PROCEEDINGS OF SCIENCE

PoS(NIC-IX)013

New measurement of the cross section of the Big Bang nucleosynthesis reaction D(α,γ)^{6}Li and its astrophysical impact

---

F. Hammache[1,2][*], **D. Galaviz**[3][†], **K. Sümmerer**[2], **S.Typel**[2], **F. Uhlig**[2], **A. Coc**[4], **F. Attallah**[2], **M. Caamano**[5], **D. Cortina**[5], **H. Geissel**[2], **M. Hellström**[2], **N. Iwasa**[6], **J. Kiener**[4], **P. Koczon**[2], **B. Kohlmeyer**[7], **P. Mohr**[3] **F. Schümann**[8], **E. Schwab**[2], **K. Schwarz**[2], **P. Senger**[2], **O. Sorlin,**[1], **V. Tatischeff**[4], **J.P . Thibaud**[4], **A. Wagner**[9], **A. Walus**[10]
1 IPN-Orsay, IN2P3-Université Paris XI, F-91406 Orsay Cedex, France
2 GSI,Postfach 110552, D-64220 Darmstadt, Germany
3 TU-Darmstadt, D-64220 Darmstadt, Germany
4 CSNSM, IN2P3-Université Paris XI, F-91405 Orsay Cedex, France
5 Universidad de Santiago de Compostela, E-15706 Santiago de Compostela, Spain
6 RIKEN, Hirosawa, Wako, Saitama 351-01, Japan
7 Fachbereich Physik, Philipps Universität, D-3550 Marburg, Germany
8 Ruhr-Universität Bochum, Universitätsstr. 150, D-44780m Germany
9 Forschungszentrum Rossendorf, D-01314 Dresden, Germany
10 Institute of Physics, Jagiellonian University, PL-30-059 Krakow, Poland
E-mail: `hammache@ipno.in2p3.fr`

The recent observations of non-negligible amounts of ^{6}Li in old halo stars have renewed interest in the Big-Bang Nucleosynthesis (BBN) of ^{6}Li. The deduced primordial ^{6}Li abundance was found to be unexpectedly large compared to the BBN predictions. One important ingredient in the BBN predictions is the low-energy D(α,γ)^{6}Li cross section. Up to now, the only available experimental result for this cross section introduced an error of about a factor of 20 in the ^{6}Li abundance at the energies of astrophysical interest (Ecm $\leq$ 300 keV). This uncertainty arises from the discrepancy between the theoretical low energy dependence of the S-factor and the experimental data. Accordingly, new measurements of the cross section of the D(α,γ)^{6}Li reaction using Coulomb dissociation (CD) of ^{6}Li at 150 A MeV have been performed recently at GSI. The preliminary GSI results, which indicate a drop of the S-factor as predicted by theory will be presented as well their impact on the calculated ^{6}Li abundance as a function of the baryon-to-photon ratio.

International Symposium on Nuclear Astrophysics — Nuclei in the Cosmos — IX
June 25-30 2006
CERN, Geneva, Switzerland

---

[*] Speaker.
[†] Present address: NSCL, Michigan State University, East Lansing, MI 48824, USA

1. Introduction

One of the most puzzling questions discussed currently in the astrophysics community is related to the origin of the observed ^{6}Li in very old halo stars [1]. Indeed, the abundance plateau of the observed ^{6}Li was found to be unexpectedly high compared to the current ^{6}Li Big-Bang nucleosynthesis predictions [2]. Hence, many scenarios were proposed to try to solve this puzzle; like e.g. the pre-galactic production of ^{6}Li [3], or the production of ^{6}Li by late decays of relic particles [4]. Before seeking exotic solutions to the lithium problem, however, it is important to exclude first nuclear solutions.

Recently a new compilation of charged-particle-induced thermonuclear reaction rates has been published [5], superseding the Caughlan and Fowler one [6], and providing upper and lower limits for 80 reaction rates. Following this analysis, the impact of the uncertainties of these reaction rates on Big Bang nucleosynthesis has been studied [2]. The most dramatic effect is observed for D$(\alpha,\gamma)^6$Li which induces uncertainties of a factor of $\approx$20 on the ^{6}Li yield at the energies of astrophysical interest (Ecm $\leq$ 300 keV). This uncertainty originates from the discrepancy between the theoretical low-energy dependence of the S-factor and experimental data [7] obtained with the Coulomb break-up technique (see Kharbach and Descouvemont [8] for a recent comparison between theories and experiment). Accordingly, to reduce this uncertainty and to be able to interpret the observations of ^{6}Li abundances in very old stars, new measurements of the D$(\alpha,\gamma)^6$Li reaction were performed at GSI using Coulomb dissociation (CD) of ^{6}Li at 150 A MeV.

2. Experimental procedure

A ^{208}Pb target with 200 mg/cm^2 thickness was bombarded by a primary ^{6}Li beam of 150 A MeV energy. The ^{6}Li beam was produced by the SIS synchrotron at GSI and separated from contaminant ions by using the FRS separator.

The angles and positions as well as the energy losses of the outgoing particles after the Pb target, D and ^{4}He, were measured by two pairs of silicon strip detectors (SSD, 100 μm pitch) [12] placed at distances of 15 and 30 cm, respectively, downstream from the target.

CD events were discriminated from non-interacting beam events by their multiplicities in a 16-strip ΔE detector in front of the SSDs. An absorber was placed behind the ΔE detector to stop the ^{6}Li beam. The average ^{6}Li beam intensity at the breakup target was of the order of 5x10^4 per 4 sec spill. It was determined from the ΔE detector.

The coincident D and ^{4}He fragments resulting from breakup in the ^{208}Pb target were identified by reconstructing their vertices at the target. This removed all breakup events in layers of matter other than the target. The deuteron and ^{4}He momenta were determined from their trajectories reconstructed by using their measured positions in the SSDs and in the multi-wire chambers behind the Kaos magnetic spectrometer [12] combined with a calibration function for invariant mass deduced from GEANT simulations. From the measured opening angles between the fragments and their momenta, the relative energy (E_{rel}) between the deuteron and the α in the c.m. system could be reconstructed.

Note that a full GEANT simulation of our breakup experiment was performed by taking into account the E2 contribution from the calculation of Typel [14] and our finite detector acceptance.

We have assumed that the E1 contribution is negligible, in accordance with the theoretical predictions of Typel [14]. Concerning the nuclear breakup, its contribution was considered, at first, negligible according to Shyam calculations [11], but new calculation of the nuclear breakup component is actually under progress to have better evaluation of this component and check Shyam's predictions.

3. Preliminary results

Preliminary results for the E_{rel} distribution obtained are shown in Fig. 1. The full histogram was obtained from the simulation. The points and the histogram represent, respectively, the measured cross section and predicted Coulomb dissociation cross section using the S_{24} astrophysical S-factor calculated by Typel as a function of energy in the center of mass of D-α. As indicated by the points, our E_{rel} distribution is in good agreement with Typel's calculation around the resonance region and above the resonance up to 2.5 MeV but not below 350 keV, here our data lie systematically above the predictions. The explanation for this discrepancy is under investigation (nuclear breakup, E1-E2 interference).

It is clear that the energy resolution of the present experiment is rather poor. We find out from simulation, that it varies like $4.94\sqrt{E}$. This can be seen from the broadening of the resonance peak.

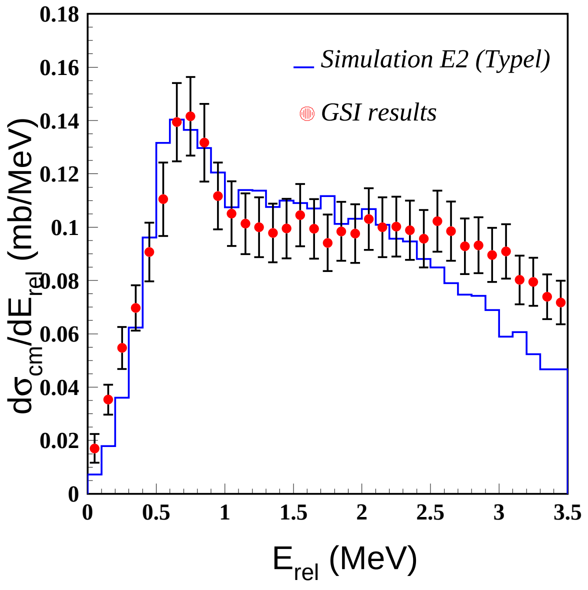

Figure 1: Differential cross sections as a function of energy in the center of mass of D-α. The error bars represent quadratic sums of statistical and systematical uncertainties related to the simulation and calibration procedure.

The differential cross sections of Fig. 1 have been converted to astrophysical S-factors (S_{24}) using the semiclassical theory of Typel and considering a pure E2 multipolarity. Our preliminary results for S_{24} visualized with a binning of 100 keV are displayed in Fig. 2 together with the previous Coulomb dissociation data of Kiener et al. and direct data of Mohr et al. [10] and Robertson et al. [9] as well as with the different calculations.

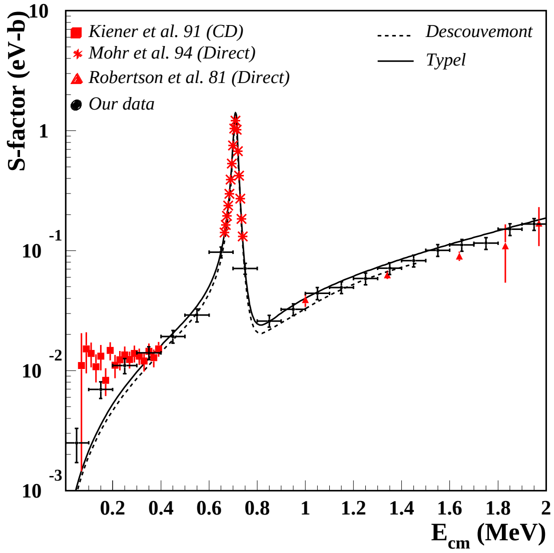

Figure 2: Preliminary results for the S_{24}factors obtained from the present experiment together with those from previous CD experiment [7] and existing direct measurements [9, 10]. The various solid curves are the calculations of Typel and Descouvemont, respectively.

The GSI data are in good agreement with the direct measurements of Mohr et al. and Robertson et al. in the resonance region and above. They agree with the Kiener et al. data at energies above 250 keV but not below. While the previous CD data show a constant low-energy S-factor, the GSI S-factors decrease with decreasing energy. One can also notice that the energy dependence of the GSI S-factors shows a similar behavior as those of Typel's and Descouvemont's calculations, even though these calculations show a discrepancy of about a factor of 1.5 to 2 in the energy range between 50 keV to 350 KeV. However, this discrepancy is much smaller than what existed previously with Kiener et al. data. Hence, if we consider only GSI data, this implies a considerable reduction of the uncertainties in the D(α,γ)^{6}Li cross sections considered in the NACRE compilation which were evaluated from the discrepancy between the previous experimental data [7] and the calculations.

A calculation of the new ^{6}Li reaction rate was performed by fitting the GSI S-factors with an R-matrix calculation and considering these data in the energy range of interest as an upper limit for the calculation. The obtained new ^{6}Li reaction rate was introduced in the BBN model of Coc et al. [15] to evaluate the primordial ^{6}Li abundance as a function of η or the baryonic density of the Universe. The results obtained are displayed in Fig. 3. The dashed lines are the extreme limits of the previously evaluated ^{6}Li abundances; the red full line is the new upper limit of the BBN ^{6}Li abundances calculated with the present ^{6}Li rates.

At the baryonic density deduced from observations of the anisotropies of the cosmic microwave background by the Wilkinson Microwave Anisotropy Probe (WMAP), a BBN value of about $\sim 1.5\times10^{-14}$ is inferred for ^{6}Li/H abundance. This value is 1000 times less than the recent obervations of Asplund et al. [1]. This represents a major cosmological challenge. The solution for this puzzle has to be found elsewhere, it cannot be explained by uncertainties in the nuclear physics input.

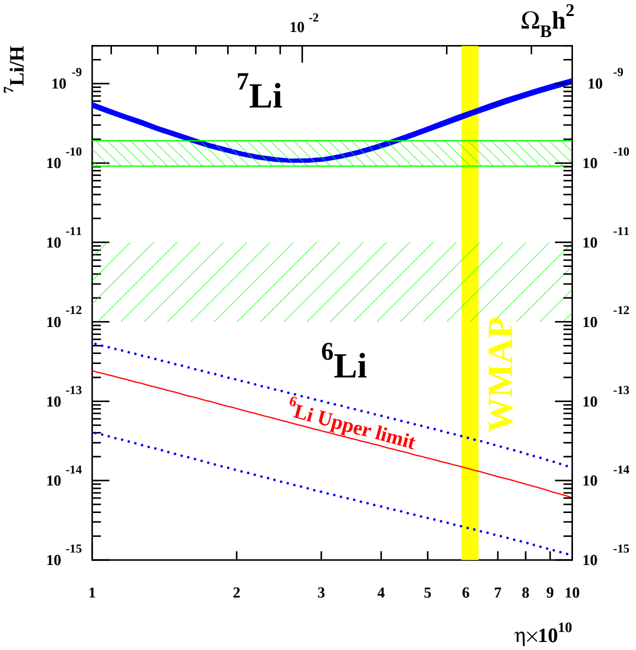

Figure 3: ^{6,7}Li abundance as a function of η, the baryon to photon ratio or the baryonic density of the Univers. The blue dashed and full lines and the red full line correspond to the BBN evaluated ^{6,7}Li abundances while the green dashed ones correspond to the observed ones. The vertical yellow line corresponds to the baryonic density of the Univers deduced by WMAP mission.

References

[1] M. Asplund et al., [astro-ph/0510636], accepted by APJ

[2] E. Vangioni-Flam et al., *Astron. Astrophys* **360** (2000) 15

[3] E. Rollinde et al., *Astrophys.J* **627** (2005) 666

[4] K. Jedamzik, [hep-ph/0512044], *Phys. Rev. D* **70** (2004) 063524

[5] C. Angulo et al., *Nucl. Phys A* **656** (1999) 3

[6] G.R. Caughlan W.A. Fowler, *At. Data Nucl. Data Tables* **40** (1988) 283

[7] J. Kiener et al., *Phys. Rev. C* **44** (1991) 2195

[8] A. Kharbach et al., *Phys. Rev. C* **58** (1998) 1066

[9] R.G.H. Robertson et al., *Phys. ReV. Lett* **47** (1991) 1867

[10] P. Mohr et al., *Phys. Rev. C* **50** (1994) 1543

[11] R. Shyam et al., *Phys. Rev. C* **44** (1991) 915

[12] N. Iwasa et al., *Phys. ReV. Lett* **83** (1999) 3960

[13] F. Schümann, Ph.D. Thesis, Ruhr-Universität Bochum (2002)

[14] S. Typel, code CDXS (2002)

[15] A. Coc et al., *Astrophys.J* **600** (2004) 544