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Measurement of the differential cross sections of $^{6}Li(d,d_0)$ for Ion Beam Analysis purposes

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ABSTRACT

In the present work, the $^{6}Li(d,d_0)^{6}Li$ elastic scattering differential cross sections were measured in the energy range $E_{d,lab}$ = 940–2000 keV for Elastic Backscattering Spectroscopy (EBS) purposes, using thin lithium targets, made by evaporating isotopically enriched ^{6}LiF powder on self-supporting carbon foils, with an ultra-thin Au layer on top for normalization purposes. The experiment was carried out in deuteron beam energy steps of 20 or 30 keV and for the laboratory scattering angles of 125°, 140°, 150°, 160°, and 170°.

1. Introduction

The accurate quantitative determination and concentration depth profiling of lithium is important for the characterization of a great variety of materials, ranging from glass and ceramics to metallic alloys and polymers. Moreover, as natural lithium is composed of two isotopes, ~92.5% ^{7}Li and ~7.5% ^{6}Li, whose relative mass difference is high, their individual analytical study is imperative. In particular, ^{6}Li has a very high neutron cross-section (~940 barns) and so readily fissions to yield tritium and helium. It has been the main source of tritium which is used in biochemical research, thermonuclear weapons and future controlled fusion. Moreover, neutron converters containing ^{6}Li can be used in conjunction with cellulose nitrate for the detection of thermal neutrons

However, the depth profiling of ^{6}Li presents a strong analytical challenge for all IBA (Ion Beam Analysis) techniques, since lithium is highly reactive and, due to its low atomic number, is usually present in relatively complex matrices along with several medium- or high-Z elements. In the field of NRA (Nuclear Reaction Analysis), the most promising reactions seem to be the $^{6}Li(p,^{3}He)$ [1], the $^{6}Li(d,p_0)$ [2] and the $^{6}Li(d,\alpha_0)$ [3] ones. The latter two are particularly important, not only because they yield isolated peaks with practically no background (due to the high Q-values involved), but mainly due to the fact that d-NRA can facilitate the simultaneous study of practically all the main light isotopes possibly coexisting in a target. The applicability of d-NRA would be greatly enhanced if one could also simultaneously analyze the resulting EBS (Elastic Backscattering Spectroscopy) spectra using the same experimental setup and conditions in a coherent way. However, as evidenced in IBANDL (Ion Beam Analysis Nuclear Data Library, https://www-nds.iaea.org/exfor/ibandl.htm), there is a complete lack of relevant deuteron elastic scattering differential cross-section datasets on ^{6}Li, for low energies particularly suitable for IBA, namely below $E_{d,lab}$ ~2.2 MeV, where the inevitable neutron background remains low.

The present work aims at contributing in this field, by providing coherent differential cross-section datasets for $^{6}Li(d,d_0)^{6}Li$ elastic scattering, in the energy range $E_{d,lab}$ = 940–2000 keV, for the laboratory scattering angles of 125°, 140°, 150°, 160°, and 170°. The experiment was carried out in deuteron beam energy steps of 20 or 30 keV using a thin lithium target, made by evaporating isotopically enriched ^{6}LiF powder on self-supporting carbon foils, with an ultra-thin Au layer on top for normalization purposes, as will be analyzed in the following sections.

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2. Experimental setup

The experiment was carried out at the 5.5 MV Tandem Accelerator of the Institute of Nuclear and Particle Physics (INPP), National Centre of Scientific Research (NCSR) "Demokritos", Athens, Greece, using deuterons accelerated to $E_{d,lab}$ = 940–2000 keV in steps of 20–30 keV. The accelerator beam energy was determined by means of the 1.737 MeV (Γ = 47 keV) and 2.08 MeV (Γ = 15.6 keV) resonances of the $^{12}C(p,p_0)$ and $^{28}Si(p,p_0)$ elastic scattering, respectively, as described in [4]. The deuterons were led to a cylindrical chamber of large dimensions (R ~40 cm) through a 2 mm collimator, located ~1 m before the target holder. The target holder was placed perpendicularly to the beam axis and in the center of the goniometer. The target used for the cross-section measurements was made at N.C.S.R. "Demokritos" using the evaporation technique. At first, a small quantity of high-purity, isotopically enriched ^{6}LiF powder (97% in ^{6}Li) was evaporated on self-supporting carbon foils and an ultra-thin Au layer was subsequently evaporated on top for normalization purposes.

The detection system consisted of five Si surface barrier detectors (SSB) with 500 μm thickness and ~13 keV resolution (value acquired from a polished Si target), which were mounted at the laboratory scattering angles of 125°, 140°, 150°, 160°, and 170°, at a distance of ~10 cm from the target, along with the corresponding electronics. The spectra from all five detectors were simultaneously recorded for each deuteron beam energy. In front of each detector vertical slits were placed in order to minimize the angular uncertainty (~1°), while subtending an adequate solid angle, and small aluminum tubes (~2–5 cm in length, 1 cm in diameter) in order to impede elastically scattered particles from the chamber walls and/ or the faraday cup from impinging in the detector, and thus contributing to the induced background under the low energy ^{6}Li elastic peaks. The beam current on the target did not exceed 70 nA in order to avoid possible overheating and subsequent deterioration of the target. During the experiment the vacuum in the scattering chamber was of the order of 10^{-7} mbar. A typical spectrum is shown in Fig. 1, along with the corresponding peak identification, for $E_{d,lab}$ = 1820 keV at 150°.

It should be noted here that during the experiment certain proton beam spectra ($E_{p,lab}$ = 1600 keV, 1700 keV) were also acquired in order to determine the enrichment of the thin target. These proton spectra were also used as an alternative means to check the ratio of the gold to lithium atoms, a key factor in determining the elastic cross section of ^{6}Li. The SPECTRW algorithm [5] was used for background subtraction and peak integration, while SIMNRA v.6.94 [6] was used for the analysis of certain EBS spectra obtained in the present work. The effects of multiple and plural scattering, the beam ripple, ZBL [7] stopping power data, and Chu and Yang's straggling model were used as implemented in the code.

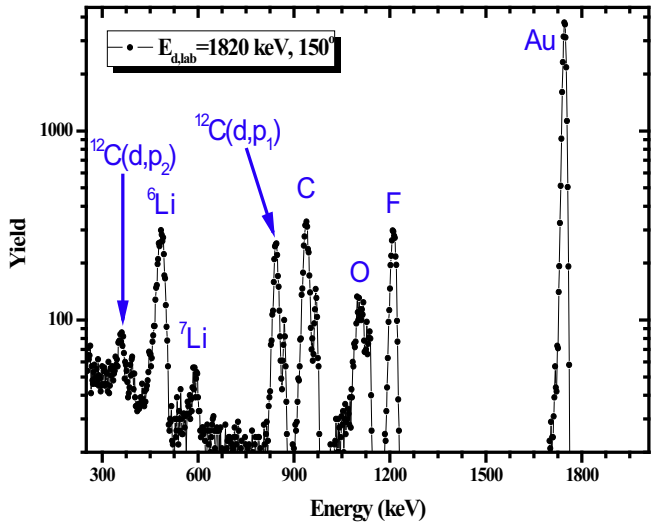

Fig. 1. Experimental deuteron spectrum at $E_{d,lab}$ = 1820 keV and 150°, along with the corresponding peak identification.

3. Data analysis, results and discussion

The determination of the differential cross-section values for ^{6}Li was carried out using the relative measurement technique [8]. The procedure involves the formula for the absolute measurement of the ^{6}Li and ^{197}Au differential cross sections at each deuteron beam energy and scattering angle:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\theta,E_d,^6Li} = \frac{Y_{^6Li}}{(Q\times\Omega)\times N_{^6Li}} \text{ and } \left(\frac{d\sigma}{d\Omega}\right)_{\theta,E_d,Au} = \frac{Y_{Au}}{(Q\times\Omega)\times N_{Au}}$$

where generally Y corresponds to the experimental yield (integrated peak counts), Q to the number of impinging deuterons, Ω to the solid angle subtended by the detector set to angle θ, and N_i to the i-target thickness in at/cm^2. So by dividing, one gets the following formula:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\theta,E_d,^6Li} = \left(\frac{d\sigma}{d\Omega}\right)_{\theta,E_d,Au} \times \frac{Y_{^6Li}}{Y_{Au}} \times \frac{N_{Au}}{N_{^6Li}}$$

The use of this relative measurement technique eliminates the need to determine the product of the solid angle by the number of impinging deuterons (Q × Ω), which always increases the uncertainty of the measured differential cross-section values.

The term $\left(\frac{d\sigma}{d\Omega}\right)_{\theta,E_d,Au}$ in the above equation is calculated from Rutherford's formula, due to the high atomic number of gold and the low deuteron beam energies used in the present experiment. The obtained values include a correction due to electron screening.

The yield ratio $\frac{Y_{^6Li}}{Y_{Au}}$ is acquired from the integration of the corresponding peaks of lithium-6 and gold in the experimental spectra. The statistical uncertainty of this process was ~1%.

The determination of the ^{6}Li:Au areal surface density ratio was based on the following assumption: lithium and fluorine maintain their respective elemental ratio due to the strong chemical bond of LiF during evaporation, therefore the equality $\frac{N_{Au}}{N_{Li}} = \frac{N_{Au}}{N_F}$ is true. It should be noted here that hereafter the term N_{Li} will represent the total amount of lithium atoms in the enriched target. Thus, the ratio in question, namely $\frac{N_{Au}}{N_{^6Li}}$, is equal to $\frac{N_{Au}}{N_{Li}\times f_{enrich}}$ (with f_{enrich} being the enrichment factor of ^{6}Li in the target), which, using the above equation, is equal to $\frac{N_{Au}}{N_{^{19}F}\times f_{enrich}}$. Consequently, the following equation: $\frac{N_{Au}}{N_{^6Li}} = \frac{N_{Au}}{N_{Li}\times f_{enrich}} = \frac{N_{Au}}{N_{^{19}F}\times f_{enrich}}$ holds, and through this the target thickness was calculated. For that purpose, the spectra with deuteron energies up to ~1200 keV were utilized, because, as shown in [9], the cross-section for deuteron elastic scattering from fluorine follows the Rutherford's formula for energies up to ~1200 keV, for the scattering angles of 140° and 150°, (deviations are always less than 2%). Thus, by properly fitting the low-energy deuteron spectra at 1160 and 1200 keV using the SIMNRA program (v. 6.94) [6] the target thickness was obtained. The results of this procedure are shown in Fig. 2a, yielding a mean value of $\overline{\left(\frac{N_{Au}}{N_{Li}}\right)} = 0.091 \pm 0.004$.

Additionally, the target thickness was determined from the simulation of the proton spectra, as an alternative means of checking the obtained value, and, as shown in Fig. 2b for $E_{p,lab}$ = 1600 keV at 170°, the simulation seems to be in good agreement with the