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Cross-section of ^{8}Li$(\alpha, n)^{11}$B: Inhomogeneous Big Bang nucleosynthesis

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Abstract. The cross-section of ^{8}Li(α,n)^{11}B has been measured at $E_{\rm cm} = 1.25$ MeV to be $\sigma(E) = 500$ mb using novel techniques, *i.e.* a ^{8}Li radioactive ion beam produced at the tandem in Catania in combination with a ^{4}He gas cell and a 4π neutron detector. The value is in fair agreement with previous work strengthening the model of inhomogeneous Big Bang nucleosynthesis.

PACS. 25.60.-t Reactions induced by unstable nuclei – 95.30.-k Fundamental aspects of astrophysics

1 Introduction

The remarkable agreement between the predictions of the primordial nucleosynthesis calculations with the observed primordial abundances of the light nuclides ^{2}H, ^{3}He, ^{4}He and ^{7}Li is considered a major triumph of the standard Big Bang model (SBBM) [1]. The SBBM assumes that during the phase of primordial nucleosynthesis the universe had a homogeneous density distribution. In view of the clumpsiness of the universe on a large scale, theoretical studies (see [2–4] and references therein) have taken into account possible inhomogeneities in baryon density arising from the quark-hadron phase transition of the universe. In these studies the universe is separated into two decoupled regions, one of which is a high-density proton-rich region and the other a low-density neutron-rich region. It is found that the observed abundances of the primordial nuclides can be explained equally well as in the SBBM, with the possible exception of ^{7}Li (see, however, [4]). A key prediction of the inhomogeneous Big Bang models (IBBM) is the production of significant amounts of $A \geqslant 12$ nuclides comparable to the abundances seen in the oldest metal-poor stars. Since the SBBM produces essentially zero metals, the presence of a "cosmic floor" of heavy elements in metal-poor stars would be a strong indicator of inhomogeneity at the time of primordial nucleosynthesis.

A key reaction in the inhomogenous nucleosynthesis is ^{8}Li(α,n)^{11}B ($Q = 6.63$ MeV). The thermal energy region is from 0.3 to 0.8 MeV for the relevant Big Bang temperature of 1×10^9 K. Thus, the cross-section $\sigma(E)$ of this reaction must be known with high accuracy in this energy region. The cross-section was inferred for the first time [5] using the inverse reaction ^{11}B(n,α)^{8}Li with data over a wide range of energies including the thermal region. However, this technique measures only the yield of ^{8}Li(α,n)^{11}B to the ^{11}B ground state, while the reaction can proceed also to excited bound states of ^{11}B. Thus, the inverse reaction measured a lower limit of $\sigma(E)$. A direct $\sigma(E)$ measurement of ^{8}Li(α,n)^{11}B requires the availability of a radioactive ^{8}Li ion beam ($T_{1/2}(^8\text{Li}) = 0.84$ s). Such experiments have been carried out [6–8]: the data with relatively large errors suggest an increase in cross-section by about a factor 5 compared to that reported in [5]. Indirect methods as well as theory did not improve the situation [9]: *e.g.*, a predicted enhancement factor of 1.3 [10] and 3.3 [11]. We report on a $\sigma(E)$ measurement at $E_{\rm cm} = 1.25$ MeV using a new experimental approach at the tandem accelerator of the Laboratori Nazionali del Sud in Catania.

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2 Setup and procedures

The setup is shown schematically in fig. 1. Briefly, the 15 MV tandem in Catania provided a ^{7}Li beam of $E_{\rm lab} =$ 24.6 MeV with a current of about 100 pnA. The beam was focused by a quadrupole doublet (QD1) onto a deuterium

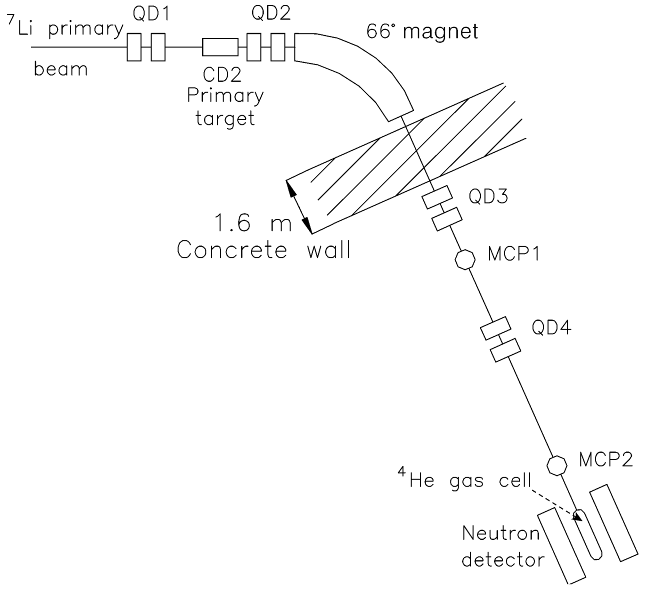

Fig. 1. Schematic diagram of the experimental setup at Catania.

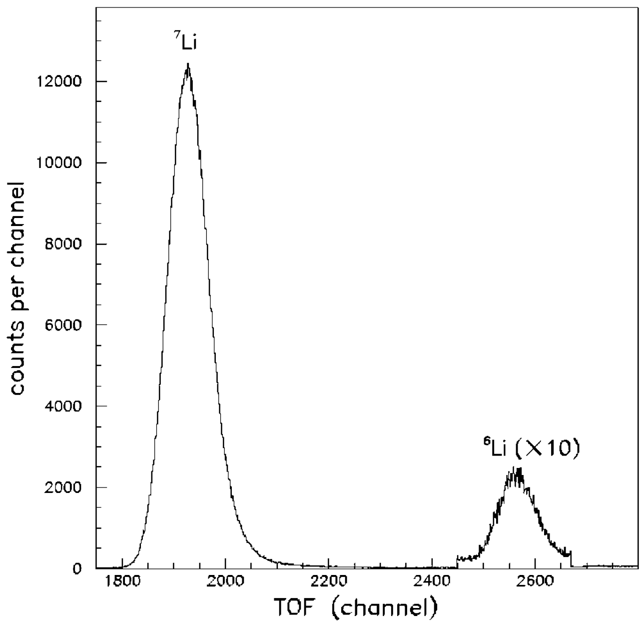

Fig. 2. TOF spectrum between the two MCPs (5 m distance) showing the ^{8}Li nuclides and the ^{7}Li leaky beam. Events in the ^{8}Li peak as well as events just outside this peak (representing essentially ^{7}Li background events) were used to search for correlated coincidence events in the neutron detector.

solid target, where ^{8}Li nuclides were produced via the reaction d(^{7}Li,p)^{8}Li ($Q = -0.19$ MeV). The ^{8}Li nuclides and the ^{7}Li projectiles left the solid target predominantly in the 3^+ charge state. The ^{8}Li nuclides were then momentum-filtered from the intense ^{7}Li primary beam by a 66° magnet in combination with a quadrupole doublet (QD2) and focused onto a ^{4}He gas cell by 2 quadrupole doublets (QD3, QD4). In the gas cell, the ^{4}He(^{8}Li,n)^{11}B reaction was initiated and identified by the produced neutrons.

2.1 ^{8}Li production rate

The primary target was a 1 mg/cm^2 thick CD_2 foil sandwiched between carbon layers of 30 μg/cm^2 thickness. After this target, the ^{7}Li ion beam had an energy of 23.7 MeV. With an assumed cross-section of 10 mb for d(^{7}Li,p)^{8}Li in the backward kinematic solution (sect. 2.2), one arrived at a ^{8}Li production rate of 4×10^5 nuclides/s. With a measured angle acceptance of 40 msr of the 66° magnet, the intensity of the ^{8}Li beam was reduced to 1×10^3 nuclides/s, consistent with observation (sect. 2.2). Beyond the magnet, the ^{8}Li nuclides (backward kinematic solution) had an energy $E_{\rm lab}(^8{\rm Li}) = 10.3 \pm 0.4$ MeV, where the quoted uncertainty reflects the momentum acceptance of the magnet.

2.2 ^{8}Li beam purification

Since the forward kinematic solution in the ^{8}Li production kinematics was in momentum p too close to that of the ^{7}Li beam ($p(^8{\rm Li})/p(^7{\rm Li}) = 0.98$), we used the backward kinematic solution ($p(^8{\rm Li})/p(^7{\rm Li}) = 0.66$) for the momentum-filtering in the magnet. In a first step, a ^{7}Li beam emerging from the primary target with the same rigidity as the ^{8}Li nuclides was produced and tuned as a "pilot beam" through the beam line up to the gas cell using quartzes and Faraday cups as monitors, where the last quartz and the last Faraday cup were installed at a respective distance of 20 and 50 cm from the entrance foil of the gas cell. In the second step, the 24.6 MeV ^{7}Li primary beam was used and the associated ^{8}Li nuclides observed in the beam line using 2 micro-channel plate detectors (MCP1 and MCP2, provided by Hamamatsu and Burle). The upstream MCP had a 40 mm diameter active area (with a 0.8 micron thick mylar foil) in order to catch a large part of the ^{8}Li nuclides, while the downstream MCP had a 25 mm diameter active area (with a 30 μg/cm^2 thick C foil), which was smaller than the 40 mm diameter of the downstream gas cell (sect. 2.3); the MCP2 was at a distance of 20 cm from the gas cell. With a 5 m distance between the MCPs, the ^{8}Li nuclides could be clearly identified by their time of flight (TOF) between the two MCPs and resolved well from the leaky ^{7}Li projectiles (fig. 2). The ^{8}Li rate was used in a final tuning of the elements of the beam line; it turned out that the optimum parameters of the beam optical elements were nearly identical to the settings found with the ^{7}Li pilot beam. The measured ^{8}Li rate was on average about 150 nuclides/s consistent with expectation in view of the MCP restrictions (50% detection efficiency via TOF and 30% angle acceptance). The TOF spectrum allowed to measure absolutely the ^{8}Li energy which was consistent with the expected value of 10.3 MeV (sect. 2.1). The ^{8}Li energy was also verified by inserting a ΔE-E telescope (Si detectors) close to and upstream of MCP2. The ΔE-E spectrum showed that no significant contaminant projectiles were located close to or within the ^{8}Li peak in fig. 2 (contamination less than 1% of the ^{8}Li peak).

2.3 ^{4}He gas cell

The gas cell had a 4 cm diameter, a 20 cm length, and an entrance window consisting of a 5 μm thick Ni foil, which could sustain a ^{4}He gas pressure of 150 mbar (cleanliness of the ^{4}He gas = 99.9999%). A Si detector (100 mm^2 active area) was placed at the end of the gas cell to measure the energy loss of the ^{8}Li nuclides in the Ni foil and in the ^{4}He gas. For the Ni foil alone (no gas), the final ^{8}Li energy of 4.80 MeV was consistent within 1% with that calculated for the foil thickness. This energy is below the 2.06 MeV threshold of the $^8\text{Li} \to {}^7\text{Li} + \text{n}$ breakup as well as the thresholds of ^{8}Li$(\alpha$,2n$)^{10}$B and ^{8}Li$(\alpha$,np$)^{10}$Be. Including the ^{4}He gas, the energy at the end of the gas cell (= 2.70 MeV) was also consistent with energy loss calculations. The mean ^{8}Li energy within the gas cell was therefore $E_{\text{lab}}(^8\text{Li}) = 3.75$ MeV or $E_{\text{cm}} = 1.25$ MeV.

2.4 Neutron detection

The neutron detection was carried out with a 4π detector consisting of 12 ^{3}He-filled proportional counters embedded in a polyethylene moderator; the detector was provided by Caltech [12,13]. The moderator was in the form of a cube, 40 cm on a side, with an 11 cm × 11 cm channel through the center, for insertion of the ^{4}He gas cell and the beam pipe. The neutrons created in the gas cell were moderated in the polyethylene material. Surrounding the 40 cm cube of polyethylene was a 4π layer of Cd shielding (0.6 mm thick), which in turn was surrounded by a 4π passive layer of polyethylene and borated paraffin, approximately 10 cm thick. This passive shielding served to absorb externally created neutrons. The 12 ^{3}He proportional counters were positioned about the beam pipe channel in a circle of about 12 cm radius. Each counter had a 3 cm diameter and a 46 cm length and was characterised by a 100% detection efficiency for thermalised neutrons. The cosmic background rate in the detector was observed to be 2 events/min, while the beam-induced background was about 12 events/min arising predominantly from the ^{7}Li primary beam interacting with the vacuum pipe walls of the 66° magnet. Using a calibrated ^{252}Cf source, the neutron detection efficiency was found to be $\varepsilon = 0.20 \pm 0.01$ (for a mean neutron energy $E_{\text{n}} = 2.35$ MeV) consistent with previous work [12]. Since the neutrons emitted in ^{4}He$(^8$Li,n$)^{11}$B at $E_{\text{cm}} = 1.25$ MeV involve energies up to about 8 MeV, we have adopted a mean value of $\varepsilon = 0.19 \pm 0.03$ according to Monte Carlo calculations [12].

The neutrons were moderated and absorbed in the detector with an observed "die-away" time of $\tau = \lambda^{-1} = 86 \pm 2\,\mu$s. A gate set on the ^{8}Li events in the TOF spectrum (fig. 2) started a time-to-amplitude (TAC) converter, whereby the stop signals of the TAC (selected time range = 1 ms) were provided by the neutron detector (*i.e.* the events from the logic *or* of the 12 ^{3}He proportional counters). If neutrons were correlated with the ^{8}Li beam, one expected a coincidence time distribution $\Delta N(t)/\Delta t$ declining exponentially with time (or rising linearly with $\exp(-\lambda t)$) according to

$$\Delta N(t)/\Delta t = N_{\text{BG}} + N_0 \lambda \exp(-\lambda t)\,, \tag{1}$$

where N_{BG} is the time-independent background contribution and N_0 is the total number of time-correlated events.

Figure 3 illustrates the results of such correlations, where data are shown *versus* the corresponding mean values of $\lambda\exp(-\lambda t)$: (a) a window set on the ^{8}Li peak and ^{4}He gas in the cell, (b) a window set on the ^{8}Li peak and no gas in the cell, and (c) a window set outside and on both sides of the ^{8}Li peak (*i.e.* on ^{7}Li background events) and ^{4}He gas in the cell. Case (c) shows no correlated events and is consistent with the "background contribution" in (a) for long decay times. Similarly, case (b) shows no correlated events, while case (a) does show such events: the results demonstrate that correlated neutron events arise only from the interaction of the ^{8}Li beam with the ^{4}He gas and thus from the reaction ^{4}He$(^8$Li,n$)^{11}$B. The total number of time-correlated neutron events is $N_0 = 122 \pm 41$ (statistical error).

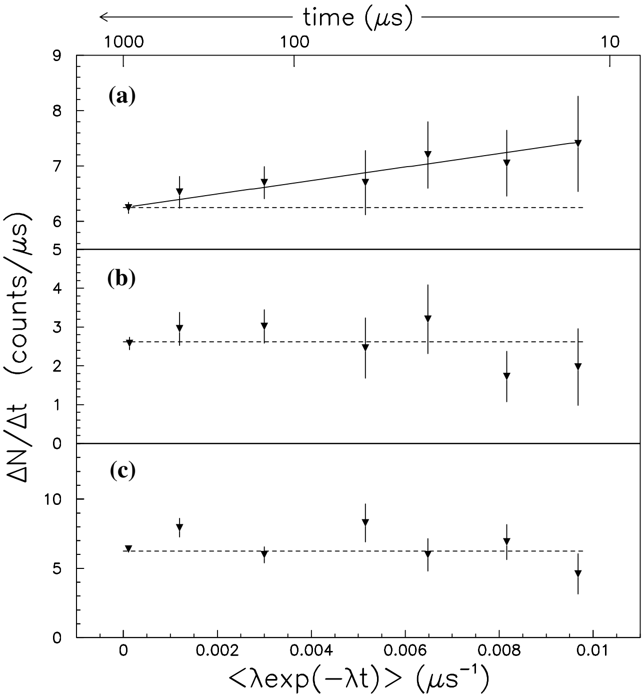

Fig. 3. TAC spectra (time range = 1 ms) for coincidence events between incident projectiles and neutrons are shown as a function of $\langle\lambda\exp(-\lambda t)\rangle$: (a) for ^{8}Li projectiles with ^{4}He gas, (b) for ^{8}Li projectiles without gas, (c) for ^{7}Li projectiles with ^{4}He gas. The solid curve in (a) represents a linear best fit to the data using $\Delta N(t)/\Delta t = N_{\text{BG}} + N_0\lambda\exp(-\lambda t)$, where N_{BG} (dashed line) is the time-independent background rate consistent with that observed in (b) and (c) and N_0 is the total number of time-correlated events. The absolute value of the background contribution in (b) is a factor-2 lower than in (a) and (c) due to a factor-2 lower current in the primary beam.

3 Result

The correlated neutron yield N_0 is related to the number of incident ^{8}Li projectiles N_{Li} (as observed by the TOF), the number of ^{4}He target nuclides N_{He} (derived from the gas pressure and length of the gas cell), the neutron detection efficiency ε, and the cross-section σ by the equation

$$N_0 = N_{\mathrm{Li}} N_{\mathrm{He}}\, \varepsilon\, \sigma\,. \qquad (2)$$

The result is $\sigma = 500 \pm 170$ (statistic) ± 70 (systematic) mb at a mean energy $E_{\mathrm{cm}} = 1.25$ MeV, consistent with previous work within experimental uncertainties [6–8]. The present work with an enhancement factor of 12 compared to the results of the inverse reaction [5] strengthens the calculations of inhomogeneous Big Bang nucleosynthesis.

It should be noted that the present work is the first result of a radioactive ion beam experiment relevant to nuclear astrophysics carried out at Catania. Within the future EXCYT project at Catania [14], a ^{8}Li ion beam will be available in 2004 with an intensity several orders of magnitude higher than that obtained in the present experiment. With such a beam current, data with high precision can be obtained with the present setup over the full astrophysical energy range of ^{4}He(^{8}Li,n)^{11}B.

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