

Excitation Functions for Deuteron-Induced Reactions on  $^{89}\text{Y}$ 

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## Abstract

Excitation functions for reactions induced by deuterons on  $^{89}\text{Y}$  were measured by activation method up to 27.2 MeV deuteron energy. The observed reactions are:  $^{89}\text{Y}(d, 2n)^{89}\text{Zr}$ ,  $^{89}\text{Y}(d, 3n)^{88}\text{Zr}$ ,  $^{89}\text{Y}(d, t)^{88}\text{Y}^*$  and  $^{89}\text{Y}(d, \alpha)^{87\text{m}}\text{Sr}$ .

## Zusammenfassung

Die Anregungsfunktionen für deuteroneninduzierte Reaktionen an  $^{89}\text{Y}$  wurden mit einer Aktivierungsmethode bis zu einer Deuteronenenergie von 27,2 MeV gemessen. Folgende Reaktionen wurden beobachtet:  $^{89}\text{Y}(d, 2n)^{89}\text{Zr}$ ,  $^{89}\text{Y}(d, 3n)^{88}\text{Zr}$ ,  $^{89}\text{Y}(d, t)^{88}\text{Y}^*$  und  $^{89}\text{Y}(d, \alpha)^{87\text{m}}\text{Sr}$ .

## Résumé

On a mesuré moyennant une méthode d'activation les fonctions d'excitation pour les réactions induites par des neutrons sur  $^{89}\text{Y}$  jusqu'aux énergies de deutérons de 27,2 MeV. Les réactions suivantes ont été observées:  $^{89}\text{Y}(d, 2n)^{89}\text{Zr}$ ,  $^{89}\text{Y}(d, 3n)^{88}\text{Zr}$ ,  $^{89}\text{Y}(d, t)^{88}\text{Y}^*$  et  $^{89}\text{Y}(d, \alpha)^{87\text{m}}\text{Sr}$ .

## I. Introduction

The isotope  $^{89}\text{Zr}$  was previously obtained by the (p, n) [1] reaction on  $^{89}\text{Y}$ ; by the (n, 2n) [2–3] reaction on  $^{90}\text{Zr}$  and by ( $\gamma$ , n) [4–5] on  $^{90}\text{Zr}$ .

The isotope  $^{88}\text{Zr}$  was studied by HYDE *et al.* [6–7] who bombarded niobium with protons.

The formation of  $^{88}\text{Y}$  was previously reported by the (p, n) [1] reaction on  $^{88}\text{Sr}$ ; by the ( $\gamma$ , n) [8] reaction on  $^{89}\text{Y}$  and by the (d,  $\alpha$ ) [9] reaction on  $^{90}\text{Zr}$ .

The reactions studied for the production of  $^{87\text{m}}\text{Sr}$  were (p, n) [1] on  $^{87}\text{Rb}$ ; (n,  $\gamma$ ) [10–11] on  $^{86}\text{Sr}$  and (n,  $\alpha$ ) [2–12] on  $^{90}\text{Zr}$ .

Calculations of the excitation functions for (d, 2n) reactions have been performed by PEMENT and WOLKE [13] for two different mechanisms: compound nucleus formation followed by evaporation of two neutrons and (d, n) stripping followed by evaporation of one neutron. They concluded that the compound nuclear mechanism predominates in (d, 2n) reactions above  $A = 47$ .

OTOZAI *et al.* [14] measured excitation functions for the deuteron induced reactions (d, p), (d, n), (d, 2n) and (d,  $\alpha$ ) on  $^{142}\text{Ce}$ . They have given a unified explanation of the results with PEASLEE's [15] theory modified by introducing the "entire absorption parameter" and they have deduced relative contributions of neutron stripping, proton stripping and entire absorption processes.

In the present work we describe the excitation functions for the nuclear reactions (d, 2n), (d, 3n), (d, t) and (d,  $\alpha$ ) on  $^{89}\text{Y}$  as a contribution to the information concerning reaction mechanisms. In addition, activation cross sections

are often useful in nuclear technology for "production of radioisotopes" and "charged particles activation analysis".

## II. Experimental Procedures

## A. Irradiations

Stacks of targets were bombarded with  $27.2 \pm 0.3$  MeV deuterons beams from the Argentina Atomic Energy Commission 60 inch Synchrocyclotron [16–17].

Yttrium foils,  $12 \text{ mg/cm}^2$  thick, of high purity were obtained from Koch Light Ltd., England. The bombarding energy at each target in the stack was calculated from a range-energy table [18]. The energy spread during degradation through the target stacks was considered to be below 200 keV for any one of the foils [19].

The monitor reaction for the intensity of the deuteron beam was  $^{27}\text{Al}(d, \alpha p)^{24}\text{Na}$ , its excitation function being well known [20]. In order to determine the deuteron flux

\* (d, t) means (d, p 2n), (d, dn) or (d, t)

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the target stacks were prepared with yttrium and aluminium foils.

### B. Counting

The cross sections were determined by an absolute measurement of the disintegration rates of the reaction products.

The foils were counted without radiochemical separation since interfering activities were negligible.

### III. Experimental Results

The measured cross sections are presented as a function of deuteron energy in Table 1. The quoted errors in the cross sections include uncertainties in the beam intensities, target weights, counting efficiencies, counting statistics, conversion coefficients, decay branching ratios and half-life values. The total error in the cross sections are thought to be 15% or less. The errors in the deuteron energies represent the uncertainty in the incident beam energy, compounded by the estimated energy spread during degradation in the stacks.

Table 1.  $\sigma$  (barn)

$E$ (MeV)	$^{89}\text{Y} (d, 2n)^{89}\text{Zr}$	$^{89}\text{Y} (d, 3n)^{88}\text{Zr}$	$^{89}\text{Y} (d, t)^{88}\text{Y}$	$^{89}\text{Y} (d, \alpha)^{87}\text{Sr}^m$
24.8±0.15	0.35 ±0.05	1.17 ±0.18	0.024 ±0.004	0.006 ±0.001
23.7±0.15	0.39 ±0.06	1.01 ±0.15	0.021 ±0.003	0.007 ±0.001
22.6±0.15	0.45 ±0.07	0.97 ±0.15	0.017 ±0.002	0.0075±0.001
21.5±0.2	0.47 ±0.07	0.64 ±0.10	0.012 ±0.002	0.0085±0.001
20.4±0.2	0.58 ±0.09	0.40 ±0.06	0.008 ±0.001	0.010 ±0.0015
19.1±0.15	0.63 ±0.09	0.23 ±0.03	0.006 ±0.001	0.011 ±0.002
16.7±0.2	0.72 ±0.11	0.062±0.009	0.0021±0.0003	0.013 ±0.002
15.7±0.2	0.71 ±0.11	0.021±0.003	0.0016±0.0002	0.012 ±0.002
13.7±0.2	0.70 ±0.10		0.0013±0.0002	0.013 ±0.002
12.0±0.25	0.61 ±0.09		0.0011±0.0001	0.012 ±0.002
10.2±0.3	0.44 ±0.07			0.012 ±0.002
8.0±0.3	0.24 ±0.04			0.007 ±0.001
5.4±0.35	0.064±0.010			0.0035±0.0005
4.7±0.5	0.041±0.006			0.0015±0.0002
3.4±0.5	0.013±0.002			

The loss of reaction products by recoil was neglected in the computation of cross sections.

In most of the measurements a characteristic gamma ray spectrum of the reaction products was counted and in every case the activity was further identified by half-life determination.

The photopeak intensities of the various gamma rays were measured with a 3" × 3" NaI (Tl) crystal and a multi-channel pulse height analyzer. Resolution of decay curves yielded 108 days  $^{88}\text{Y}$ , 78.4 hours  $^{89}\text{Zr}$ , 85 days  $^{88}\text{Zr}$ , 2.83 hours  $^{87m}\text{Sr}$  and 3.1 hours  $^{90m}\text{Y}$ .

The product of the absolute crystal efficiency and the photopeak to total ratio for each of the different gamma rays were obtained from the compilations of HEATH [21], and the data corresponding to the disintegration scheme from [22].

The data were programmed for least-square analysis on a computer, using a code ALPHA M [23–24], in FORTRAN IV language, which resolves zero-time activities from the decay data of multi-component systems. Included as standard spectra were  $^{88}\text{Y}$ ,  $^{88}\text{Zr}$ ,  $^{89}\text{Zr}$  and  $^{90m}\text{Y}$ . The spectrum of  $^{87m}\text{Sr}$  has the same shape of that of  $^{88}\text{Zr}$ ; both were computed with the same standard but with a different half-life parameter.

The cross sections of  $^{89}\text{Zr}$  were calculated with the activities measured when the  $^{89m}\text{Zr}$  had decayed completely.

The present data have been compared with the compilation reported by LANGE and MÜNDEL [25] for (d, 2n) and (d, 3n) reactions and we have found that our data are within the expected limits.

The value for 20 MeV obtained in the (d, t) reaction on  $^{89}\text{Y}$  is lower than the expected value in the cross section in function of the neutron number curve given by COHEN *et al.* [26], where:

$$\sigma(d, t) = 0.48 (N - 15) \text{ mb.}$$

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