^{10}B	0+
^{12}C	6		Stable		0+
^{13}C	7		Stable		1/2-
^{14}C	8	5700(30) y	β^-	^{14}N	0+
^{15}C	9	2.449(5) s	β^-	^{15}N	1/2+

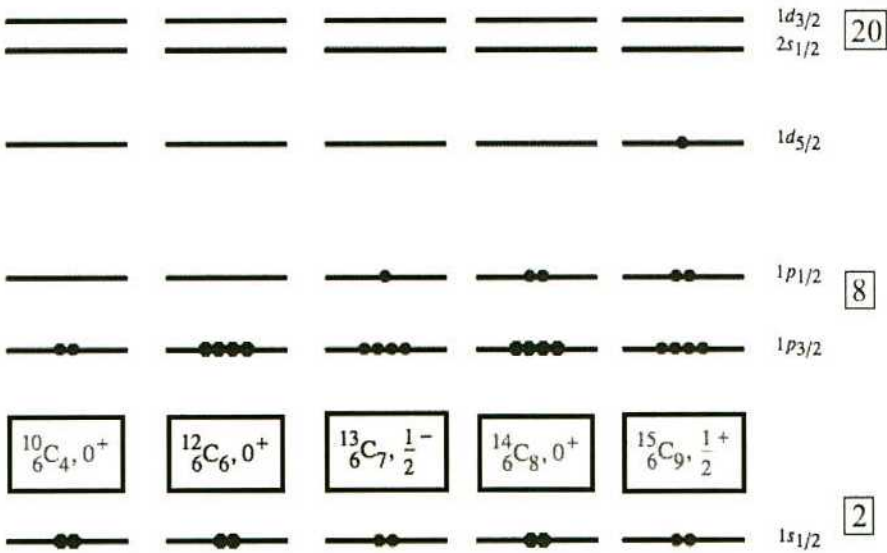


Figure 3.1. Single particle (shell model) levels up to the 2s1d shell for the carbon isotopes studied on this work (for neutrons only). The spin and parity of the ground states are also noted. Radioactive isotopes are signaled in gray.

There is still an open discussion about the influence of the neutron number on fusion cross sections (see, for example, next Section). For this reason, it is important to know the shell structures of the studied carbon isotopes, which are presented in Fig. 3.1. There are a few things to note here: i) all isotopes have protons up to the 1p_{3/2} level, ii) ^{14}C has a closed shell for neutrons, iii) ^{15}C is the only isotope

with a neutron in the $2s1d$ shell (with 1.218 MeV of separation energy from the “ ^{14}C core”), and iv) the ground state spin of ^{15}C is $1/2$ meaning that for this neutron-rich isotope the $1d_{5/2}$ and $2s_{1/2}$ levels are interchanged.

Certainly, the actual energy levels do not univocally correspond to the single particle levels of Fig. 3.1. Instead, for instance, the ^{12}C level scheme (Fig. 3.2) shows characteristics of collective states. The 0_1^+ , 2_1^+ and 4_1^+ form the ground-state rotational band. On the other hand, it was suggested that the 7.65 MeV 0_2^+ state and the 10.03 MeV 2_2^+ state (not shown in Fig. 3.2) form a rotational band having a linear chain arrangement of 3α -clusters. These collective excitations can also affect the yield of fusion reactions and they are usually accounted for in coupled-channels calculations (see Sec. 7.2).

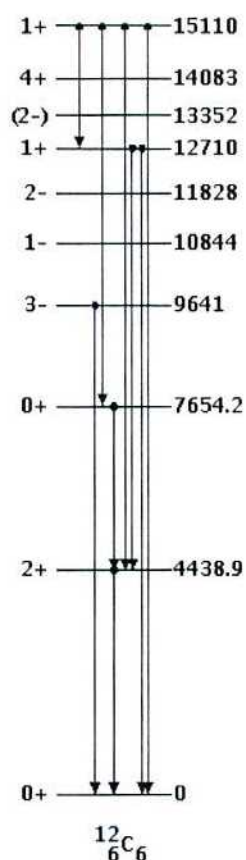


Figure 3.2. Selected experimental energy levels for ^{12}C . On the left the spin and parity of each state are given, and on the right the excitation energies in keV. (Data obtained from <http://www.nndc.bnl.gov/chart/>).

3.2. Summary of previous experiments and calculations

From the discussions in Sec. 2.3, we expect to see different features of carbon fusion depending on the energy of the system. For astrophysical applications, the very low energies ($E_{\text{c.m.}} \sim 1 - 3$ MeV) are the most important ones. On the other hand, for radioactive beam production or structure studies there is interest in the low-energy range ($E_{\text{c.m.}} \sim 10 - 50$ MeV). Nevertheless, given the difficulties[†] of measuring at very low energies, the latter is also helpful in validating models that can be extrapolated to the region of astrophysical interest.

In the low-energy range, the lower-level density in the compound nucleus can lead to structures in the excitation function. (see Fig. 2.5). At higher energies, there is interest because the fusion cross section decreases after reaching a rather constant value, for which there is no satisfactory explanation yet [Sat80].

For fusion between stable isotopes in the very-low-energy range, the excitation functions show different characteristics depending on the participating isotopes. There are several measured peaks (see Sec. 2.3.2) for $^{12}\text{C}+^{12}\text{C}$ from c.m. energies of 6.32 MeV down to 2.14 MeV. In contrast to those structures, the fusion cross sections for $^{12}\text{C}+^{13}\text{C}$ and $^{13}\text{C}+^{13}\text{C}$ behave more regularly.

The shape of the fusion excitation functions at sub-barrier energies is primarily dominated by the Coulomb barrier penetration effect. To remove this effect and reveal more details of the nuclear interaction, the cross sections of all those three carbon fusion systems are converted into the S^* -factors using the equation $S^*(E_{\text{c.m.}}) = E_{\text{c.m.}} \sigma(E_{\text{c.m.}}) \exp(87.21/\sqrt{E_{\text{c.m.}}} + 0.46E_{\text{c.m.}})$ [Tan12]. The advantage of applying this conversion over the traditional astrophysical S-factor is that the cross section ratios among the three systems are preserved.

[†] In current accelerator facilities it is an issue to produce very-low-energy beams at high intensities. It is also challenging to design a detector system with high efficiency in such a regime.

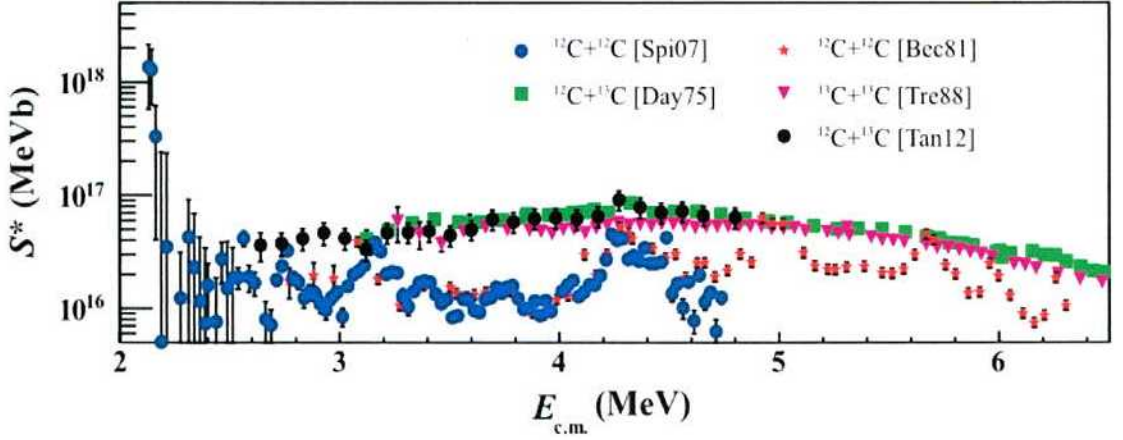


Figure 3.3. Experimental fusion cross sections for stable carbon isotopes at very-low energies, expressed as S^* -factors. (Adapted from Ref. [Tan12]).

The experimental S^* -factors for fusion between the stable carbon isotopes are shown in Fig. 3.3. In the fusion reactions involving ^{13}C , its valence neutron (see Fig 3.1) introduces an additional degree of freedom for excitation, besides the ^{12}C core excitation. Despite this, the maximum deviation among the $^{12}\text{C}+^{12}\text{C}$ peak cross sections and the $^{13}\text{C}+^{12}\text{C}$ and $^{13}\text{C}+^{13}\text{C}$ fusion cross sections is less than 30%.

There is also a measurement of $^{14}\text{C}+^{12}\text{C}$ fusion at sub-barrier energies ($E_{\text{c.m.}} = 5\text{--}8\text{ MeV}$) [Das93]. No structure was found in that work, except for a small enhancement in the excitation function at $E_{\text{c.m.}} \approx 6\text{ MeV}$. This enhancement occurs at an excitation energy $E_x = 25.35\text{ MeV}$, with a width $\Gamma = 1.75\text{ MeV}$. This is correlated with a resonance observed in the compound nucleus decay $^{26}\text{Mg} + \gamma$ (actually measured via the inverse photonuclear reaction).

At center of mass energies above $\sim 6\text{ MeV}$ the resonance structure of the carbon fusion excitation functions gives place to a rather smooth behavior. A systematic study of C+C fusion and neighboring systems for energies in the $6 < E_{\text{c.m.}} < 30\text{ MeV}$ range was carried out by Kovar et al. in 1979 [Kov79]. This study left some open questions, many of them needing radioactive ion beams to be answered. A summary of the results from that work for fusion with carbon isotopes is shown in Fig. 3.4.

3. CARBON FUSION

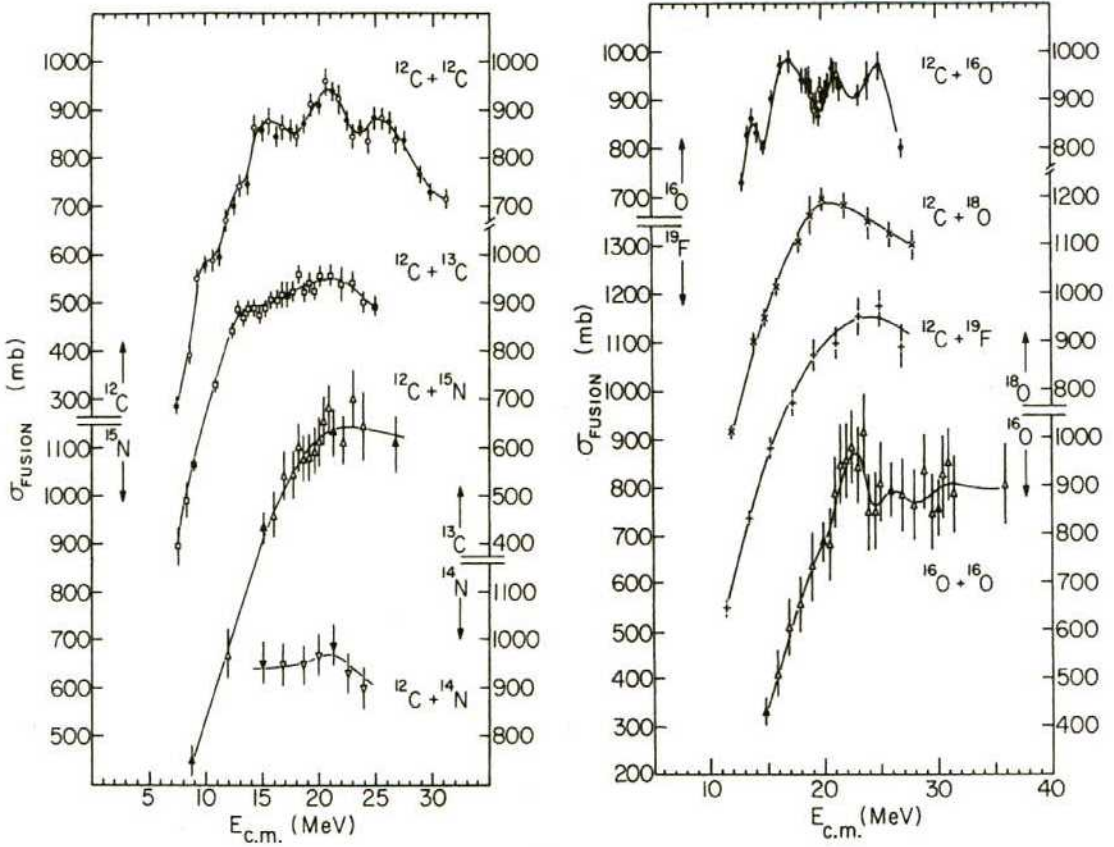


Figure 3.4. Experimental fusion cross sections for several systems involving carbon isotopes (plus $^{16}\text{O}+^{16}\text{O}$). The solid lines are included for guiding the eye. (Reproduced from Ref. [Kov79]).

The work of Kovar et al. was mainly motivated by the observation of features in the fusion cross sections that suggested the importance of the detailed structure of the interacting nuclei. These features were the observation of oscillations in the excitation functions for some systems ($^{12}\text{C}+^{12}\text{C}$, $^{16}\text{O}+^{12}\text{C}$, and $^{16}\text{O}+^{16}\text{O}$) but not for others, and the observation of significantly different maximum fusion cross sections for systems differing by a single nucleon (e.g., the $^{14,15}\text{N}+^{12}\text{C}$ fusion reactions). For the latter (see Fig. 3.5.) it is noticeable that ^{15}N , still in the $1p$ shell, has a maximum cross section typical of those nuclei with nucleons in the $2s1d$ shell.

As for the oscillations, a number of attempts were made in order to reproduce them and partial success was found with the coupled-channels method. This can be seen in Fig. 3.6. The $^{12}\text{C}+^{12}\text{C}$ system still resists an explanation, but it is

worth noting that the data from Ref. [Kov79] was the only available in that energy range, until now.

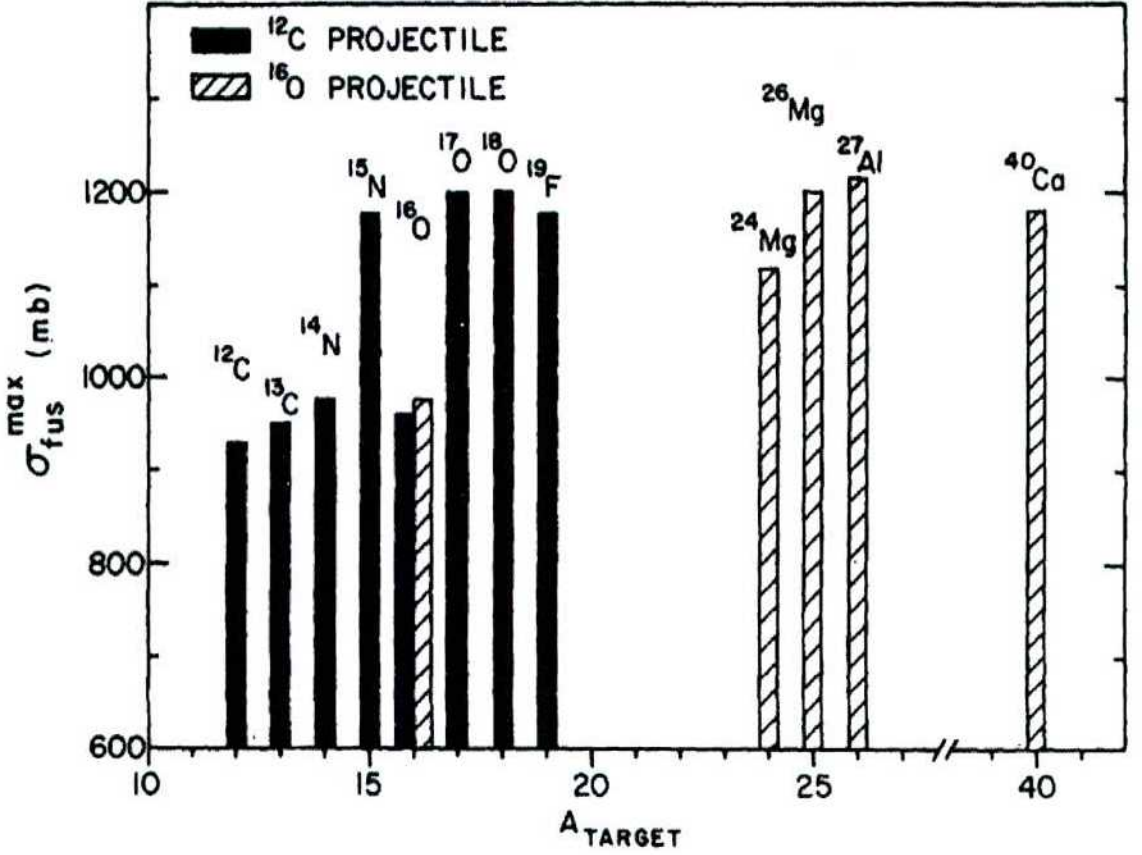


Figure 3.5. Maximum value of the fusion cross section for a number of systems involving ^{12}C and ^{16}O ions on targets in the $1p$ or $2s1d$ shells. (Adapted from Ref. [Kov79]).

In a higher energy range, there is an interesting measurement of the fusion cross sections in the $^{13,14,15}\text{C}+^{232}\text{Th}$ systems in the vicinity of the Coulomb barrier ($E_{c.m.} = 50 - 70$ MeV) [Alc11]. The motivation of this work was to find if ^{15}C is a halo nucleus with a *neutron skin*, meaning that there is a weakly-bound neutron that forms an outer skin. The authors of this study found a sub-barrier enhancement for the ^{15}C beam that does not follow the trend of the other two studied isotopes and can neither be explained with coupled-channels calculations. This is possibly an actual indication of a neutron skin.

However, the effect seen in Ref. [Alc11] has not been found in a measurement of the total *interaction cross section* at very high energies [Oza01]. Anyway, it is worth to note that here the conditions were quite different: Ozawa et al. used $^{13,14,15}\text{C}$ beams at $E_{\text{lab}} \approx 900$ MeV/nucleon impinging on a ^{12}C target. They obtained rather constant interaction cross sections of about 900 mb for the three systems.

The experimental results of the present work (Chap. 7) are located in the energy range studied in Kovar's work. This allows us to make a direct comparison with the previous data on the $^{12,13}\text{C}+^{12}\text{C}$ systems. This will help to check whether there is an actual discrepancy with calculations for the $^{12}\text{C}+^{12}\text{C}$ case. In addition, it will be possible to see if there are similar effects as the one seen in $^{14,15}\text{N}+^{12}\text{C}$ fusion.

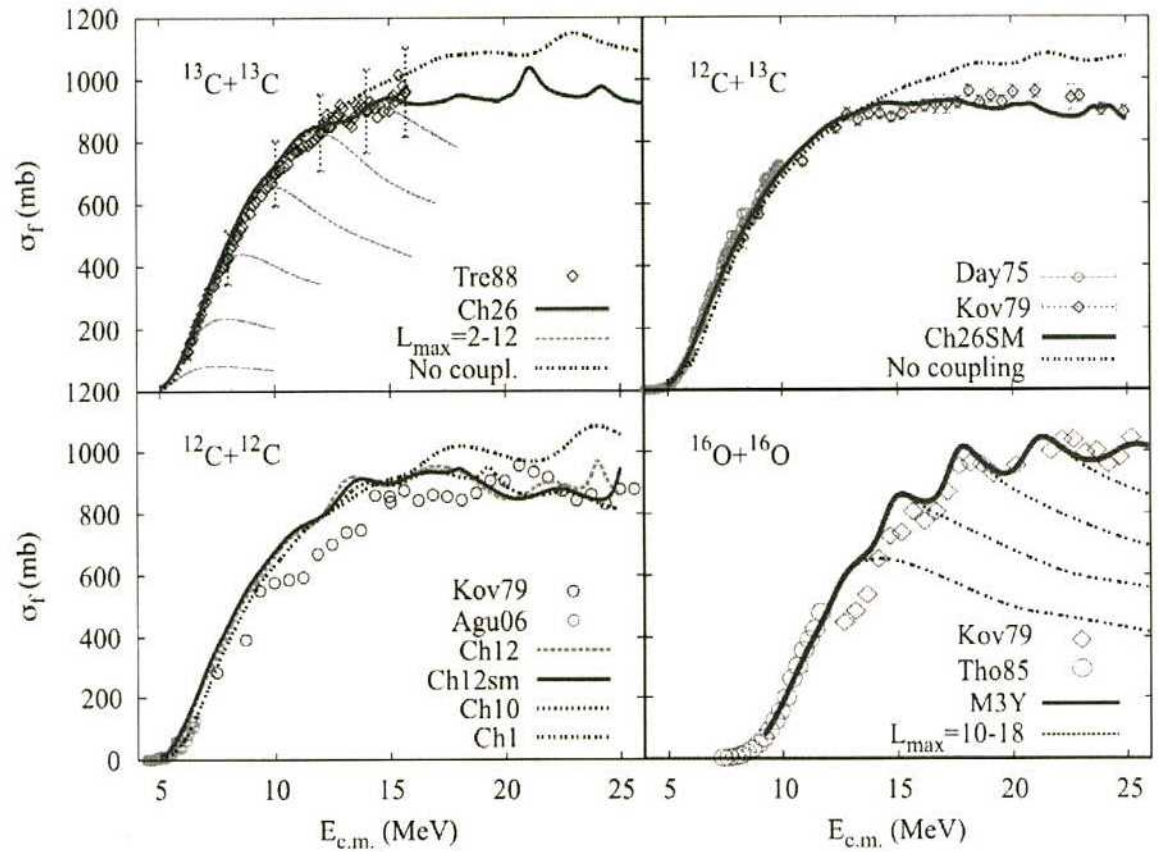
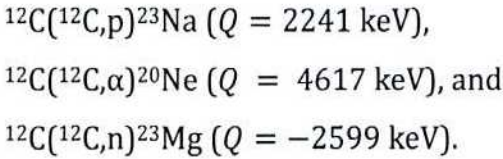


Figure 3.6. Excitation functions for the systems $^{13}\text{C}+^{13}\text{C}$, $^{12}\text{C}+^{13}\text{C}$, $^{12}\text{C}+^{12}\text{C}$, and $^{16}\text{O}+^{16}\text{O}$. The data points are taken from the literature. The curves are coupled-channel calculations from Ref. [Esb11].

3.3. Carbon burning in stellar scenarios

When helium is consumed in the center of a star, the core contracts gravitationally and the central temperature simultaneously rises until the next nuclear fuel begins to burn. The products, or *ashes*, of helium burning consist overwhelmingly of ^{12}C and ^{16}O . Of all the possible fusion reactions involving these two nuclei, $^{12}\text{C}+^{12}\text{C}$, $^{12}\text{C}+^{16}\text{O}$, and $^{16}\text{O}+^{16}\text{O}$, the first process has the smallest Coulomb barrier and, therefore, initiates the next burning stage.

The ^{24}Mg compound nucleus formed in the fusion of two ^{12}C nuclei is highly excited, with the mass difference between $^{12}\text{C}+^{12}\text{C}$ and ^{24}Mg amounting to 14 MeV, approximately. In this situation, the excess energy of the highly excited ^{24}Mg nucleus is most effectively removed by emission of light massive particles. The most likely primary reactions are [Sal52, Hoy54]:



The other possibilities, such as $^{12}\text{C}(^{12}\text{C},\gamma)^{24}\text{Mg}$ or $^{12}\text{C}(^{12}\text{C},^8\text{Be})^{16}\text{O}$, are less important at the energies where fusion occurs in stars (see, for example, [Pat69]). Note that the $^{12}\text{C}(^{12}\text{C},\text{n})^{23}\text{Mg}$ reaction is endothermic, that is, it can only occur above a threshold energy of $E_{\text{c.m.}} \approx 2.6 \text{ MeV}$.

Since the $^{12}\text{C}+^{12}\text{C}$ reaction will almost certainly proceed through many overlapping levels of the highly excited ^{24}Mg compound nucleus, it is reasonable to expect that the S-factor varies smoothly with energy.

The liberated neutrons, protons, and α -particles will be quickly consumed at elevated temperatures by initiating secondary reactions involving, for example, the ashes of helium burning (^{12}C and ^{16}O) and the heavy evaporation residues of the primary reactions (^{23}Na and ^{20}Ne). This *network* of primary and secondary reactions is referred to as *core carbon burning*, or *quiescent carbon burning*. Typical

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temperatures in core carbon burning amount to $T = 0.6\text{--}1.0\text{ GK}^\ddagger$, depending on the mass of the star. On the other hand, *explosive carbon burning* takes place in the range of $T = 1.8\text{--}2.5\text{ GK}$.

The most likely scenario for explosive carbon burning is that of an accreting neutron star which has a companion low-mass star, i.e. $M \leq M_\odot$ (either a *main sequence* or a *red giant star*). This type of binaries is often called *X-ray bursters* (XRB), for being the most important source of X-ray bursts and superbursts [Woo76, Mar77].

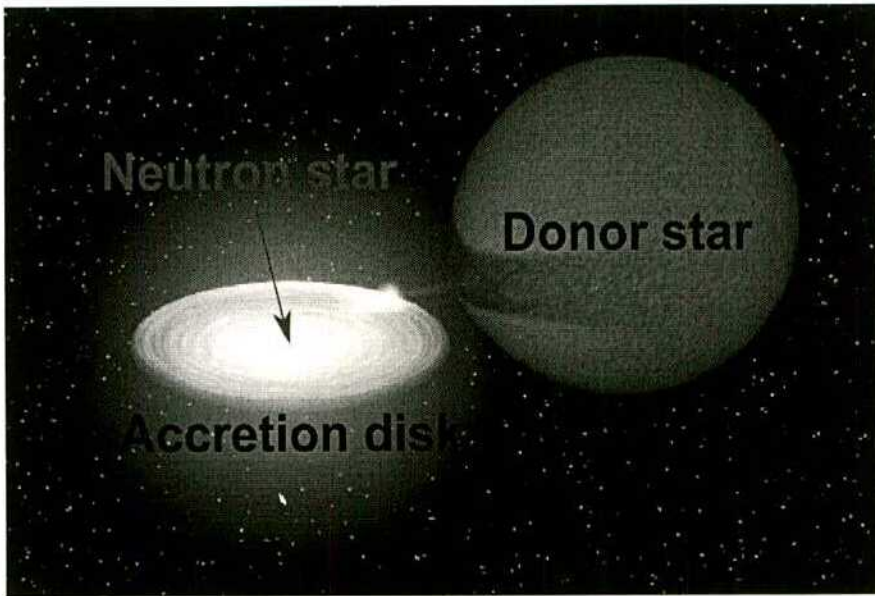


Figure 3.7. Artistic impression of an X-ray binary. (Adapted from Ref. [Par02]).

The matter that falls onto the neutron star comes from the envelope of the *donor star* and is rich in hydrogen and helium. Due to angular momentum conservation, the falling material establishes an *accretion disk* surrounding the neutron star, as represented artistically in Fig. 3.7.

Due to the high gravitational field of the neutron star, the falling matter collects on the surface and is compressed as additional material falls on top of it. The accumulation of matter causes a temperature increase. Eventually, a thermal

[‡] In astrophysics it is common to note the temperature of a star in GK (10^9 K). This temperature is then related to the nuclear system energy through the Maxwell-Boltzmann distribution ($E = k_B T/2$ is the maximum of the energy distribution) [Ili07].

instability in a thin shell is produced by the ignition of very temperature-sensitive fusion reactions, and the heating from these exothermic thermonuclear reactions cannot be compensated by readjusting the stellar structure or cooling through the surface [Han75].

As a result, a thermonuclear runaway (TNR) takes place: rising temperatures accelerate the thermonuclear reaction rates, leading to more rapid temperature rises, still faster thermonuclear reactions and so on [Sch06].

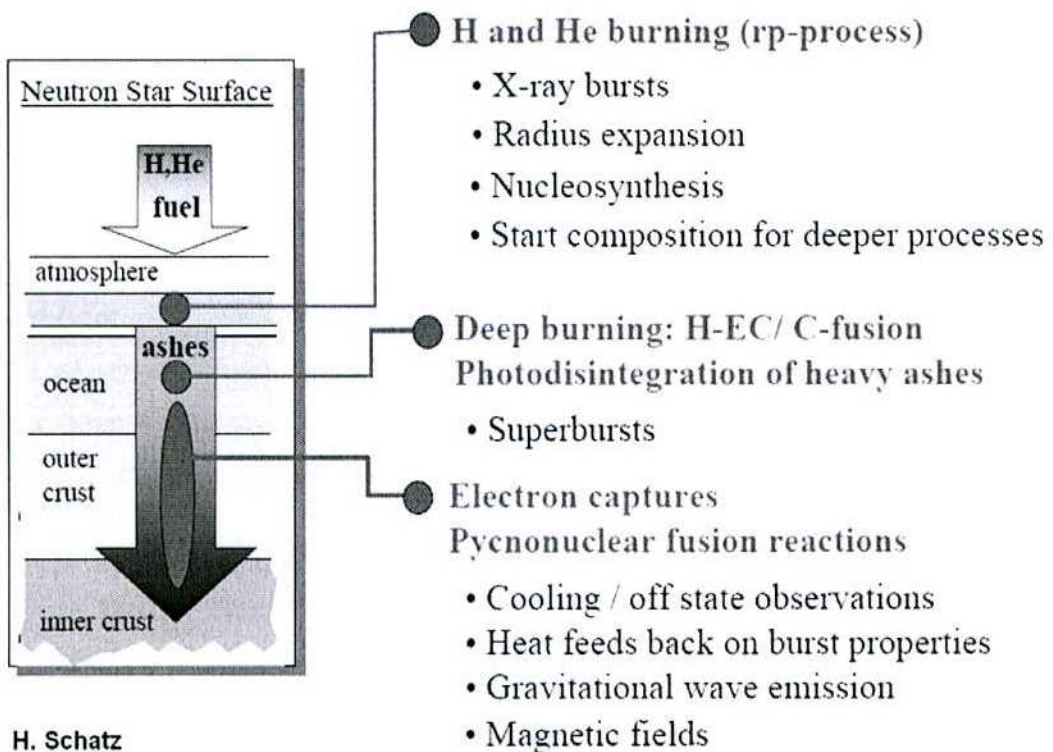


Figure 3.8. Sketch of the nuclear reactions occurring on the different shells of accreting neutron stars.

The TNR provides the conditions needed for carbon to be burned. The nuclear reactions taking place in such a scenario are depicted in Fig. 3.8. They are powered by different nuclear processes, including the 3α -reaction, the *rp*-process (rapid proton captures and β^+ -decays), and the *ap*-process (a sequence of (α, p) and (p, γ) reactions). The main nuclear flow proceeds far away from the valley of stability, reaching the proton drip line beyond $A = 38$ [Sch99]. During the final stages of the burst, the main nuclear flow is dominated by a multitude of successive

β -decays. The final composition of the star envelope depends mainly on the mass-accretion rate, but tends to favor species in the mass range $A = 60-70$ (mostly ^{64}Zn and ^{68}Ge [Woo04]). Other studies find production of additional species with masses near $A \sim 105$ [Jos10].

Deeper into the neutron star crust, density-dependent reactions dominate over thermonuclear reactions (see Fig. 3.8). In particular, *pycnonuclear reactions* occur in high-density matter when nuclei are frozen in lattice structures. Pycnonuclear reactions in neutron star crust matter are dominated by fusion between very neutron-rich carbon, oxygen, and neon isotopes at the limits of stability. The ashes of an X-ray burst are forced deeper into the crust by the weight of the freshly accreted matter. With increasing density the remnant abundance distribution is changed by a host of electron capture reactions and neutron emissions, leading to the effective processing of the ashes into very neutron-rich nuclei in the carbon to magnesium range. Close to nuclear matter densities the nuclei are forced into a lattice, surrounded by a neutralizing degenerate electron gas. Though held in a solid lattice, reactions are still possible due to the reduction of Coulomb potential by screening and the overlap of nuclear wave functions between lattice sites. These pycnonuclear reactions are highly density dependent, and unlike their more familiar thermonuclear counterpart, are not strictly temperature dependent.

The pycnonuclear fusion becomes an important process for generating energy and changing the abundance structure in stellar matter at densities in excess of 1% of nuclear matter density. Network simulations of pycnonuclear burning have been performed for neutron crust matter and show indeed fusion reactions taking place on a timescale of years [Yak06], which is the time scale observed for the superbursts.

It is worth to note that fusion of stable carbon isotopes (see Fig. 3.3) is not sufficient to explain the X-ray superburst phenomenon [Tan12]. Therefore, in order to understand this, as well as pycnonuclear reactions, there is a need for obtaining experimental data for fusion between neutron-rich isotopes.

CHAPTER 4

ATLAS EXPERIMENTAL SYSTEMS

In this Chapter, we describe the equipment at the *Argonne Tandem Linac Accelerator System* (ATLAS) facility, where the measurements for this work were performed. In Sec. 4.1 there is a short overview on radioactive ion beam (RIB) production techniques. The focus of Sec. 4.2 is on the specific techniques for RIB production used at ATLAS. Finally, in Sec. 4.3 we describe the *Enge split-pole spectrograph* (SPS), which is one of the main instruments at ATLAS, and was used in this work for energy calibration of the MUSIC detector.

4.1. Radioactive ion beam production techniques

Usually, a RIB originates from a nuclear reaction using an accelerated *primary* ion beam (coming from an ion source), and a suitable *production* target. There are mainly two methods for RIB production: *isotope separator on-line* (ISOL) and *in-flight*.

In ISOL, a primary beam of light particles (such as protons or alphas) coming from a *driver accelerator* is stopped in a thick target. The exotic nuclei that are produced diffuse out the (hot) target and are transported to an ion source. After the ion source, the species of interest is selected in a *fragment separator* and, since the energy is low at this stage, a *postaccelerator* is used in order to achieve the energy needed for the experiment. Chemical reactions between the radioactive isotopes and the target material limit the type and rate of obtainable beams but make them quite pure. A block diagram of this method is given in Fig. 4.1.

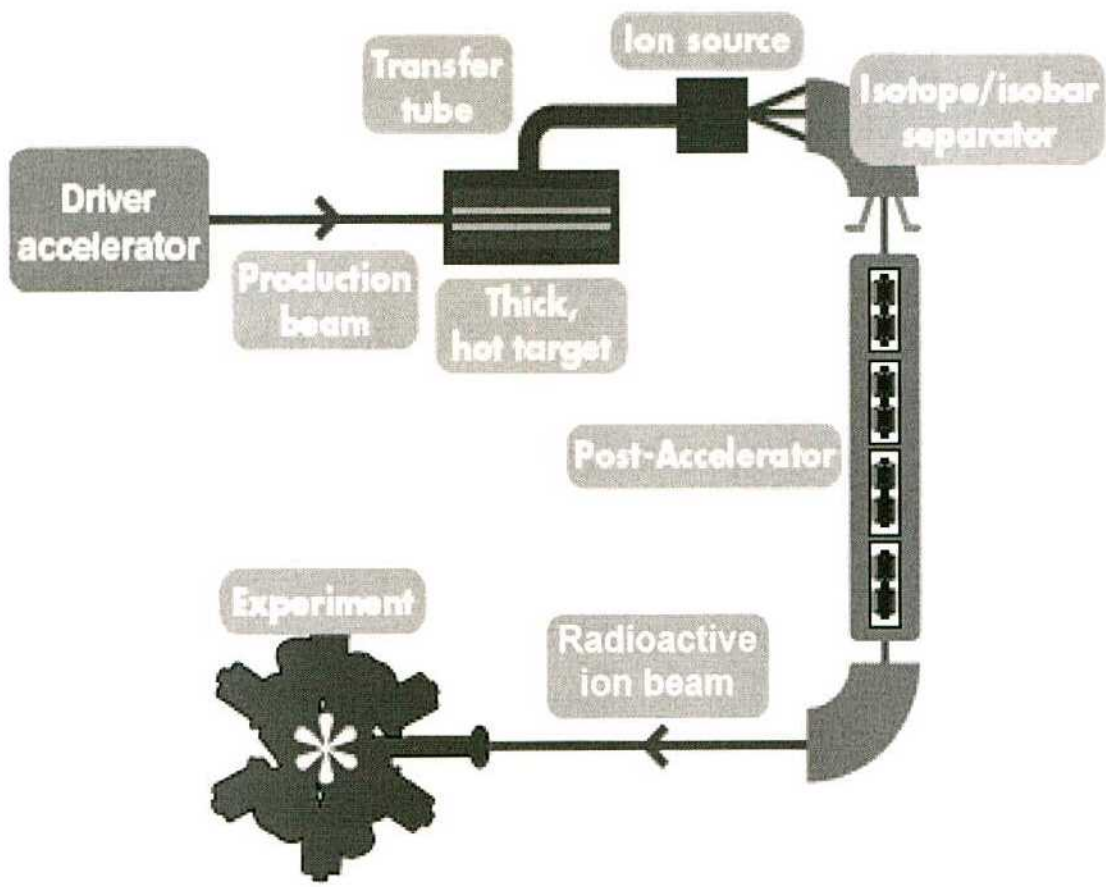


Figure 4.1. Diagram of the ISOL RIB production technique.

The in-flight technique on the other hand requires fewer resources because there is no need to reaccelerate the beam (see Fig. 4.2). The accelerated primary ions undergo fragmentation reactions in a thin target that produces the RIB at energies usable for experiments. The main restriction is the cross section of the used reaction, often limiting the final intensity of the exotic beam. Due to the negative Q -value of the production reactions, the primary beam must have rather high energies (several tens of MeV per nucleon), thus generating other undesirable products that make a so-called “cocktail” beam. The products generated in the fragmentation reactions come in a range of species and energies. Therefore, a fragment separator is needed for obtaining a reasonably pure secondary beam. Nevertheless, particle identification by the detectors is still needed for finally identifying the ion of interest within the secondary beam. As an advantage, the in-flight method is capable of

producing a wide range of short-lived isotopes with a relatively simple configuration.

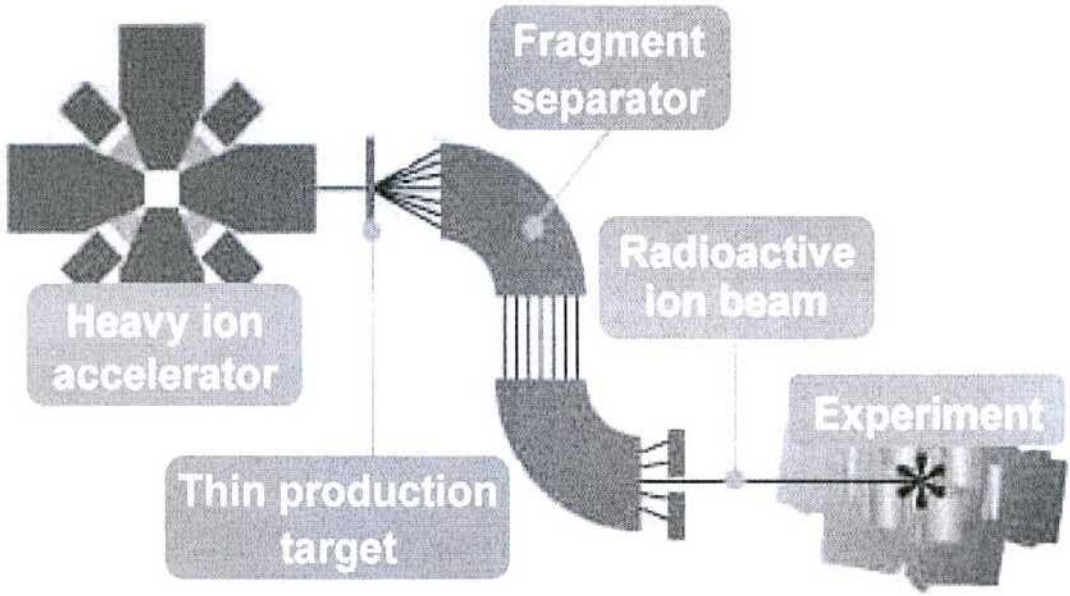


Figure 4.2. Diagram of the in-flight RIB production technique.

4.2. RIB production at the ATLAS facility

The ATLAS facility hosts the world's first superconducting *linear accelerator* (*linac*) for heavy ions. It can provide a large variety of stable beams from protons to uranium and several light radioactive beams produced via the in-flight technique.

The beam production begins in one of two *injectors*: a 9-MV *electrostatic tandem accelerator* fed by a *SNICS* (Source of Negative Ions by Cesium Sputtering) negative ion source, or a 12-MV linac with an *ECR* (Electron Cyclotron Resonance) positive ion source. If needed, the ions can be further accelerated by a 20-MV *booster* linac and, finally, another 20-MV linac called *ATLAS*. A floor-plan representation of the facility, including the different experimental areas, is shown in Fig 4.3.

All ATLAS beams come in *pulses* or *bunches*. The continuous beam from the ion sources is pulsed by means of a *chopper*. This is done to match the RF accelerating electromagnetic field of the linacs. The beam bunches in ATLAS are 3 ns wide arriving every 82 ns.

4. ATLAS EXPERIMENTAL SYSTEMS

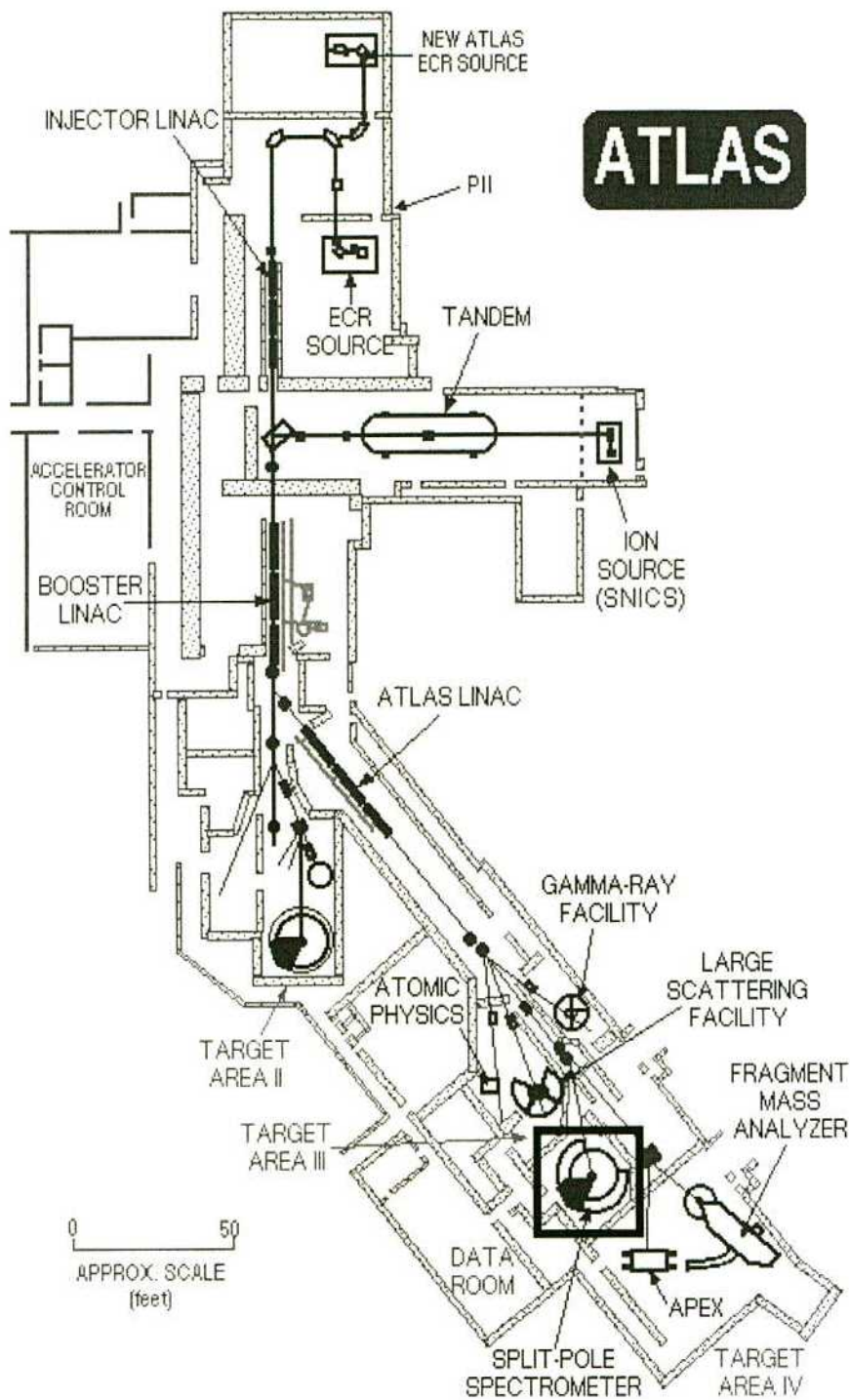


Figure 4.3. Floor plan of the ATLAS facility. The black square marks the location of the Enge split-pole spectrograph experimental area, where the MUSIC detector is installed. (Adapted from <https://www.phy.anl.gov/atlas/facility/floorplan.html>).

For an experiment, the first step is to select the injector. Using the *negative injector* (SNICS source plus tandem accelerator) gives a better quality and higher purity beam, because it requires a simpler combination of ion source and

accelerators compared to the ECR source plus linac/s combination. There is, however, a limitation: the maximum output energy of the negative ion injector is lower than the one given by the positive ion injector. Therefore, in some cases it is not possible to use the first combination.

For producing a secondary beam with the in-flight technique, the primary beam is transported to the production target in order to produce the reaction that generates the secondary beam. Generally, a proper beam must have a set of characteristics, such as: high intensity (about 10^{12} particles per second), a small beam-spot size (no more than 5 mm diameter), a small angular divergence, and a narrow energy distribution. In order to fulfill these requirements by a radioactive secondary beam, a *gas cell target* was designed and is being in use at ATLAS [Har00]. This gas target consists of a double-walled cylinder with an inner diameter of 2.54 cm and a length of 3.5 cm. The gas is contained between two 1.9 mg/cm^2 foils of *HAVAR* (a cobalt-chromium-nickel alloy). In order to increase the density of the beam and to decrease the heat damage of the cell by the intense primary beam, the volume between walls is filled with liquid nitrogen. Hydrogen, deuterium and helium gases have been used as target materials in *inverse reactions* (i.e. heavy beams on light targets such as $p(^{10}\text{B},^{10}\text{C})n$ or $d(^{14}\text{C},^{15}\text{C})p$) where the angle divergence of the secondary reaction products is small. To avoid losses in beam time due to window replacement, the gas cells are mounted in groups of three, as shown in Fig. 4.4.

In addition to the gas target, there are other essential components for the secondary beam production. In order to increase the angular acceptance of the secondary beam, there is a 2.2 T *superconducting solenoid* after the primary target. The solenoid is followed by a superconducting resonator (similar to those in the linacs) called the *RF debuncher*. While the solenoid focuses the beam in transverse direction, the resonator reduces the energy spread of the reaction products transporting more of them into the momentum acceptance of the 26° *bending magnet* placed before the experimental area. This setup is sketched in Fig. 4.5.

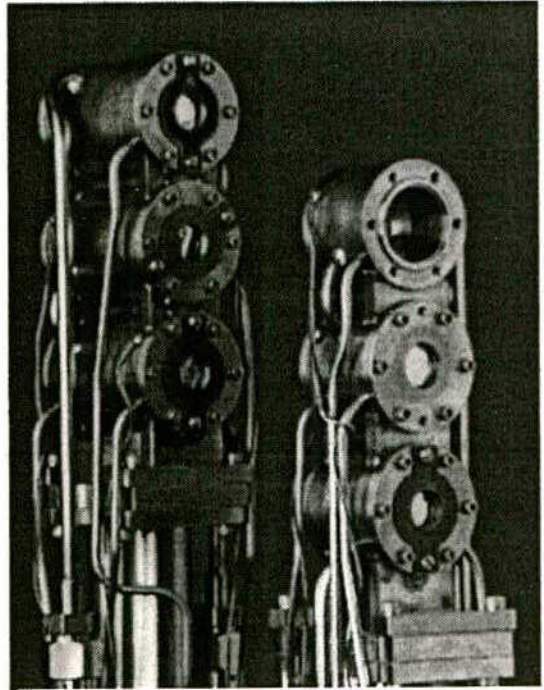
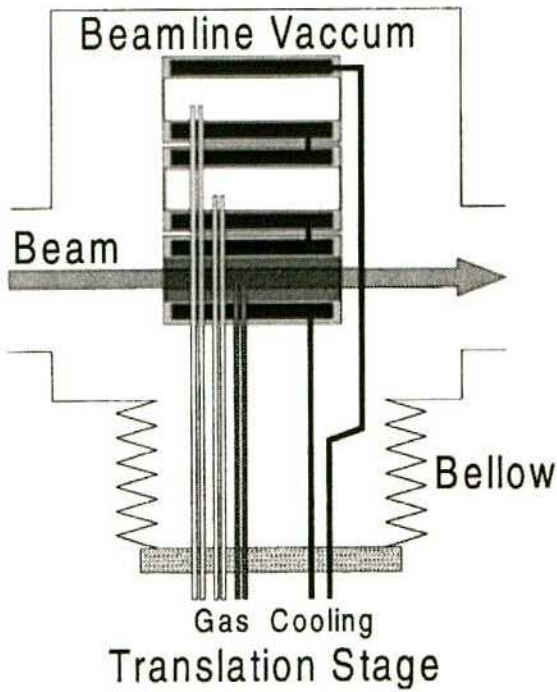


Figure 4.4. The gas target used for RIB production at ATLAS. Stacks of three cells are mounted in the beam line to avoid time losses when a window is damaged. (Adapted from Ref. [Har00]).

As already mentioned in Sec. 3.2, there are some difficulties in producing high-intensity secondary beams at energies below ~ 3 MeV. This is also the case in ATLAS. The main problem is the low transmission through the beam line, because the accelerator optics is optimized for higher energies. The situation is further complicated by the addition of the gas target, which increases the divergence of the beam.

The in-flight technique was used in this work for producing ^{10}C and ^{15}C beams. For the stable $^{12,13}\text{C}$ and the radioactive ^{14}C cases there was no need for using the mentioned gas target, since they were obtained as primary beams. The specific setup of ATLAS for the MUSIC experiments will be discussed in detail in Secs. 5.3 and 5.4.

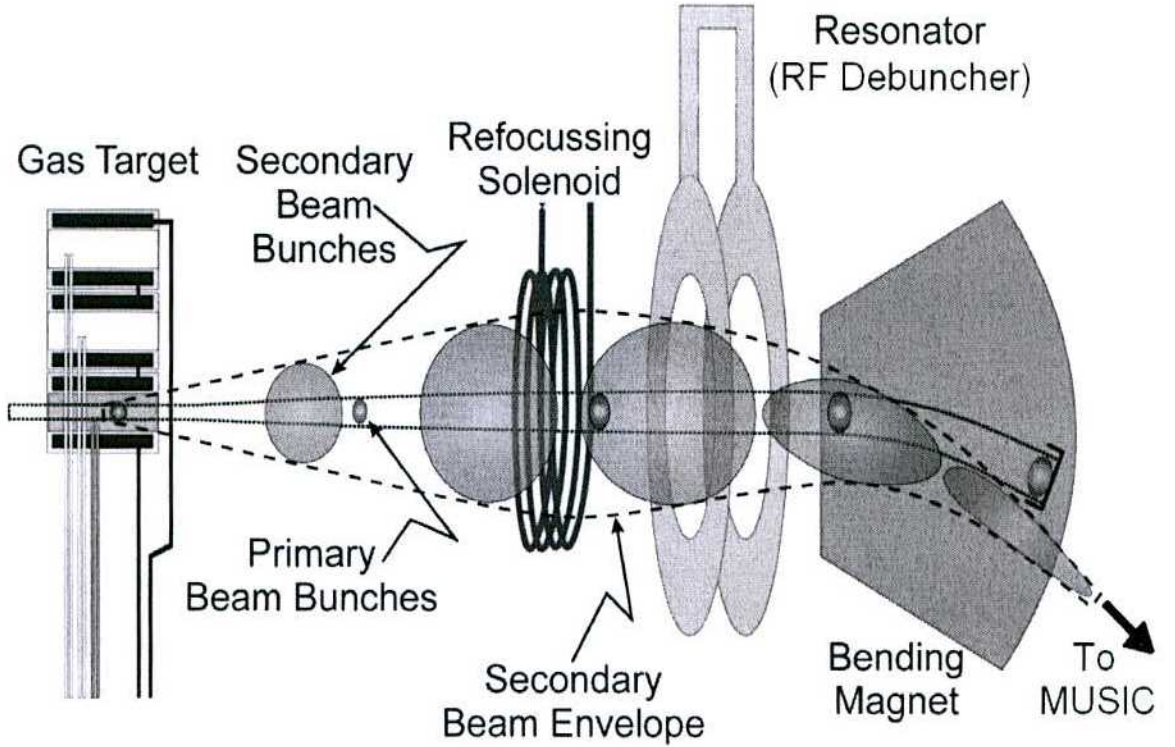


Figure 4.5. ATLAS in-flight RIB production configuration. (Adapted from Ref. [Har00]).

4.3. The Enge split-pole spectrograph

The Enge split-pole spectrograph (SPS) is a magnetic device originally designed by H. Enge. A detailed description of the instrument can be found in Ref. [Eng79].

The spectrograph was designed primarily to study nuclear reactions with light-ion projectiles but was adapted at ATLAS to study heavy ion reactions as well. It can be operated in two basic modes: vacuum or gas-filled. The vacuum mode is typically used for studies of high-resolution particle spectroscopy of the kind discussed in Ref. [Reh83]. The gas-filled mode was developed to measure with high efficiency heavy ions for cases where the products are distributed over many charge states, as is the case for experiments in *Accelerator Mass Spectrometry* (e.g., Ref. [Pau89]).

The main components of the SPS are two magnetic dipoles enclosed in a single coil and separated by a region with lower magnetic field (a schematic is

shown in Fig. 4.6). The purpose of the split between the pole pieces is to provide second-order focusing over a broad range of momenta.

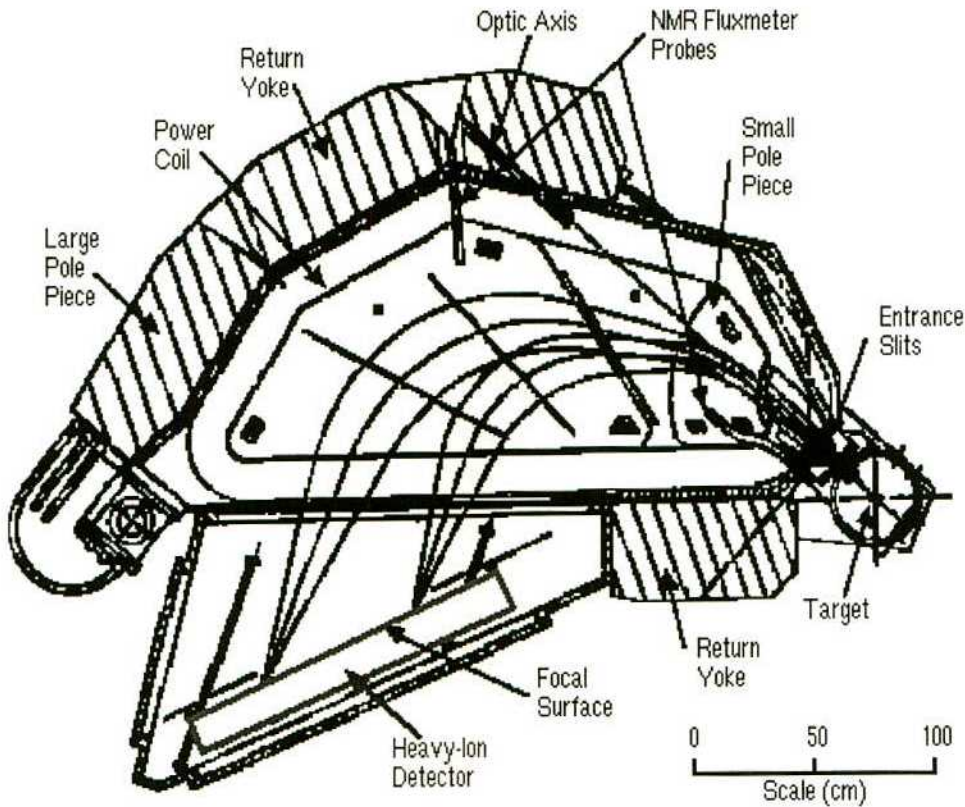


Figure 4.6. The Enge split-pole spectrograph at ATLAS. The focal-plane detector position is colored in the drawing, where there are also two trajectories with different magnetic rigidities. (Adapted from <https://www.phy.anl.gov/atlas/userbook/magspec.html>).

The maximum magnetic field is 16 kG for a current of about 450 A. The focal plane length is about one meter with a radius of curvature between 60 and 90 cm. The length of the ion trajectory from the entrance slits to the focal plane varies from 230 to 280 cm between both ends of the detector.

The usefulness of the SPS for heavy ions is largely determined by its focal-plane detector. In this case, it consists of a 60 cm long position sensitive *parallel plate avalanche counter* (PPAC) backed by a large *Bragg curve detector* [Reh88]. This system has a very good time resolution (less than 300 ps) and can be operated at high counting rates (up to 5 kHz). The intrinsic resolution of the position detector is less than 1 mm. In addition to the energy and the nuclear charge signal obtained

from the Bragg curve detector, the angle of incidence into the detector can be measured with an accuracy of better than 1° .

The SPS with its focal-plane detector allowed us to determine the beam energy after the MUSIC detector with a precision better than 1% (see Sec. 6.3).

CHAPTER 5

FUSION MEASUREMENTS: THE MUSIC ALTERNATIVE

In the present work, we used a novel technique to determine the carbon-carbon fusion excitation functions. In order to do this, we developed a new active-target detection system consisting on an ionization chamber with multi-sampling capabilities. The design and the characterization of this device were fundamental parts of this work. In this respect, the experience gained in the design and construction of a broad angular acceptance ionization chamber during P.F.F. Carnelli's master thesis [Car13] was of utmost importance.

This Chapter begins with a description of the MUSIC detector in Sec. 5.1. Followed by a general procedure of the MUSIC setup and operation in Sec. 5.2. The characteristics of the detector make it necessary to produce a low-intensity pulsed beam. For this reason, in Sec. 5.3., we provide a brief description of the accelerator tuning for the stable and radioactive beams used here. Finally, four experiments for the measurement of fusion cross sections in carbon-carbon systems were carried out with the MUSIC detector. The features of the individual experiments are presented in Sec. 5.4.

5.1. General description of the MUSIC detector

Commonly, fusion reactions are measured via the identification of the evaporation residues using a variety of experimental techniques, but here we will name a few of the most employed.

The identification of the ERs can be achieved by detecting the decay radiation from characteristic energy levels or by direct particle detection. For the first case, γ - (e.g., Refs. [Das93, Day75, Spi07]), β - (e.g., Ref. [Not10]), or X-ray measurements (e.g., Refs. [Dig86, Fer91, Pac83]) are frequently used.

For the second case, the ERs can be directly detected using $\Delta E - E_{\text{res}}$ detector *telescopes* mounted at small scattering angles. For doing this, thin Si ΔE detectors or ionization chambers have been used (see, for example, Refs. [Alc11, Kov79]). Time-of-flight (ToF) techniques, i.e. measuring the velocities and the energy of the ERs, have also been performed.

By using one of these methods, the excitation functions are obtained by varying the energy of the beam and measuring angular distributions of the ERs (in direct measurements), or by using large, high-efficiency detectors (in the decay radiation case). These experiments are often very time-consuming and have a major drawback, coming from the relative normalization between different measurements in the same experiment.

As an alternative, a Multi-sampling Ionization Chamber (MUSIC) is presented here. The MUSIC is a medium-sized gas-filled detector capable of measuring several energy points of an excitation function at the same time. It is operated as an active target, meaning the gas serves as target for the reaction and as detection medium at the same time. The projectile loses energy along its path inside the detector and fusion occurs with different energies depending on the position. Since an ER is heavier than a beam particle, it will suffer a significantly larger stopping power (see Sec. 2.4). Therefore, the detected energy loss ΔE will suddenly increase at the position where the reaction occurred and the ER will stop inside the detector. This is the signature of a fusion event.

5.1.1. Construction of the MUSIC detector

To obtain the multi-sampling capabilities, the anode of the ionization chamber is segmented in strips, following the pattern shown in Fig. 5.1 (the pattern

is etched into a copper-clad PC board). There are a total of 18 strips numbered from 0 to 17, with each strip being 1.6 cm long. The first and last strips, s_0 and s_{17} , are the so-called *control* strips, and the *active* strips are numbered from 1 to 16. The purpose of s_0 and s_{17} , and the divisions of the rest of the strips into a left (L) and right (R) part, will be further explained in Chap. 6.

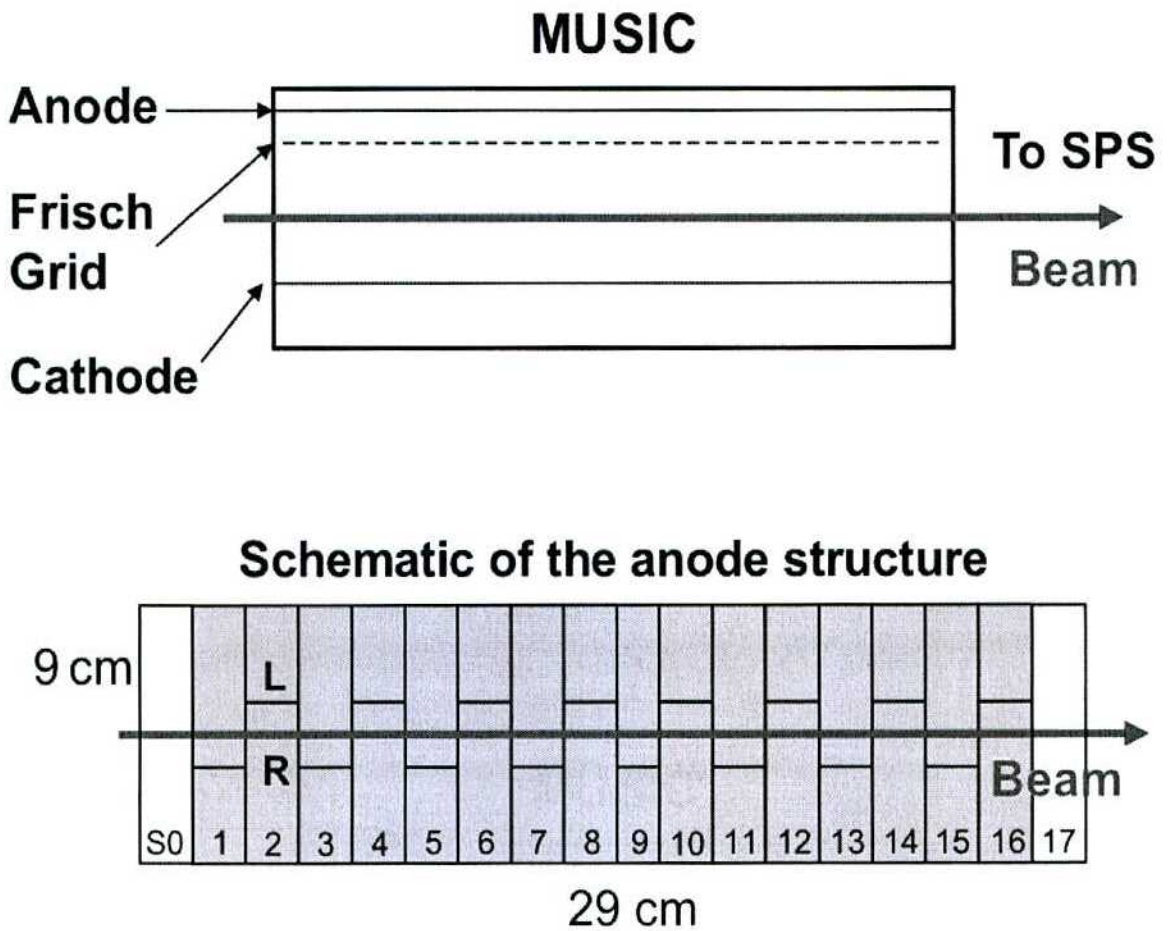


Figure 5.1. The Multi-Sampling Ionization Chamber (MUSIC). The upper panel shows, a schematic of the detector and the lower panel the structure of the anode.

A sketch of the detector is provided in Fig. 5.1 and two photographs are shown in Fig. 5.2. The detector housing consists of an aluminum box with sealed connectors for electrical and gas feedthroughs. The two gas connectors are sufficiently separated to guarantee a uniform gas distribution through the chamber.

The electric field distribution (in control plus active strips) is determined by the anode/cathode/*Frisch-grid** area of $9 \times 29 \text{ cm}^2$, and the 10-cm separation between anode and cathode. Additionally, there is a “dead volume” of gas (i.e. a gas volume with no electric field) of about 3.5 cm before s_0 . The beam enters the detector through a 2.54-cm diameter window. This entrance window was covered with a 1.5 mg/cm^2 Ti foil. The window of high-Z material was chosen to avoid the production of ERs similar of those from C+C fusion. The *Frisch-grid* is composed of $28\text{-}\mu\text{m}$ diameter gold-coated tungsten wires separated by 2 mm. The cathode is a 3-mm thick aluminum plate.

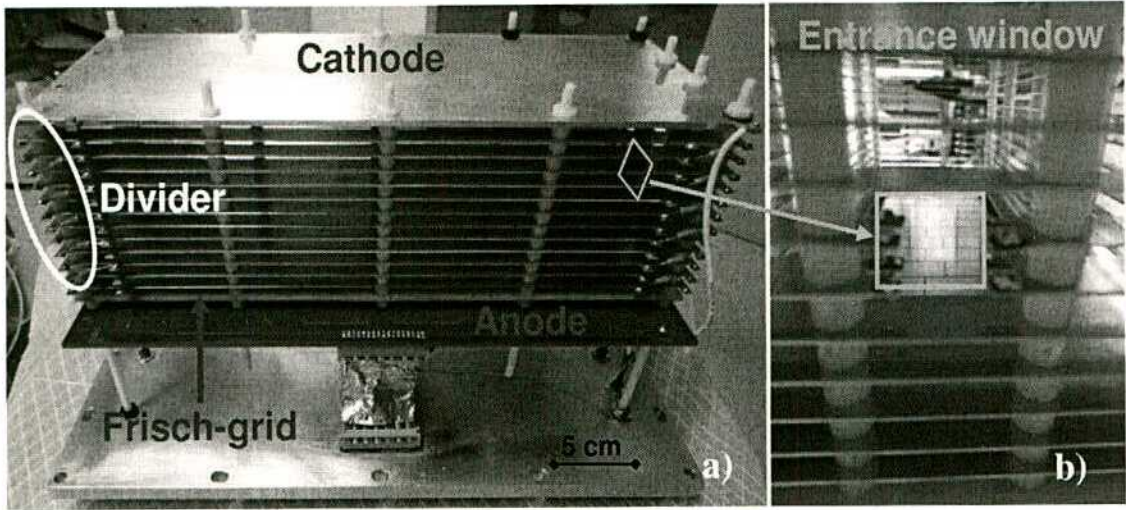


Figure 5.2. Pictures of the interior of the MUSIC detector. a) Overview of the cathode (aluminum plate on top), the resistive-divider chain, the Frisch-grid (light-brown frame) and the anode (bottom copper sheet). b) A detail of the entrance window (a section of the anode pattern can be seen as well).

A bias voltage ($V_{\text{cath}} \sim 1 \text{ kV}$) is given to the cathode and then distributed by a resistive-divider chain to the Frisch-grid, with the anode at ground potential. Hence, if $V_{\text{cath}} = V_0$, then $V_{\text{grid}} = 3/4 V_0$, and $V_{\text{anode}} = 0$.

* In a standard ionization chamber, the amplitude of the energy-loss signal depends on the distance where ionization occurs with respect to the anode. The Frisch-grid is used for eliminating this dependence [Kno89]. It needs to be placed close to the anode and the incoming particles have to enter the detector between the grid and the cathode.

5.1.2. Operational principle of the MUSIC detector

The information provided by the MUSIC detector for a single incoming particle is usefully represented in a plot of ΔE vs. *strip number*, which we will call a *trace*. As an example of the functionality of the MUSIC, Fig. 5.3 shows some experimental traces measured for the $^{15}\text{C}+^{12}\text{C}$ system. Those traces are generated by a ^{15}C beam at $E_{\text{lab}} = 49$ MeV, with the detector filled with CH_4 at a pressure of 200 mbar. In this example, the beam loses about 3.5 MeV in the entrance window, 2.5 MeV in the dead volume of gas (before s_0), and 1 MeV in s_0 . So, it reaches the first active strip (s_1) with an energy value of 42 MeV and loses a total of 23 MeV in the active volume of gas. Thus, with this beam energy and gas pressure combination, the excitation function of $^{15}\text{C}+^{12}\text{C}$ fusion is being sampled in the c.m. energy range from ~ 9 -18 MeV in 16 steps of ~ 0.6 MeV. On average the ^{15}C beam deposits about 1.4 MeV in each strip and, hence, a signal of a beam particle passing through the MUSIC without reacting consists of 18 consecutive signals of 1.1 to 1.8 MeV each (s_0 , $s_{1\text{left}}$, $s_{2\text{right}}$, $s_{3\text{left}}$, $s_{4\text{right}}$, etc., see Fig. 5.3 black lines). On the other hand, a fusion event (red lines in Fig. 5.3) begins with beam-like signals followed by a sudden increase in ΔE , finalizing with zero signals (because the ER is stopped inside the detector).

To precisely determine the incoming energy and the energy losses in the windows and in the gas of the MUSIC, the focal plane detector of the ATLAS Enge split-pole spectrograph (Sec. 4.3) was used. This procedure will be explained in the next Chapter. We will also explain how the traces are used for obtaining the fusion cross sections.

One of the advantages of the MUSIC detector is the flexibility to change the range of the excitation function probed in the experiment by raising or lowering the incident beam energy or by changing the pressure inside the ionization chamber. It is worth noting that a fusion reaction producing a heavy evaporation residue can be easily identified based on its considerably larger values in a ΔE vs. *strip* plot. Other main features for fusion experiments are the high detection efficiency, and the possibility of measuring a large part of an excitation function using only one beam

energy, thus avoiding normalization issues and optimizing the available beam time. These are two key characteristics for experiments with radioactive beams, whose intensities are several orders of magnitude lower than the ones of stable beams.

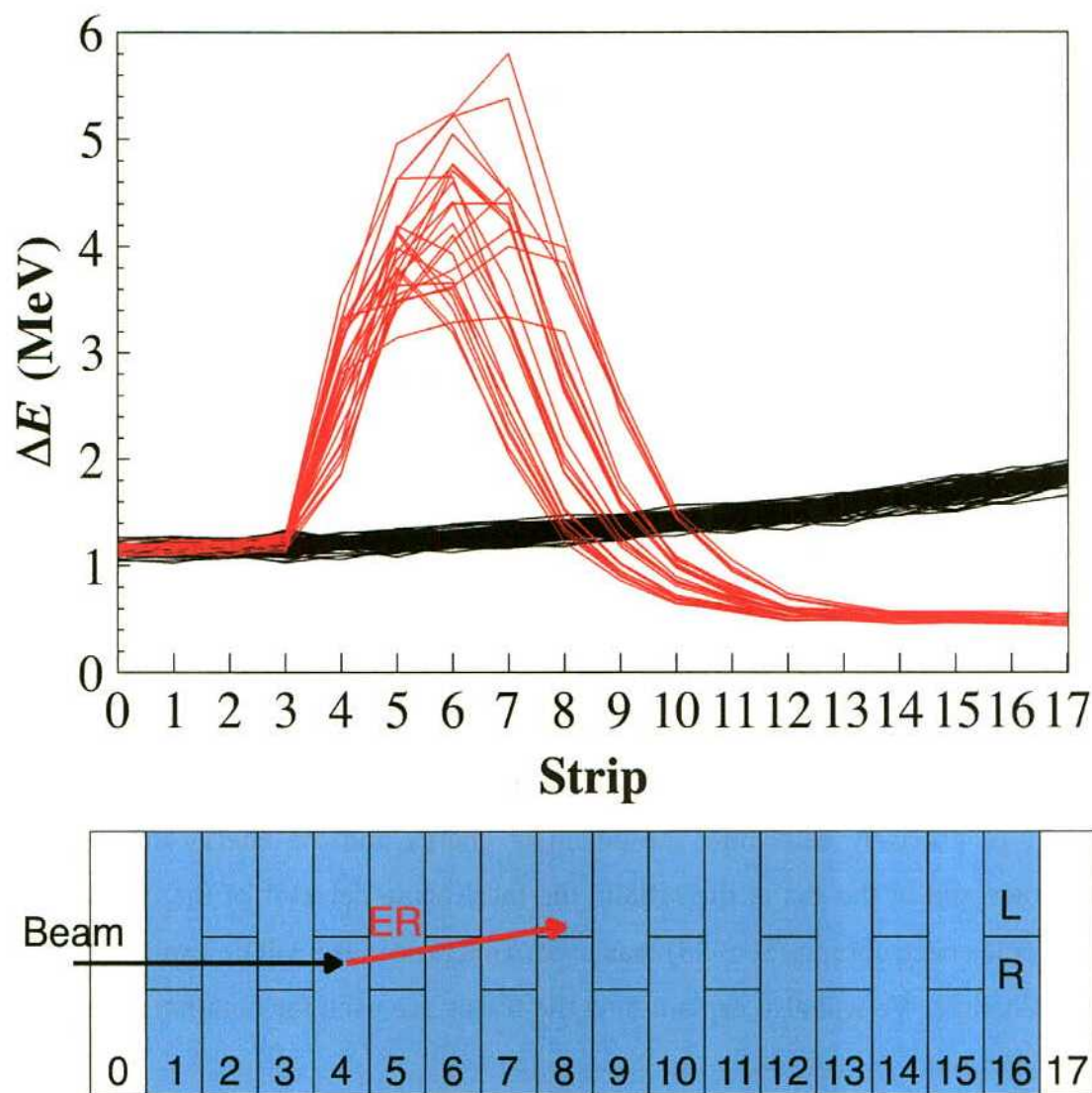


Figure 5.3. Experimental traces measured with the MUSIC detector. Black lines correspond to beam particles interacting with the gas target only by ionization. While red lines are related to fusion events occurring in strip 4. Note the presence of the fusion features described in the text, meaning a jump in ΔE followed by zero pulse height in strips higher than 12.

5.2. Setup and operation of the MUSIC detector

In what follows, we explain the main aspects of the MUSIC detector operation. First, we describe the gas pressure and bias voltage selection (Sec. 5.2.1), and then the signal processing for data acquisition (Sec. 5.2.2).

5.2.1. Gas pressure and bias voltage selection

For the optimal performance of an ionization chamber it is essential to choose the best combination of bias voltage and gas pressure. This is needed for maximizing the drift velocity of electrons produced in the ionization, avoiding the recombination of those electrons with the ionized molecules.

Before optimizing these parameters, a counting gas must be selected. Since the MUSIC detector is operated in active-target mode, the gas must on one hand include the target element of interest, and on the other hand it must have good counting capabilities. Two commonly used carbon-containing counting gases were tested in this work: methane (CH_4) and a mixture of 90% argon and 10% methane known as *P10*.

Initial tests were carried out using a ^{228}Th alpha source and testing the signal to noise ratio while bias voltage and gas pressure were varied. These tests were also repeated during the experiment with a 42 MeV ^{12}C beam. The best parameter combinations were in agreement to those giving the highest electron drift velocity according to Fig. 5.4. Setting the drift velocity to its maximum can be a good criterion for getting the optimum detector parameters, but it is not always possible in real experimental conditions. This is because first the gas pressure has to be selected for obtaining the desired energy loss in the gas, and then the bias voltage is chosen (according to Fig. 5.4) to maximize the drift velocity. It can also occur that the voltage for the maximum drift velocity is higher than the high-voltage limits of the electronics. Fortunately, this did not happen in the MUSIC detector, for the range of voltages and gas pressures used in the experiments.

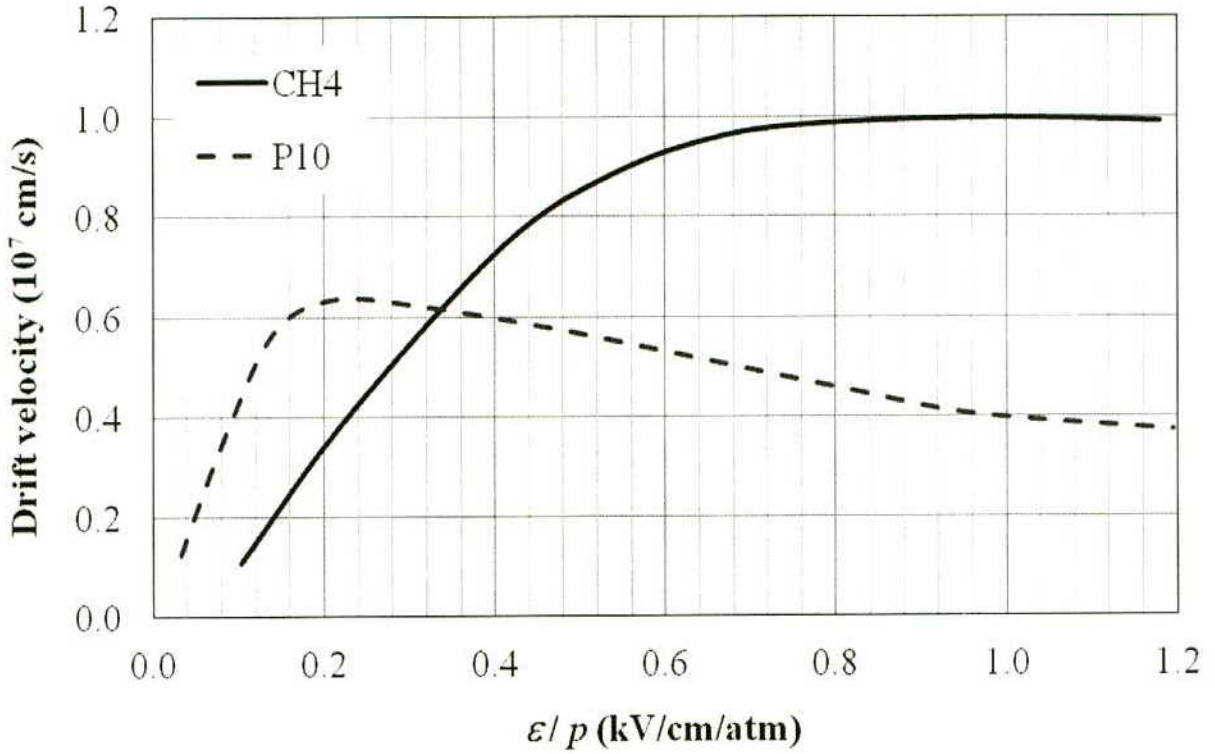


Figure 5.4. Electron drift velocity as a function of the ratio ϵ/p (electric field per gas pressure). (Data obtained from Ref. [Bor57]).

For a gas pressure of 200 mbar (~ 0.2 atm) and a bias voltage of 1 kV we have $\epsilon/p \approx 0.5$. This gas pressure was the one needed during the experiments (see Sec. 5.4), and the mentioned bias voltage produces a large drift velocity for CH_4 , which is higher than the maximum value with P10. Having such an electric field inside the ionization chamber has the additional advantage of minimizing the recombination of electrons and ionized gas molecules and, hence, a higher output signal is obtained.

As an example, Fig 5.5 shows a 2D-spectrum of ΔE vs. *strip number* obtained with a ^{228}Th alpha source, a gas pressure of 400 mbar and a bias voltage of 2 kV. This gas pressure gives energy loss signals similar to those expected in the carbon experiments (see, for example, Fig. 5.3). For comparison, we also include in Fig 5.5 the results of a simulation made with the FLUKA code [Bat07] for the same experimental conditions (see Sec. 6.1 for more details about the simulations).

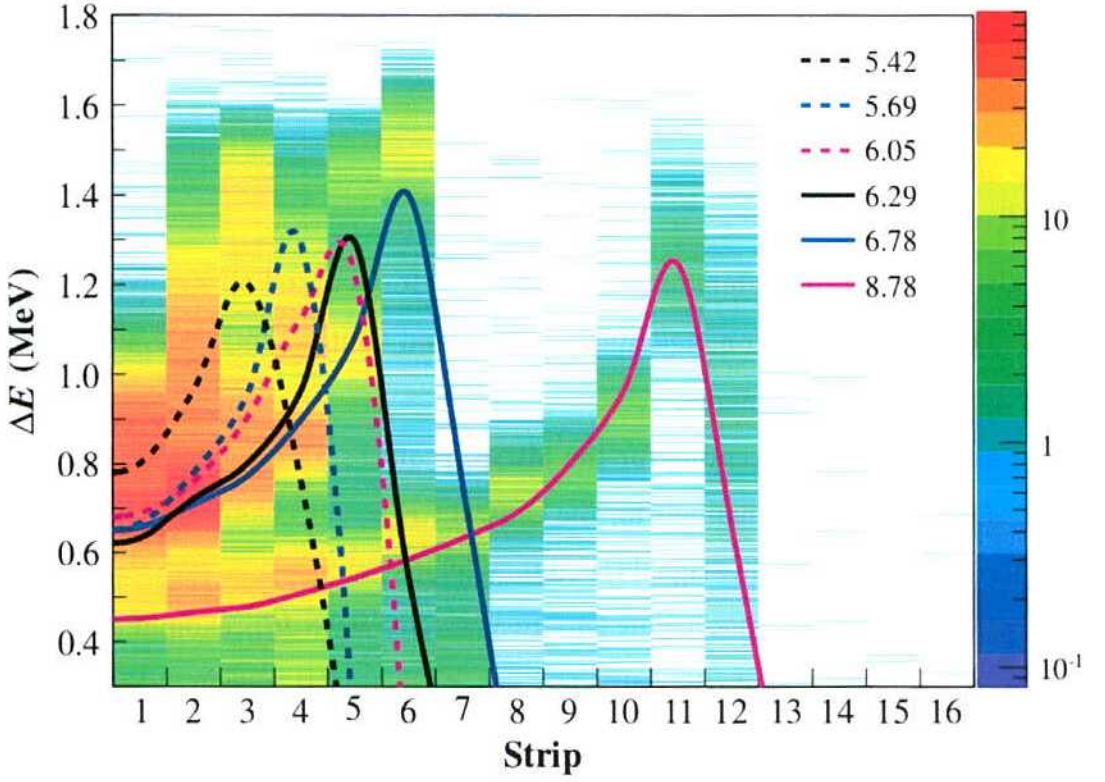


Figure 5.5. Calibrated ΔE vs. *strip* spectrum of a ^{228}Th alpha source ($p = 400$ mbar, $V = 1$ kV) compared with a FLUKA simulation. The energy in MeV for each alpha line is shown in the legend. This spectrum is the superposition of many traces (as defined in the text).

The bias voltage is provided to the MUSIC by a variable high voltage power supply (ORTEC 459), while the ionization gas pressure was controlled by a pressure-regulating gas handling system built at ANL. This gas handling system has a high precision pressure gauge and magnetic valves which, together with a vacuum pump, establish a constant flow. In this way, the pressure is maintained in a fixed preset value and at the same time the ionization gas is preserved from *degradation*[†].

To ensure that the pressure was set in a constant and uniform value, two pressure gauges were installed far from each other and from the gas input and output. The two measured values were in agreement with each other. The gas temperature was also controlled in two distant points, whose values were also in

[†] The detection gas loses molecules as ionizations occur and charges are extracted by the electric field. To avoid this, there is a constant low-rate gas flux going in and out of the detector.

agreement. These data was used in order to calculate the density needed for calculating the cross sections (see Sec. 6.3).

5.2.2. Signal processing

The acquisition system for the MUSIC detector is based on a conventional *PC to CAMAC* (Computer Automated Measurement and Control) interface, widely used in nuclear physics experiments.

Analog signal processing for the MUSIC requires 32 channels for the active strips of the anode, two channels for the control strips, one channel for the cathode, and one channel for a timing signal (i.e., a total of 36 channels).

The anode electronics begins with two *Mesytec MPR-16* preamplifiers, one for each anode side. Although the MPR-16s are designed for silicon detectors, they comply with the MUSIC signals as long as they are configured in “high power” mode, which provides a higher gain [Mes11]. Each preamplifier is then connected to a *Mesytec MSCF-16* shaper amplifier, followed by a corresponding 16-channel *Phillips 7164H* peak ADC.

On the cathode side, the signal coming from the detector goes to a *Canberra 2004* preamplifier. It is further amplified by a *Tennelec 244* amplifier, and digitized by another *Phillips 7164H* ADC.

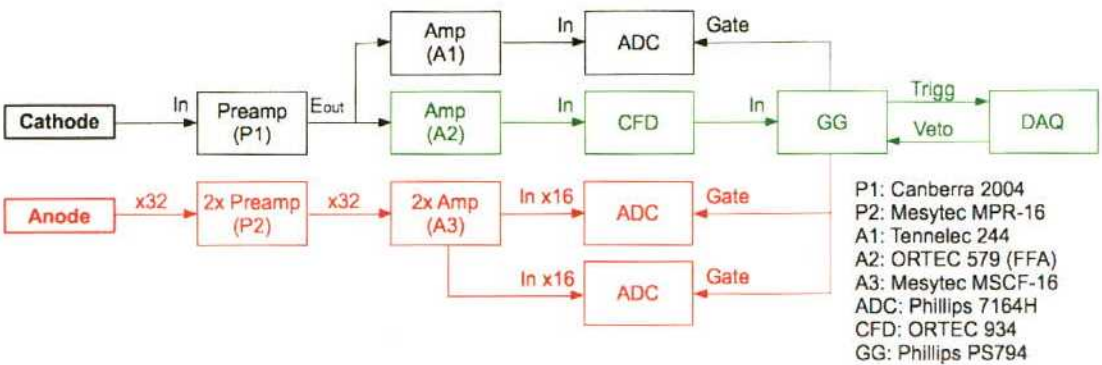


Figure 5.6. Diagram of the electronic modules and connections for the cathode (black), and anode (red) analog signals, and also for the digital trigger signal (green). The “DAQ” (data acquisition) block symbolizes the PC-CAMAC interface.

For generating the acquisition trigger, a fast digital signal is needed. In order to obtain it, the cathode signal is split and sent to an *ORTEC 579* fast filter amplifier (FFA). The output signal from the FFA is connected to an *ORTEC 934* constant fraction discriminator (CFD). From the CFD it goes to a *Phillips PS794* gate generator (GG) and then to the CAMAC controller. From the latter, there is a digital veto signal going back to the GG that blocks the trigger while an event is being processed. Figure 5.6 shows a block diagram of the described electronic modules and connections.

The analog electronics for the control strips (s_0 and s_{17}) is setup in the same way as the cathode (see the black blocks in Fig. 5.6). But, since the latter already produces the trigger, there is no need here for splitting the control strips signals after the preamplifier and sending them to a “digital” line (the green blocks in Fig. 5.6).

Given the ATLAS beam is pulsed (see Sec. 4.2) it is suited for generating a timing signal. In this case, we measure the beam time-of-flight from the instant that a particle goes out the gas cell (the *stop* signal) to the moment that a particle bunch arrives at the detector (the *start* signal). The start signal has the same period of the beam, i.e. multiples of 82 ns (see next Section). The stop signal will depend on the velocity of the incoming particle, because there is a fixed distance between the gas cell and the MUSIC (~ 16 m, see Fig. 5.7). The start and stop events are “inverted” in order to avoid too many timing signals caused by particles that do not reach the MUSIC detector. We will call this timing signal *RF-ToF*, and its utility will be clear in the next Chapter. This signal is processed with a *time-to-amplitude converter* (TAC) electronic module, in particular an *ORTEC 567*, and then it is directly sent to a Phillips 7164H ADC.

With this configuration, each event is generated when there is a signal produced in the cathode. When that happens, the 36 analog signals are digitalized by the ADCs and transferred to a PC by the CAMAC controller. Further processing and data storage is achieved by custom software based on ROOT that, basically, saves the data in a *tree* format. Although, in this way, the data are compressed, there is no loss of information [Roo13]. See Sec. 6.2 and App. A for more details.

5.3. Tuning ATLAS for the MUSIC carbon fusion experiments

Since the tuning process for the present experiments was non-standard, a brief overview is given below. The first step is selecting the injector and accelerators according to the ion species and the final energy (see Sec. 4.2). Then, the transport and focusing of the primary beam is achieved by standard beam-transport elements such as *magnetic quadrupole doublets* and *steerers*. The beam is then transferred to the corresponding experimental area with a conventional bending magnet or to the gas target if a secondary beam is needed (see Fig. 5.7).

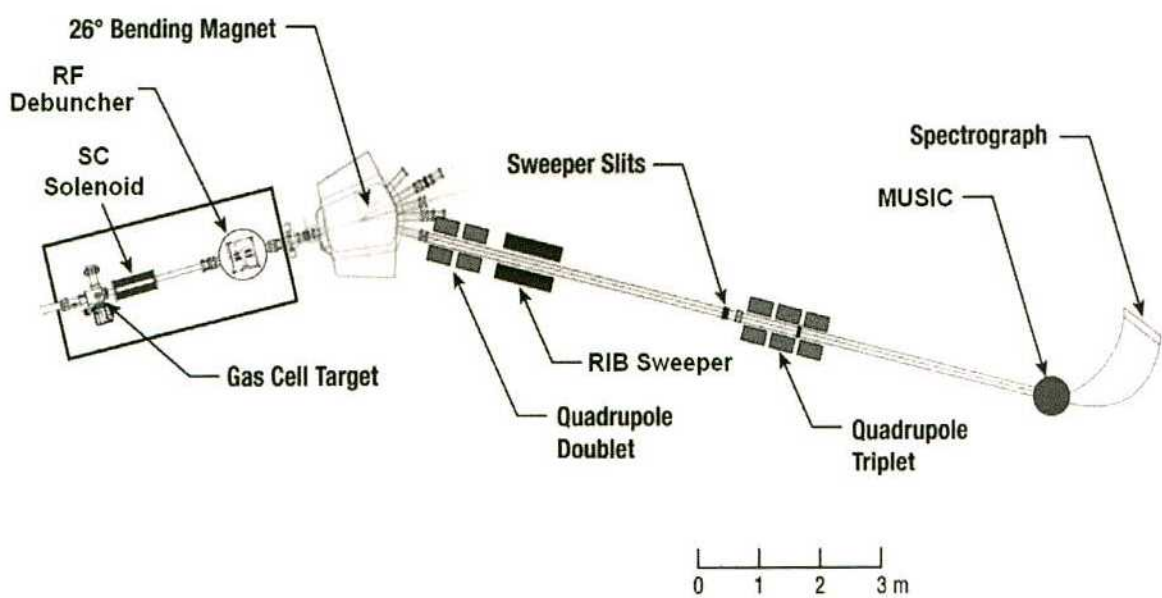


Figure 5.7. Floor plan of the beam line between the gas cell and the MUSIC detector, both separated by a total distance of 16 m. (Adapted from Ref. [Bac14]).

When a secondary beam is required, the devices described in Sec. 4.2 are included in the tuning process. In this case, the main concern is about the purity of the beam. At ATLAS, the first separation between the beam of interest and the contaminants is made by the magnetic rigidity[‡] of the ions, using the bending magnet. However, ions from the production beam with lower charge states can

[‡] The magnetic rigidity is defined as the product of an applied magnetic field B and the radius of curvature ρ of a charged particle's trajectory. It is obtained by the equation $B\rho = \sqrt{2mE}/q$, where m , E and q are the mass, laboratory energy and charge state of the ion, respectively.

match the secondary beam rigidity if they also have a lower energy E_1 , by satisfying the relation:

$$E_1 = E_2 \frac{q_1^2 m_2}{q_2^2 m_1}, \quad (5.1)$$

where the subscripts 1 and 2 correspond to the primary and secondary beams, respectively.

While the ions may have the same magnetic rigidity, they will have different velocities. Thus, over a distance L they will separate due to their different time-of-flight. This separation is given by:

$$\Delta\text{ToF} = \frac{L}{B\rho} \left(\frac{m_1}{q_1} - \frac{m_2}{q_2} \right). \quad (5.2)$$

To improve the secondary beam purity, a new device was recently constructed and installed at ATLAS. This is the so-called *RIB sweeper* [Bac14]. It consists of two plates, parallel to each other and to the beam direction, capable of providing a sine-wave transverse electric field. When it is present, this field deflects undesired beam particles onto a pair of slits (see Fig. 5.7). For example, the ΔToF for a 30 MeV $^{10}\text{B}^{5+}$ primary beam and a 43 MeV $^{10}\text{C}^{6+}$ secondary beam is of 111 ns, which is within the range of operation of the RIB sweeper.

For both primary and secondary beams, the correct identification of fusion events with the MUSIC detector requires that only one incoming particle is inside the detector (see Sec. 6.2). For carbon isotopes of energies around 45 MeV the transit time inside the detector is of about 10 ns, but the electrons generated in the gas ionization have drift times of about 2 μs . Since the ATLAS beam comes in 3-ns wide pulses separated by 82 ns there is a need to use the so-called *RF sweeper*. This device is similar in construction to the RIB sweeper but it uses a square-wave electric field and it is located before the linacs. The RF sweeper period can be adjusted to multiples of the beam period (82 ns). This allows controlling the intensity of the beam (actually the time between two successive bunches).

A single particle each 82 ns is equivalent to a mean beam current of 2 ppA (particle picoamperes), but even with such an intensity there is an appreciable

probability of having more than one particle in the same pulse. If a *Poisson distribution* is assumed for this process, the probability of having k particles in a bunch is

$$P_k = \frac{\lambda^k e^{-\lambda}}{k!}, \quad (5.3)$$

where $\lambda = IT$, with I the intensity of the beam in particles per second, and $T = 82$ ns the beam pulse period. The ratio between the probabilities of having one and two particles goes as

$$P_1/P_2 = \frac{2}{\lambda} = \rho. \quad (5.4)$$

Taking into account the definition of λ , the beam intensity to obtain a given first to second peak ratio ρ must be

$$I_\rho = \frac{2I_0}{\rho}, \quad (5.5)$$

where $I_0 = 1/T$. Therefore, controlling the rate of bunches with two (or more) particles can be done adjusting the beam intensity, which is made by means of attenuators.

As an example of this, Fig. 5.8 shows three cathode spectra with different attenuator/RF sweeper settings for a 42 MeV ^{12}C beam. Here attenuators were used to reduce the beam intensity to obtain a better ρ (see Eq. (5.5)). The RF sweeper was used to further reduce the beam intensity to acceptable values for the electron drift times and for data acquisition (i.e., low dead times). In those spectra, the lowest-energy peak belongs to events where only one beam particle was inside the MUSIC detector. The second peak, counting from left to right, corresponds to a bunch of two particles, and so on (the n th peak belongs to n particles going through the ionization gas). This is easily understood given the cathode signal represents the total energy deposited by the incoming particles, so two particles deposit twice the energy of one, giving rise to a signal with twice the amplitude.

Varying the attenuator/RF sweeper settings affects the total beam rate and the peak ratio ρ , as predicted by Eqs. 5.1-5.3 and shown in Figs. 5.8 and 5.9. It is clear that there is a way of almost completely eliminating bunches with more than

one particle, but at the cost of very low first-peak rates (for higher ρ , in Eq. (5.5), the beam intensity must decrease, affecting not only that ratio but also P_1 itself).

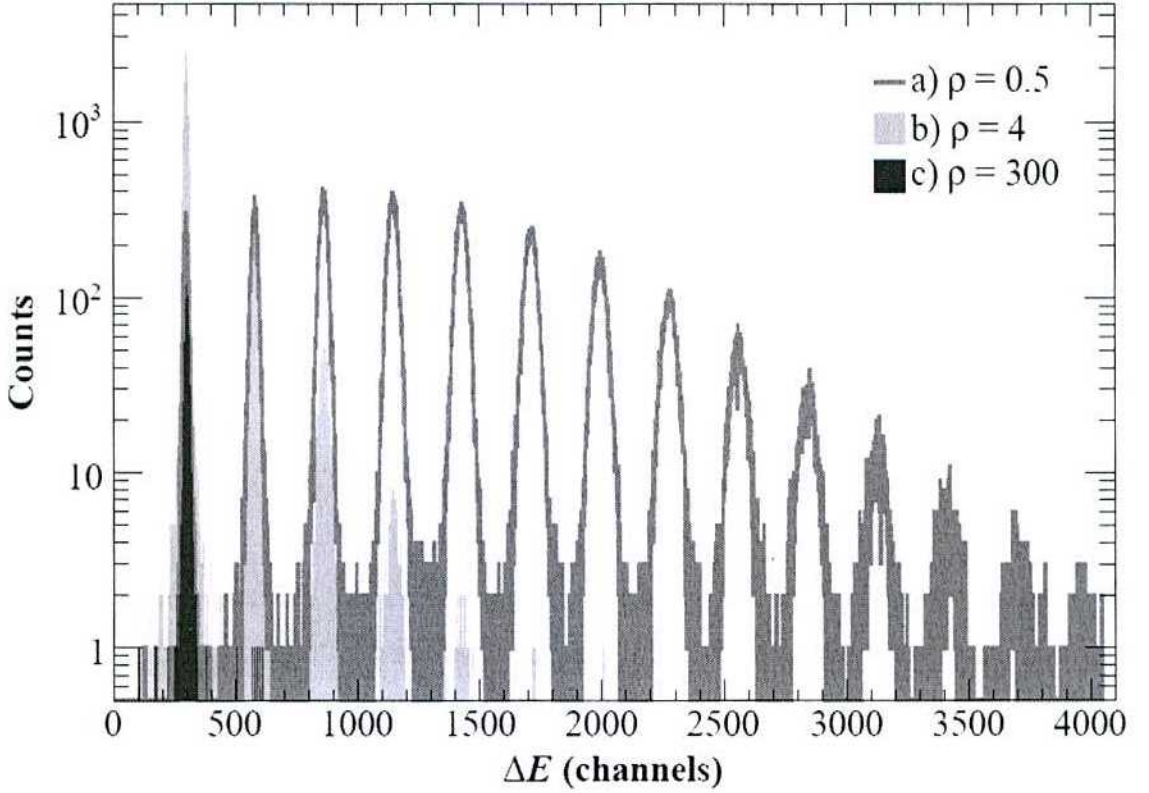


Figure 5.8. Cathode spectra obtained with an RF sweeper ratio of 1/1000 and different attenuators giving: a) Beam intensity of $5 \times 10^7 \text{ s}^{-1}$, total rate in the MUSIC of $1 \times 10^4 \text{ s}^{-1}$, and $\rho = 0.5$; b) Beam intensity of $6 \times 10^6 \text{ s}^{-1}$, total rate in the MUSIC of 2300 s^{-1} , and $\rho = 4$; and c) Beam intensity of $8 \times 10^4 \text{ s}^{-1}$, total rate in the MUSIC of 15 s^{-1} , and $\rho = 300$.

Since the events of interest are clearly separated in the cathode spectrum (see the first peaks in Fig. 5.8), it is possible to select them off-line. So it is not a great problem to these undesired events, given the total rate is still acceptable. A good measuring condition is the one depicted in spectrum b) of Fig. 5.8, where $\rho = 4$ is worse than in spectrum c) but the rate of first-peak events is higher, with a total rate that has a tolerable dead time. In fact, the highest possible rate for the first peak corresponds to $\rho = 1$, but in this case the limitation comes from the total rate, which can generate unacceptable dead time for the data acquisition system (see Fig. 5.9).

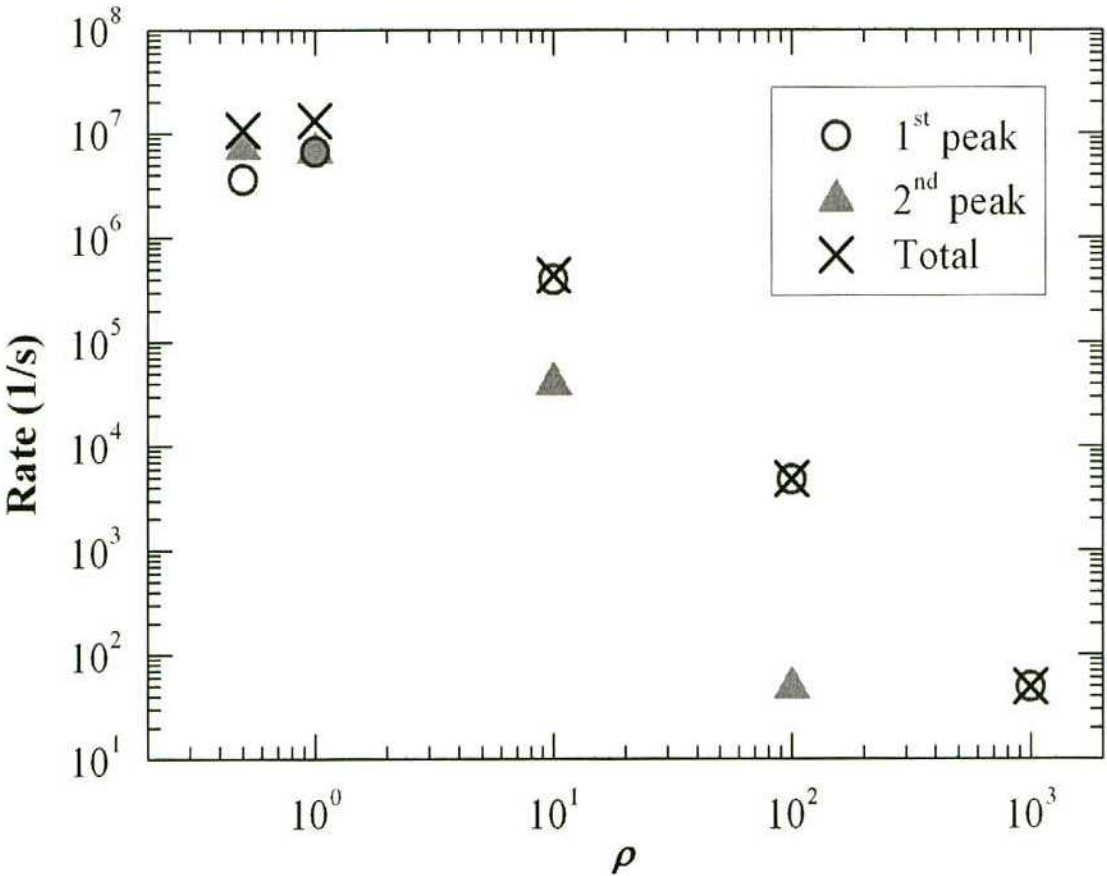


Figure 5.9. Calculated first-peak, second-peak and total rates as a function of the ratio between the first and the second peak ρ (without RF sweeper). As ρ increases, the second peak (and further ones) tends to disappear, but the rate of the first peak also decreases.

Now that the generalities of the MUSIC operation have been explained, we will discuss the specific details of the settings for the four experiments.

5.4. Features of the carbon fusion experiments

The common procedure for the primary beam experiments consisted concisely of: i) tuning the beam up to a *Faraday-cup* in front of the MUSIC detector, ii) adjusting the settings for attenuators/RF sweeper, iii) optimizing the bias voltage and the electronic gains, followed by iv) the data acquisition. For radioactive secondary beams, tuning was more complex and required an additional step using the primary beam as a *guide beam*. This was done for the coarse adjustments of the accelerator optics, which were then scaled for transporting the secondary beam.

The main parameters of the MUSIC experiments are shown in Table 5.1. There were four experiments: one for the ^{10}C beam, one for the ^{12}C beam, one for the ^{13}C beam (two different beam energies), and finally one for the $^{14,15}\text{C}$ beams. This last experiment was made in two steps: first the $^{14}\text{C}+^{12}\text{C}$ fusion was measured, and then ^{14}C was used for producing the secondary beam to obtain the $^{15}\text{C}+^{12}\text{C}$ fusion cross sections.

Table 5.1. Main parameters of the MUSIC experiments: beam isotope, beam laboratory energy (before reaching the MUSIC), ionization gas pressure, center of mass energy range for the $^X\text{C}+^{12}\text{C}$ system (considering strips 1 to 16), beam intensity before attenuators/RF sweeper, total beam rate entering the MUSIC, and data acquisition time.

Isotope	E_{lab} (MeV)	Pressure (mbar)	$E_{\text{c.m.}}$ range (MeV)	Intensity (s^{-1})	MUSIC rate (s^{-1})	Duration (h)
^{10}C	43	240	9.5 - 19.9	5×10^4	500	20
^{12}C	42	200	8.6 - 18.4	5×10^{11}	3,000	10
^{13}C	45	200	9.9 - 18.3	3×10^{11}	4,000	20
	36	200	7.6 - 14.0	2×10^{11}	4,000	15
^{14}C	45	200	8.8 - 17.5	9×10^{10}	2,000	15
^{15}C	49	200	8.9 - 18.3	8×10^5	1,000	15

In all cases the used ionization gas was non-enriched methane (CH_4), thus the target was always ^{12}C . The correction for the 1% contamination from ^{13}C was in all cases smaller than the statistical uncertainty.

There was obviously no need of secondary beam production for the stable ^{12}C and ^{13}C . Even radioactive ^{14}C was obtained as a primary beam from an available sample at ANL. That is why the intensities were clearly higher for those three isotopes (see Table 5.1).

On the other hand, it was necessary to choose appropriate production reactions in order to obtain ^{10}C and ^{15}C beams. The first one was produced using a ^{10}B beam via the time-inverse charge-exchange reaction $p(^{10}\text{B}, ^{10}\text{C})n$. For that, the gas target (discussed in Sec. 4.2) was filled with H_2 gas at a pressure of 1.3 atm and kept at a temperature of 90 K.

The energy of the primary beam was selected according to the direct proton on ^{10}B reaction experimental cross sections [Ear63, Seg66], shown in Fig. 5.10. The

two available data sets have some discrepancies, but agree up to proton energy of 8 MeV (80 MeV for ^{10}B), where the cross sections are almost at a maximum. To be compatible with the rest of the measurements, a ^{10}C energy of around 45 MeV was needed. Taking into account energy losses in the gas target and the negative Q-value of the reaction, the energy of ^{10}B was calculated to be 60 MeV (6 MeV for protons in Fig. 5.10). The production cross section, however, is quite small for that energy, and so 80 MeV was chosen for the energy of the ^{10}B primary beam. In this way, a 66 MeV ^{10}C beam was obtained whose energy was further decreased to 43 MeV by means of a 12-mg/cm² aluminum absorber. The disadvantage of this procedure comes from the energy and angular straggling added by the absorber. From a LISE++ calculation an estimate of 430 keV (FWHM) was found for the former, and 1.2 degrees for the latter.

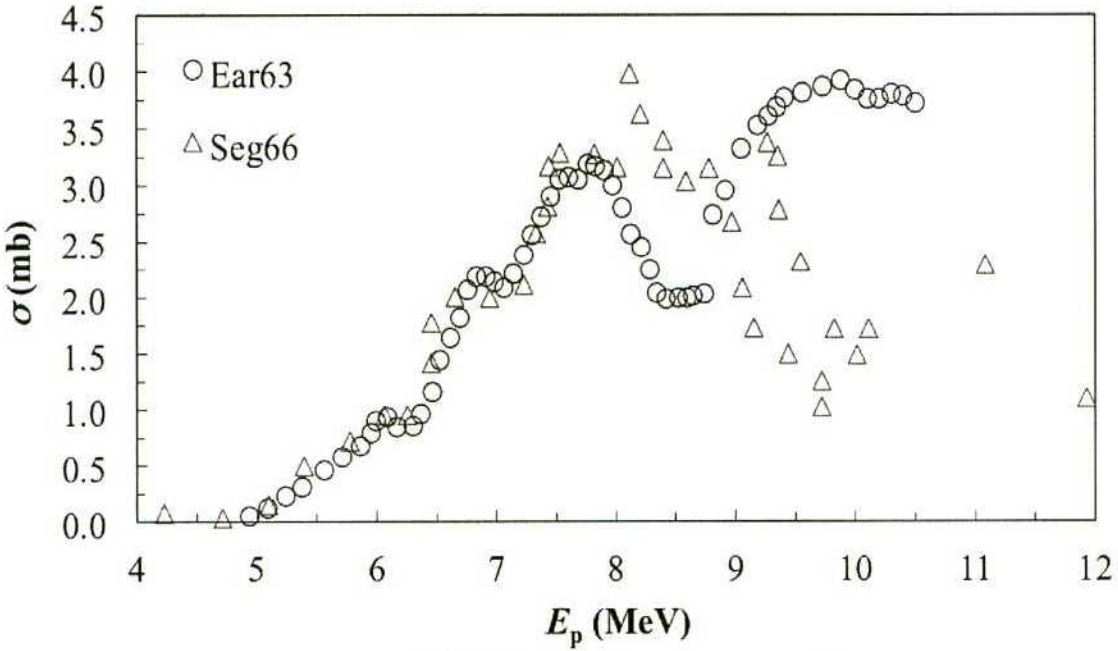


Figure 5.10. Experimental cross sections for the $^{10}\text{B}(\text{p},\text{n})^{10}\text{C}$ reaction obtained from Refs. [Ear63] and [Seg66].

For the ^{15}C case, the primary beam was ^{14}C at 70 MeV impinging on a gas target filled with deuterium (D_2) gas. The pressure and temperature were again 1.3 atm and 90 K, respectively. The chosen reaction was $\text{d}(^{14}\text{C},^{15}\text{C})\text{p}$. Accounting for the energy losses and Q-value, a 70 MeV ^{14}C beam produces a 49 MeV ^{15}C secondary

beam. This value was somewhat higher than requested, but it was found to have better yield and transmission while tuning. No absorber was used in this case to lower the secondary beam energy.

Due to the relatively high energies of the primary beams needed for ^{10}C and ^{15}C production, the positive ion injector and the booster linac were used in those cases. The rest of the beams (primaries only) were obtained using the negative injector alone.

In the next Chapter we will take into consideration the topics discussed in the last two Chapters. This will help in interpreting the information provided by the MUSIC detector and obtaining the fusion excitation functions from it.

CHAPTER 6

DATA ANALYSIS

In the present Chapter we discuss the procedure to obtain fusion excitation functions from the raw data obtained with the MUSIC detector. For doing this, first we have simulated the processes occurring in the detector in order to see how fusion events look and how we can distinguish them from similar interfering signals. The simulations were carried out using the Monte Carlo code FLUKA [Bat07] and are presented in Sec. 6.1. Using the information provided by the simulations we developed a method to clearly identify fusion events, which is described in Sec 6.2. The same method was then applied for finally deriving the excitation functions as explained in Sec. 6.3.

6.1. Monte Carlo simulations of processes in the MUSIC detector

The code FLUKA, used in the present work, is a general-purpose tool for calculations of particle transport and interactions with matter. It has the same capabilities as the other well-known code Geant4 [Ago03]. Much work has been done to benchmark both codes, but mainly for high-energy physics. Nevertheless, they have specific reliable routines for handling heavy ions at energies of several MeV/nucleon. There is evidence of FLUKA being more accurate in that energy regime [Boe10]. For nucleus-nucleus interactions at energies below 100 MeV/nucleon, FLUKA makes use of the *Boltzmann master equation* (BME) theory, which has been studied and used in Monte Carlo simulations for many years [Cav01]. For the ion evaporation process with $A < 30$ it uses the *Fermi break-up model* [Fer50]. Energy losses are simulated through a wide range of models that

includes the Bethe formula (see Sec. 2.4), *Barkas Z^3 correction*, and *Bloch Z^4 correction*, among others (for details see [Flu11] and references therein). Nevertheless, the default value for the CH₄ ionization potential in FLUKA was found to be wrong, so it was modified for this work in order to reproduce the energy losses predicted by SRIM or LISE++, depending on the carbon isotope (see Sec. 6.3).

For most applications, no programming is required to make use of FLUKA. But a number of user interface routines written in Fortran77 are available. For the simulations presented here, a custom user routine was coded to translate the FLUKA output to the same format as the experimental data files. An interface between Fortran77 and C++ was also necessary for producing ROOT tree files. In this way it was possible to apply exactly the same analysis procedure for both simulated and experimental data.

An input file is needed in order to run FLUKA. In that file the geometry of the detector and other parameters are defined, the most important being the beam energy distribution, the physical processes, and the materials.

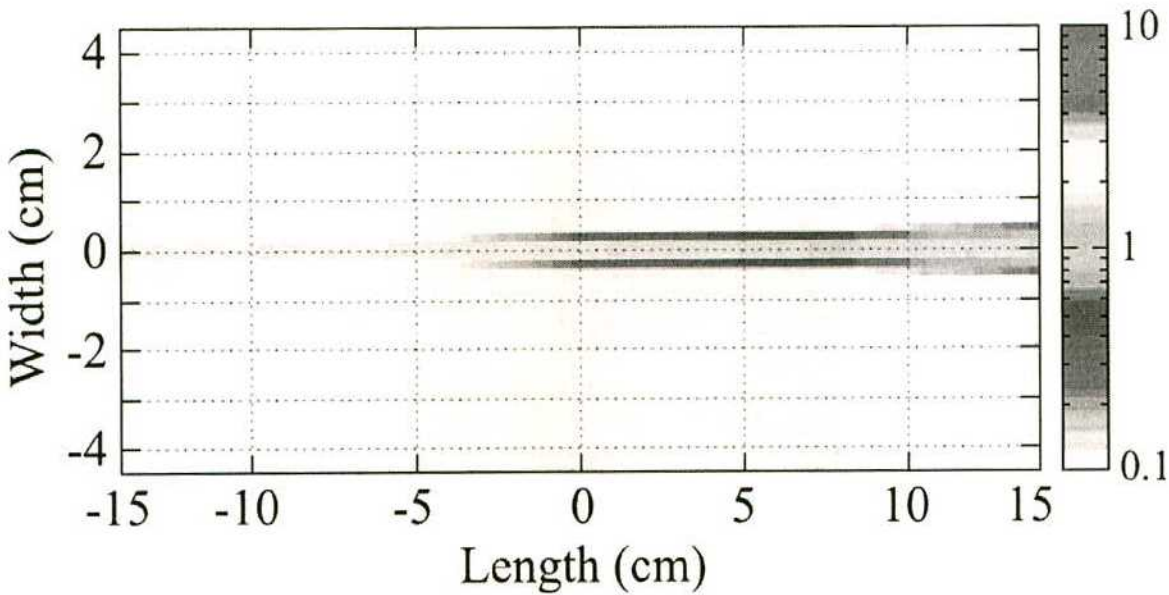


Figure 6.1. FLUKA energy deposition plot for a 45 MeV ¹³C beam, and the secondary particles generated. In this simulation the MUSIC detector is filled with CH₄ at 200 mbar and room temperature. The color code corresponds to the deposited energy in MeV.

Results from FLUKA simulations are shown in Figs. 6.1 and 6.2. The first one illustrates the deposited energy of all transported particles. This is a rather qualitative plot that gives a quick look on how particles scatter through the gas inside the MUSIC detector. The second plot shows the number of occurrences for different particles and is more useful for the subject of this work. Establishing a gate for heavy ERs ($Z > 6$) in the spectrum of Fig. 6.2, it is possible to work with the traces (ΔE vs. *strip*) of those events only.

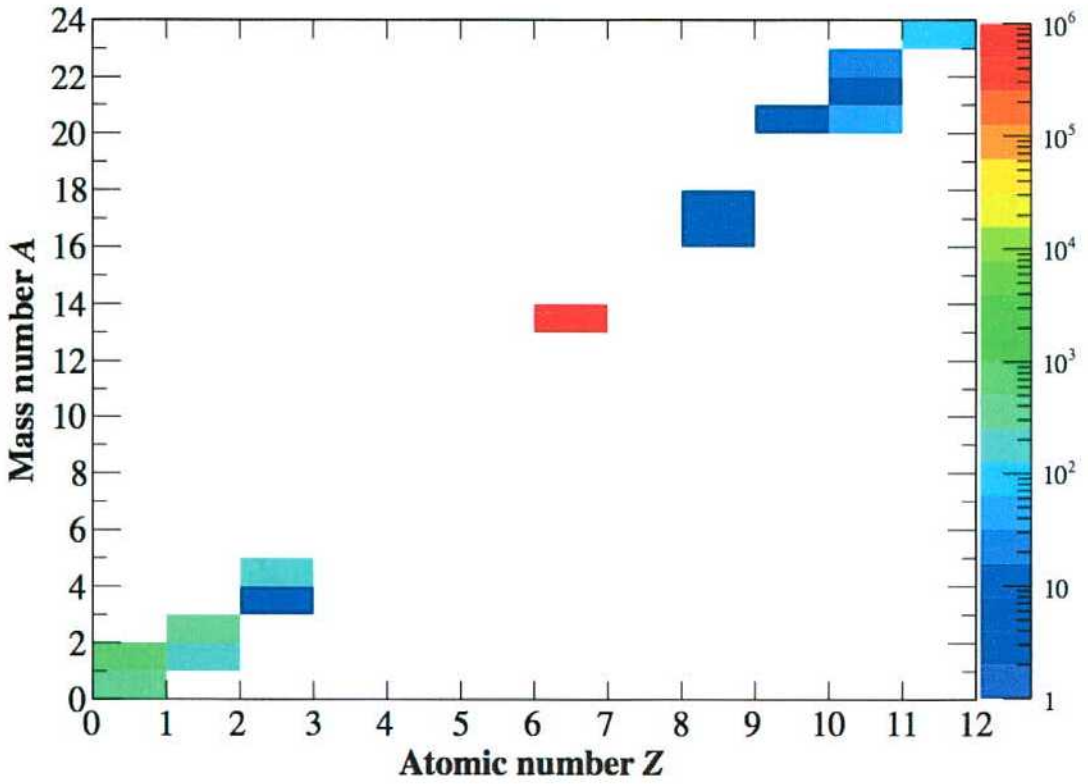


Figure 6.2. FLUKA histogram of mass number A versus atomic number Z for the beam and ERs in the same conditions as in Fig. 6.1. The color code corresponds to the number of occurrences of each particle.

A fusion event produces significant signals in only one side of the detector (for a given strip). This is because there is only one heavy ER after fusion. We call this a *multiplicity-one* event. So it is important to look not only to the total energy deposited in one strip, but also to how large is the fraction of this energy deposited

in each side of the strip. To illustrate this, a set of simulated fusion traces for the three most frequent ERs are compared with an experimental fusion trace in Fig. 6.3.

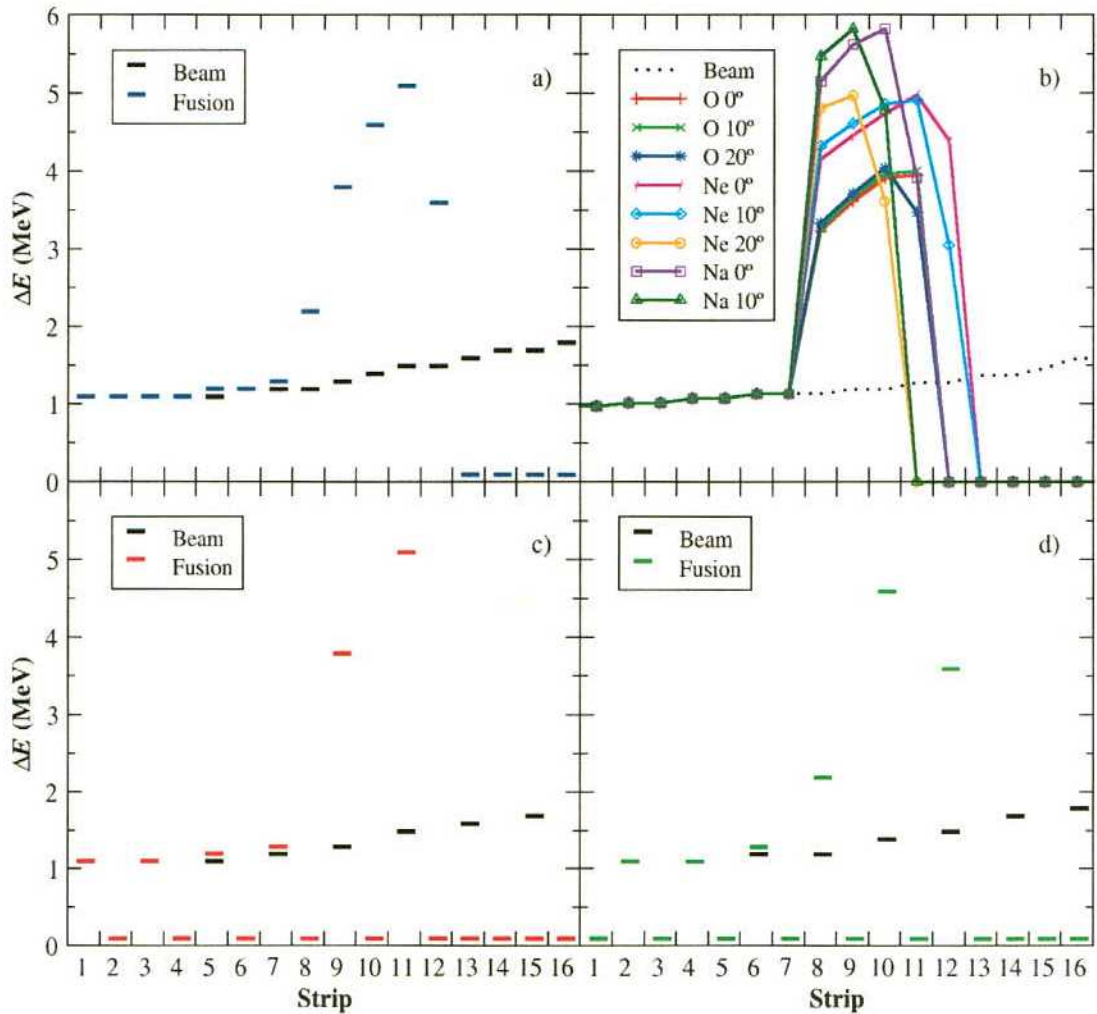


Figure 6.3. Comparison between experimental and simulated fusion signals occurring in strip number 8: a) a fusion event measured with the MUSIC, b) FLUKA simulated fusion events, c) left side signals for the measured event, d) right side signals for the measured event. This is an example of a multiplicity-one event.

According to the simulations, we have to take care of other kind of events that may look as fusion. These are the *multiplicity-two* events produced by scattering (elastic or inelastic), where the projectile and the recoil nucleus of the target both deposit energy in the detector. An example can be seen in Fig. 6.4, showing why it is important to pay attention to the separate signals on both sides of the strips. While multiplicity-two events also show a jump in the trace plot as fusion events do, the

former have signals in both sides of the same strip. This feature is manifested in Fig. 6.4.

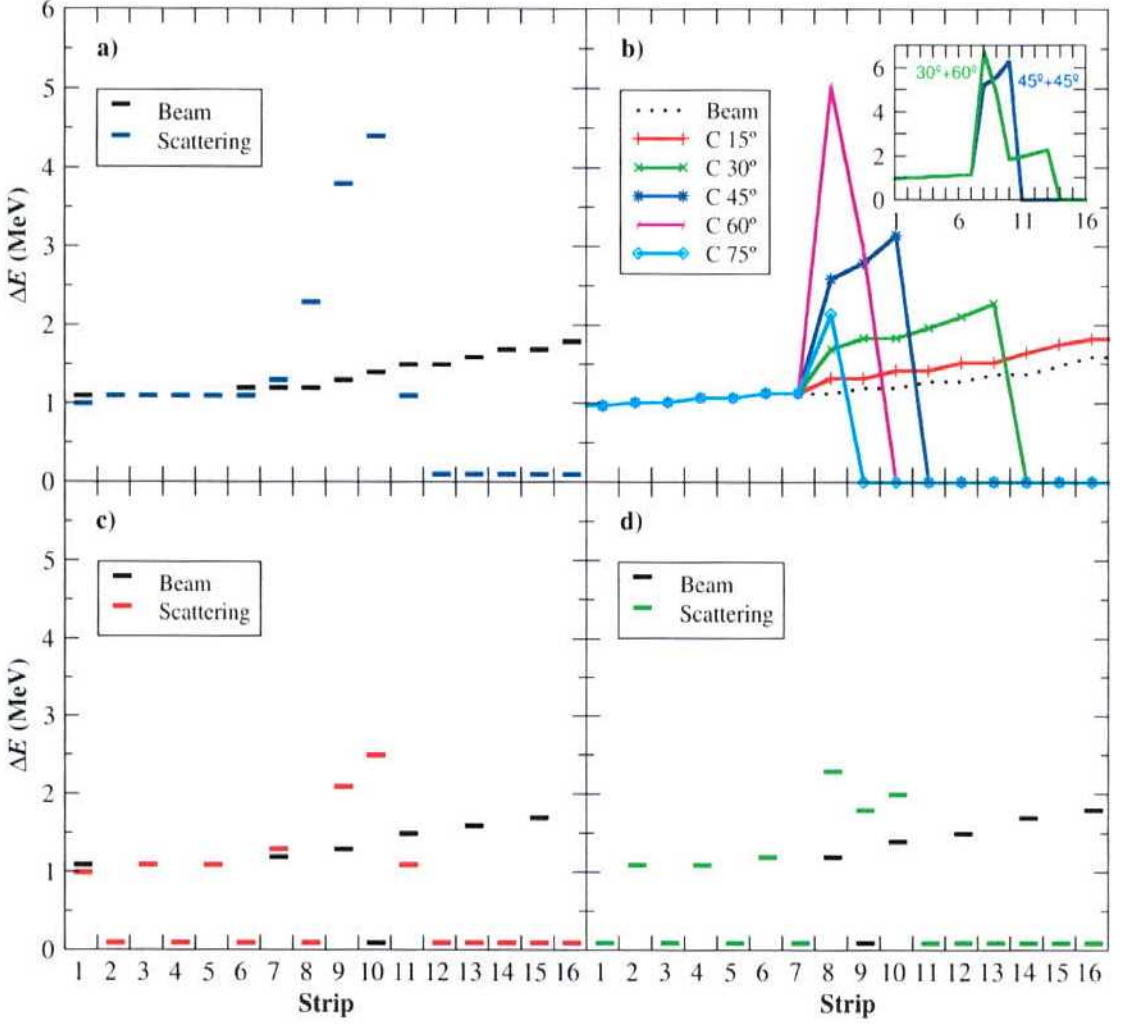


Figure 6.4. Experimental and simulated traces for a scattering occurring in strip number 8: a) a scattering event measured with the MUSIC (sum of both scattered particles), b) FLUKA scattering simulated events (for one particle only), c) left side signals for the measured event, d) right side signals for the measured event. To obtain the simulated signals for both scattered particles, two traces of b) have to be summed (e.g., $30^\circ+60^\circ$, $45^\circ+45^\circ$ as shown in the insert). Note that after the beam-like pattern, there are signals in both sides of the same strip. This is an example of a multiplicity-two event.

Using the simulations, we investigated the possibility of obtaining the cross sections for the production of individual ERs with different Z separately. While this is not needed for determining the total fusion cross sections, it can be useful for understanding the underlying evaporation mechanism. From Fig. 6.3b it can be

argued that the ERs with different Zs are grouped by their maximum energy loss $\Delta E_{\max}$, or even by the *trace length* (taken from the strip where there is a jump in ΔE to the first strip with zero signal). If that would be the case, we could obtain the experimental yields for different ERs by analyzing the traces.

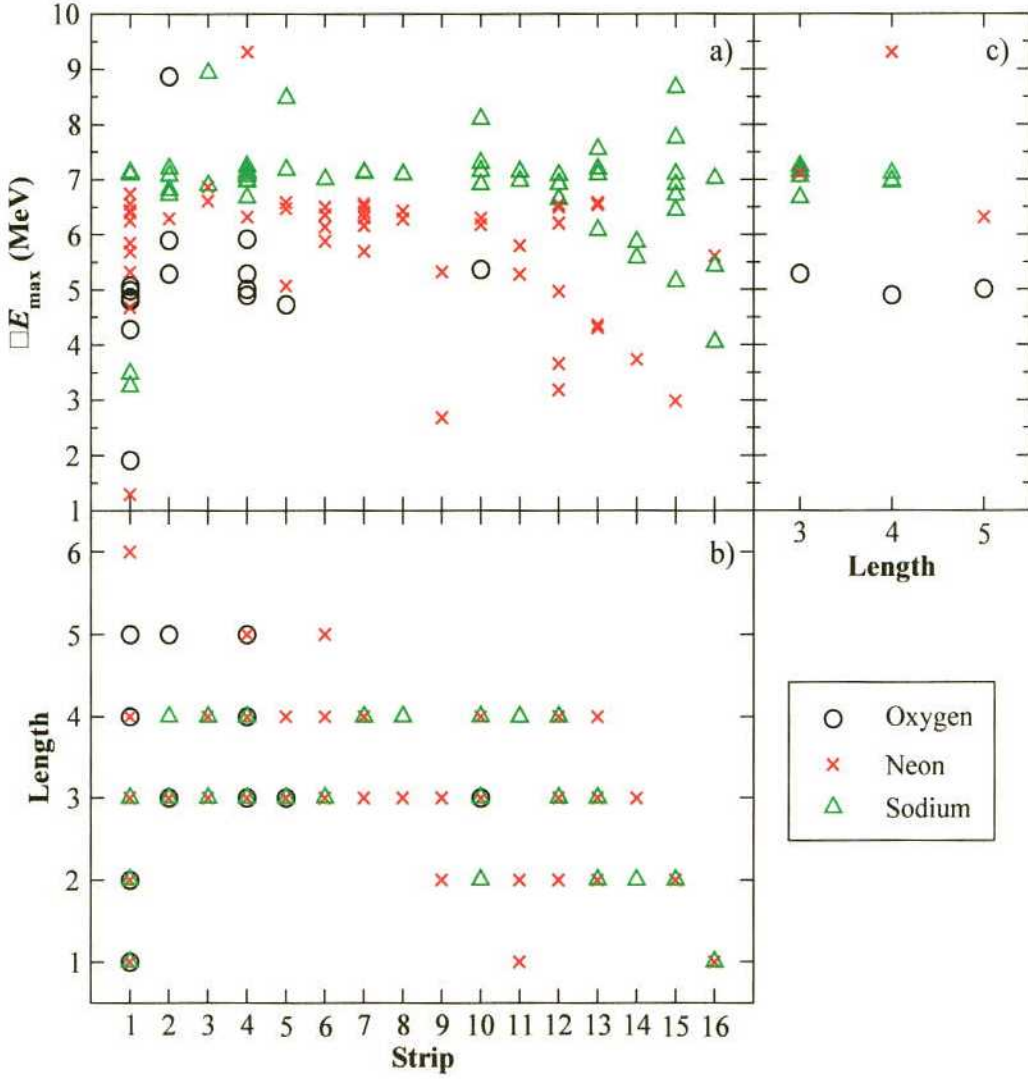


Figure 6.5. Fusion traces parameters for a simulated ^{13}C beam at 45 MeV, with 200 mbar of gas pressure. a) Maximum energy loss $\Delta E_{\max}$ as a function of strip number. b) Trace length, as defined in the text, as a function of strip number. c) $\Delta E_{\max}$ vs. *length* for strip number 4. In all cases the data are for the three more abundant ERs.

To explore this idea, we analyzed a simulation of one million events with a beam of ^{13}C at 45 MeV and a gas pressure of 200 mbar. In Fig. 6.5 there are three plots showing some results of that simulation. First, in Fig. 6.5a, $\Delta E_{\max}$ values for the

three principal ERs (O, Ne, Na) are shown as a function of the strip number. Although there are some indications of different ΔE values for the O, Ne, and Na residues the separation is not sufficient to clearly identify the individual elements. The same happens if instead of the $\Delta E_{\max}$ we consider the trace length as depicted in Fig 6.5b. If we combine these two variables in order to see if they are correlated, we still find that there is no clear way of separating the different ERs, as it can be seen for example in Fig. 6.5c for strip number 4. So at present there is no clear method for obtaining a Z-identification of the individual ER yields with the current analysis.

It should also be stated that reactions occurring with a hydrogen nucleus in CH_4 produces only a beam-like trace. This is caused by the large difference in masses between the beam and hydrogen, and by the relatively high energies used in the experiments.

6.2. Fusion identification process

With the information extracted from the experiment, and confirmed by the simulations, a criterion was developed for the identification of fusion events (and for the elimination of multiplicity-two cases). Under this criterion the traces must pass a series of tests in order to be recognized as fusion events.

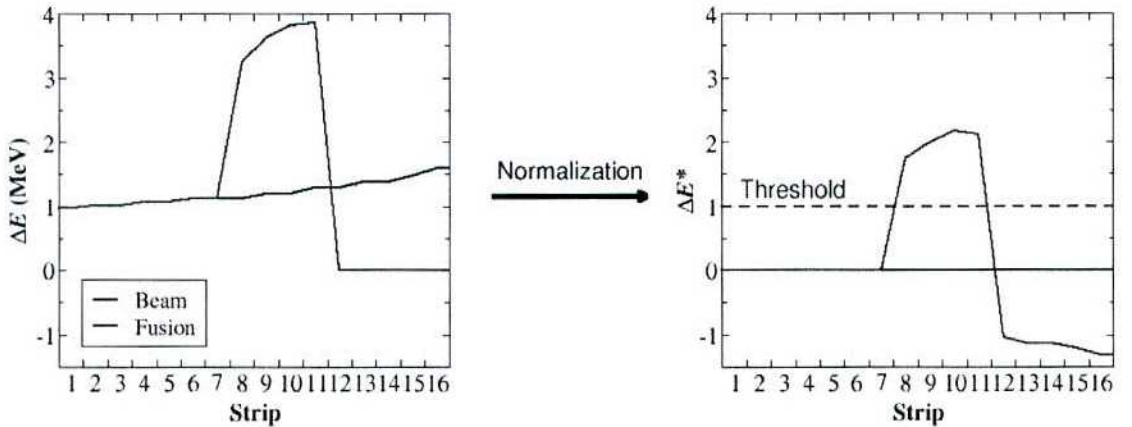


Figure 6.6. Beam and fusion traces normalized for the analysis. An example of the (constant) threshold for fusion identification is drawn in the panel on the right.

The identification process begins by reading an event, which comprises a total of 36 values: the 34 anode signals, the cathode signal, and the timing signal (see Sec. 5.2.2). If there is a contaminant beam reaching the MUSIC detector, the information given by the cathode and timing signals is used for selecting only the beam of interest (see below).

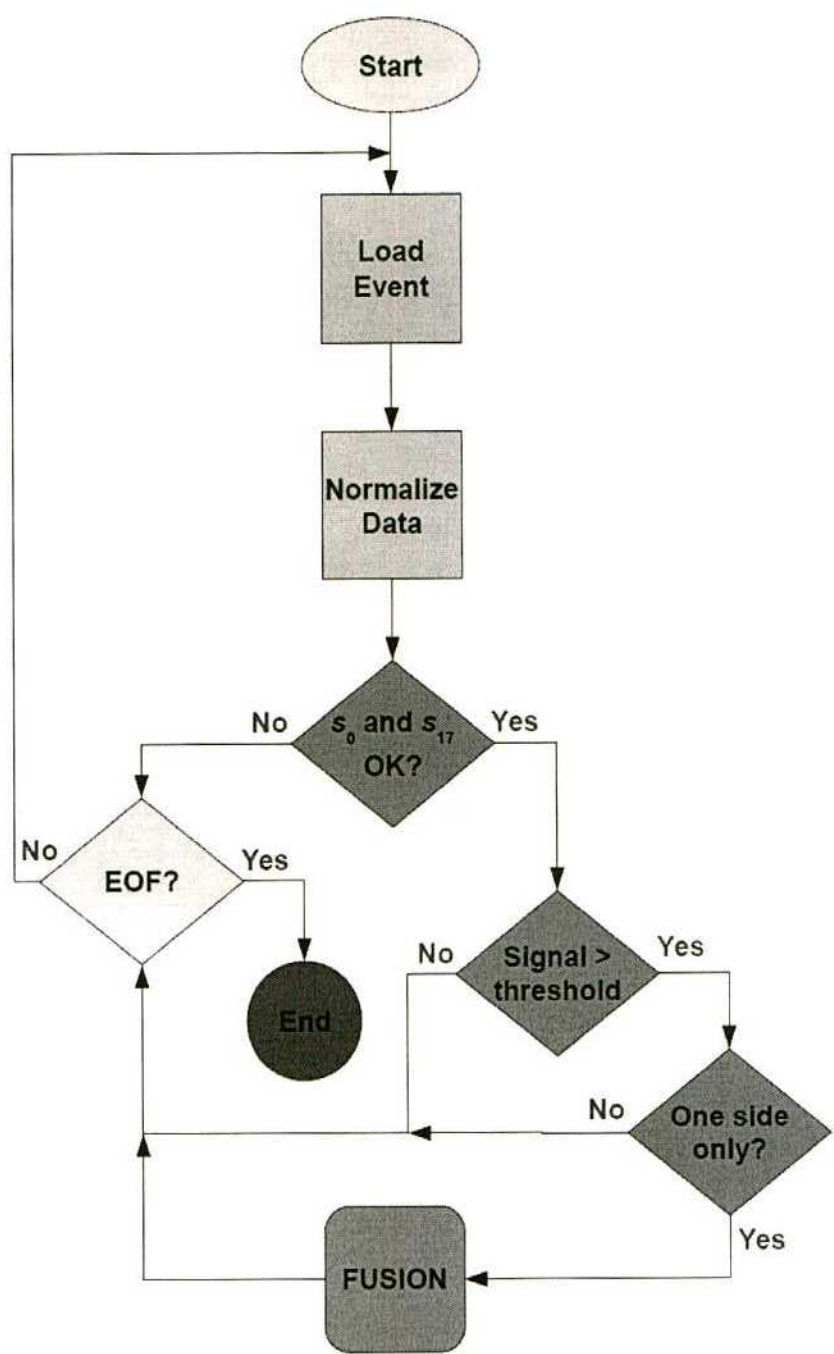


Figure 6.7. Block diagram of the process used for fusion event identification.

Once the event is read, the anode signals are normalized to a constant value and the carbon beam signal is subtracted. This is done to correct for fluctuations and the rise of ΔE signals with increasing strip number. In this way, it is possible to set a constant threshold for fusion identification. After this step, a beam trace is represented by a constant line at zero in the normalized ΔE^* vs. *strip* plot (see Fig. 6.6).

The next step uses the control strips (s_0 and s_{17}) for eliminating reactions occurring in the entrance and/or exit windows. For a valid event, in s_0 there must be a $\Delta E^* = 0$ signal, i.e. a beam signal. On the other hand, it has to be $\Delta E^* < 0$ in s_{17} , meaning that the particle (possibly an ER) has stopped inside the detector. An example of this is given in Fig. 6.6.

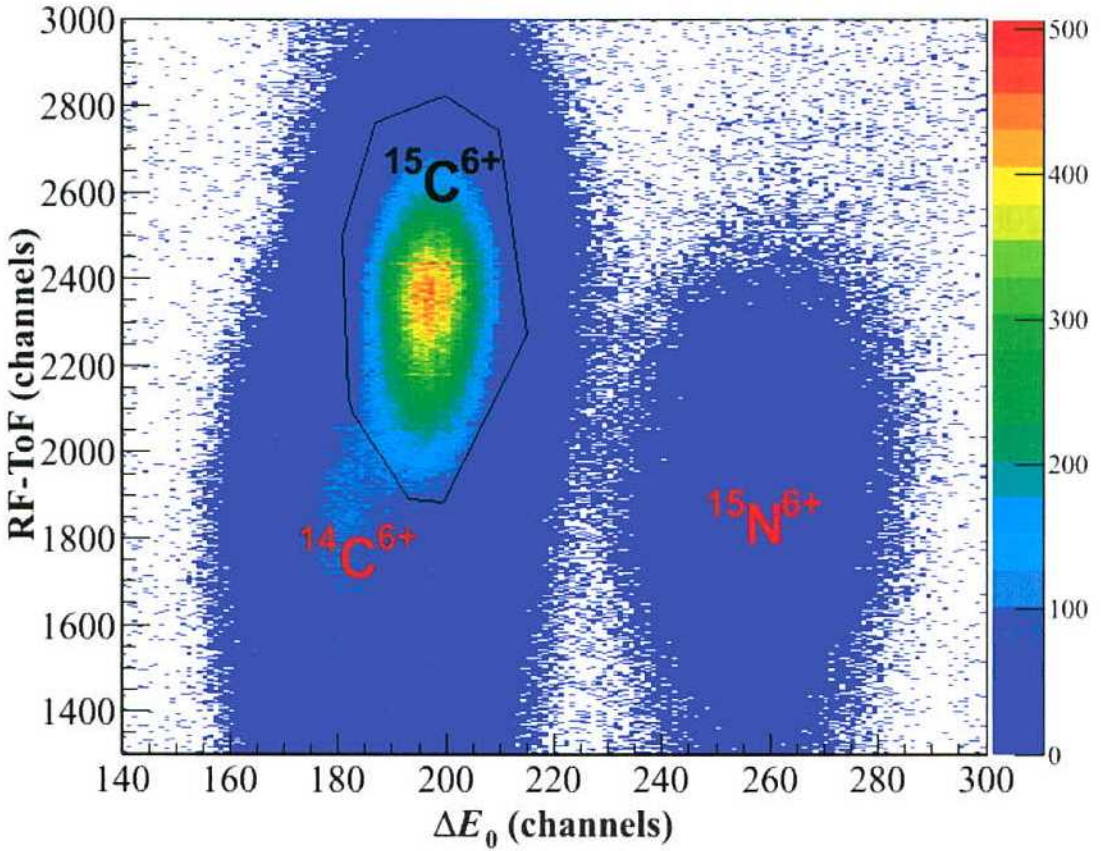


Figure 6.8. Plot of ΔE_0 vs. RF-ToF for a 49 MeV ^{15}C secondary beam showing the contaminants generated by the primary beam.

At this stage, the trace is tested to fulfill the fusion event features mentioned in Sec. 6.1. First, the ΔE^* signal must go from zero (the beam) to over a threshold that depends on each isotope. Then, in the following strips there must be signals in one side of the detector only. It is not necessary to request here that the signals go below zero because it has already been checked with the help of the control strip s_{17} . This process continues on an event-by-event basis until the end of the data file (EOF) is reached. Figure 6.7 shows a block diagram of the entire identification process.

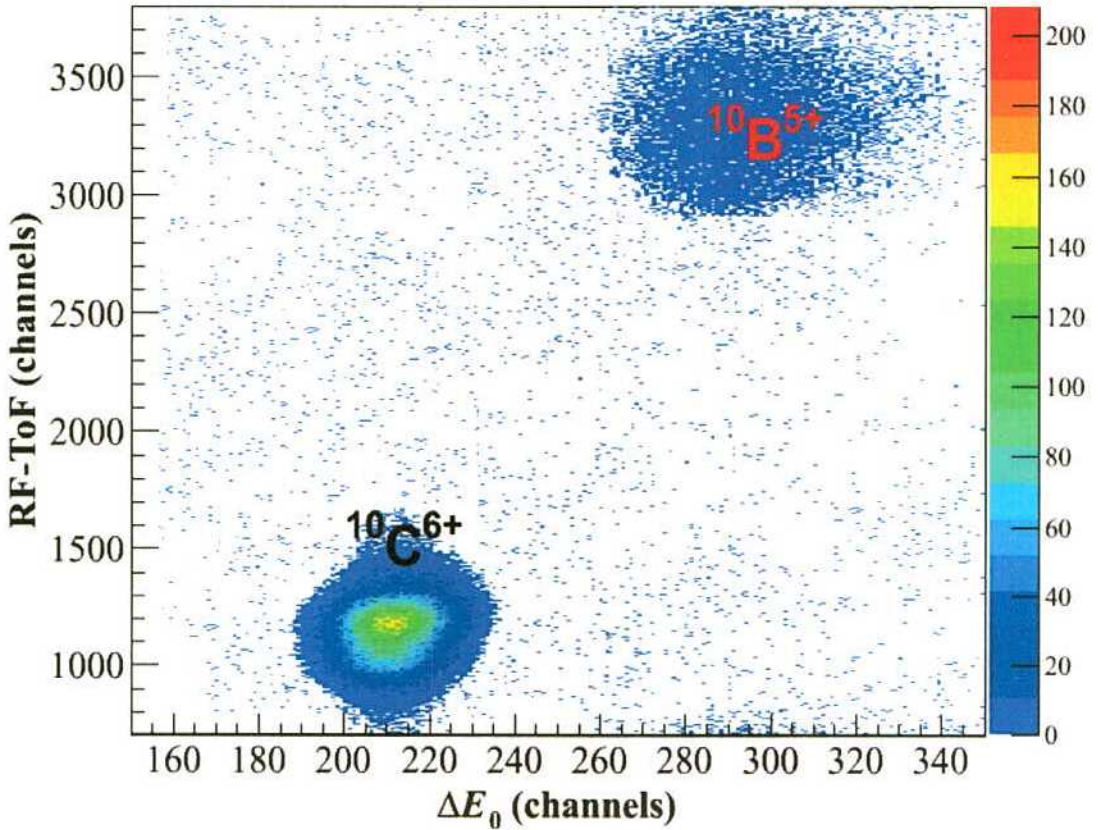


Figure 6.9. ΔE_0 vs. RF-ToF for a ^{10}C at 43 MeV secondary beam and the well-separated ^{10}B primary beam.

With radioactive beams there is another complication in the data analysis coming from the impurity of the beam. For the production of a $^{15}\text{C}^{6+}$ beam via the $d(^{14}\text{C}, ^{15}\text{C})p$ reaction, interference from the primary particles of $^{14}\text{C}^{6+}$ is mostly reduced by the RIB sweeper (see Sec. 5.3). The same happens for most of the contributions from the $^{15}\text{N}^{6+}$ particles produced via the $d(^{14}\text{C}, ^{15}\text{N})n$ reaction.

Nevertheless, the high intensity of the primary beam makes it difficult to completely eliminate the contaminants in this way. Fortunately, both contaminants can still be separated from the beam of interest in the ΔE_0 vs. RF-ToF spectrum, as shown in Fig 6.8.

For the ^{10}C case, the primary beam has a significant different ToF (111 ns more than the secondary beam) and is strongly suppressed by the RIB sweeper. This is exhibited in Fig. 6.9 where the ΔE_0 vs. RF-ToF spectrum is almost free of background in the secondary beam zone.

Finally, the fusion identification process explained above was implemented as a ROOT C++ tree class [Roo13] code that is available in App. A. This was first verified with the simulations using previously known traces from ERs. The analysis was further validated by applying it to experimental data from $^{12,13}\text{C}$, for which previous experimental data obtained with different techniques exist. An explanation on how the experimental excitation functions are obtained is given in the following Section, and the results will be presented in Sec. 7.1.

6.3. Deriving the experimental excitation functions

The first step in determining the experimental fusion excitation functions is using the identification process explained in the last Section. The result of this procedure is a number of identified fusion events per strip $N_{\text{fus}}^{(s)}$, and the total number of beam-like events N_{tot} . With this information, a cross section per strip is calculated according to the next equation:

$$\sigma_{\text{fus}}^{(s)} = \frac{N_{\text{fus}}^{(s)}}{N_{\text{tot}}\omega_s}, \quad (6.1)$$

where ω_s is the *areal density* (atoms per area unit) of ^{12}C (in CH_4) for the strip s , obtained using the law of ideal gases at the measured gas pressure and temperature (see Sec. 5.2.1).

For obtaining an excitation function, an energy value must be associated to each strip. In order to do this, energy loss calculations were carried out using two

6. DATA ANALYSIS

different options: SRIM 2013 [Zie10] and LISE++ 9.7 [Tar08]. SRIM is a well-known stopping-power code that makes use of state-of-the-art models and experimental data fits. On the other hand, LISE++ is a code for beam transport simulation and spectrometers design. It has a stopping power module based on the Lindhard-Soerensen model [Lin96], which is recognized for accurately reproducing experimental data [Gei02].

Selected results of the energy loss calculations are included in Fig. 6.10, where it is clear that SRIM gives higher energy losses than LISE++.

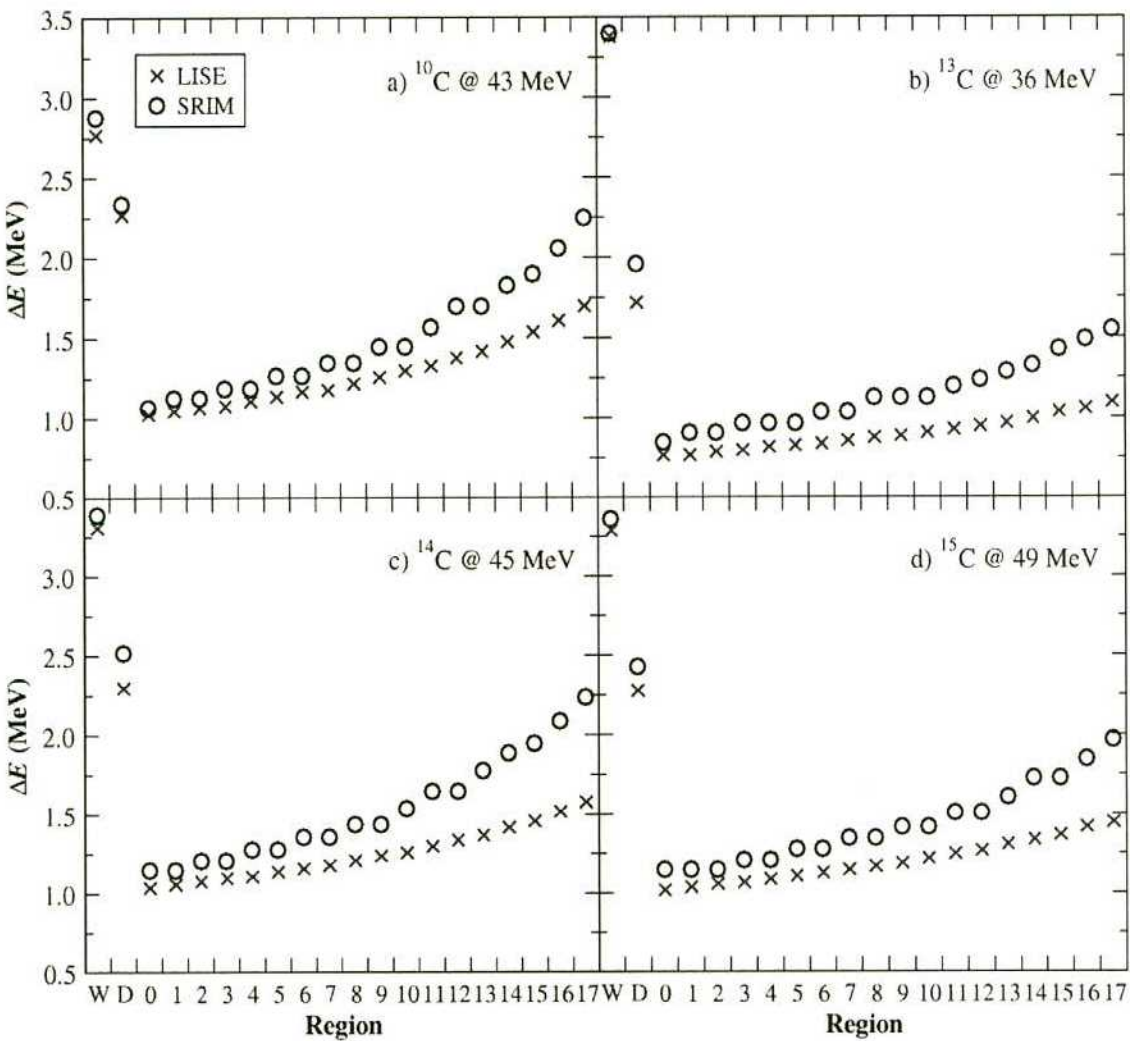


Figure 6.10. Comparison between SRIM and LISE++ energy loss calculations for different beams and energies (CH_4 at 200 mbar). W and D correspond to the entrance window and the dead layer of gas before strip 0, respectively. The numbers from 0 to 17 denote the strips.

For deciding which code is more suitable to describe energy losses in the MUSIC detector, the calculations were compared to energy measurements obtained with the Enge split-pole spectrograph (SPS). In this case, only the outgoing beam energy can be measured, providing a composite effect of energy losses in the windows and in the gas. To overcome this limitation, the measurements were done for several gas pressures. As a result of this (see Fig 6.11), LISE++ was chosen for calculating the energy values used in the excitation functions for all the systems except for $^{15}\text{C}+^{12}\text{C}$. (Taking into account these measurements, the ionization potential of CH_4 in FLUKA was changed to better reproduce energy losses of the different beams).

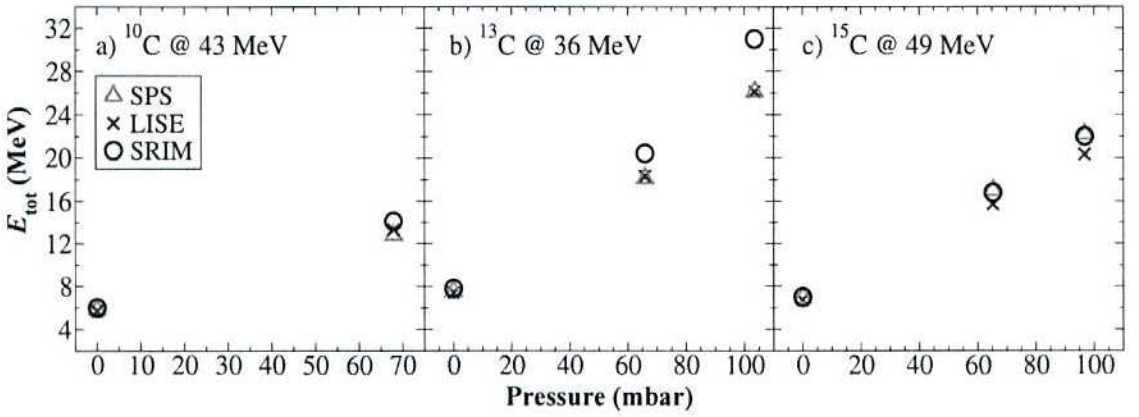


Figure 6.11. Comparison between calculated (SRIM, LISE++) and experimental (SPS) total energy losses in the MUSIC detector, as a function of the gas pressure. LISE++ shows better agreement with the experimental data for ^{10}C and ^{13}C . On the other hand, SRIM seems to be more accurate for ^{15}C .

Knowing the energy losses, the energy value corresponding to each strip is calculated taking into account their finite size. First, the energy at the beginning of strip 0 $E_0^{(\text{in})}$ is determined by

$$E_0^{(\text{in})} = E_{\text{beam}} - \Delta E_W - \Delta E_D, \quad (6.2)$$

where W and D correspond to the entrance window and the dead layer of gas before strip 0, respectively. Then, the outgoing energy after strip 0 is:

$$E_0^{(\text{out})} = E_0^{(\text{in})} - \Delta E_0 = E_{\text{beam}} - \Delta E_W - \Delta E_D - \Delta E_0. \quad (6.3)$$

Finally, assuming that the fusion occurs in the middle of the strip, the energy associated to strip 0 is:

$$E_0 = \frac{E_0^{(\text{in})} + E_0^{(\text{out})}}{2} = E_0^{(\text{in})} - \frac{\Delta E_0}{2}. \quad (6.4)$$

The energy associated to each subsequent strip is obtained by subtracting the successive calculated energy losses from the beam energy. In general, for strip s :

$$E_s = E_{\text{beam}} - \Delta E_W - \Delta E_D - \sum_{i=0}^{s-1} \Delta E_i - \frac{\Delta E_s}{2}. \quad (6.5)$$

6.4. Estimation of the uncertainties

With the procedure described in the last Section, the excitation functions have uncertainties both in the cross sections and in the corresponding energies.

First, the cross sections have a statistical uncertainty depending on the number of fusion events per strip ($N_{\text{fus}}^{(s)}$). For the current experiments, it ranged from 5% to 20%. This clearly depends on the beam rate and the total measuring time (it will be analyzed case-by-case in Sec. 7.1). Higher statistical uncertainties are obtained, as expected, with the secondary beams, because the beam rate was lower and the measuring time was shorter (more time for beam tuning was needed). The obvious solution is to take longer measurement times. This is of course difficult given the high demand for beam time at ATLAS. Anyway, a possible solution for this will be discussed in Chapter 8.

The cross sections also have a systematic source of uncertainty caused by the areal density per strip ω_s . This depends on the gas pressure and temperature measurements. Given that precise measurements of both parameters were obtained, we can ensure that the overall contribution to ω_s is below 1%. Finally, there is an extra systematic uncertainty coming from the fact that in CH_4 there is a natural 1% component of the stable ^{13}C isotope. The cross sections in this work were corrected for this effect. If needed, this can be reduced using ^{12}C -enriched methane gas.

The uncertainty in the energy values originates from the finite size of the strips, causing fusion to occur at different positions, and hence with different

energies in the same strip. In this case, the reported total uncertainty is the calculated energy loss in the strip. So, for strip s the corresponding energy would be:

$$E_s \pm \Delta E_s/2. \quad (6.6)$$

Given that ΔE_s grows with s (see Fig 6.10), so will do the uncertainty in E_s . In any case, for the current experiments it varied between 1% and 5%, growing with strip number. There is not much we can do with this source of uncertainty. One option is to reduce the size of the strips, but this would cause the electronic signals to be smaller, to the point that noise interference starts to be a problem. Then, for avoiding this, the gas pressure could be increased, but it would reduce the sampled energy range. Raising the bias voltage could help, but not indefinitely because the drift velocity of the electrons has a maximum value and it may cause sparks inside the detector.

Having discussed the analysis method, in the next Chapter the results of this analysis are presented. They will also be compared with other experimental data and with theoretical calculations.

CHAPTER 7

RESULTS AND DISCUSSION

After understanding the processes occurring in the MUSIC detector and establishing a method for obtaining the experimental excitation functions, in this Chapter the results for the five isotopes are presented in Sec. 7.1. Next, in Sec. 7.2, the results are compared with calculations from different models. To finish, in Sec. 7.3 we present an analysis of the average cross sections to assess the effect of the neutron number in the fusion process.

7.1. Experimental excitation functions for carbon fusion reactions

In this Section the experimental excitation functions obtained with the MUSIC detector are presented and compared with previous experimental data introduced in Sec. 3.2 (when available).

To start with, the experimental excitation function for $^{12}\text{C}+^{12}\text{C}$ is presented in Fig. 7.1. There is a fall-off towards lower energies, but it is not smooth. There are hints of a structure manifest as slope changes at about 9, 12 and 15 MeV (every 3 MeV). The average uncertainties are of 8% for the cross sections and 3% for the energies. Despite this, the mentioned structure can still be recognized.

For the $^{13}\text{C}+^{12}\text{C}$ case we performed two measurements with different beam energies, but the same gas pressure. The intention was to study the operation of the detector and the consistency of the analysis process with a set of overlapping measurements. This test gave satisfactory results as shown in Fig. 7.2. It also extends the studied energy range towards lower energies.

The $^{13}\text{C}+^{12}\text{C}$ excitation function has a similar shape as the one for $^{12}\text{C}+^{12}\text{C}$. There is only a hint of an oscillation with a maximum at about 17 MeV. Nevertheless, this oscillation is unclear given its amplitude (~ 50 mb) and the magnitude of the uncertainties (6% for σ_f and 2% for $E_{\text{c.m.}}$, on average).

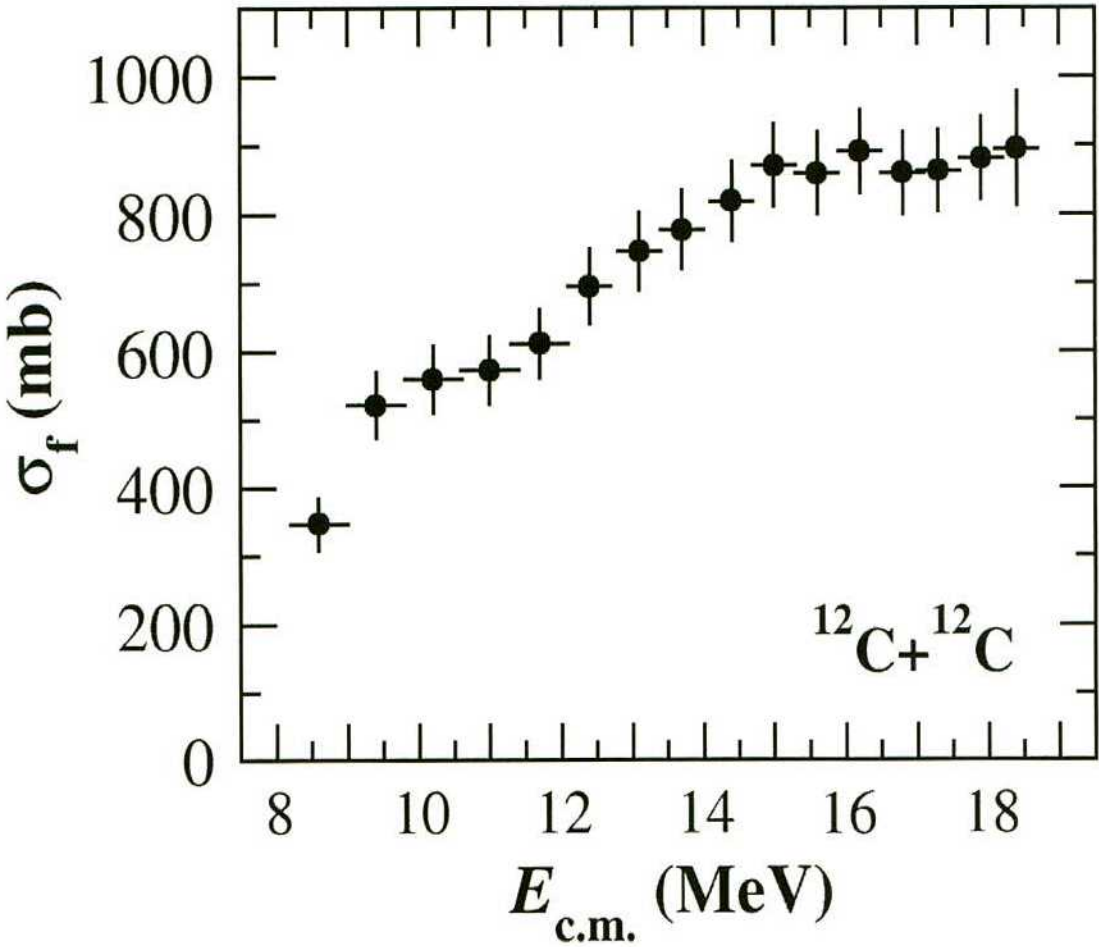


Figure 7.1. Experimental $^{12}\text{C}+^{12}\text{C}$ fusion excitation function from the present work.

For $^{14}\text{C}+^{12}\text{C}$ there is no evidence of structures in the present energy range. The excitation function shows a fall-off, as for the other cases. The uncertainties are, on average, of 7% in σ_f and 2% in $E_{\text{c.m.}}$.

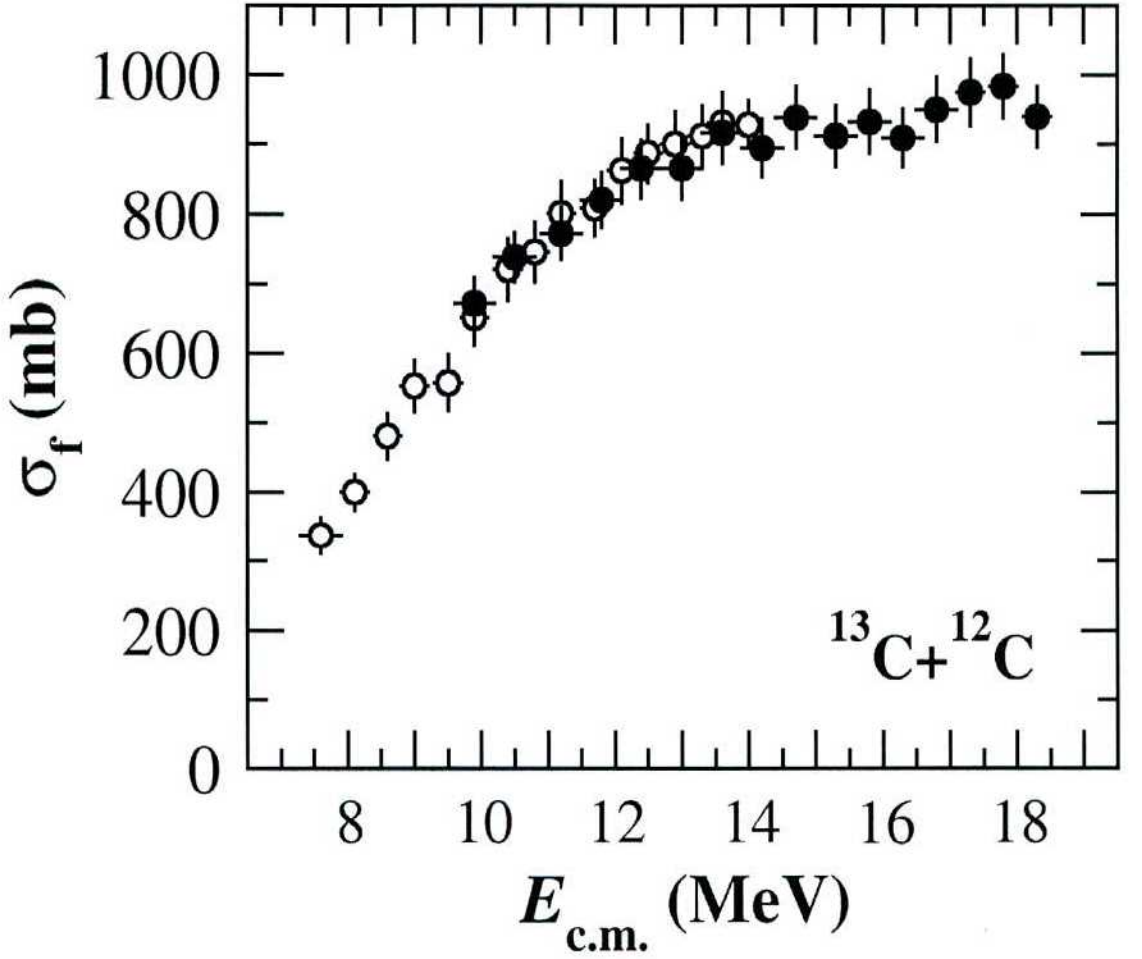


Figure 7.2. Experimental $^{13}\text{C}+^{12}\text{C}$ fusion excitation functions from the present work for two different beam energies. Solid circles: ^{13}C beam at 45 MeV. Open circles: ^{13}C beam at 36 MeV.

The experimental data for $^{10}\text{C}+^{12}\text{C}$ and $^{15}\text{C}+^{12}\text{C}$ are the first measurements obtained and are for the first time presented in this thesis in Figs. 7.4 and 7.5, respectively. The shape of the excitation functions is the same as for the other cases, meaning that there is a plateau at the higher energies and a fall-off in the lower energies.

In the $^{10}\text{C}+^{12}\text{C}$ excitation function, the fall-off is steeper than the ones observed in the other systems, but the uncertainties in σ_f are larger (18%, on average). The uncertainties in $E_{\text{c.m.}}$ are of the same order than the rest (2%, on average).

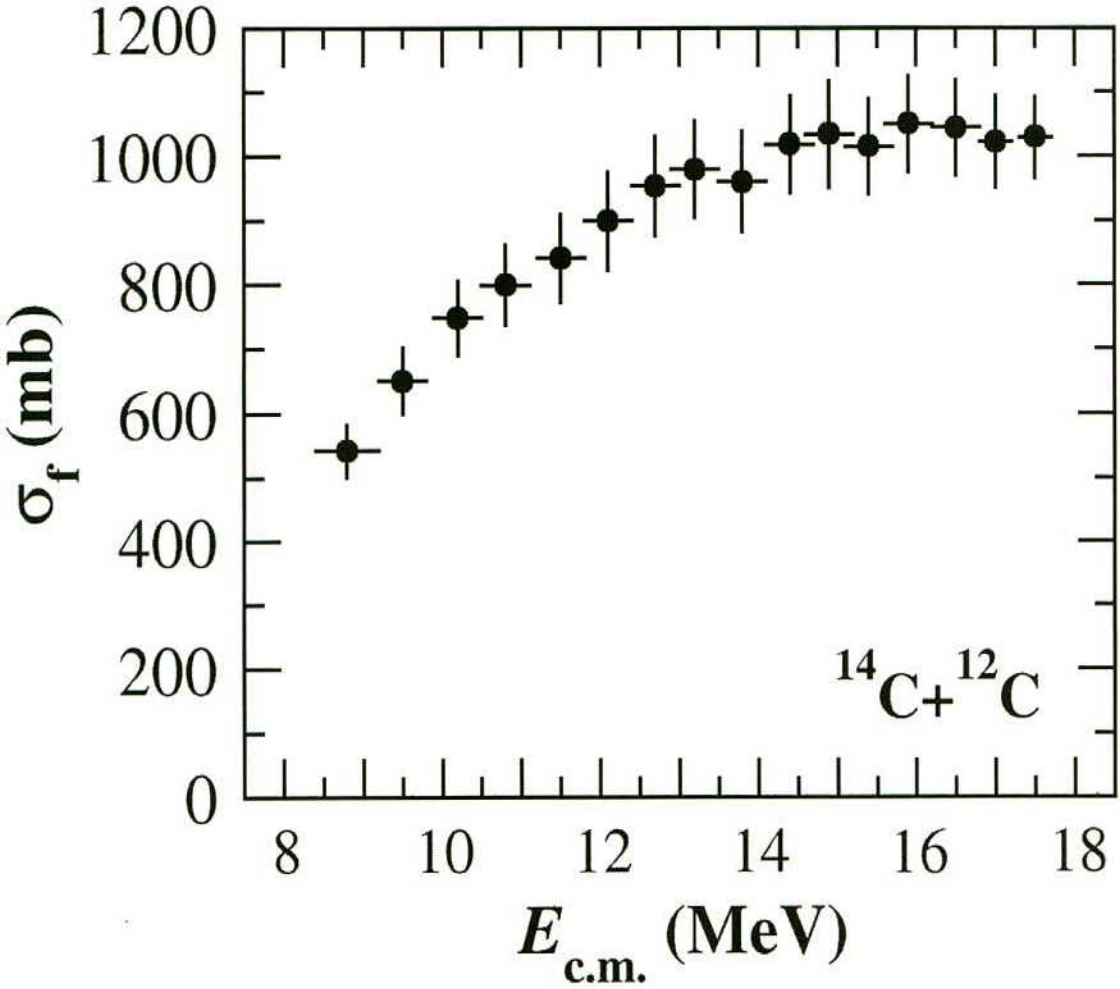


Figure 7.3. Experimental $^{14}\text{C}+^{12}\text{C}$ fusion excitation function from the present work.

For $^{15}\text{C}+^{12}\text{C}$, on the other hand, the plateau is quite flat considering that the average uncertainty on σ_f is about 12%. In this case, the fall-off is almost out of the measured energy range.

Actually, since we studied roughly the same energy range for all isotopes (see Table 5.1), there are variations in the extension of the plateau and the energy where the cross sections start falling. This can be associated with the barrier height B for each system: the cross sections begin falling when the energy gets close to the interaction barrier.

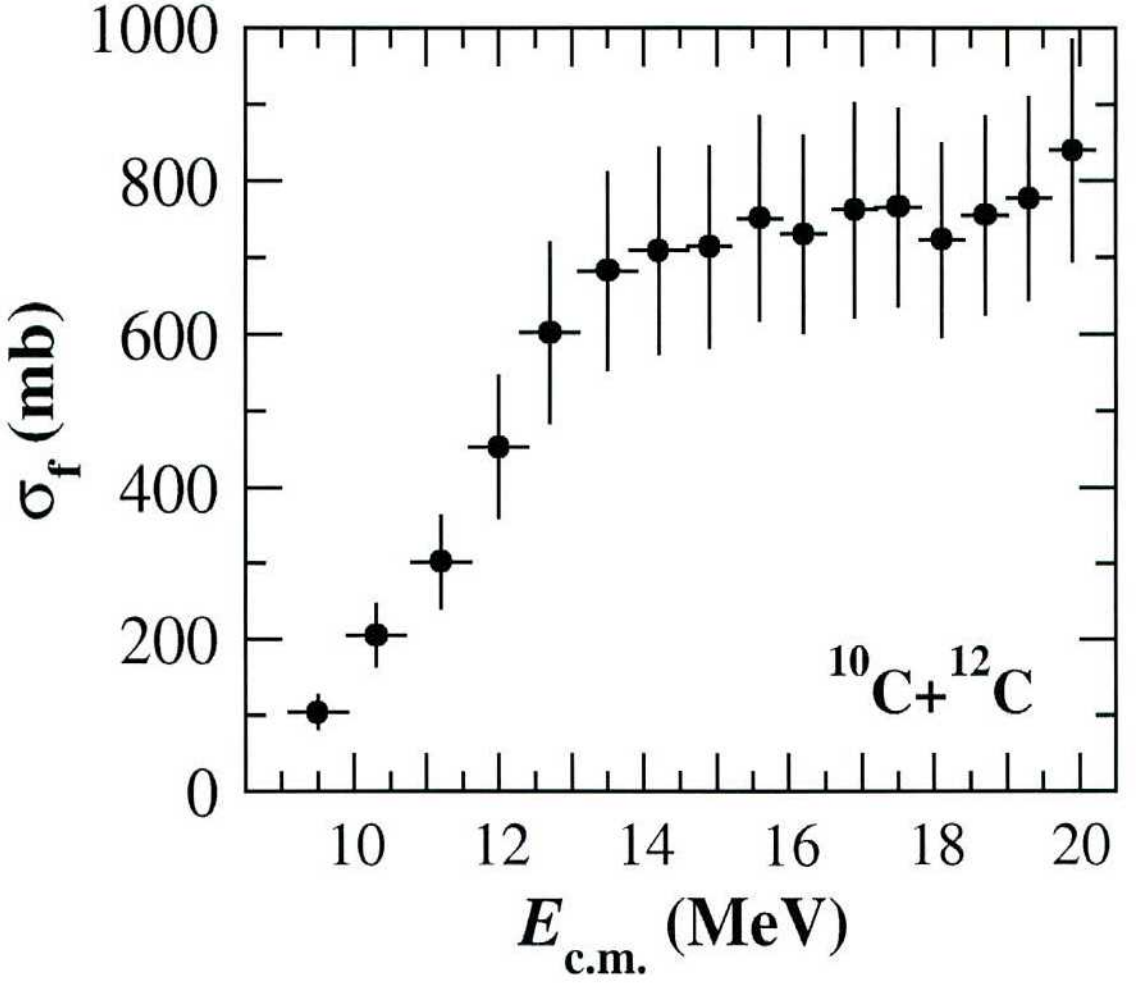


Figure 7.4. Experimental $^{10}\text{C}+^{12}\text{C}$ fusion excitation function from the present work.

To illustrate this we first calculated the average cross sections σ_{avg} in the range $E_{c.m.} = 14 - 17$ MeV (common to all measurements). Then, we define the energy E_{fall} where the fall-off starts as the one where the cross sections fall below 80% of σ_{avg} . Finally, we compared this energy to the values of the Coulomb barrier (calculated with Eq. (2.3)) and the interaction barrier height predicted by an empirical model [Bas74]. The result of this calculation is presented in Table 7.1. It is found that E_{fall} follows the same trend as the Coulomb or interaction barrier values, which decrease as the neutron number grows. The only exception is that E_{fall} for ^{14}C is higher than the value for ^{13}C . This could be possibly related to the fact that ^{14}C has a closed shell for neutrons. The data presented in Table 7.1 suggest that fusion might

be enhanced when neutrons are added to the carbon nucleus. This observation will be further discussed in the following Sections.

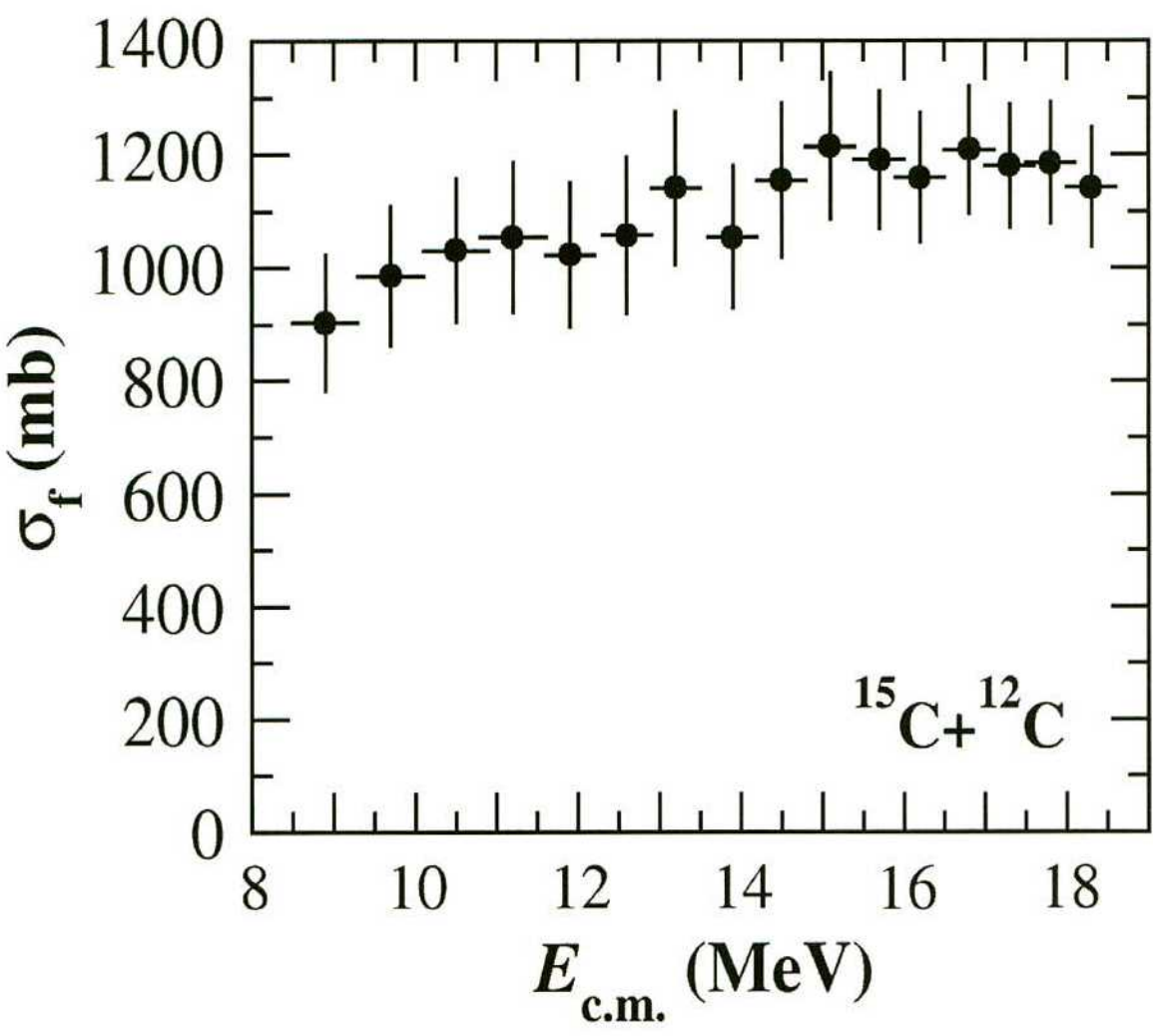


Figure 7.5. Experimental $^{15}\text{C}+^{12}\text{C}$ fusion excitation function from the present work.

In general terms, within the uncertainties and for the studied energy range, there are no hints of resonances and all the presented excitation functions vary rather smoothly as it was expected from the discussion in Sec. 2.3. Nevertheless, to confirm this statement, it is necessary to further reduce the uncertainties in the cross sections, especially for the $^{10,15}\text{C}$ cases where they are about 10-15% for the higher energies and 15-20% for the lower ones. These uncertainties are statistically dominated. Reducing them would imply higher beam intensity and/or longer beam

time, which are both beyond present capabilities. Solutions for this situation will be discussed in the next Chapter.

Table 7.1. Comparison of the energy value E_{fall} where the cross sections start falling (below $0.8\sigma_{\text{avg}}$), the Coulomb barrier of Eq. (2.3), and the interaction barrier height B from the empirical model of Ref. [Bas74]. The three values follow almost the same trend, with the exception of E_{fall} for ^{14}C , a nucleus which has a closed neutron shell. All values are in MeV.

Isotope	E_{fall}	V_{CB}	B
^{10}C	12.5	9.72	6.32
^{12}C	12.2	9.43	6.11
^{13}C	10.5	9.31	6.02
^{14}C	10.8	9.19	5.95
^{15}C	8.9	9.08	5.87

A comparison of the MUSIC results with previous experimental data is presented in Fig. 7.6. For the $^{12}\text{C}+^{12}\text{C}$ case (Fig 7.6a), our data agree with the previous experimental data set and thus confirm the existence of subtle structures that are not observed in the $^{12,13}\text{C}+^{13}\text{C}$ fusion systems (see Fig. 3.6, Fig. 7.6b, and next Section).

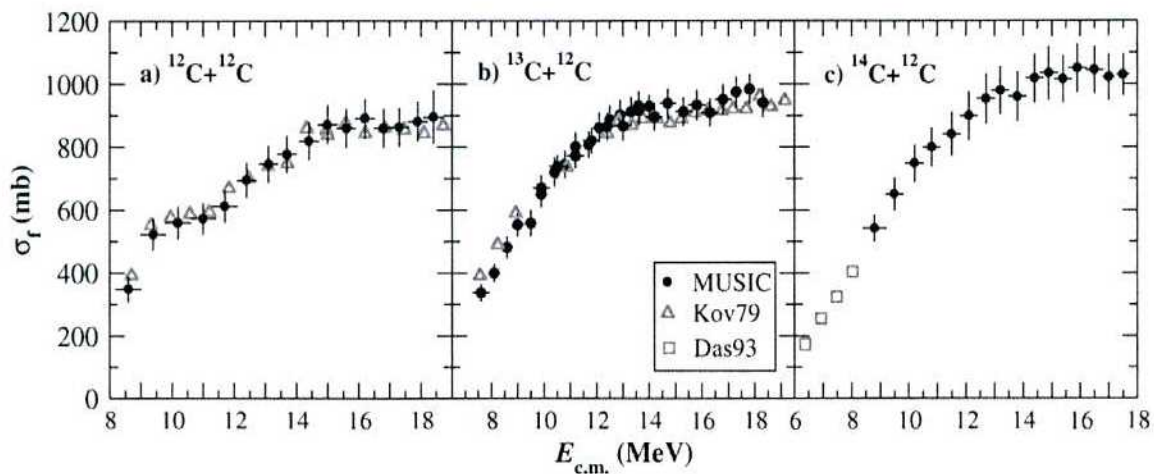


Figure 7.6. Experimental data comparison between results from the present work and from previous experiments.

For $^{13}\text{C}+^{12}\text{C}$ (Fig. 7.2b), there is also a very good agreement between our data (both measurements) and the experimental data from Ref. [Kov79].

The excellent agreement obtained in the comparison between the available data of previous experiments and those obtained here using the MUSIC detector, and applying the above-described data reduction procedure (Sec. 6.2), corroborates the novel measuring method developed in this work.

For $^{14}\text{C}+^{12}\text{C}$ there are some data points in the $5 < E_{\text{c.m.}} < 8$ MeV range [Das93], which are included in Fig. 7.6c for comparison with our values. The old and new data seem to be consistent, despite no actual overlap exists.

In the cases of the radioactive carbon beams ^{10}C , ^{14}C and ^{15}C , no previous data for the corresponding energy ranges are available. A comparison with theory will be given in the next Section.

To finish this Section, in Table 7.2 all the measured cross sections are listed, as a function of energy, with the corresponding uncertainties.

Table 7.2. Experimental values for the fusion cross sections and calculated values for the energies, with their corresponding absolute uncertainties.

^{12}C (45 MeV)					^{13}C (36 MeV)					^{13}C (45 MeV)				
$E_{\text{c.m.}}$ (MeV)	$\delta E_{\text{c.m.}}$ (MeV)	σ_{f} (mb)	$\delta \sigma_{\text{f}}$ (mb)		$E_{\text{c.m.}}$ (MeV)	$\delta E_{\text{c.m.}}$ (MeV)	σ_{f} (mb)	$\delta \sigma_{\text{f}}$ (mb)		$E_{\text{c.m.}}$ (MeV)	$\delta E_{\text{c.m.}}$ (MeV)	σ_{f} (mb)	$\delta \sigma_{\text{f}}$ (mb)	
8.6	0.4	348	38		7.6	0.3	337	26		9.9	0.3	671	38	
9.4	0.4	522	48		8.1	0.2	400	26		10.5	0.3	738	35	
10.2	0.4	560	49		8.6	0.2	481	33		11.2	0.3	772	37	
11.0	0.4	573	49		9.0	0.2	553	36		11.8	0.3	820	40	
11.7	0.4	612	50		9.5	0.2	558	40		12.4	0.3	865	42	
12.4	0.3	695	54		9.9	0.2	651	40		13.0	0.3	866	44	
13.1	0.3	746	56		10.4	0.2	720	44		13.6	0.3	916	44	
13.7	0.3	777	57		10.8	0.2	745	42		14.2	0.3	895	42	
14.4	0.3	819	58		11.2	0.2	801	45		14.7	0.3	939	45	
15.0	0.3	871	60		11.7	0.2	808	40		15.3	0.3	912	44	
15.6	0.3	859	60		12.1	0.2	862	46		15.8	0.3	933	46	
16.2	0.3	891	61		12.5	0.2	887	42		16.3	0.3	910	42	
16.8	0.3	860	60		12.9	0.2	901	46		16.8	0.3	951	46	
17.3	0.3	863	60		13.3	0.2	912	44		17.3	0.2	975	48	
17.9	0.3	881	60		13.6	0.2	931	45		17.8	0.2	984	45	
18.4	0.3	1679	83		14.0	0.2	929	35		18.3	0.2	940	44	

Table 7.2 (cont.). Experimental values for the fusion cross sections and calculated values for the energies, with their corresponding absolute uncertainties.

^{10}C (43 MeV)					^{14}C (45 MeV)					^{15}C (49 MeV)				
$E_{\text{c.m.}}$ (MeV)	$\delta E_{\text{c.m.}}$ (MeV)	σ_{f} (mb)	$\delta \sigma_{\text{f}}$ (mb)		$E_{\text{c.m.}}$ (MeV)	$\delta E_{\text{c.m.}}$ (MeV)	σ_{f} (mb)	$\delta \sigma_{\text{f}}$ (mb)		$E_{\text{c.m.}}$ (MeV)	$\delta E_{\text{c.m.}}$ (MeV)	σ_{f} (mb)	$\delta \sigma_{\text{f}}$ (mb)	
9.5	0.4	104	21		8.8	0.4	542	41		8.9	0.4	903	120	
10.3	0.4	205	40		9.5	0.3	651	51		9.7	0.4	986	123	
11.2	0.4	302	61		10.2	0.3	748	57		10.5	0.4	1031	126	
12.0	0.4	453	92		10.8	0.3	799	61		11.2	0.4	1054	132	
12.7	0.4	602	117		11.5	0.3	841	68		11.9	0.3	1023	127	
13.5	0.4	683	128		12.1	0.3	899	76		12.6	0.3	1058	137	
14.2	0.4	709	133		12.7	0.3	953	78		13.2	0.3	1141	134	
14.9	0.3	714	130		13.2	0.3	979	75		13.9	0.3	1054	125	
15.6	0.3	751	133		13.8	0.3	960	78		14.5	0.3	1153	135	
16.2	0.3	730	128		14.4	0.3	1018	76		15.1	0.3	1214	128	
16.9	0.3	762	139		14.9	0.3	1034	83		15.7	0.3	1190	121	
17.5	0.3	766	128		15.4	0.3	1015	74		16.2	0.3	1159	114	
18.1	0.3	723	125		15.9	0.3	1050	75		16.8	0.3	1208	112	
18.7	0.3	755	129		16.5	0.3	1044	74		17.3	0.3	1180	108	
19.3	0.3	777	132		17.0	0.2	1022	72		17.8	0.3	1185	106	
19.9	0.3	840	144		17.5	0.2	1029	64		18.3	0.3	1142	104	

7.2. Comparison with theoretical models

In this Section, the obtained experimental data are compared with the predictions obtained from coupled-channel calculations [Esb11] and from a recent analytical model for fusion reactions [Yak10].

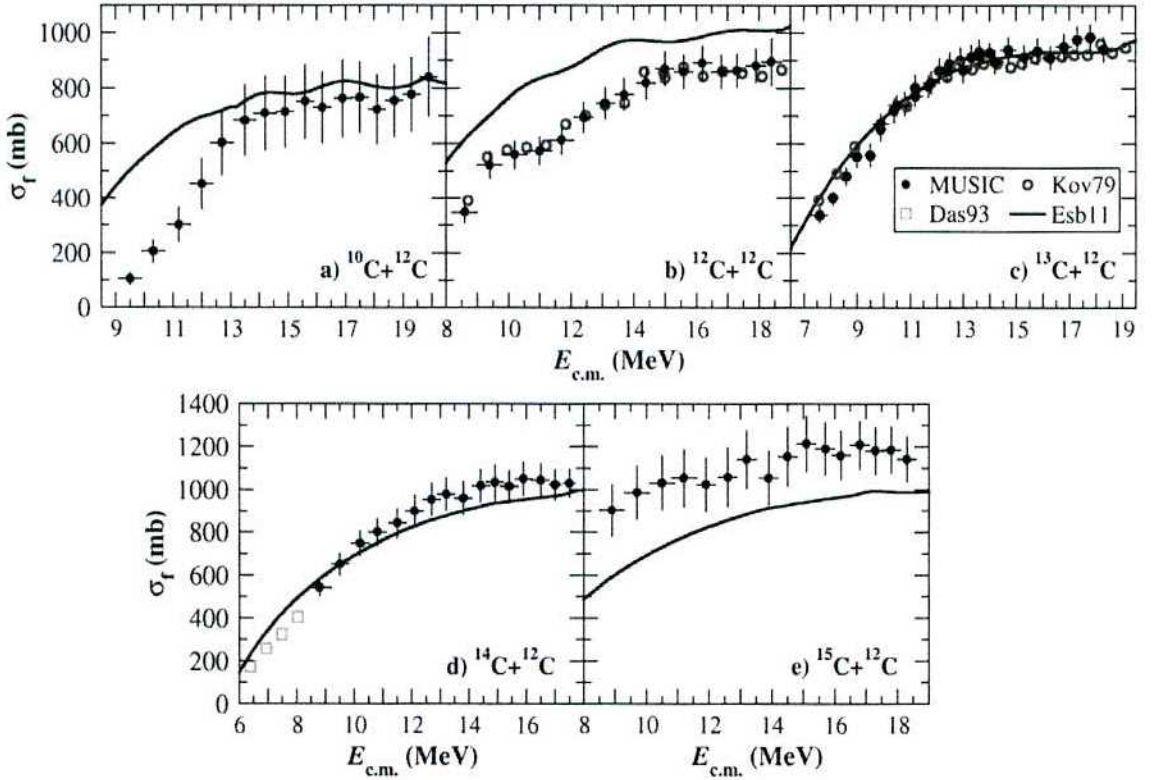


Figure 7.7. Comparison of experimental data with coupled-channels calculations. Solid circles: Experimental data for all the carbon fusion reactions measured with the MUSIC detector. Open symbols: Experimental data for $^{12,13,14}\text{C}+^{12}\text{C}$ from Refs. [Kov79, Das93]. Solid lines: Theoretical cross sections from Ref. [Esb11].

The model from Ref. [Yak10] gives the astrophysical S-factors for fusion in an analytic form in terms of four physically meaningful parameters: the height of the Coulomb barrier, the strength of the nucleon-nucleon interaction through the strong force, the peak broadening of the effective interaction barrier, and one parameter to describe the transition from sub-barrier energies to energies above the Coulomb barrier. The parameters of the potential were fitted to a large number of reactions

involving stable and unstable nuclei calculated with the Saõ Paulo Potential (SPP) and the barrier penetration model (see Chapter 2).

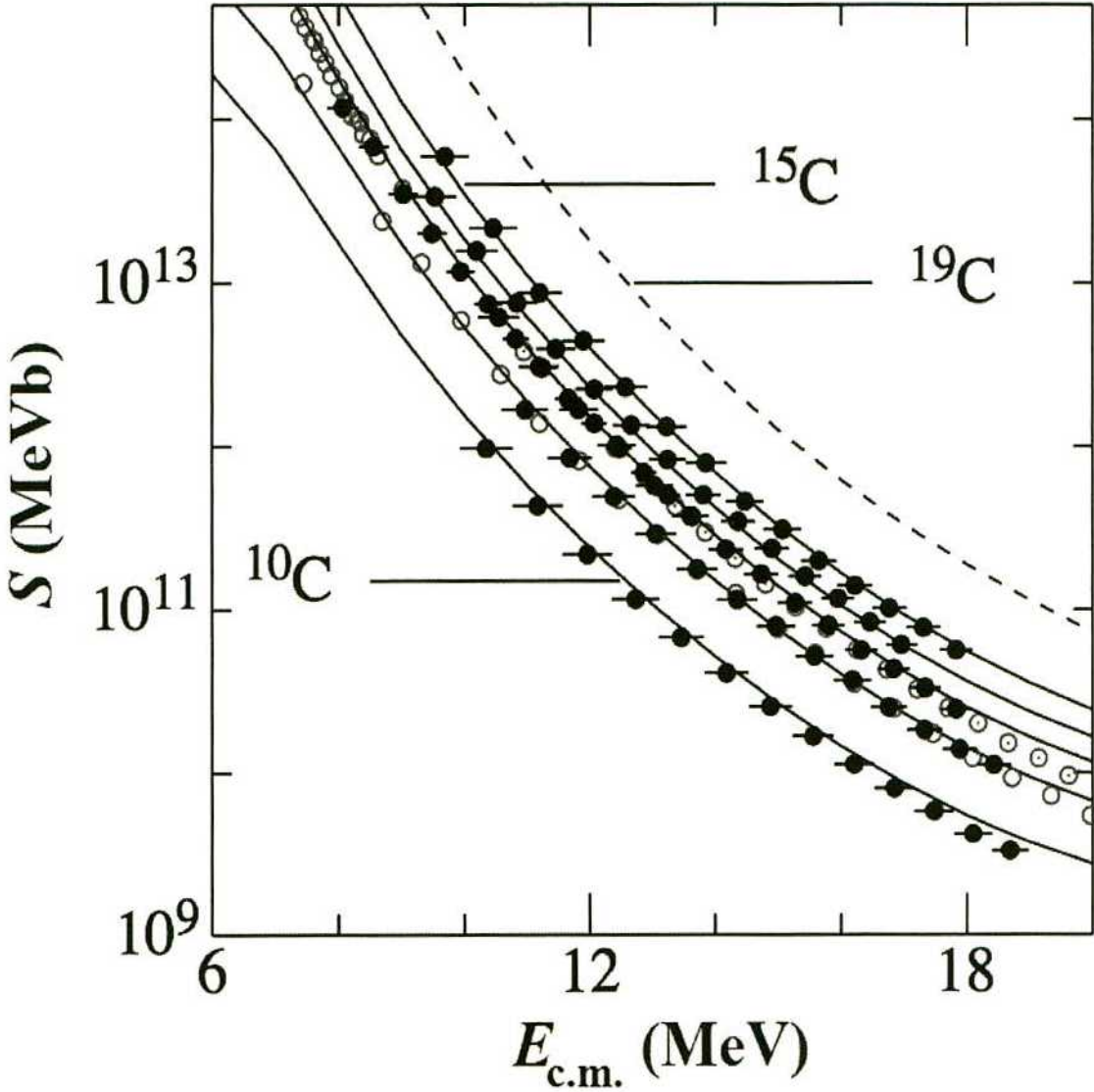


Figure 7.8. Comparison of experimental data with an analytical fusion model. Solid circles: Experimental data for the S-factors in the carbon fusion reactions measured with the MUSIC detector. Open circles: Experimental data for $^{12,13}\text{C}+^{12}\text{C}$ from Ref. [Kov79]. Solid lines: Theoretical S-factors for the studied systems obtained with the model of Yakovlev et al. [Yak10]. Dashed line: Theoretical S-factors for the system $^{19}\text{C}+^{12}\text{C}$, also from Ref. [Yak10].

In Fig. 7.7 we compare our results with the predictions from coupled-channel calculations of Ref. [Esb11]. These calculations were done using a double-folding potential. They also include couplings to one- and two-phonon excitations as well as mutual quadrupole and octupole excitations in projectile and target. There is a good

agreement with our experimental data, at least with respect to the shapes of the excitation functions. The $^{13}\text{C}+^{12}\text{C}$ system is the best reproduced by the calculations. There is still a disagreement for $^{12}\text{C}+^{12}\text{C}$ in the energy range studied in this work that was already observed in the previous data from Ref. [Kov79]. There is a good agreement for the $^{14}\text{C}+^{12}\text{C}$ system, which is not seen for the other radioactive beams. For $^{10}\text{C}+^{12}\text{C}$ there is a 100% overestimation of the experimental cross sections up to $E_{\text{c.m.}} = 12$ MeV. Finally, the cross sections for $^{15}\text{C}+^{12}\text{C}$ are underpredicted by about 20%, on average, over the whole energy range.

In Fig. 7.8, we include the fusion cross sections for all the studied carbon systems converted to astrophysical S-factors (solid circles) and the calculations from the Yakovlev et. al model (solid lines). The red circles are the data for the $^{12,13}\text{C}+^{12}\text{C}$ systems from Ref. [Kov79]. Also shown, as a dashed line, is the theoretical prediction for a ^{19}C beam, which is the heaviest carbon isotope to be available at the next generation *FRIB* facility [MSU14] with intensities exceeding 10^3 particles/s.

The overall agreement between the experimental data and the model predictions is very good, even for radioactive beams. However, there is an overestimation of about 10% at higher energies ($E_{\text{c.m.}} \geq 14$ MeV). Of course we must take into account that this is a phenomenological model with parameters fitted to cross sections generated with the SPP, and no actual experimental data so far.

In the next Section, we will analyze the dependence of the fusion cross sections with the neutron number, by means of the average cross section.

7.3. Analysis of the average fusion cross sections

To further compare the MUSIC detector data with experiments and calculations, we averaged the fusion cross sections over the $14 < E_{\text{c.m.}} < 17$ MeV energy range. The energy region was chosen to lie within the plateau of the measured excitation functions of all data sets.

For the comparison, we will plot the cross sections as a function of the *neutron excess* $N - Z$, which is a standard way for assessing the effect of neutrons in nuclear interactions.

After averaging, we calculated the *reduced cross sections* σ_{red} defined as:

$$\sigma_{\text{red}} = \frac{\sigma_f}{\pi R^2}, \quad (7.1)$$

where $R = 1.2(A_a^{1/3} + A_A^{1/3})$ fm. This conversion takes standard geometrical size effects into account.

Although we eliminated the geometrical effects by using Eq. (7.1), the reduced fusion cross sections for the carbon isotopes experience an additional 20% increase going from ^{10}C to ^{15}C , as shown in Fig 7.9. A similar increase is observed for fusion of ^{12}C with the neighboring stable nitrogen and oxygen isotopes, also shown in Fig 7.9. For these elements, however, the increase occurs in one step, going from $N - Z = 0$ ($1p$ shell) to $N - Z = 1$ ($2s1d$ shell) isotopes. Therefore, there is no hint in the new experimental data for an effect similar to the one seen in $^{15}\text{N}+^{12}\text{C}$ (also shown in Fig. 3.5).

A comparison between theoretical and experimental average fusion cross sections σ_{avg} for all the systems studied in this work is shown in Fig. 7.10. The solid line is the prediction of Yakovlev et al. [Yak10], which in the mass range ^{12}C - ^{15}C agrees with the data to better than 4%, but overpredicts the average cross section for $^{10}\text{C}+^{12}\text{C}$ by about 13%. The dashed line is the prediction of coupled-channel calculations by Esbensen et al. [Esb11]. These average cross sections are also in good agreement, better than 10%, for all carbon isotopes (including ^{10}C) with a somewhat shallower slope of σ_{avg} towards the heavier carbon isotopes. The dotted curve for $^{12,13,14}\text{C}$ ($N - Z = 0,1,2$) is the result of a time dependent Hartree-Fock calculation from Umar et al. [Uma12]. These values are generally larger than the experimental cross sections, due to the fact that TDHF calculations describe the sum of fusion and transfer channels.

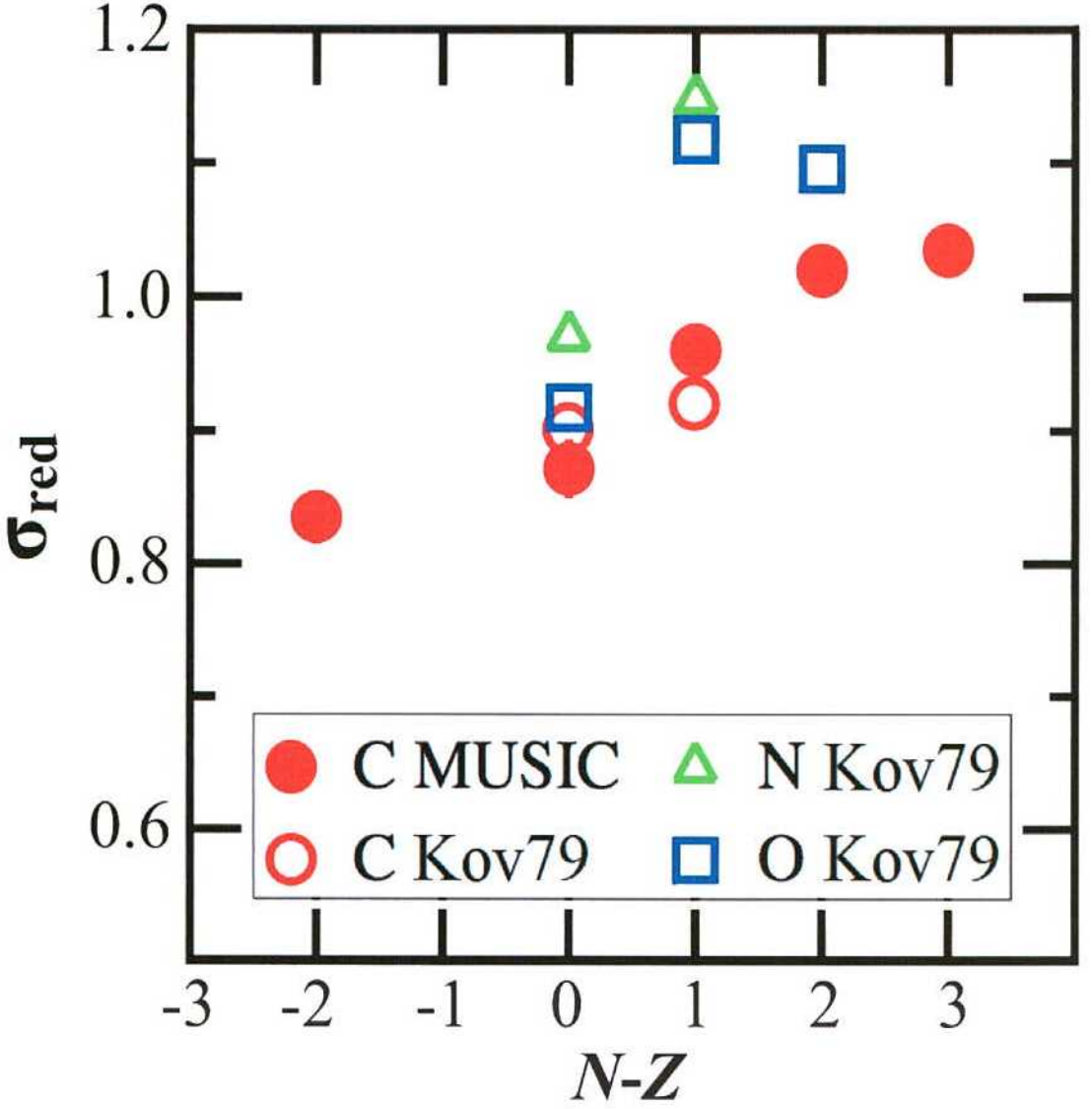


Figure 7.9. Experimental reduced cross sections σ_{red} as a function of neutron excess $N - Z$. Solid circles: Reduced cross sections (see text for details) averaged in the energy range $14 < E_{\text{c.m.}} < 17$ MeV for the carbon fusion reactions studied with the MUSIC detector. Open symbols: Experimental data for $^{12,13}\text{C}+^{12}\text{C}$ (red circles), $^{14,15}\text{N}+^{12}\text{C}$ (green triangles) and $^{16,17,18}\text{O}+^{12}\text{C}$ (blue squares) from Ref. [Kov79].

It has been argued that the dynamics of the neutron-rich skin might lead to a striking enhancement of the fusion cross sections [Uma12]. While this has been found in, for example, the fusion of $^{15}\text{C}+^{232}\text{Th}$ [Alc11] at energies in the vicinity of the Coulomb barrier, no effect has been seen in the interaction cross sections obtained from high-energy C+C scattering of Ref. [Oza01] (both mentioned in Sec. 3.2). In this work we observed the mentioned 20% increase in σ_{red} comparing ^{15}C with ^{10}C (Fig.

7.9), which is underestimated by models (Fig. 7.10). This might be a suggestion that fusion is actually enhanced by the ^{15}C neutron structure.

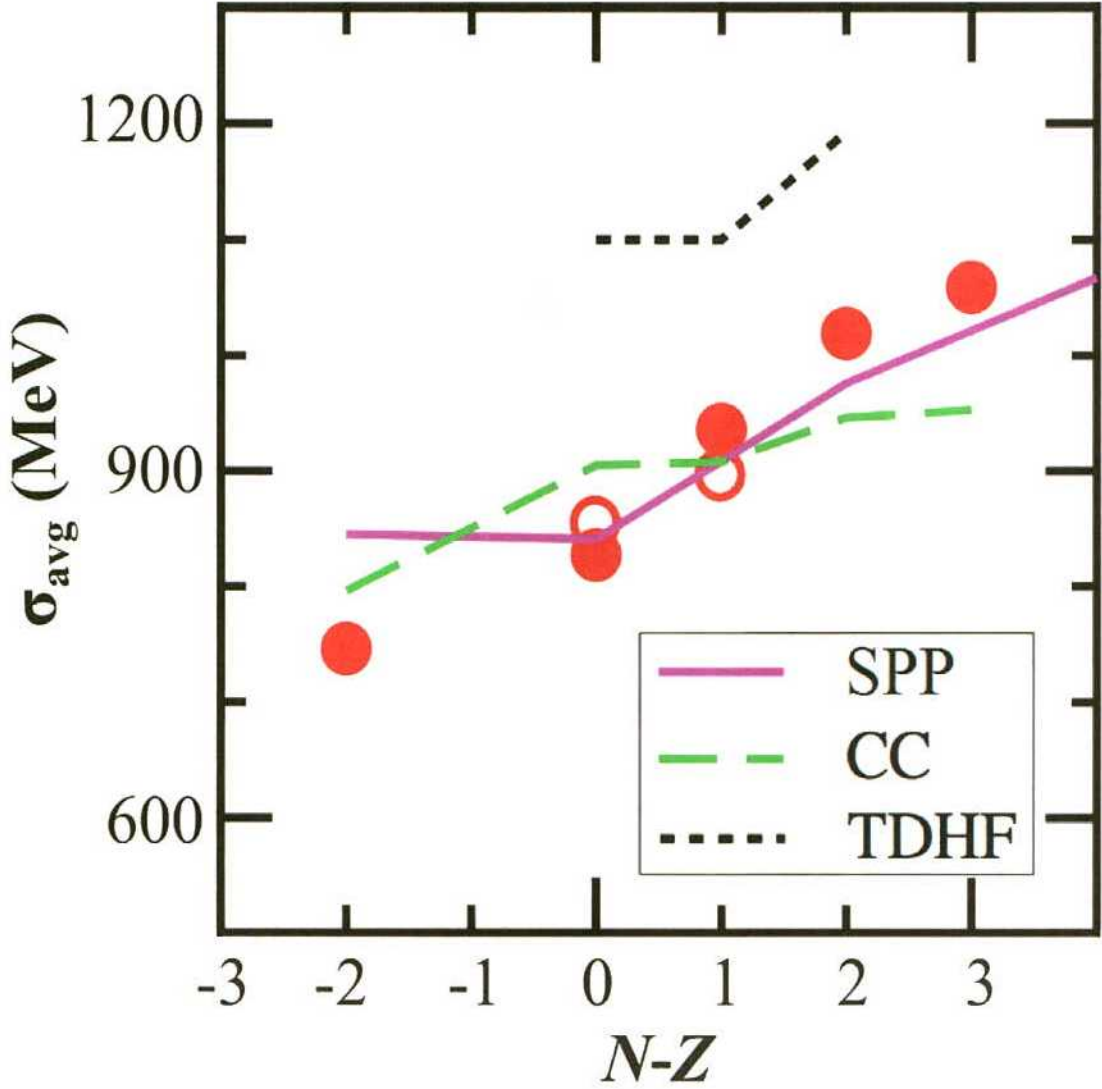


Figure 7.10. Comparison of the experimental averaged cross sections for the studied carbon systems with theoretical predictions. Solid circles: experimental data obtained with the MUSIC detector. Open circles: experimental data from Ref. [Kov79]. Solid line (SPP): prediction from the model of Yakovlev et al. [Yak10]. Dashed line (CC): cross section predicted by coupled-channels calculations from Ref. [Esb11]. Dotted line (TDHF): cross section predicted by time-dependent Hartree-Fock calculations [Uma12].

The good agreement between theoretical predictions and experimental data is very encouraging, both for the understanding of the fusion process as for astrophysical applications. For example, fusion reactions occurring in the crust of neutron stars, such as $^{24}\text{C}+^{24}\text{C}$, will remain outside of our experimental capabilities

for the foreseeable future. Comparisons between theory and experiment, like the one presented here, allow calibrating the calculations for cases that cannot be studied in the laboratory.

Taking into account the considerations made on Chap. 6 and the evidence presented so far in this Chapter, it is possible to conclude that the MUSIC detector is a powerful and reliable tool for the measurement of fusion excitation functions in low-mass systems. This fact opens a wide range of experiments that can be studied in the future, especially with radioactive beams.

CHAPTER 8

CONCLUSIONS

Over the last few years much effort has been devoted to understand the nuclear processes that create the elements in the Universe. It is evident that the progress in this field comes from experimental facilities as well as from simulating the complex nuclear reaction networks. In the first case, the development of new ion beam techniques and detection/identification systems made possible measurements of extremely-low cross sections at energies occurring in stellar environments, that were deemed impossible two or three decades ago. In the second case, the arrival of supercomputers allows us to identify nuclear paths that are critical to nucleosynthesis, to develop models of nuclear reactions and to produce reliable estimates of the reaction rates.

Contributing to this scientific development, in the present report we presented a novel detector and experimental method for obtaining fusion excitation functions efficiently. In this respect, a summary of the main properties of the MUSIC detector is given in Sec. 8.1, followed by some ideas on how to further improve the technique. We then review the experimental results in Sec. 8.2. The results obtained so far are encouraging and show the potential of the MUSIC detector for studying fusion in other nuclear systems, which will be discussed in Sec. 8.3.

8.1. Performance of the MUSIC detector

We have obtained fusion excitation functions using a new, high-efficiency gaseous detector with a segmented anode. This allowed us to determine in a single

measurement a large part of the excitation function, thus saving considerable time and eliminating difficulties with the relative normalization of the cross sections.

The performance of the MUSIC detector was tested offline with alpha particles and then in experiments with stable $^{12,13}\text{C}$ beams. The agreement with data from the literature was very good.

In addition to the test experiments, the Monte Carlo simulations using the code FLUKA were extremely useful, especially for understanding how to identify the most important nuclear processes and how to extract the fusion cross sections. In this way, we obtained a full characterization of the detector that we can use to predict its response in future experiments (see Sec. 8.3 for some examples).

The performance of the detector was exceptional for the beams used in the present experiments. This includes the ionization gas, the electronics and the acquisition system. In the first case, the gas handling system was very important for guaranteeing a uniform gas density, thus reducing the uncertainty in the cross sections. On the other hand, the electronics and DAQ configuration permitted the data analysis on a multiparameter, event-by-event basis and the separation of the particles of interest when contaminants were present in the beam.

Of course, the most important part of elimination of the beam contaminants could only be achieved through the use of new RIB production systems at the ATLAS in-flight facility. In particular, the RIB sweeper was used for the first time and was found to work in a reproducible manner. In this way it was possible to obtain a rather clean beam with a high rate of one-particle bunches.

The main downside of the MUSIC detector is the relatively low beam rates it can tolerate due to the requirement of having only one particle per bunch. However, in Sec. 5.3 we saw that it was possible to increase the rate of these events at the cost of a higher acquisition dead time (see Fig. 5.9). A method for avoiding this is placing a transmission detector (either gaseous or solid) that can operate at higher count rates in front of the MUSIC detector. In this way, it is possible to filter out bunches with two or more particles. This can be achieved by setting a veto signal produced when the transmission detector identifies an undesired event. Then, the total rate

can be raised and the acquisition system will only process the events of interest (one particle per bunch), thus preventing dead time.

In Sec. 6.1, we saw from the simulations that it was not possible to determine the yields of each particular ER element separately, but only the sum of all. That was because the energy losses in a trace not only depend on the ion species but also on the evaporation angle. However, with the information provided by both sides of the strips we actually get only a projection of the trajectories on the anode plane. So, for reconstructing a complete trajectory we would also need the particle distance to the anode. This can be obtained measuring the elapsed time from a signal in strip 0 (a particle enters the detector) and a signal in strip s , which we call Δt_s . Since we know the distance between strips and the energy (velocity) of the particle, we can estimate Δt_s . But, actually, if we have a nanosecond time resolution we can determine the additional time contribution coming from the drift of the ionization electrons to the anode. This drift time is associated to the distance of the particle to the anode. Then, comparing the measured Δt_s with its expected value we can get, strip-by-strip, the distance to the anode and use it to reconstruct the particle trajectory and find out the evaporation angle of a residue. In practice, this is done using a multi-channel time to amplitude converter. The *Phillips 7186* is a commercial electronic module that fulfills the requirements mentioned above (common start, 16 channels, and 25 ps resolution).

8.2. The experimental excitation functions

The excitation functions measured in the present work were obtained with carbon beams (of masses $A = 10, 12, 13, 14, 15$) at laboratory energy of about 3.5 MeV/nucleon, on average. The center of mass energy range was between about 9 and 18 MeV. This range is slightly above the Coulomb barrier (around 9 MeV, using the standard definition of Eq. (2.3)). It is also above typical values of the interaction barrier heights given by empirical models (around 6 MeV, see Table 7.1).

8. CONCLUSIONS

For that reason, we expected to see excitation functions without significant structures (such as wide resonances). Even more, the excitation functions should have a regular shape, i.e. constant at higher energies and perhaps showing a fall-off towards the lowest values of the studied energy range. The observed behavior confirmed these expectations, with $^{12}\text{C}+^{12}\text{C}$ being an exception, since the corresponding excitation function showed hints of a periodical structure, repeating every 3 MeV, superimposed on an anticipated smooth shape.

The other excitation functions are indeed smooth. They present the described fall-off, but at energies that are different for each system. The fall-off in the fusion cross section values are demonstrated to be related to the presence of the interaction barrier. As a matter of fact, we have seen (in Table 7.1) that the energies where the fall-offs started are strongly correlated to the mentioned barrier heights. This happens for all systems except for $^{14}\text{C}+^{12}\text{C}$, where the ^{14}C beam has a magic neutron number.

Other slight variations from the rather usual behavior of the excitation functions appear in the $^{10}\text{C}+^{12}\text{C}$ and $^{15}\text{C}+^{12}\text{C}$ systems. In the former, a steeper fall-off is observed, and in the latter the fall-off seems to happen at energies outside of the measured range (this is likely to happen for the reasons discussed in the last paragraph). Anyhow, both cases have the highest uncertainties in the cross sections (18% for ^{10}C , 12% for ^{15}C), and this has to be taken into account in the discussions.

The uncertainties in the cross sections (statistically dominated) were somewhat lower for the rest of the systems due to higher primary beam intensities. On average, these uncertainties were of: 8% for ^{12}C , 6% for ^{13}C , and 7% for ^{14}C . There is also included a systematic contribution of about 1% in these uncertainties, coming from the calculation of the ionization gas density and from the natural fraction of ^{13}C in methane.

On the other hand, the uncertainties on the energy values of the excitation functions are systematic and were estimated to be of 2%, on average, for all systems.

As already mentioned, the excitation functions for the $^{12}\text{C}+^{12}\text{C}$ and $^{13}\text{C}+^{12}\text{C}$ systems [Kov79] have been successfully reproduced. We can affirm something

similar for $^{14}\text{C}+^{12}\text{C}$ where we found consistency with previous data [Das93], although there is not an actual overlapping. On the other hand, in this work we obtained for the first time a data set for this system in the medium-energy range.

It is also the first time that fusion cross sections using radioactive ^{10}C and ^{15}C beams on a ^{12}C target have ever been obtained experimentally.

The comparison with three different models shows a good agreement. The three of them are state-of-the-art models, going from a rather simple 1D barrier-penetration with fitted parameters [Yak10], through a well-known coupled-channels approach [Esb11], to a complex dynamical Hartree-Fock calculation with many internal degrees of freedom [Uma12].

The coupled-channel calculations, including one- and two-phonon couplings, proved to be especially accurate in the $^{13,14}\text{C}+^{12}\text{C}$ systems, but showed important deviations in the rest (about 10%). Meanwhile, we obtained a good agreement with tunneling calculations using the São Paulo Potential, except for the ^{10}C results (a 13% overestimation). Finally, the time-dependent Hartree-Fock estimations showed the poorest agreement perhaps caused by the inclusion of transfer reactions in the definition of fusion cross sections. This led them to be above our cross sections by a 20%, though showing the same trend.

As a conclusion, we can state that the carbon fusion cross sections show a smooth increase with neutron excess. This increase was of 20%, going from ^{10}C to ^{15}C . Even more, no odd behavior was observed so far in the studied energy range, as the one present in $^{14,15}\text{N}+^{12}\text{C}$ systems, which differ by only one neutron as in the case of $^{14,15}\text{C}+^{12}\text{C}$.

8.3. Perspectives

The present work has opened a wide range of possibilities for measuring fusion excitation functions in other systems. Indeed, the high efficiency of the active target, implemented in this thesis through the development of the MUSIC detector, makes this technique ideal to address many nuclear physics quests of astrophysical

interest. These processes still remain as the main unknown parameters for quantitatively describing the quiescent and explosive stellar nucleosynthesis. Moreover, in combination with the radioactive beams available at the ATLAS facility, the present knowledge of the reaction processes between stable nuclei can be expanded to numerous radioactive nuclides.

As a continuation of the present work, current efforts are being made at ATLAS for producing a ^{16}C beam. So far, an intensity of 10^3 particle/s was obtained. This intensity is on the threshold for an acceptable MUSIC experiment. After the facility upgrade that is ongoing, this option will be probably available.

In close relation with this work, ^{13}C -enriched methane ($^{13}\text{CH}_4$) is available on the market. This would allow for measurements with a ^{13}C target. It is also possible to produce $^{14}\text{CH}_4$, but this cannot be used currently in the laboratory for radiological safety reasons.

We can also think about other gases to act as an active target. For example, for continue researching on reactions related to X-ray superbursts, it would be interesting to study neutron-rich O+O and Ne+Ne fusion. In this case, oxygen cannot be used as a counting gas for its large electron affinity, which produces much recombination [Kno89], leaving us with neon as a valid option.

From the astrophysics point of view, neon isotopes are thought to be more abundant than oxygen, and even carbon, in neutron stars crusts [Ili07]. The *Program Advisory Committee* of ANL has already accepted an experiment with the MUSIC detector for measuring neon fusion reactions. The beams to be used are the stable isotopes $^{20,22}\text{Ne}$ and the radioactive ^{24}Ne , on ^{20}Ne - and ^{22}Ne -enriched gaseous active targets.

We can also think in measuring at lower energies than the ones studied here. In Sec. 4.2 we discussed the complications found in the ATLAS facility (and other current accelerator facilities) to produce a high-intensity beam of very-low energies. However, we performed a FLUKA simulation of a 12 MeV ^{12}C beam on the MUSIC detector with an ionization gas pressure of 25 mbar. This beam would reach strip 1 with 6 MeV (losing 6 MeV in the entrance window, dead volume of gas and strip 0).

Then, the excitation function would be sampled in the $E_{\text{c.m.}} \approx 0.5 - 3$ MeV range. In this case, the energy loss would be 0.4 MeV, on average, on each strip. So, if this beam could be feasible at ATLAS with an acceptable intensity, and sufficient beam time was available, it might be possible for the MUSIC technique to obtain an excitation function in this energy regime.

In this thesis, we have demonstrated that the MUSIC detector is a powerful device for the measurement of fusion reactions with radioactive beams. This program will continue giving valuable information about the fusion process in the upcoming years.

As for the new data, it is hoped that it will help the scientific community to improve the fundamental understanding of the fusion mechanism, especially how nuclear structure affects the fusion process in low-mass systems.

Even though we obtained data in a region away from the energies of astrophysical interest, they are still useful for an extrapolation leading to a better explanation of the X-ray superburst phenomenon.

8. CONCLUSIONS

CONCLUSIONES

En los últimos años se ha dedicado un gran esfuerzo para entender los procesos nucleares por los que se crean los elementos en el Universo. Es evidente que el progreso en este campo viene tanto de las instalaciones experimentales como también de la simulación de redes complejas de reacciones nucleares. En el primer caso, el desarrollo de técnicas de producción de haces radiactivos y de novedosos sistemas de detección/identificación hacen posible la medición de secciones eficaces extremadamente bajas a energías usuales en ambientes estelares, que eran consideradas imposibles dos o tres décadas atrás. En el segundo caso, la existencia de supercomputadoras permite identificar caminos nucleares críticos en la nucleosíntesis, desarrollar modelos de reacciones nucleares y producir estimaciones confiables de tasas de reacción.

Para contribuir a este desarrollo científico, en el presente informe presentamos un método experimental ingenioso para la obtención eficiente de funciones excitación de fusión. En este orden, resumimos las características principales del detector MUSIC en la Sec. 8.1, seguido de algunas ideas para perfeccionar la técnica. Luego, en la Sec. 8.2 sintetizamos los resultados experimentales obtenidos. Ciertamente, estos resultados son alentadores y mostraron el potencial del detector MUSIC para estudiar la reacción de fusión en otros sistemas nucleares, que serán discutidos en la Sec. 8.3

8.1. Desempeño del detector MUSIC

Hemos obtenido las funciones excitación de fusión usando un nuevo detector gaseoso de alta eficiencia con ánodo segmentado. El mismo nos permitió determinar una gran parte de las funciones excitación en una sola medición, ahorrando de esta

manera una cantidad de tiempo considerable y eliminando las dificultades que provienen de la normalización relativa de las secciones eficaces.

El desempeño del detector MUSIC fue probado primero con una fuente de partículas alfa y luego en los experimentos con haces estables de $^{12,13}\text{C}$. El acuerdo con los datos disponibles en la literatura fue excelente.

Además de los experimentos de prueba mencionados, las simulaciones Monte Carlo con el código FLUKA fueron de extrema utilidad, especialmente para entender cómo identificar los procesos nucleares más importantes y luego extraer las secciones eficaces de fusión. De esta manera, conseguimos una caracterización completa del detector que podemos usar para predecir su respuesta en futuros experimentos (algunos ejemplos serán presentados en la Sec. 8.3).

La respuesta del detector fue excepcional para los haces utilizados. En esto se incluyen el gas de detección, la electrónica y el sistema de adquisición (DAQ, por su acrónimo en inglés). En el primer caso, el sistema de control de gases fue muy importante para garantizar la uniformidad de la densidad del gas, reduciendo de esta manera la incerteza en las secciones eficaces. Por otro lado, la configuración de la electrónica y el DAQ permitió el análisis multiparamétrico, evento por evento, de los datos y la separación de las partículas de interés cuando se encontraron contaminantes en el haz.

Por supuesto, la principal remoción de contaminantes fue sólo posible con el uso de los nuevos sistemas de producción de haces radiactivos de la instalación ATLAS. En particular, se utilizó por primera vez un generador de campo eléctrico variable (llamado *RIB sweeper*) dedicado a esta tarea. El mismo se puede utilizar ahora de manera confiable y consistente. De esta manera, se pudieron obtener haces relativamente libres de contaminantes con las características especiales que el detector MUSIC necesita (una alta intensidad de pulsos de haz conteniendo una sola partícula).

La principal desventaja del detector MUSIC es la relativa baja intensidad de partículas que tolera, dado el requerimiento de una sola partícula por pulso de haz. De todas formas, en la Sec. 5.3 vimos que es posible aumentar la tasa de estos pulsos

con el costo de tener una alta tasa total, y por lo tanto un alto tiempo muerto de adquisición (ver la Fig. 5.9). Una forma de evitar esto es situando frente al detector MUSIC un detector de transmisión (sólido o gaseoso) que tolere altas tasas de conteo. De este modo, es posible filtrar los pulsos con dos o más partículas. Esto se consigue con una señal de veto producida cuando el detector de transmisión identifica un evento no deseado. Entonces, la tasa total de partículas puede ser elevada y el sistema de adquisición sólo procesará los eventos de interés (de una partícula por pulso), previniendo así el tiempo muerto.

En la Sec. 6.1, vimos con las simulaciones que no era posible determinar las secciones eficaces de producción de cada residuo de evaporación por separado, sino la suma de todos ellos. La causa de esto es que las pérdidas de energía dentro del detector no sólo dependen de la especie iónica sino también del ángulo de evaporación. Pero solamente con la información dada por ambos lados del ánodo se obtiene en realidad una proyección de las trayectorias sobre el plano del mismo. Para reconstruir una trayectoria completa necesitaríamos también la distancia de la partícula al ánodo. Esto se puede obtener midiendo el lapso de tiempo entre una señal en el segmento 0 (cuando una partícula entra en el detector) y una señal en el segmento número s , tiempo al que llamaremos Δt_s . Dado que conocemos la distancia entre segmentos y la velocidad (en realidad, la energía) de la partícula, podemos estimar Δt_s . Pero si además contamos con una buena resolución temporal (del orden de los nanosegundos), entonces es posible determinar el tiempo de deriva hacia el ánodo de los electrones producidos en la ionización. Este tiempo de deriva está asociado a la distancia de la partícula al ánodo. Luego, comparando la medición de Δt_s con su valor esperado podemos obtener, segmento por segmento, la distancia al ánodo y usarla para reconstruir la trayectoria de la partícula, especialmente el ángulo de eyección de un residuo de evaporación. En la práctica, esto se hace usando un conversor tiempo-amplitud multicanal. El módulo electrónico *Phillips 7186* está disponible en el mercado y posee los requisitos mencionados (inicio común, dieciséis canales y resolución temporal de 25 ps).

8.2. Sobre las funciones excitación experimentales

Las funciones excitación medidas en el presente trabajo fueron obtenidas con haces de carbono (de masas $A = 10, 12, 13, 14, 15$) a energías de laboratorio de 3,5 MeV/nucleón, en promedio. El rango cubierto de energías en el centro de masas estuvo entre 9 y 8 MeV, aproximadamente. Este rango está un poco por encima de la barrera coulombiana (cercana a los 9 MeV, de acuerdo a la definición estándar dada en la Ec. (2.3)). Está también por encima de los valores típicos de alturas para la barrera de interacción dada por modelos empíricos (alrededor de los 6 MeV según la Tabla 7.1).

Por esa razón, esperábamos ver funciones excitación sin estructuras significativas (tales como resonancias anchas). Más aún, las funciones excitación deberían tener una forma regular, casi constantes o tal vez con una caída hacia las energías más bajas del rango estudiado. El comportamiento finalmente observado confirmó estas expectativas. Salvo por el sistema $^{12}\text{C}+^{12}\text{C}$ donde la correspondiente función excitación mostró una estructura periódica, repetida cada 3 MeV, montada sobre la caída suave anticipada.

El resto de las funciones excitación son efectivamente suaves. Presentan la caída descrita, pero en diferentes energías para cada sistema. De todos modos, este también es un comportamiento predecible. Se ha demostrado que la caída en las secciones eficaces de fusión está relacionada con la presencia de la barrera de interacción. De hecho, vimos (en la Tabla 7.1) que las energías donde comienzan las caídas están fuertemente correlacionadas con las mencionadas alturas de las barreras. Esto sucede para todos los sistemas a excepción de $^{14}\text{C}+^{12}\text{C}$, donde el haz de ^{14}C tiene un número mágico de neutrones.

Otras leves variaciones respecto del comportamiento usual de las funciones excitación aparecen en los sistemas $^{10}\text{C}+^{12}\text{C}$ y $^{15}\text{C}+^{12}\text{C}$. En el primero, se observa una caída más pronunciada, y en el último la caída parece suceder a energías fuera del rango estudiado (esto es de todas formas esperable por lo discutido en el párrafo anterior). Hay que notar que en ambos casos se presentan las mayores incertezas en

las secciones eficaces (18% para ^{10}C y 12% para ^{15}C), lo que debe ser tenido en cuenta cuando se busca identificar características salientes.

Las incertezas en las secciones eficaces (principalmente de carácter estadístico) fueron menores para el resto de los sistemas dado la mayor intensidad de los haces primarios. En promedio, estas incertezas fueron: 8% para ^{12}C , 6% para ^{13}C y 7% para ^{14}C . Se incluye en esos valores una contribución sistemática de aproximadamente 1%, proveniente del cálculo para la densidad del gas y por la fracción natural de ^{13}C que existe en el metano.

Por otro lado, las incertezas en los valores de energía de las funciones excitación fueron estimados en un 2%, para todos los sistemas.

Como ya se dijo, las funciones excitación para los sistemas conocidos ($^{12}\text{C}+^{12}\text{C}$ y $^{13}\text{C}+^{12}\text{C}$) [Kov79] fueron reproducidas exitosamente. Podemos afirmar algo similar para $^{14}\text{C}+^{12}\text{C}$ donde encontramos consistencia con datos anteriores [Das93], aunque no se observe un solapamiento. Por su parte, los datos para este sistema fueron medidos por primera vez en este rango de energías.

Es también la primera vez que se obtiene experimentalmente la fusión con haces radiactivos de ^{10}C y ^{15}C sobre un blanco de ^{12}C .

La comparación con tres modelos distintos mostró un buen acuerdo. Los tres son ejemplos del estado del arte, yendo de un simple modelo unidimensional de penetración de barrera [Yak10], pasando por una bien conocida aproximación de canales acoplados [Esb11], hasta un complejo cálculo dinámico de Hartree-Fock con varios grados de libertad internos [Uma12].

Los cálculos de canales acoplados, incluyendo acoplamientos de uno y dos fonones, probaron ser certeros para los sistemas $^{13,14}\text{C}+^{12}\text{C}$, pero mostraron desviaciones importantes en el resto (de alrededor del 10%). Por su parte, obtuvimos un buen acuerdo con los cálculos de penetración usando el Potencial de São Paulo, excepto para los resultados correspondientes a ^{10}C (con una sobreestimación del 13%). Finalmente, las predicciones del modelo de Hartree-Fock dependiente del tiempo presentaron limitaciones para su comparación dado que mezclan las reacciones de fusión con las de transferencia. Esto causó que estuvieran

por encima de nuestras secciones eficaces en un 20%, aunque muestran la misma tendencia.

Como conclusión, podemos sostener que las secciones eficaces de fusión de carbono mostraron un incremento suave como función del exceso de neutrones. Este incremento fue de un 20%, yendo de ^{10}C a ^{15}C . Más aún, no se observó ningún comportamiento anómalo en el rango de energías estudiado, como el presente en los sistemas $^{14,15}\text{N}+^{12}\text{C}$, que difieren en sólo un neutrón tal como $^{14,15}\text{C}+^{12}\text{C}$.

8.3. Perspectivas

El presente trabajo ha abierto un amplio rango de posibilidades para medir funciones excitación de fusión en distintos sistemas. Justamente, la alta eficiencia del blanco activo, implementado en esta tesis a través del desarrollo del detector MUSIC, hace que esta técnica sea ideal para emprender estudios de física nuclear con interés astrofísico. Estos procesos siguen siendo la gran incógnita para describir cuantitativamente la nucleosíntesis estelar estable y explosiva. Más aún, en combinación con los haces radiactivos de la instalación ATLAS, el conocimiento actual de los procesos de reacción entre núcleos estables puede ser expandido a muchos nucleídos radiactivos.

Como continuación del presente trabajo, se están llevando a cabo esfuerzos en la instalación ATLAS para producir un haz de ^{16}C . Hasta ahora, se obtuvo una intensidad de 10^3 partículas/s, la cual está en el límite para un experimento aceptable con el detector MUSIC. Cuando finalice la reforma de la instalación que se encuentra en progreso, esta opción probablemente estará disponible.

En clara relación con este trabajo, se puede encontrar en el mercado gas metano enriquecido en ^{13}C ($^{13}\text{CH}_4$). Con el mismo, se pueden investigar reacciones con ^{13}C como blanco. Es también posible producir $^{14}\text{CH}_4$, pero no puede ser utilizado actualmente en el laboratorio por razones de seguridad radiológica.

Podemos incluso pensar en otros gases para actuar como blanco activo. Por ejemplo, para continuar investigando sobre reacciones relacionadas con las

súperllamaradas de rayos X, sería interesante estudiar la fusión de isótopos ricos en neutrones de oxígeno y neón. En este caso, el oxígeno no puede usarse como un gas de detección por su gran afinidad electrónica, la cual produce una alta tasa de recombinación de iones [Kno89], dejándonos al neón como opción válida.

Desde el punto de vista astrofísico, se piensa que en las cortezas de las estrellas de neutrones los isótopos de neón son más abundantes que los de oxígeno, incluso que los de carbono [Ili07]. Precisamente, el Comité Asesor (PAC, por sus siglas en inglés) del Laboratorio Nacional de Argonne ya ha aceptado un experimento con el detector MUSIC para la medición de reacciones de fusión con neón. Los haces que serán utilizados son los isótopos estables $^{20,22}\text{Ne}$ y el radiactivo ^{24}Ne , sobre blancos activos gaseosos enriquecidos en ^{20}Ne y ^{22}Ne .

Incluso podemos pensar en mediciones a más bajas energías que las aquí estudiadas. En la Sec. 4.2 discutimos las complicaciones halladas en la instalación ATLAS (compartidas con otras instalaciones) para producir un haz de alta intensidad a muy bajas energías. De todas formas, simulamos con el código FLUKA un haz de ^{12}C a 12 MeV y al detector MUSIC con una presión de gas de 25 mbar. Este haz alcanzaría el segmento 1 con una energía de 6 MeV (perdiendo 6 MeV en la ventana de entrada, el volumen muerto de gas y el segmento 0). De esta forma, la función excitación sería obtenida en el rango $E_{\text{c.m.}} \approx 0.5 - 3$ MeV. En este caso, la pérdida de energía sería de 0,4 MeV por segmento, en promedio. Entonces, si fuera posible producir este haz con una intensidad aceptable, podríamos obtener con el detector MUSIC dicha función excitación en este régimen de energías.

En esta tesis, hemos demostrado que el detector MUSIC es un equipo poderoso para mediciones de reacciones de fusión con haces radiactivos. Y probablemente continuará entregando información valiosa sobre el proceso de fusión en los años venideros.

Con respecto a los nuevos datos obtenidos, se espera que ayude a la comunidad científica en la comprensión de los fundamentos del mecanismo de fusión, especialmente en cómo afecta la estructura nuclear al proceso de fusión en sistemas livianos.

CONCLUSIONES

A pesar de que los datos aquí obtenidos se encuentran lejos de las energías de interés astrofísico, de todas maneras son útiles para ser extrapolados y así conducir a una mejor explicación del fenómeno de súperllamaradas de rayos X.

APPENDIX A

ROOT CLASS FOR FUSION EVENTS

IDENTIFICATION

Here it is included the source code for the custom ROOT C++ tree class [Roo13] used in the data analysis. For an explanation of its functionality see Sec. 6.2, especially Fig. 6.7 where there is a block diagram of the process.

Class fus.C

```
1      #define fus_cxx
2      #include "fus.h"
3
4      #include <TH1.h>
5      #include <TH2.h>
6      #include <TGraph.h>
7      #include <TStyle.h>
8      #include <TCanvas.h>
9      #include "TFile.h"
10
11     #include <cstdio>
12     #include <iostream>
13     #include <iomanip>
14     #include <sstream>
15     #include <string>
16     #include <fstream>
17
18     void fus::Loop() {
19
20         if (fChain == 0) return;
21         Long64_t nentries = fChain->GetEntriesFast();
22
23         Double_t cathmin, cathmax, ezero, ethrmax, ethrmin, efus, escatt, emax;
24         Double_t elef[18] = {0.}, eright[18] = {0.}, esum[18] = {0.}, beaml[18],
25         beamr[18],
```

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```
26         xs[16] = {0.};
27         Int_t i = 0, j = 0, ncath = 0, nfus = 0, nscatt = 0, nhi = 0, sfus = 0, smax =
28 1;
29         Bool_t gapu = 0, gapd = 0, hi = 0, lo = 0, fus = 0, scatt = 0;
30         Bool_t high[16] = {0};
31
32         std::ostringstream sout;
33
34         sout.str(""); sout << "run" << std::setfill('0') << std::setw(2) << runn <<
35 "_out.dat";
36         ofstream outfil(sout.str().c_str());
37         if (outfil.is_open()) outfil << "Fus#\tSeg\tEvt#" << endl;
38         else cout << "Unable to open output file" << endl;
39
40         ifstream beafil("beam14.dat"); ifstream parfil("param14.dat");
41
42         if (parfil.is_open()) {
43
44             parfil >> cathmin; parfil.ignore(75, '\n');
45             parfil >> cathmax; parfil.ignore(75, '\n');
46             parfil >> ezero; parfil.ignore(75, '\n');
47             parfil >> ethrmax; parfil.ignore(75, '\n');
48             parfil >> ethrmin; parfil.ignore(75, '\n');
49             parfil >> efus; parfil.ignore(75, '\n');
50             parfil >> escatt; parfil.ignore(75, '\n');
51             parfil.close();
52
53         }
54         else cout << "Unable to open parameter data file" << endl;
55
56         if (beafil.is_open()) {
57
58             j = 0;
59             while (beafil.good()) { beafil >> beaml[j] >> beamr[j]; j++; }
60             beafil.close();
61
62         }
63         else cout << "Unable to open beam data file" << endl;
64
65         for (Long64_t jentry = 0; jentry < nentries; jentry++) {
66
67             Long64_t ientry = LoadTree(jentry);
68             if (ientry < 0) break;
69             fChain->GetEntry(jentry);
70
71             if (i < 15) {
72
```


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```

73         i++;
74
75         eleft[i] = edepl - beaml[i];
76         eright[i] = edepr - beamr[i];
77         esum[i] = eleft[i] + eright[i];
78
79         if (esum[i] > ethrmax) high[i-1] = 1;
80         if (esum[i] > ethrmax/2) nhi++;
81
82     )
83
84     else {
85
86         eleft[16] = edepl - beaml[16];
87         eright[16] = edepr - beamr[16];
88         esum[16] = eleft[16] + eright[16];
89
90         if (esum[16] > ethrmax) high[15] = 1;
91         if (esum[16] > ethrmax/2) nhi++;
92
93         strip0 = strip0 - beaml[0];
94         strip17 = strip17 - beaml[17];
95
96         if (strip0 < 2*ezero) {
97
98             ncath++;
99
100            lo = 1;
101
102            esum[0] = strip0; esum[17] = strip17;
103
104            emax = high[0];
105
106            for (j = 1; j < 16; j++) {
107
108                if (emax <= high[j]) { emax = high[j]; smax = j + 1; }
109
110                if ((esum[j+1] - esum[j]) > ethrmax) gapu = 1;
111                if (esum[j+1] < ethrmin) gapd = 1;
112
113                if ((esum[j] > ethrmax || esum[j+1] > ethrmax)) hi = 1;
114
115            }
116
117            if (nhi > 8 || strip17 > 0) lo = 0;
118            if (esum[smax+1] > escatt && esum[smax+2] > escatt) lo = 0;
119

```

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```
120         fus = hi*lo*gapu;
121         if (fus == 0) fus = hi*lo*gapd;
122
123         if (fus == 1) {
124
125             nfus++;
126
127             for (j = 1; j < 17; j++) {
128
129                 if (esum[j] > efus && sfus == 0) {
130
131                     if ((esum[j] / 1.3) < efus) sfus = j + 1;
132                     else { sfus = j; if (sfus == 0) sfus = 1; }
133
134                 }
135
136             }
137
138             xs[16-sfus] = xs[16-sfus] + 1;
139
140             cout << "Fusion " << nfus << " in strip " << sfus << endl;
141             if (outfil.is_open()) outfil << nfus << "\t" << sfus <<
142 "\t" << jentry
143 << endl;
144             else cout << "Unable to open output file" << endl;
145
146         }
147
148     }
149
150     for (j = 0; j < 16; j++) high[j] = 0;
151     i = 0; hi = 0; lo = 0; fus = 0; gapu = 0; gapd = 0; scatt = 0; sfus = 0;
152     smax = 1;
153     nscatt = 0; nhi = 0;
154
155 }
156
157 }
158
159 if (outfil.is_open()) {
160
161     outfil << endl;
162     outfil << "Total events = " << ncath << endl;
163     outfil << "Fusion events = " << nfus << endl;
164     outfil << endl;
165     outfil << "Seg\tFusevts" << endl;
166
```

```
167         )
168         else cout << "Unable to open output file" << endl;
169
170         for (j = 0; j < 16; j++) {
171
172             if (outfil.is_open()) outfil << (16-j) << "\t" << xs[j] << endl;
173             else cout << "Unable to open output file" << endl;
174
175         }
176
177         outfil.close();
178
179     }
```


A. ROOT CLASS FOR FUSION EVENTS IDENTIFICATION

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