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SCATTERING AND STRIPPING OF DEUTERONS ON He^4 BETWEEN 21 AND 28 MeV

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Abstract: The angular distributions of elastically scattered deuterons on He^4 have been measured at 21.3, 24.3, 25.8 and 27.3 MeV laboratory energy. Particularly at 21.3 MeV the shape is qualitatively consistent with some lower energy measurements, at 8 MeV and at 10.3 MeV, performed by Burge *et al.* and Allred *et al.*, respectively. Between 24.3 and 27.3 MeV an additional oscillation in the elastic differential cross section is presumably related with the appearance of an F component, in addition to the S, P and D components, used to fit the data at lower energies by Gammel, Hill and Thaler, assuming a model of interaction of the nucleons of the deuteron with a He^4 "lump" or "fundamental" particle. The angular distribution of the stripping reaction He^4(d, p)He^5 was also measured at 24.3 and 27.3 MeV. The residual nucleus is left in a virtual ground state and it is very short lived. The proton group seems to be the "head" of a continuum of the three body deuteron break up process. Some indications of an oscillatory behaviour of the differential cross section were obtained. Some reasonable PWBA fits were calculated for $l_n = 1$ and strikingly small interaction radii, $r_0 = 1.2$ fm at 27.3 MeV and $r_0 = 1.3$ fm at 24.3 MeV. The corresponding reduced widths are $\theta^2 = 0.0031$ and $\theta^2 = 0.0033$, respectively.

1. Introduction

In the recent past Gammel, Hill and Thaler 1) have developed a model for the d+He^4 interaction, treating He^4 as a fundamental particle, and assuming that the nucleons in the deuteron interact with it through the optical model potential, and between themselves through nucleon-nucleon potential. With such a hybrid treatment, partly detailed and partly lumped, they were able to calculate the phase shifts of the experimental data of Gallonsky *et al.* 2) on elastic scattering of deuterons on He^4 up to 4.5 MeV (laboratory energy), in agreement with Gallonsky and Mc Ellistrem's 3) analysis of the latter. They also analysed the data of Burge *et al.* 4) at 8 MeV and of Allred *et al.* 5) at 10.3 MeV. From the phase shifts they also calculated some quantities related to the production or analysis of polarized deuterons. The treatment just outlined was carried out assuming that the deuterons wave function is not distorted and neglecting deuteron break up during the interaction. The theoretical fits to the angular distributions at 8 MeV and at 10.3 MeV are nevertheless remarkably good.

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Present investigation was stimulated by the detailed theoretical treatment of the d-He^4 interaction, as well as some further developments promised by Gammel, Hill and Thaler [1]) in order to take into account deuteron break up effects, presumably important in the 20 to 30 MeV laboratory bombarding energy. The angular distribution for the elastic scattering process was measured at four energies in the aforesaid energy region, selecting convenient energy steps.

It is well known that a phase shift analysis of the elastic angular distribution as a function of energy is a powerful method, repeatedly employed to obtain information about the excited states of the nucleus formed by the projectile and the target. In the present case it is the Li^6 nucleus.

The reaction He^4(d, p)He^5 was also studied. It provides a means to reach the levels of He^5. The angular distribution of protons leaving He^5 in the virtual ground state may yield information about its properties. It is a very short lived nucleus and a summary of experimental values of the instability and level widths for the ground state is given by Craig *et al.* [6]). The most precise value is [7]) $\Gamma = 0.55 \pm 0.03$ MeV. The He^4 nucleus is a configuration $s^4(0^+$ state), whereas the He^5 ground state is an s^4p configuration ($\frac{3}{2}^-$state). Apparently the (d, p) reaction on He^4 should be ideally suitable to ascertain the validity of the single particle and surface nature assumption for the interaction. The captured neutron should definitely fall beyond the tightly bound alpha particle core (a doubly magic nucleus), on an $l = 1$ orbit. The instability of He^5 may be considered a consequence of the very small interaction of the neutron with the core.

2. Experimental Procedure

The experiment was performed using the external deuteron beam [8]) facilities of the Buenos Aires 180-cm synchrocyclotron and a scattering chamber with windows every five degrees [9]), provided with cylindrical brass collimators to define the geometry for work with gaseous targets [10]). The reaction products were detected with CsI(Tl) crystals of convenient thickness and a phototube EMI 6097. The measurements of the elastic process He^4 (d, d)He^4 at backward angles was performed detecting the He^4 recoils with a thin solid state detector, Ortec type N, together with a low noise preamplifier. The pulses of both detection systems were amplified and analysed with multi-channel pulse-height analysers, a 512-channel based on time conversion and rather slow, and a fast twenty channel. In the first stages of the experiment spectra were taken with a single-channel pulse-height analyser, in complete agreement with later multi-channel spectra on reiteration.

Proton spectra were obtained directly and also through aluminium filters to stop all particles with the exception of protons. In the latter case the CsI(Tl) crystal was 0.35 mm thick to reduce the gamma pile up to a minimum, and the aluminium filters were at each angle of appropriate thickness to leave the ground state protons just in range of the crystal.

The scattering chamber was filled with helium 99.9% pure to some 660 mm of Hg in order that the atmospheric pressure on the chamber lid helped provide the necessary air tightness. The chamber was permanently connected to a manometer and, generally speaking, was free of leaks over extended periods of time. Therefore the helium gas purity was certainly preserved during the experiment.

The beam energy is known to within 1% mainly due to the method employed to perform the measurement, through the mean range in aluminium. The beam was degraded in energy with stacks of calibrated aluminium foils and collimated with graphite diaphragms. The beam intensity dropped significantly only at 21.3 MeV, due to the divergence as a consequence of multiple scattering and the presence of defining diaphragms.

The solid state detector, in contradistinction to the scintillator that was moved in the outside of the chamber, was placed on a movable arm inside the chamber, immersed in the He^4 gas. The collimation was obtained by means of two vertical slits machined on the same graphite block in a single operation of the milling machine to insure that they were parallel. A third slit, wider than the previous ones, was machined in between in order to obstruct any lateral view of the beam line.

3. Results and Conclusions

3.1. GENERAL

Figs. 3, 4, 7, 8 and 9 contain the experimentally determined absolute differential cross sections, referred to the centre-of-mass system; the conversion was effected with the help of tables prepared by Marion *et al.* [11]). The Rutherford differential cross section at 27.3 MeV is shown in fig. 3 together with the elastic scattering angular distributions. The experimental points in fig. 3 are plotted without error bars, but instead the fluctuations on reiteration of measurements are given. The stripping angular distributions of figs. 7 and 8 contain information on the background subtraction ambiguity, which is fairly large. Fig. 9 contains an independent measurement at 27.3 MeV with a slightly thicker crystal of CsI(Tl) together with a reiteration set of points.

Taking into consideration that the elastic scattering is predominantly due to nuclear interaction, and that the He^4 nucleus is a tightly bound structure, it is to be expected that the elastic scattering cross section may be approximately represented by

$$\mathrm{d}\sigma_{\mathrm{el}}/\mathrm{d}\Omega \approx R^2 J_1^2(2kR \sin \tfrac{1}{2}\theta)/4 \sin^2 \tfrac{1}{2}\theta, \qquad (1)$$

where k is the wave number of the scattered particle, R is the interaction radius and J_1 is the first order Bessel function. Expression (1) can be derived [12]) through the use of an optical analogy, considering the scattering of the particle associated waves by a black disk. In principle its validity should be restricted to the forward angles up to the point where the replacement of sin θ by θ is already a poor approximation. Nevertheless, on occasions, the oscillatory behaviour is well described over the entire angular range by the diffraction formulas derived quite generally by Blair [13], using precisely $2kR\ \sin\frac{1}{2}\theta$ as the argument of the Bessel function, instead of $kR\theta$. Finally it is worth while to point out that expression (1) arises also in the diffraction problems on a circular hole (Fraunhofer problems), and also on a sphere, i.e., the important fact is the shape of the cross section presented to the beam by the diffracting obstacle.

The stripping angular distributions were analysed in terms of the PWBA using the formulae in the form given by Macfarlane and French [14], together with tables calculated by Lubitz [15]. The stripping reaction $He^4(d, p)He^5$ corresponds to an unbound case, and the l value of the captured nucleon is rather unambiguous: it is the first nucleon beyond the s shell (p shell) and therefore $l = 1$.

3.2. ANGULAR DISTRIBUTIONS

3.2.1. *Elastic Scattering*

Fig. 1 contains a charged particle sample spectrum obtained at $\theta_{lab} = 15°$, and fig. 2 exhibits some solid state detector spectra of He^4 recoils. The latter were obtained using the necessary bias to put in range the recoils. Thereby very clean spectra were obtained, with a very good ratio of peak to background. The combination of both detection techniques permitted the measurement of the elastic scattering angular distribution between 15° and 170° in the CM system. The cross section calculation for the cylindrical collimator and for the slit geometry was performed following a treatment due to Silverstein [16]. The absolute cross section values obtained with both types of detectors and substantially different geometry and detection radii, coincide within the normal fluctuations on reiteration with any of them. Nevertheless an independent measurement was performed at 90° simulating a solid target geometry.

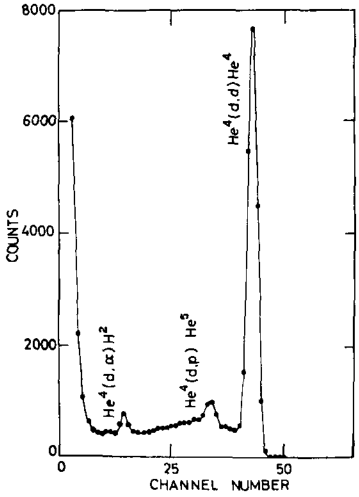

Fig. 1. Charged particle spectrum obtained at 15° lab. using 27.3 MeV deuterons on He^4 detected with a scintillator.

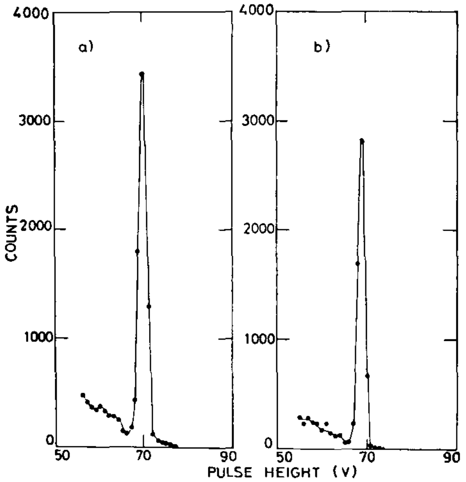

Fig. 2. Solid state detector spectra of the He^4 recoils, $E_d = 25.8$ MeV. (a) Spectrum taken at 7° lab. (corresponding to 166° CM). (b) Spectrum taken at 10° lab. (corresponding to 160° CM).

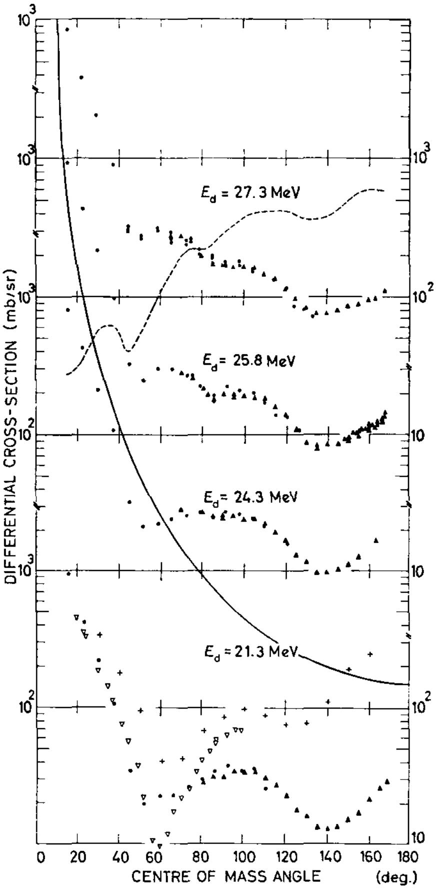

Fig. 3. Elastic scattering angular distributions. ● scintillator points, ▲ solid state detector points, + ref. 4) ($E_d = 8$ MeV), ▽ ref. 5) ($E_d = 10.3$ MeV). The solid line is the Rutherford cross section, and the broken line is the ratio of the measured cross section to the Rutherford cross section (27.3 MeV). The ratio ought to be read on the right-hand scale.

A 1 cm wide slit was placed very close to the beam line, making possible a direct measurement to be performed without an additional collimation and subsequent correction due to penumbra. The subsequent calculation was performed using a conventional target thickness and solid angle, assuming that the target was concentrated at the centre of the chamber. The agreement with the scintillator and solid state de-

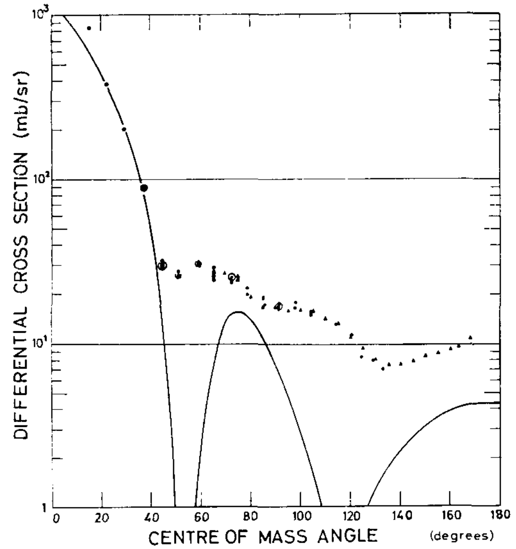

Fig. 4. The elastic scattering angular distribution at 27.3 MeV bombarding energy together with the optical diffraction curve $R = 3.8$ fm. ● scintillator points, ▲ solid state detector points, ○ two coincident values. The solid line is $KJ_1^2(2kR \sin \frac{1}{2}\theta)/4 \sin^2 \frac{1}{2}\theta$.

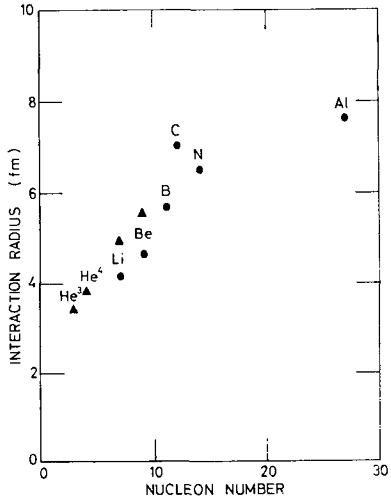

Fig. 5. A plot of deuteron-nucleus interaction radii as a function of nucleon number. The values are not quite comparable because they correspond to different centre-of-mass energy. The circles are points from successive extrema, and the triangles are points from first minima.

tector values was excellent. Fig. 3 exhibits the measured angular distributions together with two earlier measurements at lower energies [4, 5]). There is a definite resemblance of the 21.3 MeV angular distribution with the 8 MeV one. The difference is precisely notable at backward angles, were the higher energy angular distributions exhibit a decreasing trend with increasing energy. The physical interpretation is obvious; at higher energies more deuteron break up results on the processes with small impact parameter (at lower energies they would recoil without break up). The total cross section for the elastic process is smaller than at 8 MeV by approximately one order of magnitude. At 24.3 MeV the ample hill between 60° and 140° CM starts showing a tendency to split, and in fact it gives place to a pair of oscillations at 25.8 and 27.3 MeV. It is worth while pointing out that over a large energy range no distinct change is observed in the forward shape of the elastic differential cross section, nor in its absolute value. The Coulomb cross section at 27.3 MeV is plotted along with the experimental points in fig. 3; even at the smallest measured angles it is some factor of 20 smaller than the measured cross section, and therefore the latter is mainly due to nuclear interaction.

The discontinuity in the oscillatory behaviour of the elastic differential cross section with energy, may be probably ascribed to the contribution of an F wave phase shift, in the light of Gammel, Hill and Thaler's [1]) theoretical treatment. Therefore a simple diffraction analysis, although Coulomb effects are small, would yield ambiguous results. Table 1 contains the results that would be obtained out of the position of succesive maxima and minima, for the nuclear interaction radii, using the expression

TABLE 1

Interaction radii obtained through diffraction analysis of the elastic scattering angular distribution using expression (2)

Energy (MeV)	Maxima (degrees)	Minima (degrees)	Interaction radius (fm)	Average interaction radius (fm)
27.3	62		5.7	
and	100			
		50		5.7
25.8		85	5.7	
		135	5.7	
21.3		50		
and			2.8	2.8
24.3		137		

$$R_i = \pi/2k(\sin \tfrac{1}{2}\theta_{i+1} - \sin \tfrac{1}{2}\theta_i) \tag{2}$$

obtained simply from (1), θ_i is the angle of the chosen extremum for the computation.

Alternatively it would be more reasonable to attempt a fit of (1) to the experimental angular distribution and subsequently obtain the interaction radius from the position of the first minimum. Fig. 4 contains the "best fit" for the 27.3 MeV data. It is certainly good for the small angle region and it describes the general trend of the angular distribution for larger angles, although it does not give account of the pair of oscillations mentioned previously. At lower energies the large angle behaviour of the cross section would be quantitatively off by one order of magnitude in the studied energy range. Nevertheless the small angle behaviour is definitely well represented, independently of energy. The first minimum position yields an interaction radius $R_i = 3.8$ fm. Fig. 5 contains a plot of this result together with others obtained from several previous experiments, and also from a recent one in collaboration with O. M. Bilaniuk on deuteron-He^3 scattering [17]).

3.2.2. *The Stripping Reaction* $He^4(d, p)He^5$

Some recent work [18]) has been performed concerning deuteron break up on D, T and He^4. The reaction can proceed through the formation and subsequent decay of He^5

$$He^4+d \to He^5+p \to He^4+p+n \tag{3}$$

or directly as a three body process

$$He^4+d \to He^4+p+n. \tag{4}$$

The spectra obtained in the experiment reported here indicate that both mechanisms operate simultaneously, with comparable cross section. Fig. 6 contains some sample spectra obtained using the technique described earlier. The discrete proton group of eq. (3) is the head of a proton continuum from the process as described by eq. (4). The proton group can be seen also in fig. 1, the shape of the background also points to the existence of a continuum.

Angular distributions were measured at 24.3 and 27.3 MeV, and there was no obvious reason to measure additional ones at intermediate energies. The negative Q value of the reaction as well as the unfavorable kinematics turned unadvisable a measurement at lower energies. The fact that the proton group is the head of a significant continuum implied some ambiguity in the background subtraction. The angular distributions are contained in figs. 7 and 8, where the experimental points are plotted considering two extreme choices of the background subtraction. Fig. 9 contains an independent measurement at 27.3 MeV, here the cross section was evaluated subtracting background systematically as indicated by curve I in the previous figures; no error bars are drawn but some reiteration points are plotted to give an idea of the overall reproducibility. Good agreement was obtained between the proton peak evaluation from spectra like the ones shown in fig. 1 or the filtered spectra of fig. 6. It is worth while to point out that, not only the angular distributions of the discrete proton group was found to be peaked in the forward direction, as it was already observed by other experimenters [7, 18]), but also the continuum exhibited a rather similar behaviour.

A PWBA fit was obtained for the stripping angular distributions, using the unbound case functions with $l = 1$ and $r_0 = 1.2$ fm at 27.3 MeV; $r_0 = 1.3$ fm. at 24.3 MeV The so-called interaction radii of the PWBA fit are exceedingly small. Perhaps more reasonable parameters are obtained taking into consideration wave distortion. Furthermore, the experimental points in fig. 9 seem to exhibit an oscillatory behaviour, thereby differing fundamentally with the plane wave theoretical curves. The reduced widths are $\theta^2 = 0.0031$ at 27.3 MeV and $\theta^2 = 0.0033$ at 24.3 MeV.

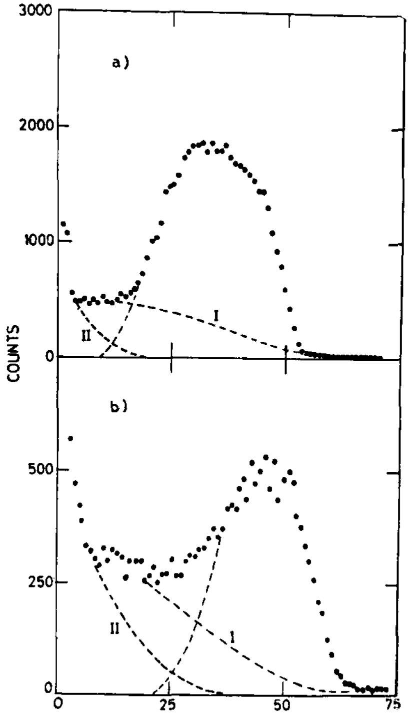

Fig. 6. Sample spectra of the He^4(d, p)He^5 reaction. (a) Spectrum obtained at 15° lab with 27.3 MeV deuterons; (b) Spectrum obtained at 15° lab with 24.3 MeV deuterons. These spectra are obtained with a 0.35 mm thick CsI(Tl) crystal and aluminium filters leaving the residual range of the protons just within the crystal. The extreme background subtraction curves are labelled I and II.

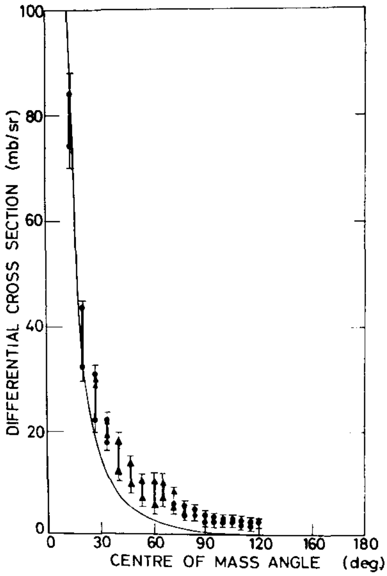

Fig. 7. Angular distribution of the He^4(d, p)He^5 reaction at 27.3 MeV bombarding energy. The thick line is due to background uncertainty. The solid line is the PWBA fit for $l = 1$ and $r_0 = 1.2$ fm. ● run 1962, ▲ run 1961.

3.2.3. *Conclusions*

No evidence was obtained in the present experiment for excited states of the He^4 nucleus as no inelastic deuteron group was observed in the particle spectra. The rather strong change of the shape of the elastic angular distribution with energy points to some resonances in the interaction of the deuteron-helium system. The rather high cross section for the (d, p) process together with the strong decrease of the elastic cross section for recoil processes, strongly points to the need of considering the deuteron break up in the theoretical approach of Gammel, Hill and Thaler [1]). Therefore the problem should be formulated in terms of a general complex optical potential, together with the spin orbit interaction. It should be noted that the angular range of the measurements reported here is the largest available yet, and that the energy dependence is also known with enough detail. It is therefore expected that it will be possible to obtain a set of self-consistent parameters if the model is correct, over the entire energy range.

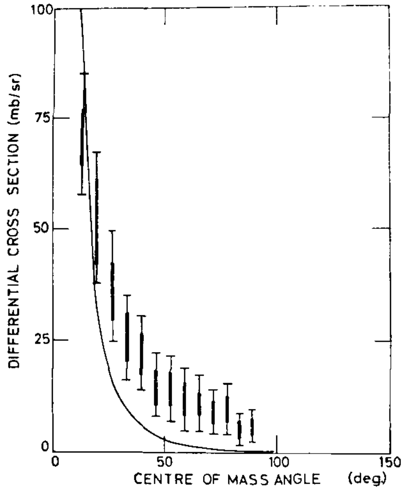

Fig. 8. Angular distribution of the $He^4(d, p)He^5$ reaction at 24.3 MeV bombarding energy. The thick line is due to background uncertainty. The solid line is the PWBA fit for $l = 1$ and $r_0 = 1.3$ fm.

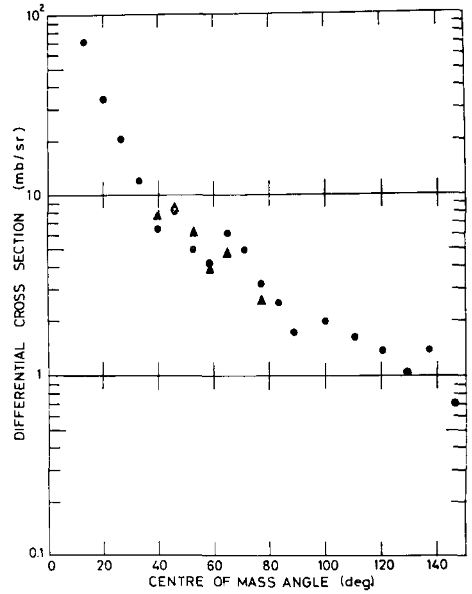

Fig. 9. Independent measurement of the angular distribution of the $He^4(d, p)He^5$ reaction at 27.3 MeV bombarding energy. Background subtraction was performed uniformly using curves I indicated in fig. 6. ● main run (1963), ▲ reproducibility points.

Once the theoretical model is determined, it will be simple to take into account the wave distortion of the projectile, in order to calculate the differential cross section for the stripping process. The wave distortion of the product (the out-going proton) can be obtained from existing angular distributions [19]), and if necessary also included in the computation. If a good agreement is obtained it would mean an independent confirmation of the model. It will then be possible to predict not only the polarization of the elastically scattered deuterons but also of the protons from the stripping process.

The apparent oscillatory behaviour of the stripping angular distribution shown in fig. 9 may be related to some diffraction component in the process. The weak interaction of the proton and the neutron in the deuteron may allow some diffraction scattering of the proton on the just formed He^5 nucleus.

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