Particle Leaking, Cross-Section Ratio $^{10}\text{B}(n,\alpha)^{7}\text{Li}$, and Excitation Function of the Reaction $^{10}\text{B}(n,\alpha)^{7}\text{Li}$ at MeV Energies

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Abstract. The $^{10}\text{B}(n,\alpha)^{7}\text{Li}$ reaction was studied in the energy range between 1.5 MeV and 5.6 MeV at the 7-MV Van de Graaff accelerator of IRMM by using a gridded ionisation chamber, signal digitisation, and an intrinsic $^{238}\text{U}$ neutron monitor. The aim was to obtain accurate data for the IAEA Coordinated Research Project (CRP) on the improvement of standard cross sections for light elements. The effect of particle leaking was discovered and its implications investigated. The determination of the cross section $\sigma(\alpha_0+\alpha_1)$ strongly benefits from it but measurements of angular distributions, individual cross sections $\sigma(\alpha_0)$ and $\sigma(\alpha_1)$, and the branching ratio $\alpha_0/\alpha_1$ are negatively affected. The correct number of reaction events was obtained by identification of unknown particle signatures in the energy spectra as $^{10}\text{B}(n,\alpha)^{7}\text{Li}$ events in the form of quasi $^{7}\text{Li}+\alpha$ particles created by particle leaking. The cross-section ratio $^{10}\text{B}(n,\alpha)^{7}\text{Li}/^{238}\text{U}(n,\alpha)$ was measured and the excitation function of $^{10}\text{B}(n,\alpha)^{7}\text{Li}$ determined by simultaneously detecting the charged particles from the boron disintegration in the forward hemisphere and the $^{238}\text{U}$ fission fragments in the backward hemisphere. The IRMM cross sections are compared to experimental data of other groups and to predictions of the ENDF/B-VI.8, JENDL-3.3, and JEF-2.2 evaluations.

INTRODUCTION

There is a need to update the database of experimental data for standards evaluations in the frame of the IAEA CRP on the improvement of standard cross sections for light elements. IRMM contributes to this international effort by performing measurements at its experimental facilities.

The present paper is a report on the measurement of the excitation function of the $^{10}\text{B}(n,\alpha)^{7}\text{Li}$ reaction and cross-section ratio $^{10}\text{B}(n,\alpha)^{7}\text{Li}/^{238}\text{U}(n,\alpha)$ in the energy range from 1.5 MeV to 5.6 MeV by using a new technique developed at IRMM.

EXPERIMENT

Neutrons were produced at the 7-MV Van de Graaff accelerator of IRMM by the $^{7}\text{Li}(p,n)^{8}\text{Be}$ reaction using two TiT targets with nominal thicknesses of 1.902 and 2.080 mg/cm$^2$.

Details of the new technique will be published elsewhere [1]. The basic elements are a gridded ionisation chamber (GIC), a fast waveform digitizer, and advanced off-line analysis. The GIC was installed with its axis parallel to the beam line and detected the products of the $^{10}\text{B}(n,\alpha)^{7}\text{Li}$ reaction in the forward hemisphere. The cathode-to-grid and the grid-to-anode distances were 40 and 3 mm, respectively. A second ionisation chamber without a grid on the other side of the cathode, with a cathode-to-anode distance of 3 mm, was used for the detection of the fission fragments of the $^{238}\text{U}(n,f)$ reaction. The boron target (94% $^{10}\text{B}$) with a thickness of 30 $\mu$g/cm$^2$ and diameter of 28 mm was mounted on the cathode side facing the grid and the $^{238}\text{U}$ sample (a $^{238}\text{UO}_4$ layer with a diameter of 25 mm containing 532.6 $\mu$g/cm$^2$ of $^{238}\text{U}$) on the opposite side. The anode and cathode signals were digitized and stored as a function of time. Signal
amplitudes and the origin of the particle track were determined by off-line analysis. The former were used to determine the energy and emission angle of the particle [2]. The latter was utilised for the suppression of the gaseous background [1]. The fission chamber with the back-to-back geometry of the $^{238}$U to the $^{10}$B sample functions as an intrinsic neutron monitor. Ar(90%)CH₄(10%), Kr(95%)CH₄(5%), and Kr(97%)CO₂(3%) gas mixtures were used as detector medium.

RESULTS AND DISCUSSION

Figure 1 shows a two-dimensional signal-amplitude spectrum of the cathode versus the anode for a neutron energy of 2.8 MeV after suppression of the gaseous background. It is a map of identified particle signatures for emission in the forward hemisphere. At large emission angles the $\alpha$ particles and their associated $^7$Li ions are both emitted forward due to reaction kinematics and induce in the GIC a signal proportional to the sum of their energies. The result is the creation of the double or quasi $^7$Li+$\alpha$ particle group at the high-energy side of the spectrum. This migration of $^7$Li and $\alpha$ particles from their single-particle groups to the new group was named particle leaking and is the subject of a recent publication [3].

Expected were two short vertical lines at $Q(\alpha_1)+E_n$ and $Q(\alpha_0)+E_n$, where the $Q(\alpha_1)$ and $Q(\alpha_0)$ values correspond to the first excited and ground states of $^7$Li, and $E_n$ is the neutron energy. The distribution of the quasi $^7$Li+$\alpha$ particles is continuous instead, due to the large energy losses of the $^7$Li and $\alpha$ particles in the boron target. The reaction kinematics in the laboratory (LAB) and centre-of-mass (CM) coordinate systems is schematically shown in Fig. 2. Associated $^7$Li and $\alpha$ particles emitted in the forward hemisphere between the critical angle $\theta_0$ [3] and 90° induce the particle leaking effect. A high resolution of the particle groups was obtained by using the emission angle $\theta$ and energy in CM as is shown in Fig. 3. The $\cos(\theta_{\text{lab}})$ was determined from the ratio of the pulse amplitudes of the cathode and anode. The LAB energy $E_{\text{lab}}$ was obtained from the amplitude of the anode signal by using for energy calibration the two lines of the thermal neutron component of $^{10}$B(n,$\alpha$) Li. The same $Q(\alpha_0)$ value was assumed for all particles for the conversion of $E_{\text{lab}}$ to the CM energy $E_{\text{cm}}$. The analysis programme allows the definition of a region of interest.

FIGURE 1. Two-dimensional pulse-amplitude spectrum of cathode versus anode.

FIGURE 2. Schematic drawing of the reaction kinematics in the LAB and CM coordinate systems.

FIGURE 3. Two-dimensional $\cos(\theta)$-E (bottom) and energy (top) spectra of emitted charged particles.
(ROI) in the two-dimensional spectrum of \( \cos(\theta) \) versus energy (Fig. 3, bottom), as indicated by the dashed line, which contains the fast neutron component of \(^{10}\text{B}(n,\alpha)^{7}\text{Li}\). The energy spectrum of the particles in the ROI (Fig. 3, top) was obtained in this way. It contains only the particles emitted in the forward hemisphere. Their number is equal to the total number of the \(^{10}\text{B}(n,\alpha)^{7}\text{Li}\) events, because the number of backward-emitted \(\alpha\) particles is equal to the number of their associated \(^{7}\text{Li}\) partners recorded in this spectrum. There is no loss of events caused by the target thickness. Due to the forward emission of both associated particles, one is always detected if and when the other is stopped in the target.

The next step was the analysis of the monitor signals for the determination of the number of \(^{238}\text{U}(n,\text{fission})\) events. A clear separation between the weak line of the fission fragments and the strong background component of \(\alpha\) particles from the spontaneous decay of \(^{238}\text{U}\) was achieved due to the small gap of the fission chamber as is shown in Fig. 4.

From the number of the \(^{10}\text{B}(n,\alpha)^{7}\text{Li}\) and \(^{238}\text{U}(n,\text{fission})\) events and using the known number of \(^{10}\text{B}\) and \(^{238}\text{U}\) target atoms the cross-section ratio \(\frac{\sigma(10\text{B})}{\sigma(238\text{U})}\) was obtained in the energy range from 1.5 to 5.6 MeV. It is shown in Fig. 5 together with results of the ENDF/B-VI, JEF-2.2, and JENDL-3.3 evaluations. The error bars are due to statistical uncertainties. Their relative values are less than 5%. Uncertainties of 5% and 0.8% of the \(^{10}\text{B}\) and \(^{238}\text{U}\) target atoms, respectively, were not included.

The cross section of the \(^{10}\text{B}(\alpha,\alpha)^{7}\text{Li}\) reaction was obtained from the cross-section ratio \(\sigma(10\text{B})/\sigma(238\text{U})\) by using the \(^{238}\text{U}\) cross section of ENDF/B-VI. The excitation function is shown in Fig. 6. Predictions of the previously mentioned evaluations and the experimental values of Bichsel et al. [4] and Davis et al. [5] were also plotted for comparison. The relative uncertainties are identical to the ones of the cross-section ratio because \(\sigma(238\text{U})\) was considered as an absolute standard.

Finally the implications of particle leaking are demonstrated in Fig. 7. The forward angular distributions (Fig. 7, bottom) and the branching ratio as function of angle (Fig. 7, top) are truncated at large emission angles and cannot be determined in the region of the quasi \(^{7}\text{Li}+\alpha\) particles between the critical angle \(\theta_0\) and 90°. The curve shown in this range of angles is an approximation obtained by assuming that the quasi \(^{7}\text{Li}+\alpha\) particles are single \(\alpha\) particles. The
FIGURE 6. Excitation function of the $^{10}$B(n,α)$^7$Li reaction.

FIGURE 7. Angular distributions (bottom) and branching ratio (top) as function of angle in the lab coordinate system. The purpose of this curve was only to show the strength of the particle leaking effect.

CONCLUSIONS

The cross-section ratio $\sigma(10B)/\sigma(238U)$ and the cross section $\sigma(10B)$ were determined by taking into account the particle leaking effect. The measured data are currently used as input for evaluation codes within the IAEA CRP on the improvement of reaction standards for light elements.

REFERENCES

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