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STUDY OF DEUTERON-INDUCED REACTIONS ON ^{7}LI AT $E_d = 180$ keV

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Abstract: The $d + {}^7Li \rightarrow \alpha + \alpha + n$ reaction has been investigated at $E_d = 180$ keV using both $\alpha - \alpha$ and $\alpha - n$ coincidence measurement techniques. An experimental technique has been developed for studying nuclear reactions induced by low-energy charged particles. The analysis of the results obtained confirms the predominance of the $\alpha + {}^5He$ rather than the $n + {}^8Be$ reaction channel. In the case of the $\alpha - n$ coincidence measurement, the agreement of the data with the Phillips-Griffy-Biedenharn model can be improved by including a contribution of the direct three-body break-up.

1. Introduction

Nuclear reactions occurring when a natural lithium target is bombarded by low-energy protons and deuterons have been studied by several groups of authors for various purposes and employing different techniques[1,2]. The following reaction channels are opened for an incident energy of 180 keV:

$$^7Li\,(p, \alpha)^4He \qquad Q = 17.35 \text{ MeV}, \qquad (1)$$

$$^6Li\,(p, \alpha)^3He \qquad Q = 4.02 \text{ MeV}, \qquad (2)$$

$$^6Li\,(d, \alpha)^4He \qquad Q = 22.37 \text{ MeV}, \qquad (3)$$

$$^7Li\,(d, \alpha)^5He_{gs}\,(\alpha, n) \qquad Q = 14.17 \text{ MeV}, \qquad (4)$$

$$^7Li\,(d, \alpha)^8Be_{gs}\,(\alpha, \alpha) \qquad Q = 15.03 \text{ MeV}, \qquad (5)$$

$$^7Li\,(d, \alpha)\,\alpha n \qquad Q = 15.122 \text{ MeV}, \qquad (6)$$

The two-body reactions (1) and (2) are of significant astrophysical interest and the cross sections for these reactions have been recently measured[3] in the energy range from $E_p = 20$ keV to 1 MeV.

Deuteron-induced reactions on ^{7}Li with three outgoing particles have been the subject of extensive studies in the last few years. Earlier experiments[2], in which only one of the outgoing particles was detected, led to inconclusive results due to the incomplete definition of the kinematics and the continua resulting from the decay of wide excited states of the intermediate ^{5}He and ^{8}Be nuclei involved in the reactions (4) to (6). However, in both single-counter and coincidence experiments, the widths of the ^{5}He and ^{8}Be first excited states seemed to be in disagreement with the values obtained from α — n and α — α elastic scattering data[4,5]. Attempts have been made to explain the width and shape of these states considering the formation of a compound ^{9}Be nucleus[6] or applying the density-of-state model of Phillipset al.[7]. In either case the overall agreement between the observed and calculated distributions is rather poor and the widths determined experimentally are larger than the natural ones. As pointed out by Roy et al.[8]) this fact had to be related to the three-body character of the reactio nand some specific three-body efects, such as the phase space and the direct three-body break-up.

In the present experiment the d + ^{7}Li reaction was studied at E = 180 keV using α — α and α — n correlation measurement techniques. The analysis of the data was performed in the framework of Phillips-Griffy-Biedenharn model[7] and the single-level approximation of the Wigner-Eisenbud dispersion theory[9].

2. *Experimental procedure*

An experimental technique was developed for studying kinematically complete three.body nuclear reactions induced by low-energy charged particles. The Cockcroft-Walton accelerator of the Institute »Ruđer Bošković« was used as a source of incident charged particles of an energy up to 200 keV. A scattering chamber

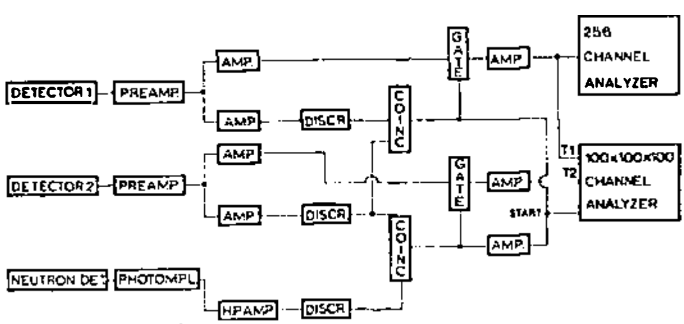

Fig. 1. Electronic set-up used for a simultaneous measurement of α — α and α — n coincidence.

with two tantalum discs in front of the chamber defining the incident beam was constructed. A target holder was mounted in the centre of the chamber, allowing the target to be rotated around the beam axis. The detector holders were constructed in such a way that the angle of one of the detectors could be changed from the outside of the chamber and the other detector had a fixed position in the chamber.

Two α particles were detected in coincidence by two surface barrier detectors and an electronic set-up, as shown in Fig. 1. A 7.6 × 7.4 cm Ne218 liquid scintillator was used simultaneously to detect neutrons in coincidence with one of the α particles (Fig. 1). In order to determine the threshold and the efficiency of the

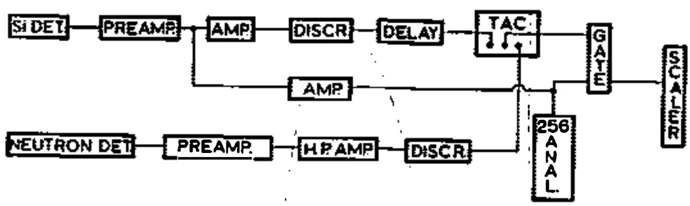

Fig. 2. Electronic set-up used for calibration of the neutron counter.

neutron counter, the two-body reactions d + d → n + ^{3}He, Q = 3.28 MeV and d + T → n + ^{4}He, Q = 17.59 MeV were used. The charged particles from these reactions were detected at 90° and scaled both separately and in coincidence with the corresponding neutrons (Fig. 2). In this way the efficiency curve for the neutron counter shown in Fig. 3 was obtained. A similar method of correlation measure-

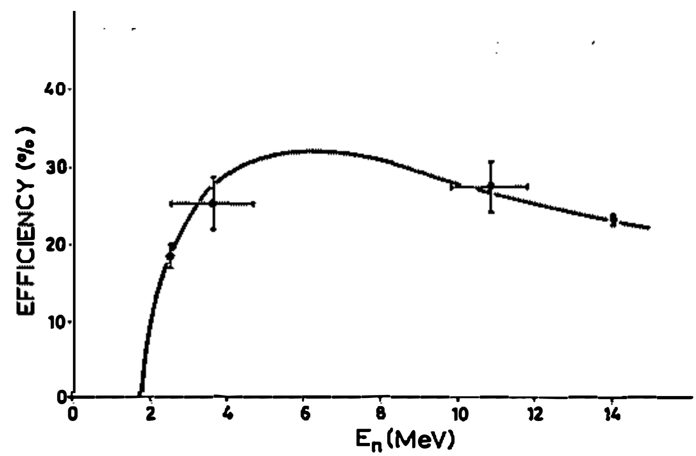

Fig. 3. Neutron-counter efficiency curve. Data at E_n = 2.4 MeV and 14 MeV are from d + d and d + T reactions respectively. Data at E_n = 3 MeV and 10 MeV are from the ^{7}Li(d, n) $^8B_{g.s.}$ reactions, where both neutrons and recoil particles were detected. Solid curve is the calculated efficiency.

ment of two α particles from the p + ^{7}Li $\to \alpha + \alpha$ reaction was used to determine the exact angular position of the movable detector (Fig. 4). The whole system was calibrated using an ^{241}Am source, together with α particles from reactions (1) and (2). The target was made by vacuum evaporation of LiF (200 mg/cm^2) on a thin Ni foil. Since the target contained both ^{7}Li and ^{6}Li, the ^{6}Li (d, α)^{4}He reaction was used for relative normalization of the three-body coincidence spectra.

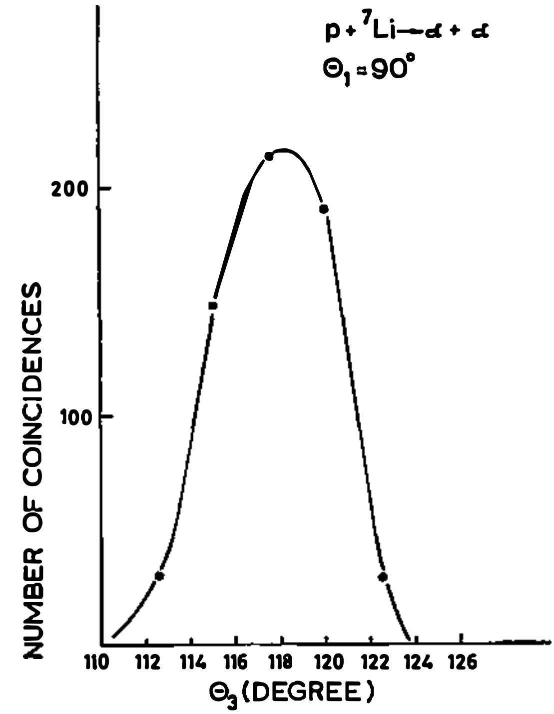

Fig. 4. Determination of the exact angle of the movable detector using the maximum number of coincidences from the ^{7}Li (p, α)^4 He reaction. Θ_3 is 180° − $\Theta_{\alpha 2}$.

3. *Results*

In order to obtain information about the mechanism of the reaction and the properties of the intermediate ^{5}He and ^{8}Be states, $\alpha - \alpha$ and α − n correlation spectra were taken in the reaction plane for the pairs of angles $\Theta_{\alpha 1} = 60°$, $\Theta_{\alpha 2} = 115°$; $\Theta_n = 60°$, $\Theta_\alpha = 110°$ and $\Theta_n = 130°$, $\Theta_\alpha = 70°$. All $\alpha - \alpha$ coincidence events were spread around the kinematical locus (Fig. 5) because of the energy losses of α particles in the target. For the angle 60°, 115°, only one final state interaction, n − α in ^{5}He$_{g.s.}$ can occur. The data indeed show pronounced peaks at position corresponding to ^{5}He$_{g.s.}$. The spectra of α particle obtained as a pro-

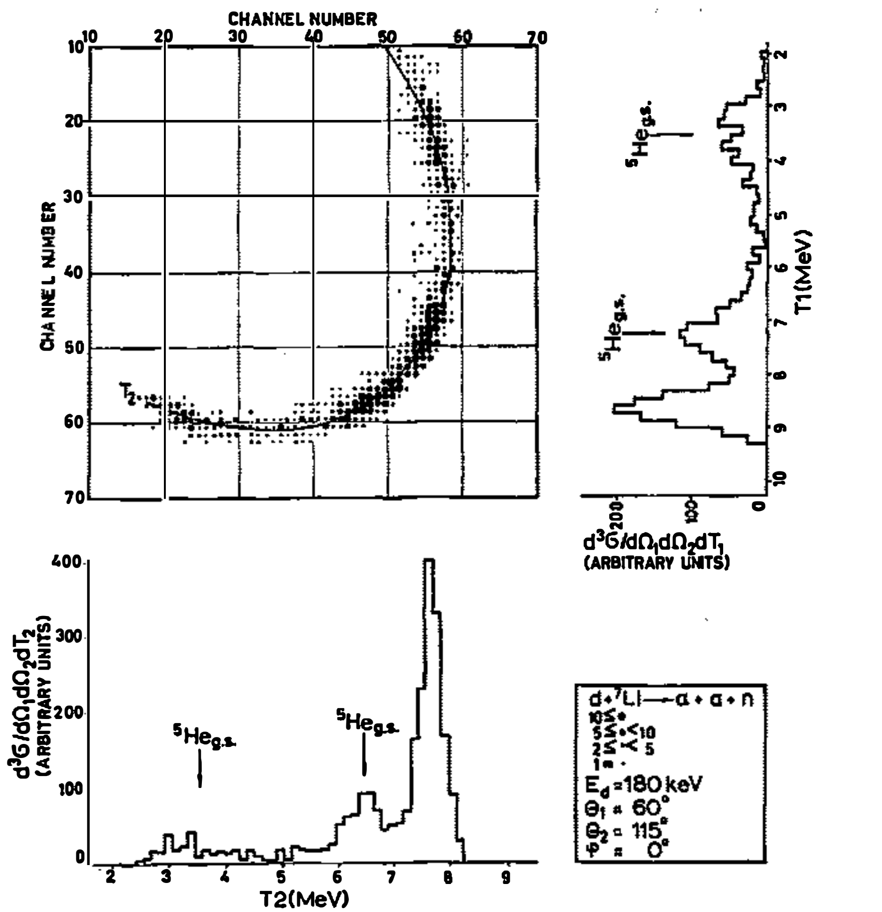

Fig. 5. Two-dimensional representation of the $\alpha_1 - \alpha_2$ coincidence date for $\Theta_{\alpha 1} = 60°$ and $\Theta_{\alpha 2} = 115°$, respectively.

jection of the α — n locuses are shown in Figs. 6 and 7. Fig. 8 represents the calculated excitation energies of the ^{5}He and ^{8}Be nuclei for $\Theta_n = 130°$ and $\Theta_\alpha = 70°$. At these kinematic conditions (and falso for $\Theta_n = 60°$ and $\Theta_\alpha = 110°$), the ground and first excited states of both the ^{5}He and ^{8}Be nuclei may occur. However, the ^{8}Be ground-state peak was not observed because it fell in the energy region excluded by the threshold of the experimental set-up. The ^{5}He ground-state peak occurred at the end of the locus and therefore could not be resolved from the phase-space projection peak.

4. *Analysis and discussion*

As predicted by the kinematics, a qualitative analysis of the data showed that the reaction proceeds through the formation of ^{5}He and ^{8}Be intermediate nuclei. A predominance of the $\alpha + {}^5$He channel was observed, in agreement with the results of other groups[6]. In order to reproduce the shape and width of the ^5He ^8Be spectra, the differential cross section was calculated using the expression

$$\frac{d^3\sigma}{dT_1\, d\Omega_1\, d\Omega_2} \cong |A|^2 \, d(PSF),$$

where A is the matrix element for the reaction and d (PSF) is the phase-space factor[10].

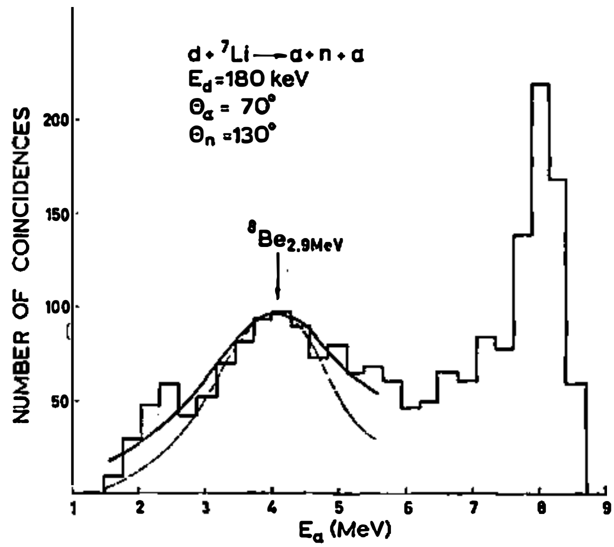

Fig. 6. Projected α-particle spectra obtained by α — n correlation measurement for $\Theta_\alpha = 110°$ and $\Theta_n = 60°$, respectively. The solid line is calculation based on the Breit-Wigner term and PGB density-of-state function including a contribution of 15% of a direct three-body decay. The dotted curve is calculated without this contribution.

An attempt was made to fit the spectra representing the matrix element by a Breit-Wigner term[9]. For the position and the width of the ^5He ground state and the ^8Be first excited state, the values were taken from Ref.[5]. However, the calculated spectrum for the ^8Be first excited state with $\Gamma = 1.45$ MeV was too narrow.

An analysis based on the Phillips-Griffy-Biedenharn density-of-state function gave satisfactory results in the case of the ^5He ground state appearing in the $\alpha - \alpha$ correlation spectra (Fig. 9). The expression

$$\varrho_l^{(1)}(E) = \frac{d}{dE}(\delta_l + \varnothing_l)$$

was used, with the values for the nuclear and the hard-sphere phase-shifts ϱ_l and $\varnothing_l$, respectively, taken from Ref.[11].

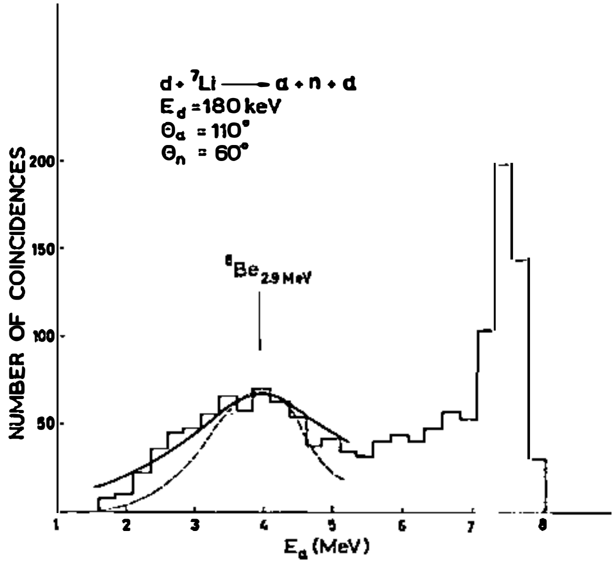

Fig. 7. Projected α-particle spectra obtained by α — n correlation measurements for $\Theta_\alpha = 70°$ and $\Theta_n = 73°$, respectively. The solid line is calculation based on the Breit-Wigner term and PGB density-of-state funcition including a contribution of 15% of a direct three-body decay. The dotted curve is calculated without this contribution.

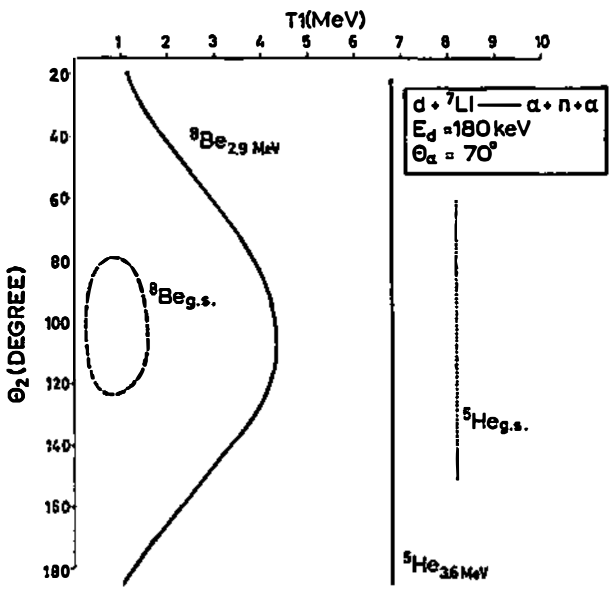

Fig. 8. Calculated α — α and α — n relative-energy curves for $\Theta_\alpha = 70°$.

Applied to the peak of the ^{8}Be first excited state, the same calculation could not explain its width and the presence of a continuum between this peak and the phase-space projection peak at the end of the spectrum (the dotted curves in Figs. 6 and 7). The kinematically possible contribution of the ^{5}He first excited state to the continuum was excluded on the basis of the arguments given in Ref.[12]

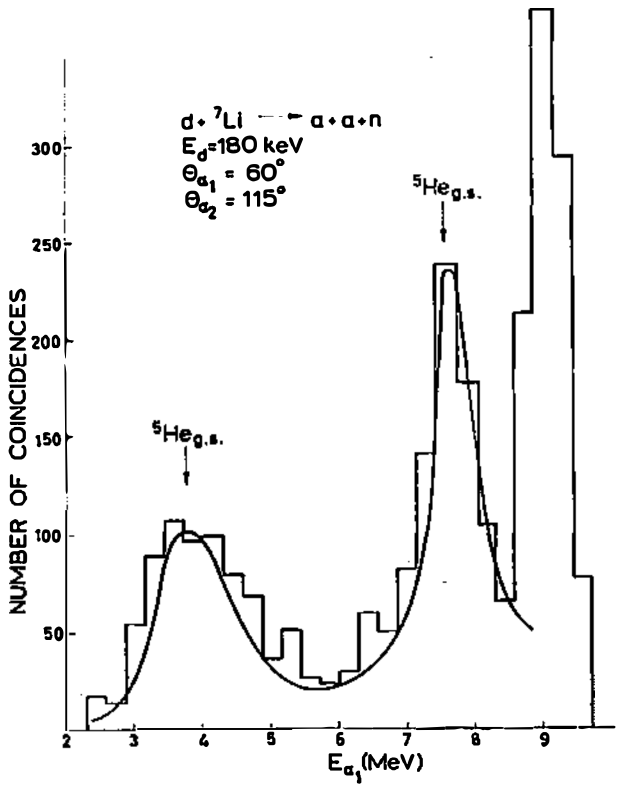

Fig. 9. Projected α-particle spectra obtained by $\alpha - \alpha$ correlation measurements for $\Theta_{\alpha_1} = 60°$ and $\Theta_{\alpha_2} = 115°$. The solid lines represent the calculated cross section, using the $\varrho_l^{(1)}(E)$ density-of-state function.

for the same reaction. Following the idea given in Ref.[8], a contribution of 15% of a direct three-body decay was included in the calculation of the cross section, assuming that the matrix element is constant. Although a value of 15% is rather large (the solid curves in Figs. 6 and 7), it gave a better explanation of the overall features of the experimental spectra.

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PROUČAVANJE REAKCIJA INDUCIRANIH DEUTERONIMA NA ^{7}Li KOD $E_d = 180$ keV

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Sadržaj

Razvijena je eksperimentalna tehnika za proučavanje nuklearnih reakcija induciranih niskoenergetskim nabijenim česticama. Nuklearna reakcija d + ^{7}Li → α + + α + n je ispitivana kod upadne energije deuterona $E_d = 180$ keV mjerenjem $\alpha - \alpha$ i $\alpha -$ n koincidencija. Opisana je eksperimentalna tehnika i mjereni korelacioni spektri. Izračunat je diferencijalni udarni presjek koristeći Breit-Wignerovu formulu i Phillips-Griffy-Biedenharn model.

Analiza rezultata ukazuje da se proces odvija više preko α + ^{5}He nego n + ^{8}Be izlaznog kanala. Kod analize $\alpha -$ n koincidencije bolje slaganje eksperimentalnih i teoretskih rezultata dobija se uzevši u obzir i neposredni raspad u tri tijela.