Nuclear Instruments and Methods in Physics Research B 268 (2010) 1793–1796

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Elastic scattering of ^{7}Li + ^{27}Al at several angles in the 7–11 MeV energy range

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ARTICLE INFO

Article history:
Available online 25 February 2010

Keywords:
Elastic scattering
Rutherford backscattering
Optical Model, ^{7}Li + ^{27}Al system

ABSTRACT

Elastic cross sections for the ^{7}Li + ^{27}Al system were measured at laboratory energies between 7 and 11 MeV in steps of 0.25 MeV, and angles between 135° and 170° in steps of 5°. Excitation functions for the elastic scattering were measured using an array of eight Si surface-barrier detectors whereas a solid-state telescope was used to estimate and subtract background from other reactions. Contamination from α particles arising from the ^{7}Li breakup process at $E_{lab} \geqslant 10$ MeV makes the use of these energies inadvisable for RBS applications. The present results are compared with previous data obtained at 165° ($E_{lab} \leqslant 6$ MeV), 140° and 170° ($E_{lab} \leqslant 8$ MeV). The experimental data were analyzed in terms of the Optical Model. Two different energy-independent potentials were found. These optical potentials allow an interpolation with physical meaning to other energies and scattering angles. The experimental cross sections will be uploaded to the IBANDL database.

1. Introduction

Rutherford backscattering spectroscopy (RBS) using ions heavier than protons and α particles (HIRBS) offers several advantages over conventional RBS such as better sensitivity and improved depth and mass resolution for the analysis of elements with high atomic number [1–4]. HIRBS has been used to measure the concentration profile induced by the diffusion of a heavy element within a matrix of a lighter one, avoiding surface effects that could disturb the diffusion process [5–7]. The application of HIRBS to diffusion measurements allows the gap in depth sensitivity to be bridged between different techniques, such as RBS and the serial sectioning technique. In many cases at the high bombarding energies which are needed to explore a profile in depth, the scattering of the heavy ion from the matrix element cannot be described as purely Rutherford scattering. In those cases detailed knowledge of the experimental scattering cross sections as a function of energy is needed. For the particular case of ^{7}Li on ^{27}Al, several excitation functions have been reported [2,8–10] and they were compiled in the IBANDL database [11]. There are additional data by Figueira et al. [12] already published as angular distributions, but they are not included in the IBANDL database since they cover just a few energies at the angles relevant to HIRBS studies. However, the work of Figueira triggered theoretical studies in the scattering of ^{7}Li on ^{27}Al [13], and therefore a fair amount of guidance about the theoretical models is available to describe our experimental results and they will be further discussed herein.

In Section 2, the experimental details are given with emphasis on the normalization method used to obtain the ^{7}Li elastic scattering cross sections. Data analysis and experimental results with their interpretation are described in Sections 3 and 4, respectively. Section 5 presents the summary and conclusions.

2. Experimental details

For the present experiment the $^{7}Li^{2+}$ beam was supplied by the 20 UD tandem accelerator TANDAR at Buenos Aires, Argentina. Typical beam currents were about 50 nA. In order to detect and identify the reaction products of the ^{7}Li + ^{27}Al system, an array of eight solid-state Si surface-barrier detectors (150 μm thick) was placed in a 76-cm-diameter scattering chamber (Fig. 1). The solid angle of the detectors in the array increased from 0.3 msr for the first detector at 135° to 0.8 msr for the eighth detector at 170° (the angular apertures ranged from 0.3° to 0.7°). Their energy resolution (FWHM) ranged from 25 to 60 keV. A solid-state telescope detector (partial energy-loss detector ΔE 15 μm thick, residual energy detector E_{res} 150 μm thick) was placed at 135° in the

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doi:10.1016/j.nimb.2010.02.076

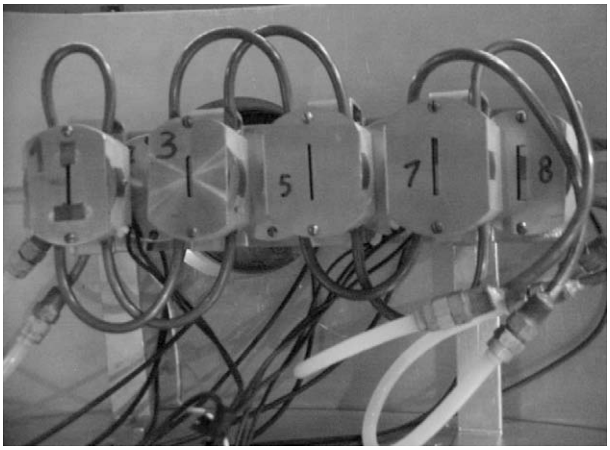

Fig. 1. The array of eight silicon surface-barrier detectors. Part of the liquid N_2 refrigeration system is also shown in the figure (not used in the present experiment).

scattering chamber (opposite hemisphere referred to the array) in order to get an insight into the background produced from the break-up of the ^{7}Li projectile. At energies above the nominal Coulomb barrier for the present reaction ($E_{\mathrm{lab\ CB}}$ = 8.4 MeV [14]), the background is mainly composed of light particles (protons, deuterons and alpha particles).

At the end of the scattering chamber and far away from the target, a Faraday cup connected to a digital current integrator provided a measurement of the beam intensity and, hence, a redundant method (the main normalization method is described below) for the determination of the ^{7}Li elastic scattering cross section. An additional solid-state Si surface-barrier detector was placed at 28° subtending a solid angle of 0.03 msr with an angular aperture of 0.2°. This detector, called the monitor, was used in two ways. First, for normalization purposes, when the current integrated in the Faraday cup was used to calculate the cross sections. Second, as another detector which provided valuable data when the cross sections were normalized with respect to the gold cross sections. The target was a ^{27}Al metal foil with a very thin ^{197}Au evaporated layer, with nominal thicknesses of 175 and 15 μg/cm^2, respectively. More accurate thicknesses (175 and 13 μg/cm^2, respectively, with an uncertainty of 7%) were obtained using the values for the solid angles of the monitor and total charge integrated in the Faraday cup and the data at the lower four energies where the scattering is pure Rutherford for both targets. These more accurate values were used only to calculate the energies at the middle of each layer. The use of this composite target proved to be very useful to obtain absolute values for the ^{7}Li elastic scattering cross sections.

The data acquisition system consisted of conventional slow (for the analog-signals)/fast (for the triggers) electronics that fed two ADC modules: an octal ADC (Silena 4418/V) for the eight-detector array and a quad ADC (Ortec AD811) for the telescope. The detectors of the array were operated in singles mode, whereas the detectors of the telescope worked in coincidence mode. Hence, the data were analyzed from sets of eight one-dimensional energy spectra for the eight-detector array plus a two-dimensional Δ*E*-*Eres* spectrum obtained from the telescope. Although no direct identification in atomic number was performed in the main array of detectors, transfer and inelastic scattering channels could be easily identified and separated from the elastic peak since they contribute to different and separable positions in the one-dimensional energy spectra. As it was mentioned above, absolute values of the cross sections could be obtained using a Faraday cup assuming a determined charge state distribution after the target, knowing the ^{27}Al target thickness and the detector solid angles (geometrically measured). However, these three magnitudes and, additionally, dead-time corrections, introduce large uncertainties. To circumvent this problem, the final cross section values were obtained using the elastic scattering of the ^{7}Li + ^{197}Au reaction cross sections. This reaction can be reliably assumed to be purely Rutherford scattering for the whole energy range used in the present experiment (the corresponding Coulomb barrier is close to 31 MeV [14]). The cross sections of interest, σ_{Al}, at the laboratory angle θ^i of the *i*th detector is calculated as

$$\sigma_{\mathrm{Al}}(\theta^i) = \frac{A^i_{\mathrm{Al}}}{A^i_{\mathrm{Au}}}\frac{Nt_{\mathrm{Au}}}{Nt_{Al}}\sigma_{\mathrm{Au}}(\theta^i), \quad (1)$$

where A^i_{Al} and A^i_{Au} are the net (background-subtracted) peak areas in the *i*th detector corresponding to the elastic scattering of ^{7}Li ions on Al and Au. Similarly, Nt_{Al} and Nt_{Au} are the number of Al and Au target atoms. Dividing by $\sigma_{\mathrm{Al,Ruth}}$, for all energies at which the scattering on gold is purely Rutherford we obtain:

$$\frac{\sigma_{\mathrm{Al}}(\theta^i)}{\sigma_{\mathrm{Al,Ruth}}(\theta^i)} = \frac{A^i_{\mathrm{Al}}}{A^i_{\mathrm{Au}}}\frac{Nt_{\mathrm{Au}}}{Nt_{\mathrm{Al}}}\frac{\sigma_{\mathrm{Au,Ruth}}(\theta^i)}{\sigma_{\mathrm{Al,Ruth}}(\theta^i)}, \quad (2)$$

which is the same as Eq. (1) of Ref. [2]. The $Nt_{\mathrm{Al}}/Nt_{\mathrm{Au}}$ ratio was calculated from the ratio of the elastic peaks in the monitor spectra as

$$\frac{Nt_{\mathrm{Al}}}{Nt_{\mathrm{Au}}} = \frac{\sigma_{\mathrm{Au,Ruth}}}{\sigma_{\mathrm{Al,Ruth}}}\frac{A^{\mathrm{Mon}}_{\mathrm{Al}}}{A^{\mathrm{Mon}}_{\mathrm{Au}}}. \quad (3)$$

At the monitor detector angle, θ^{Mon} = 28°, the elastic scattering cross section for the ^{7}Li + ^{27}Al system can be reliably described by the Rutherford scattering formula for energies below 8 MeV [12]. Hence, for this determination we averaged the monitor data in Eq. (3) for four energies up to 7.75 MeV, resulting in $Nt_{\mathrm{Al}}/Nt_{\mathrm{Au}}$ = 95.6 with an uncertainty of 1%. In Eqs. (1)–(3), all the cross sections are evaluated at the energies that the projectiles reach at the middle of the respective target. For the aluminium target facing the beam, an energy loss through a layer $Nt_{\mathrm{Al}}/2$ was considered, while for the gold target, the layer was taken as $Nt_{\mathrm{Al}} + Nt_{\mathrm{Au}}/2$. The energy losses were calculated with the code SRIM2008 based on Ref. [15].

The projectile breakup to α particles (Z = 2 in $E_{res} - \Delta E$ plot) starts to be important at 9 MeV where it introduces a systematic uncertainty of about 5% that keeps increasing until 11 MeV where it reaches about 30%. This can be seen in a typical telescope two-dimensional spectrum as shown in Fig. 2, in which the different groups corresponding to Z = 1, 2 and 3 (from left to right) are displayed. In fact, the two Z = 3 groups correspond to ^{7}Li nucleus scattered from ^{197}Au and iron from contaminations, but the ^{7}Li ions scattered in ^{27}Al did not have enough energy as to pass through the Δ*E* detector. Nevertheless, filtering out all events with non-zero E_{res} signal, a clear peak of these ions could be obtained in the one-dimensional Δ*E* spectra. On the other side, from the number of ^{7}Li scattered on ^{197}Au at the telescope and at detector 1 (both at θ = 135°), the ratio of their solid angles was obtained. Hence, knowing a precise number of ^{7}Li ions scattered in ^{27}Al from the telescope, a criterion for fixing the integration limits in the one-dimensional spectra was established and applied to all other seven detectors. Moreover, the telescope two-dimensional spectra made possible the verification that the α background is fairly constant in energy and that a linear interpolation of its level between the elastic peak extremes (the beginning and the end of a peak) in a one-dimensional spectrum was a reasonable approximation.

The overall uncertainty of the results ranges from 3% to 5% up to 10 MeV and then increases up to about 20% at 11 MeV, due to the increase of the breakup process of the ^{7}Li projectile. A summary of the experimental results is displayed in Fig. 3, which shows the