Deuteron Scattering on $^6$Li at an Energy of 25 MeV

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Abstract—At an energy of 25 MeV and in the angular range $7^\circ-175^\circ$ in the laboratory frame, angular distributions were measured for elastic deuteron scattering on $^6$Li nuclei and for the respective inelastic-scattering processes accompanied by the transitions to the ground state ($1^+$) of the $^6$Li nucleus and to its excited state at $E_x = 2.186$ MeV ($J^\pi = 3^+$). The resulting data were analyzed on the basis of the optical model of the nucleus and the coupled-reaction-channel method with allowance for the mechanism of alpha-particle-cluster exchange. It is shown that only upon including, in the analysis, channel coupling and the exchange mechanism can the experimental cross sections for elastic and inelastic scattering be reproduced over the entire range of angles.

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1. INTRODUCTION

Investigation of deuteron interaction with lithium nuclei is not only of a purely academic interest, but it is also of great importance for applications in view of the role that lithium plays in nuclear technologies—in particular, in the most advanced projects of thermonuclear reactors involving D + T plasma. With aim of tritium production, it is proposed that lithium will enter into the composition of the envelope closest to the plasma-burning region. This technology requires high-precision data on the cross sections for deuteron interaction with lithium nuclei. Such data can be obtained both from experiments and from calculations on the basis of specific nuclear models by using potentials of deuteron interaction with lithium nuclei. As a rule, the respective potentials are extracted from an analysis of elastic $d + ^6$Li scattering within the optical model of the nucleus.

It is well known, however, that the application of this model to deuteron scattering on light nuclei runs into serious difficulties. The main ones are the following: the level density in the compound system is relatively low, which leads to an insufficient averaging over resonance states, and the number of nucleons in colliding nuclei is small, which causes the enhancement of cluster effects and of the nonlocality of the interaction. Specifically, channel coupling and spin–orbit interaction may play a significant role for the $d + ^6$Li system. Moreover, both the projectile particle ($d$) and the target nucleus ($^6$Li) have very low dissociation thresholds with respect to the channels $d \rightarrow n + p$ and $^6$Li $\rightarrow d + \alpha$, and this is a complicating circumstance since, in analyzing the respective scattering process, it is necessary to take into account coupling to a continuum. In view of this, it is not surprising that a global optical-model description of deuteron scattering does not include the region of $A < 12$ nuclei [1–5].

The present study is devoted to exploring deuteron scattering on $^6$Li nuclei at a projectile energy of 25 MeV. Previously, similar investigations were performed at the energies of $E_d = 4–12$ MeV [6–8], 14.7 MeV [9, 10], and 19.6 MeV [11, 12]. At the higher energies of 50 [13] and 171 MeV [14], measurements for the respective elastic-scattering process were performed over a restricted angular range. In the first case, the differential cross sections were obtained predominantly over the energy range $80^\circ–150^\circ$, while, in the second case, these observables were determined for forward-hemisphere angles in the range $10^\circ–60^\circ$. In the investigations performed at energies in the range between 4 and 12 MeV, the experimental cross sections can be described quite satisfactorily on the basis of the standard optical model. Yet, Bingham et al. [7] had to increase the range of the real part of the potential to values exceeding considerably conventional values in order to match the calculated cross sections with their experimental counterparts. In [8], an acceptable description was attained by setting the depth of the spin–orbit

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potential \( (V_{so}) \) to about 30 MeV, which is almost four times as great as a typical phenomenological value of about 8 MeV. An analysis of the scattering process at the energies of \( E_d = 14.7 \) \cite{10} and 19.6 MeV \cite{11, 12} revealed that the standard optical model is unable to explain the growth of the cross sections at large angles. Only upon taking into account, along with potential scattering, the mechanism involving the exchange of an alpha-particle cluster, \( ^6\text{Li}(d, ^6\text{Li})d \), this mechanism being indistinguishable from elastic scattering, could experimental data be reproduced in this region of angles. This complies with the results of M. Avrigeanu et al. \cite{15}, who were able to describe experimental data only within the coupled-reaction-channel (CRC) method with allowance for the exchange mechanism.

The fact that the exchange mechanism manifests itself strongly at higher energies is surprising. Here, it would be natural to expect an inverse effect, since, as the projectile energy increases, the probability of the exchange mechanism should decrease both owing to a decrease in the interaction time and owing to an increase in the momentum transfer at which the alpha-particle transfer and the role of channel-coupling effects in deuteron scattering on \( ^6\text{Li} \) nuclei at the energy of 25 MeV.

2. EXPERIMENTAL PROCEDURE AND RESULTS OF MEASUREMENTS

Our measurements were performed in a beam of 25–MeV deuterons that was extracted from the isochronous cyclotron U-150M of the Institute of Nuclear Physics at the National Nuclear Center (Almaty, Republic of Kazakhstan). The target used was arranged at the center of a vacuum scattering chamber, its inner diameter being 715 mm. The chamber had two independently rotating platforms for installing detectors.

The size of the beam spot at the target was about 3 mm, the angular spread of deuterons incident to the target being within \( \pm 0.7^\circ \). A beam of required dimensions was formed by a collimator situated at the inlet of the scattering chamber and equipped with two guiding and one antiscattering tantalum diaphragm. In order to reduce the background of neutrons and gamma rays from the collimator diaphragms and a Faraday cylinder, cylindrical insertions from lead and borated paraffin were arranged downstream of the guiding diaphragms and upstream of the Faraday cylinder. These insertions were about 200 mm in length and had holes 15 to 25 mm in diameter. For the same purpose, graphite plates were arranged in front of the diaphragm first from the cyclotron and at the bottom of the Faraday cylinder.

For targets, we employed foils from metallic lithium enriched in \( ^6\text{Li} \) to 96%. They were produced by means of a thermal evaporation onto thin (about 10 \( \mu \)g/cm\(^2\) in thickness) alundum (\( \text{Al}_2\text{O}_3 \)) films and, after that, were transported in a special container equipped with a vacuum gate valve to the scattering chamber without breaking a vacuum. The target thicknesses were 0.2 to 0.4 mg/cm\(^2\) and were determined on the basis of the energy loss of alpha particles from a \(^{226}\text{Ra} \) source arranged within the scattering chamber. The thicknesses in question were measured both immediately before the experiment and after its completion.

The deuteron flux was tested by means of a Faraday cylinder arranged downstream of the scattering chamber. This flux was additionally monitored with the aid of a silicon detector by the number of particle counts within a specific energy bin, the thickness of its sensitive area being 1 mm. The monitoring detector was fixed at an angle of 20° above the beam trajectory within the scattering chamber.

Scattered deuterons were recorded by two telescopes of silicon counters installed in the regions of the forward and backward hemispheres of reaction-product emission angles. They consisted of thin transmission (\( \Delta E \)) detectors (50 to 100 \( \mu \)m in thickness) and thick (about 1 and 2.3 mm in thickness) total-absorption detectors (\( E \)). Scattered deuterons were separated from other charged reaction products by means an electronic system of a two-dimensional (\( \Delta E, E \)) analysis, this system being implemented on the basis of a PC with the aid of the Win-EDE code \cite{16}.

The solid angle was \( 1.2 \times 10^{-4} \) sr. The energy resolution was within the range 300–350 keV at small angles and within the range 350–450 keV at large