Experimental investigation of the $^{8}\mathrm{Li} \rightarrow {}^{7}\mathrm{Li} + \mathrm{n}$ Coulomb breakup process

Excerpts from the PhD Thesis of

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Introduction

The thesis presents and discusses the results of the experimental evaluation of the $^{8}\mathrm{Li} \rightarrow {}^{7}\mathrm{Li} + \mathrm{n}$ Coulomb breakup nuclear reaction. The experiment was carried out with the Coupled Cyclotron Facility of the National Superconducting Cyclotron Laboratory (NSCL).

The investigated nuclear reaction, which has relevance in astrophysics, is the inverse of the $^{7}\mathrm{Li} + \mathrm{n} \rightarrow {}^{8}\mathrm{Li}$ neutron capture process. For some of the short-lived nuclei involved in r-processes, it is impossible to measure their neutron capture cross section due to the lack of a target. It is sometimes possible, however, to measure the time-reversed inverse process from which the cross section of the direct process can be deduced by theoretical methods. The $^{7}\mathrm{Li}(\mathrm{n},\gamma)^{8}\mathrm{Li}$ process and its time-reversed counterpart are connected by the quantum mechanical

$$\sigma(\gamma,\mathrm{n}) = \frac{2\mu E_{\mathrm{d}}}{\hbar^2}\frac{\hbar^2 c^2}{E_\gamma^2}\frac{(2j_{^7\mathrm{Li}}+1)(2j_{\mathrm{n}}+1)}{(2j_{^8\mathrm{Li}}+1)2}\sigma(\mathrm{n},\gamma), \qquad (1)$$

detailed balance theorem, where E_{d} denotes the decay energy of the (γ,n) photodissociation, i.e. the neutron energy in the center of mass system and $E_\gamma = E_{\mathrm{d}} + S_{\mathrm{n}}$ is the photon energy. $\mu = \frac{m_{\mathrm{n}} \cdot m_{^7\mathrm{Li}}}{m_{\mathrm{n}} + m_{^7\mathrm{Li}}}$ denotes the reduced mass of the $^{7}\mathrm{Li}+\mathrm{n}$ system, and $j_{^7\mathrm{Li}}$, $j_{^8\mathrm{Li}}$ and j_{n} represent the spins of the reaction participants. After the $d\sigma_{\mathrm{Cb}}/dE_\gamma$ excitation function of the $^{8}\mathrm{Li} \rightarrow {}^{7}\mathrm{Li}+\mathrm{n}$ Coulomb breakup process has been measured, the $^{7}\mathrm{Li}$ neutron capture cross section can be inferred according to the (1) formula.

The $^{7}\mathrm{Li}$ neutron capture cross section has already been measured by direct methods, covering the entire neutron energy range of astrophysical importance. The main purpose of the experimental evaluation was to check the procedure by which astrophysical capture cross sections are usually derived from the measured Coulomb breakup inverse process. A matching result should validate the method for future application.

The experimental setup is shown in Fig. 1 [1]. The 69.5 MeV/u $^{8}\mathrm{Li}$ beam nu-

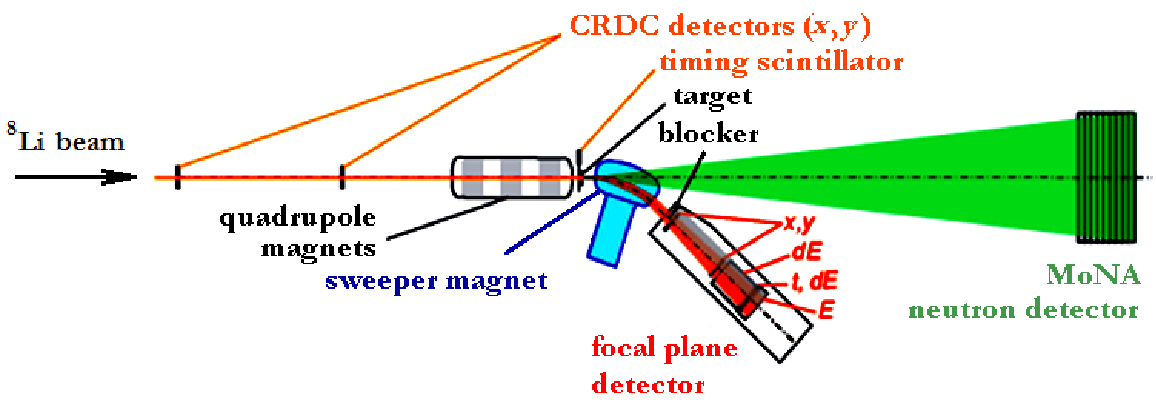

Figure 1: The experimental setup. The 69.5 MeV/u ^{8}Li beam nuclei may break-up when colliding into the target. The ^{7}Li fragments and the neutrons are separated by the sweeper magnet and detected by two dedicated detector systems.

clei generated by the A1900 particle separator collide into a lead (or carbon) target, after passing through two CRDC (Cathode Readout Drift Chamber) detectors and a focusing quadrupole triplet. The thin plastic scintillator just before the target provides the common-stop signal for the time of flight measurement and counts the number of incoming particles.

The target-generated fragments or other charged particles are deflected by the sweeper magnet, and the generated neutrons fly freely towards the neutron detector called MoNA (Modular Neutron Array). The fragments having a specific pulse–charge ratio reach the fragment detection system after the magnetic deflection, where the detectors measure their direction and identify them.

Work objectives

The primary goal of the experimental evaluation was the determination of the excitation function of the $^{8}\mathrm{Li} \to {}^{7}\mathrm{Li} + \mathrm{n}$ breakup process, where the main task was the complete kinematic reconstruction of the $^{8}\mathrm{Li} \to {}^{7}\mathrm{Li} + \mathrm{n}$ decay events, i.e. the determination of the momentum of the incoming ^{8}Li and the ^{7}Li and n fragments dissociating from within the target, just before and after the nuclear reaction.

From the measured momenta of the ^{8}Li, ^{7}Li and n particles, we have to calculate the impact parameter of the projectile and the decay energy in the nuclear reaction. After the efficiencies for all detectors have been determined using a Monte Carlo simulation of the detector system and the reaction mechanism, we have to estimate the efficiency and systematic error of the measurement, which is a function of the decay energy. Based on the decay energy spectrum, we have to calculate the excitation function of the breakup reaction from which the nuclear contribution has to be subtracted based on carbon-target measurement data. From the resulting Coulomb breakup excitation function, the neutron capture cross section can be deduced using the detailed balance theorem in Eq. (1) and the results of the virtual photon theory. The resulting neutron capture cross section has to be discussed in comparison to the available direct capture measurement data.

Methods

The recorded 40 GB binary data set was processed with programming codes that were written in C++, Perl and SQL languages.

The momentum reconstruction for each of the incoming ^{8}Li, ^{7}Li and n particles required a precise calibration of the elements of the complex detector system. I had to develop a procedure to determine the momenta of the ^{7}Li fragments at the target based on the measured position data. This procedure required a detailed field map of the sweeper magnet and the tracking of the particles on an event by event basis. The momentum of the ^{7}Li fragment was determined by the reconstruction of its track through the magnet using an adaptive differential equation method and iteration. The field map of the sweeper magnet was determined with a mashing method based on measurement data. The missing fringe field was extrapolated by Enge functions.

The acceptance, which is the most relevant factor in the efficiency of the measurement, was calculated by using a Monte Carlo simulation of the full detector system as well as the reaction mechanism.

The neutron capture cross section as a function of the neutron energy was calculated from the measured excitation function of the Coulomb dissociation process using the detailed balance theorem and techniques from the virtual photon theory.

Results

1. Determination of the excitation function of the ^{8}Li → ^{7}Li + n breakup process at 69.5 MeV/nucleon beam energy [1,2]

- The decay energy in the ^{8}Li → ^{7}Li + n decay process (see Fig. 2) was determined using a new method for the momentum reconstruction of the charged particles based on an event by event tracking of the fragments through the magnetic field.

- The time resolution of the complex neutron detector array consisting of 288 individual detector elements was constricted to 1.15 ns FWHM. The improved time resolution resulted in a higher accuracy in the reconstructed neutron momentum. The time calibration method based on a combined analysis of muon, radioactive source and prompt gamma data.

- The impact parameter distribution of the ^{8}Li projectiles was determined in the breakup events.

- The nuclear contribution to the Coulomb breakup events in the excitation function was estimated based on carbon target data. The contribution was between 3—5%, which corresponds to former results found in other breakup processes.

2. Derivation of the neutron capture cross section via an inverse method in the 30 keV—1 MeV neutron energy range [2]

- The neutron capture cross section of ^{7}Li was determined based on the measured $d\sigma_{\mathrm{Cb}}/dE_{\gamma}$ excitation function of the Coulomb breakup process (see Fig. 3).

- It was the first time that the inverse reaction method was applied to the determination of the neutron capture cross sections of s-wave neutrons. I compared my results to those from direct measurements.

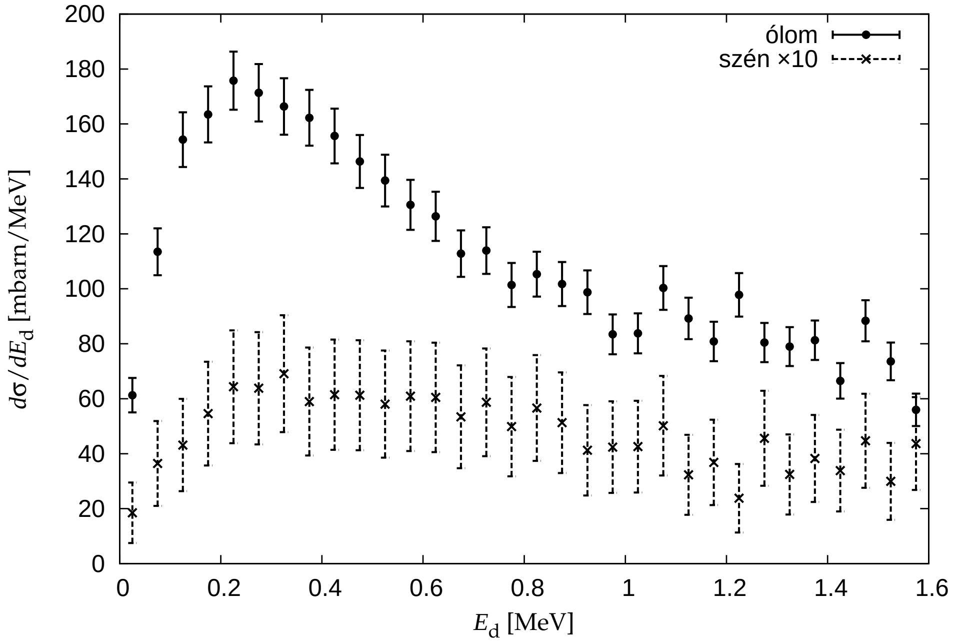

Figure 2: Current results of the $d\sigma_{\mathrm{Cb}}/dE_{\mathrm{d}}$ excitation function for 69.5 MeV/nucleon ^{8}Li projectiles on lead and carbon targets. For the sake of visibility, carbon target data are multiplied by a factor of ten.

- When comparing the results to those from direct measurements it was found that the inverse method of Coulomb dissociation can be successfully applied to the determination of neutron capture cross sections of short-lived nuclei involved in the r-process.

3. Determination of the energy dependence of the neutron capture cross section [2]

- Based on my experimental results it was found that the neutron capture cross section deviates from the $1/v$ law at neutron energies higher than 300 keV, which corresponds to predictions of theoretical models.

- The extent of deviation from the $1/v$ law was determined and parametrized up to the highest neutron energies.

- The $s_0 = (6.2 \pm 0.3) \cdot 10^{-3}$ b(eV)$^{1/2}$ coefficient of the low energetic neutron capture cross section, which follows the $1/v$ law, was calculated. This value matches exactly with that obtained from the corresponding direct capture measurement.

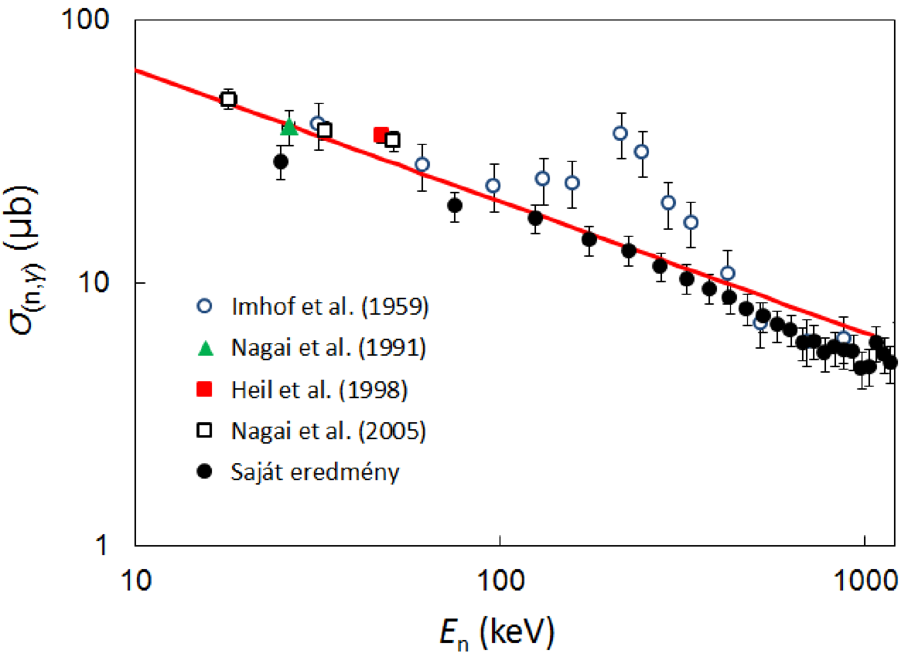

Figure 3: Current results of the $\sigma_{E1}(n,\gamma)$ neutron capture cross section as a function of the neutron energy in the center of mass system (solid circles). The cross section is compared to former results from direct neutron capture measurements: Imhof et al. (open circles), Nagai et al. (solid triangle and open squares) and Heil et al. (solid squares). The solid line is an $1/v$ fit to the low energy neutron capture data of Blackmon et al. [2].

Conclusions

According to Fig. 3, our results correlate well with those published earlier: above the 254 keV neutron energy, there is only 10% difference between the neutron capture cross section by Imhof et al. (open circles) and that of mine. The main result of the experimental evaluation was the determination of the s_0 coefficient in the neutron capture cross section of the ^{7}Li nucleus, which can be parametrized in the $\sigma_{E1}(n,\gamma)(E_n) = s_0(1 + s_1 E_n + s_2 E_n{}^2)/E_n^{1/2}$ form. The received value in the lab system was $s_0 = (6.2 \pm 0.3) \cdot 10^{-3}$ b(eV)$^{1/2}$ which replicates the coefficient $(6.3 \pm 0.3) \cdot 10^{-3}$ b(eV)$^{1/2}$ of the most recent experimental value of Blackmon et al. [2] Our results show that, corresponding to the former theoretical predictions, the neutron capture cross section deviates from the $1/v$-shaped energy dependence of the capture cross section for s-wave neutrons above 200 keV [2].

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