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MEASUREMENT OF PROTON-INDUCED REACTIONS ON LITHIUM AT ULTRA-LOW ENERGIES*

S. Thulichery [a], K. Czerski [a], R. Dubey [a], Gokul Das H [a]
A. Kowalska [b], M. Kaczmarski [a], N. Targosz–Ślęczka [a]
M. Valat [a]

[a]Institute of Physics, University of Szczecin, 70-451 Szczecin, Poland
[b]Institute of Mathematics, Physics and Chemistry
Maritime University of Szczecin, 70-500 Szczecin, Poland

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Nuclear reactions involving lithium isotopes are important for Big Bang nucleosynthesis and for explaining the depletion of lithium observed in stars. In particular, the ^{6}Li$(p,\alpha)^3$He and ^{7}Li$(p,\alpha)^4$He reactions play a significant role in the formation and destruction of light nuclei in astrophysical environments. Experimental data at energies below 20 keV are scarce due to the strong influence of electron screening in metallic targets. To investigate this region, measurements were performed at the Ultra High Vacuum accelerator facility of the University of Szczecin using a magnesium–lithium alloy target (55% Mg, 45% Li). Thick target yields were measured for proton beam energies between 13 and 26 keV with currents up to 1 mA. From these data, a high screening energy of $U_e = 3.9 \pm 0.6$ keV was determined. For comparison, the ^{2}H$(d,p)^3$H reaction was also studied on the same target, giving $U_e = 1.5 \pm 0.19$ keV. These results indicate that MgLi alloys provide exceptionally strong screening and are promising for future low-energy fusion studies.

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1. Introduction

Nuclear reactions involving lithium isotopes are of great importance in both astrophysics and fusion research. In particular, the ^{6}Li$(p,\alpha)^3$He and ^{7}Li$(p,\alpha)^4$He reactions play key roles in Big Bang nucleosynthesis and in explaining the depletion of lithium observed in stellar environments [1]. Precise measurements of these reactions at low energies are essential for modeling the formation and destruction of light elements in the early universe.

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However, experimental studies in this energy region are challenging because the reaction cross sections decrease rapidly with energy and are strongly affected by electron screening. The lowest projectile energy at which these reactions were measured before is 25 keV [2–5]. In metallic targets, bound and conduction electrons partially shield the Coulomb repulsion between the interacting nuclei, enhancing the measured cross section compared to the bare-nucleus value. Understanding this effect is crucial for obtaining accurate astrophysical S-factors and for improving models of nuclear processes in stellar and laboratory conditions.

To explore these effects, low-energy measurements of lithium reactions in metallic environments are particularly valuable. Such studies help to quantify the magnitude of the screening potential and reveal how the target's electronic structure influences fusion enhancement at sub-Coulomb energies.

2. Experimental setup

Experiments were carried out at the Ultra High Vacuum (UHV) accelerator facility of the University of Szczecin, Poland [6]. Proton beams with energies of 13–26 keV and deuteron beams with energies of 5.5–26 keV, both at currents of 200–1000 μA, were produced in an ECR ion source, magnetically analyzed, and focused onto a 15 mm diameter, 1 mm thick MgLi target (55% Mg, 45% Li). Reaction products were detected with a 100 μm thick PIPS Si detector (100 mm^2 active area) positioned at 135° relative to the beam axis. The detector signal was processed using a standard NIM electronics chain and recorded with a TUKAN Multi Channel Analyser (MCA). A 1 μm Al foil was placed in front of the detector to suppress elastically-scattered ions. Target was cooled down by an air cooling system and its surface purity was monitored using Auger Electron Spectroscopy (AES).

The experimental enhancement factor is obtained by taking the ratio between the experimental thick target yield and the theoretical yield without screening [7]

$$F(E) = \frac{Y_{\rm scr}(E)}{Y_{\rm bare}(E)} = \frac{\int_0^E \sigma_{\rm scr}(E) \left(\frac{{\rm d}E}{{\rm d}x}\right)^{-1} {\rm d}E}{\int_0^E \sigma_{\rm bare}(E) \left(\frac{{\rm d}E}{{\rm d}x}\right)^{-1} {\rm d}E}\,, \tag{1}$$

where the screened cross section is defined as

$$\sigma_{\rm scr} = \frac{S(E)}{\sqrt{E_{\rm G}(E+U_e)}}\, P(E+U_e)\,. \tag{2}$$

Here, $S(E)$ denotes the energy-dependent astrophysical S-factor, and U_e is the screening energy. The Gamow energy $E_{\rm G}$ takes the values 986 keV, 7606 keV, and 7658 keV for the ^{2}H$(d,p)^3$H, ^{6}Li$(p,\alpha)^3$He, and ^{7}Li$(p,\alpha)^4$He reactions, respectively. In the presence of electron screening, the penetration probability $P(E)$ is modified to $P(E+U_e)$ and is defined as [8]

$$P(E+U_e) = \sqrt{\frac{E_{\mathrm{G}}}{E+U_e}} \exp\left(-\sqrt{\frac{E_{\mathrm{G}}}{E+U_e}}\right) . \tag{3}$$

3. Results and discussions

3.1. Proton-induced reaction on Li in MgLi

During the measurements, an 8.80 MeV α particle from the $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$ reaction, as well as a 1.72 MeV α and a 2.30 MeV $^3\mathrm{He}$ from the $^6\mathrm{Li}(p,\alpha)^3\mathrm{He}$ reaction, were observed.

To extract the electron screening energy from the experimental data, the S-factor of the bare-nucleus cross section was taken into account. The thick target yield was then fitted by treating the electron screening energy U_e and a normalization factor accounting for the geometrical efficiency of the experimental setup as free parameters. The model was fitted to the experimental data using these parameters according to the relation

$$Y(E) = \frac{Ze}{\epsilon}\frac{\mathrm{d}N_p}{\mathrm{d}q} , \tag{4}$$

where N_p is the number of incoming protons (with $Z=1$) expressed in terms of their charge q, and ϵ is the detector efficiency, taken to be 100%. The experimental yield is then compared to a theoretical one, which takes into account an increase of the penetration factor through the Coulomb barrier due to the electron screening effect

$$\begin{aligned} Y_{\mathrm{scr}}(E) &= N\int_0^R \sigma_{\mathrm{scr}}(E)\,\mathrm{d}x \\ &= N\int_0^E \frac{\sigma_{\mathrm{scr}}(E)}{\left|\frac{\mathrm{d}E}{\mathrm{d}x}\right|}\,\mathrm{d}E \simeq \frac{2NS(E)}{C\sqrt{E_{\mathrm{G}}}} \exp\left(-\sqrt{\frac{E_{\mathrm{G}}}{E+U_e}}\right) . \end{aligned} \tag{5}$$

Here, N denotes the target atomic density of reaction centers, and C is the stopping power constant [9]. A notably high screening energy of $U_e = 3.8 \pm 0.6$ keV was determined. The thick target yield measured for the same reaction at different times is presented in Fig. 1 (a). The observed variation in yield arises from the migration of $^6\mathrm{Li}$ atoms toward the target surface over time, resulting in increased yield in later measurements.

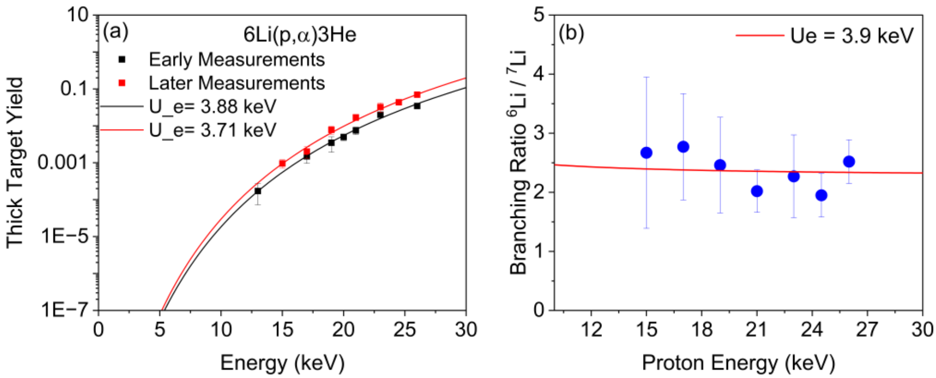

Fig. 1. (a) Thick target yield *versus* proton energy spectrum of the ^{6}Li$(p,\alpha)^3$He reaction; (b) Branching ratio of ^{6}Li$(p,\alpha)^3$He and ^{7}Li$(p,\alpha)^4$He (uncorrected for natural isotopic composition of Li).

The experimental branching ratio between the ^{6}Li$(p,\alpha)^3$He and ^{7}Li$(p,\alpha)^4$He reaction yields is shown in Fig. 1 (b). These values have not been corrected for the natural isotopic abundance of lithium, which is 7.6% for ^{6}Li and 92.4% for ^{7}Li, nor for theoretical $S(E)$-factors. The experimental data indicate that the ^{6}Li$(p,\alpha)^3$He branch is more dominant than the competing ^{7}Li$(p,\alpha)^4$He reaction, which is attributed to the lower reduced mass and the Gamow energy associated with proton-induced reactions on ^{6}Li.

3.2. DD reactions on MgLi

To verify the results obtained from the proton-induced reactions, additional measurements were performed for the ^{2}H$(d,p)^3$H reaction. To study this reaction, we used the same MgLi target, which was implanted by deuterons until the saturation deuteron density was reached. Since the screening energy should scale with the atomic number Z of the target nucleus, we expect that its value for the DD reaction is 3 times lower than that measured for reactions on Li isotopes ($Z_{\rm H} : Z_{\rm Li} = 1 : 3$). However, the experimental data could not be fitted with a single screening energy value. The yields corresponding to higher deuteron energies were best fitted with a larger U_e, while those at lower deuteron energies were consistent only with a smaller U_e. This behavior is attributed to carbon contamination on the surface of the MgLi target, which modified the effective screening conditions during the measurements.

The post irradiation image of the target is shown in Fig. 2 (b). During irradiation, carbon atoms within the target migrated toward the surface, forming a thin carbon layer, as confirmed by the Auger Electron Spectroscopy.

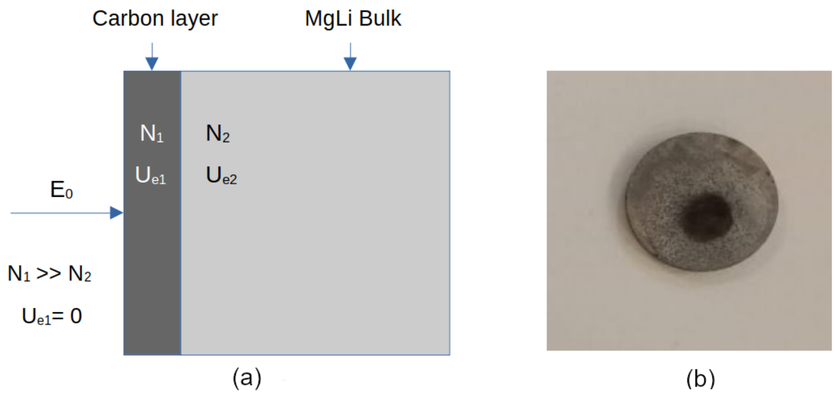

Fig. 2. (a) Two-layer model with carbon on the surface (the schematic diagram is not drawn to scale); (b) Target sample with contamination.

A two-layer model of the target was therefore proposed in Fig. 2 (a), consisting of a carbon-rich surface layer only a few nanometers thick, where the deuteron density (N) is extremely high but the screening potential is nearly zero, and a bulk MgLi layer beneath it, where the deuteron density is relatively low but the screening potential is higher due to the large number of free electrons. A parametric fit based on this two-layer model yielded a screening energy of $U_e = 1.5 \pm 0.19$ keV, in good agreement with theoretical expectations. The corresponding experimental enhancement factor was also determined (see Fig. 3 (b)). Both theoretical curves, with and without the two-layer model, are shown in Fig. 3 (a).

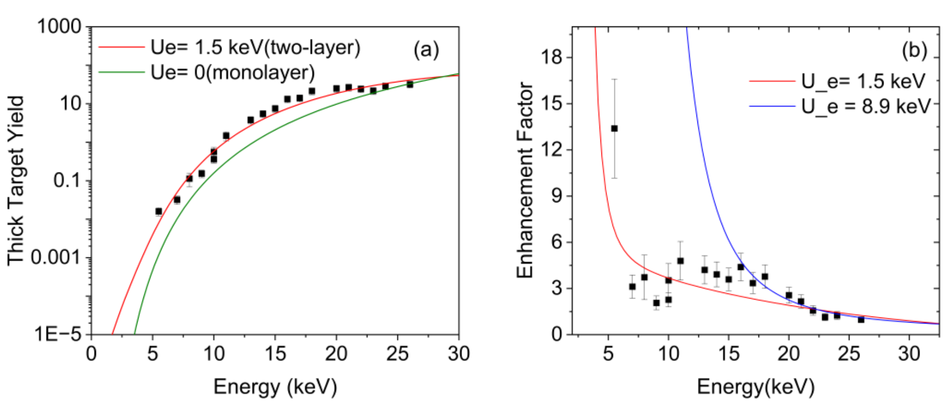

Fig. 3. (a) Parametric fit using a two-layer model $U_e = 1.5 \pm 0.19$ keV compared to the screening curve for $U_e = 0$; (b) Enhancement factor fitted using a two-layer model and high screening energy value which fitted the higher energy yields.

4. Conclusions

We could measure the ^{6}Li$(p,\alpha)^3$He and ^{7}Li$(p,\alpha)^4$He reactions at the lowest proton energy of 13 keV, which corresponds to more than two orders of magnitude lower reaction yield value than measured before [4]. The experimental data could be fitted with a constant astrophysical S-factor and a very large screening energy, $U_e = 3.8 \pm 0.6$ keV. The ^{6}Li/^{7}Li branching ratio slightly increases for lowering proton energies, which can be explained by the smaller Gamow energy for the reaction on ^{6}Li.

For the DD fusion reaction, the extracted screening energy $U_e = 1.5 \pm 0.19$ keV is approximately one-third of that obtained for the Li$+p$ reactions, which is consistent with theoretical expectations based on atomic number scaling. The strong electron screening observed in MgLi indicates that this material is a promising candidate for studying enhanced low-energy fusion processes. Compared to metallic environments previously studied under ultra-high vacuum conditions such as Zr ($U_e = 0.34$ keV) [9], MgLi exhibits a significantly higher screening energy, underscoring the influence of its electronic structure on fusion enhancement.

Future work will focus on extending the measurements to proton energies below 5 keV and performing comparative studies with other target materials to refine electron screening models and further elucidate the mechanisms governing screening effects in metallic systems.

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