Study of the Big-Bang nucleosynthesis reaction $D(\alpha,\gamma)^6Li$ by Coulomb Dissociation of ^6Li

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1 Astrophysical motivation

Primordial nucleosynthesis, together with the expansion of the galaxies and the 2.7 K microwave background radiation, is one of the three observational corner stones of the standard Big Bang model. Comparison between theoretical primordial abundances of ^{4}He, D, ^{3}He and ^{7}Li and those determined from astronomical observations have lead to an impressive agreement spanning 10 orders of magnitude. As these abundances depend on the baryon to photon ratio, η, one can deduce Ω_B, the baryonic density of the Universe and the proportion of baryonic dark matter from this comparison. At present, two ranges of values (roughly around $\Omega_B \approx$0.015 or 0.04) are compatible with the observationally determined ^{4}He, D and ^{7}Li primordial abundances, both leading to a large baryonic dark matter component with respect to luminous matter, $\Omega_L \approx$0.003 [1].

Yields of other light isotopes (^{6}Li, ^{9}Be and ^{10,11}B) calculated within the standard model of Big Bang nucleosynthesis are very small (their origin is mainly the α+α reaction and the spallation of CNO by cosmic rays in the interstellar medium). With such small values, the determination of their primordial abundances from observation remains hopeless with the possible exception of ^{6}Li. Determination of the ^{6}Li/^{7}Li ratio in very old stars has recently reached 0.050$\pm$0.019[2]. One may thus expect that with improved instrumentation, ^{6}Li/^{7}Li ratios as small as $\approx 10^{-3}$ will become observable. If this can be achieved in the oldest halo stars, the primordial ^{6}Li abundance could be determined. An interpretation of such observations depends on a precise knowledge of the $D(\alpha,\gamma)^6$Li reaction rate, however.

Recently a new compilation of charged-particle induced thermonuclear reaction rates has been published[3], superseding the Caughlan and Fowler one[4], and providing upper and lower limits for 80 reaction rates. Following this nuclear physics analysis, the impact of these uncertainties on Big Bang nucleosynthesis has been studied[1]. The most dramatic effect is observed for $D(\alpha,\gamma)^6Li$ which induces uncertainties of a factor of $\approx$20 on the ^6Li yield (Fig. 1). This rate uncertainty originates from the discrepancy between the theoretical low energy dependence of the S–factor and experimental data[5] obtained with the Coulomb break–up technique (see Kharbach and Descouvemont[6] for a recent comparison between theories and experiment). Accordingly, to reduce this uncertainty and to be able to estimate the feasibility of observation of primordial ^6Li abundances in very old stars, new measurements of the $D(\alpha,\gamma)^6Li$ reaction are required.

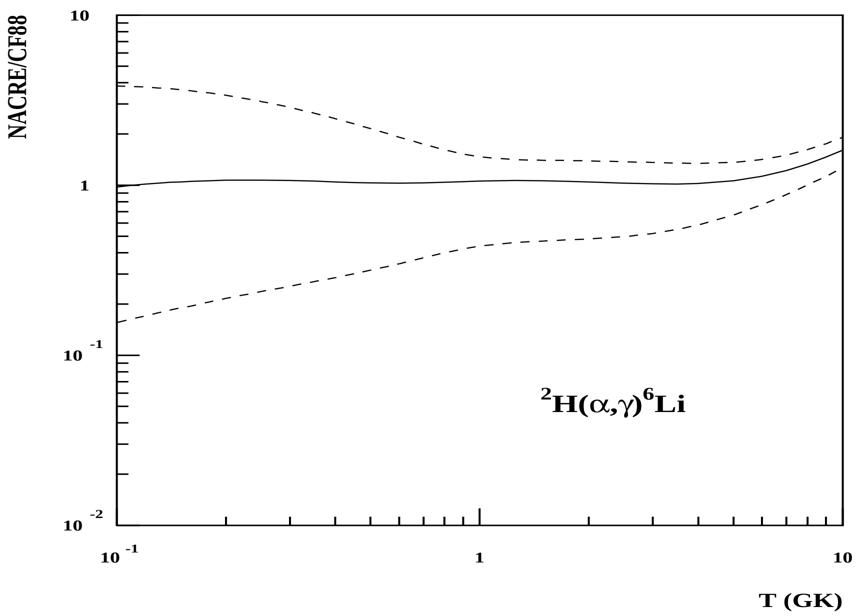

Figure 1: The $D(\alpha,\gamma)^6Li$ reaction rate as a function of temperature. The ratios between the nominal (solid line) and upper and lower (dashed lines) NACRE[3] rates relative to the CF88[4] one show the large uncertainties.

2 Previous experiments

The astrophysical reaction rate of the $D(\alpha,\gamma)^6Li$ reaction at stellar energies ($E_{cm} \leq$ 400 keV) is dominated by the radiative E2 capture from d-scattering waves in the α+D channel (including the $J=3^+$ resonance at E=0.711 keV) into the ^6Li ground state.

Experimental data of this reaction have been obtained by Robertson et al. [7] in direct kinematics at energies above 1 MeV and by Mohr et al. [8] in the energy range around the 3^+ resonance (see Fig. 2). Direct measurements in the energy range of astrophysical interest (50 keV$\leq E_{c.m} \leq$ 400 keV) were not possible because of too low cross sections, around 29 pb at $E_{c.m}$=100 keV. Kiener et al. [5] have therefore investigated this region by means of the

Coulomb dissociation(CD) of 26 A MeV ^{6}Li projectiles in the Coulomb field of a ^{208}Pb nucleus. Such a measurement has been shown to be largely free from nuclear background [9], despite the relatively large Q-value of 1.47 MeV. The method takes advantage of the large enhancement for E2-multipolarity in medium-energy CD.

At and above the 711 keV resonance, the theoretical calculations are in very good agreement with the existing data [7, 8] but not at the low energies where a disagreement with the Kiener et al. data was observed (Fig. 2.). The Kiener et al. experimental data suggest a rather constant S-factor below 400 keV while the theoretical curves [6] drop with decreasing energy.

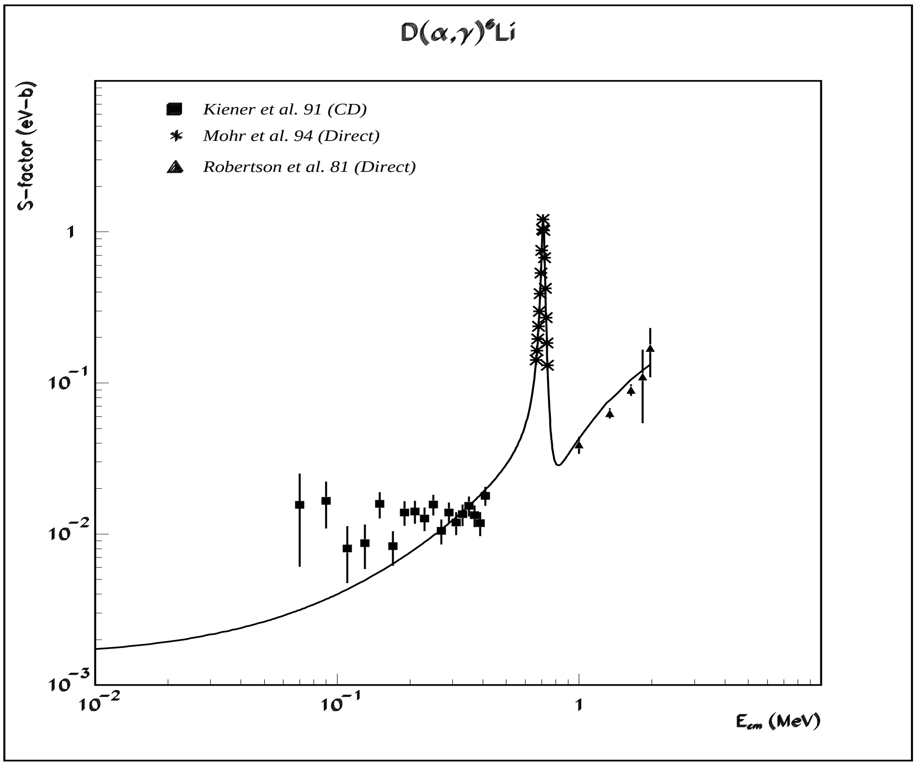

Figure 2: Experimental S-factors of D$(\alpha, \gamma)^6$Li below [5], at [8], and above [7] the 3^+ resonance compared to the direct capture calculation of Mohr et al. [8] (solid line).

3 Proposed GSI Experiment

We propose to study the reaction D$(\alpha, \gamma)^6$Li by means of the CD of ^{6}Li at 150 A MeV in a Pb target of 50 mg/cm^2. Compared to the energy of 26 A MeV used by Kiener et al., an incident energy of 150 A MeV has several advantages:
(i) the stronger forward focusing allows for a more complete angular coverage;
(ii) CD is enhanced, also relative to a (possible) nuclear background;
(iii) as a consequence of both effects, a better statistical precision can be obtained.

The calculated distribution of CD cross sections (based on the theoretical description of Ref. [8]) is plotted in Fig. 3 as a function of the D-α relative energy, E_{cm}.

The experimental setup will be very similar to the one used successfully to measure the CD of ^{8}B [10]. It consists of PPAC detectors to track the incident beam before the breakup target, and two pairs of Si strip detectors with 100 μm pitch plus a 16-strip ΔE detector to identify and track the beam or the breakup particles downstream from the target. The large-acceptance spectrometer KaoS will be used to measure the particle momenta. Trajectories will be reconstructed from the angles and positions measured in the Si strip detectors before KaoS and from those measured in two large-area MWPC behind KaoS. CD events are discriminated from non-interacting beam events by their multiplicities in the 16-strip ΔE detector.

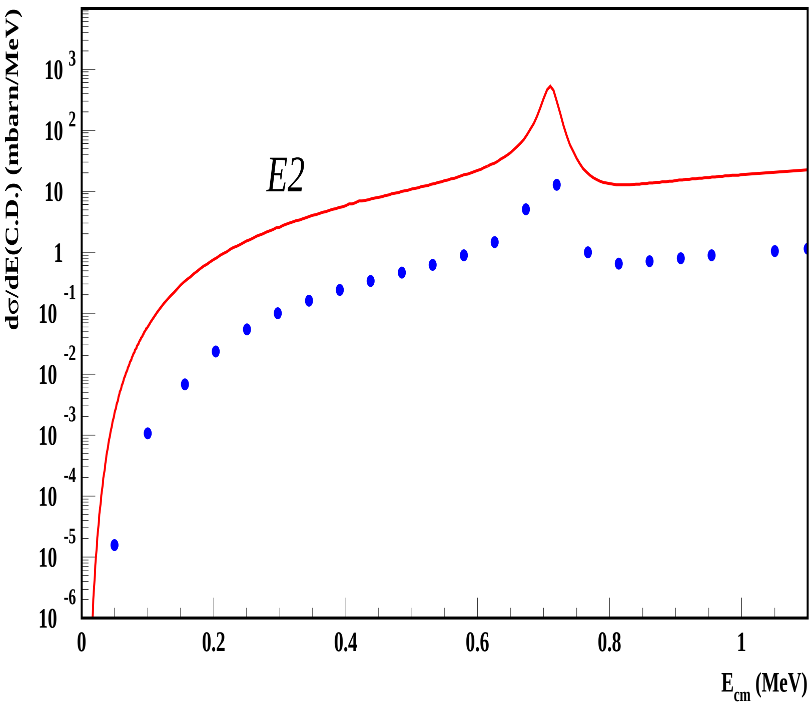

Figure 3: Calculated differential Coulomb dissociation cross section of ^{6}Li at 150 A MeV as a function of energy. The solid points are the integrated cross sections for $E_{c.m}$ intervals of 50 keV.

4 Count-rate estimates and beam time request

As can be seen from Table 1, the predicted CD cross sections per 50 keV bin amount to 0.0011 mb, 0.023 mb and 0.460 mb for c.m. energies of 100 keV, 200 keV and 500 keV respectively . With a ^{6}Li beam intensity of about 2.5×10^5/s and a 100 mg/cm^2 Pb target, this translates into count rates of 7, 140 and 3420 per day, respectively. Within a 8-day production run, we would expect totals of about 56, 1117 and 27360 events respectively. To set up the experiment and calibrate the KaoS focal plane, we estimate another day. The experiment should preferentially be performed before the KaoS spectrometer is moved from its current position to give way to the new LAND/ALADIN setup in Cave C.

$E_{c.m}$	σ^{cap} nb	$\sigma^{Coul.Diss}$ mb/50 keV	events/ 8 days
100 keV	0.029	0.0011	56
200 keV	0.211	0.023	1117
500 keV	2.300	0.460	27360

Table 1: Predicted Coulomb Dissociation cross sections and events rates

We ask for the following amounts of beam time:

Topic	Primary beam	calibration	Production
C.D. of ^{6}Li	^{6}Li 150 A MeV $\leq 2.5\times10^5$/s	1 day	8 days

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