Experimental Study of Nuclear Reactions for Astrophysics

J. Cruz[1,2], A. P. Jesus[1,2], Hélio Luis, Micaela Fonseca, J. P. Ribeiro[2,3]

Objectives

A precise knowledge of nuclear reactions cross sections (or S-factor) of light elements is crucial for the understanding of the evolution of the very early universe.

Since these reactions occur in stars at very low energies (Gamow peak), with extremely low cross sections decreasing exponentially with energy, efforts to measure it at theses energies requires pure targets, low background environments and very stable accelerator machines. The going-on work program is related to:

1. Measurement at ITN of cross sections and angular distributions of the reaction $^{7}Li(p,\alpha)^{4}He$ and $^{6}Li(p,\alpha)^{3}He$.
2. Experimental work on reaction cross-sections at relevant energies (around the solar Gamow peak) under LUNA (Laboratory for Underground Nuclear Astrophysics) collaboration, namely the reaction $^{14}N(p,\gamma)^{15}O$.

Results

1. Lithium is one of the most interesting and puzzling elements in the field of nucleosynthesis. Its most abundant isotope, ^{7}Li, has the rather unique status of requiring three entirely different nucleosynthetic processes, which are not completely understood.

   The reactions $^{7}Li(p,\alpha)^{4}He$ and $^{6}Li(p,\alpha)^{3}He$ are the major reactions of Li destruction, having thus a crucial contribution to Li abundances. Even though there are several different cross sections measurements for these reactions, they lead to different astrophysical S-factors at relevant energies.

   At ITN, the experimental set-up for nuclear reactions measurements has been modified and optimized to study this reaction; lithium targets were made by implantation and evaporation and tested for stability, impurity content and depth profile (fig.1).

   Preliminar measurements of the angular distributions have been made.

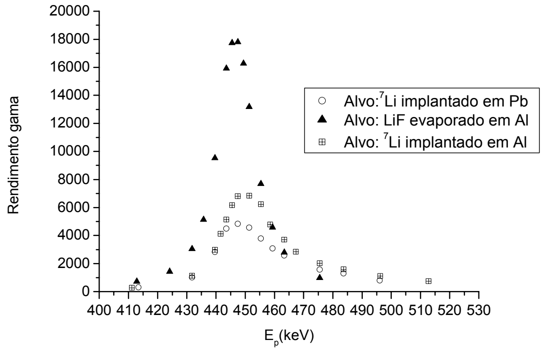

Fig. 1. Experimental profiles of Li in several samples, obtained with $^{7}Li(p,\gamma)^{8}Be$ reaction

2. At Gran Sasso work on the $^{14}N(p,\gamma)^{15}O$ reaction, using gas targets and BGO detectors (fig. 2), has proceeded down to 80 keV. Although information related with capture for different states will not be available with this kind of set-up, lower energies than before have been attained leading to a more accurate value of the S astrophysical factor for total capture. Data analysis is going on.

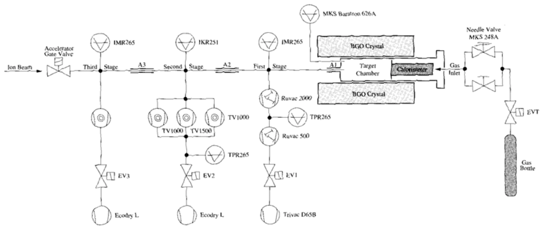

Fig. 2 Gas-target set-up at Gran Sasso, showing gas target chamber involved by BGO detectors.

---

[1] Dep. Física da Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa

[2] Centro de Física Nuclear da Universidade de Lisboa

[3] Dep. Física da Faculdade de Ciências da Universidade de Lisboa

Electron Screening Effects in Nuclear Reactions

J. Cruz[1,2], A. P. Jesus[1,2], Hélio Luis, J. P. Ribeiro[2,3]

Objectives

The cross-section σ(E) of a charged-particle-induced nuclear reaction is enhanced at low energies by the electron clouds surrounding the interactions nuclides, with an enhancement factor:

$$f_{lab}(E) = \sigma_s(E)/\sigma_b(E) = E(E+U_e)^{-1} \times \exp(\pi\eta U_e/E) \geq 1$$

with σ_s and σ_b respectively the screened and bare cross sections, $2\pi\eta$ the Sommerfeld parameter and U_e the electron screening potential energy [1].

Recently, the investigation of the electron screening potential for the d+d reaction in deuterated metals has lead to surprising results. For the d(d,p) reaction using a D_2-gas-target one finds $U_e = 25 \pm 5$ eV, in good agreement with the theoretical value (i.e. adiabatic limit) $U_e = Z_1Z_2e^2/R_a = 26$ eV - with R_a the atomic Bohr radius. However, significantly higher U_e values are observed [2], of the order of 300 eV, if deuterium-implanted metals (49 different samples) are used, while no enhanced values are found in deuterium-implanted semiconductors and insulators. Since metals are characterised by quasi-free electrons (compared to the cases of semiconductors and insulators), one may consider these metallic electrons behave like free electrons in a plasma, for which one can use the Debye-Hückel radius $R_D = 69(T/n_{eff}\rho)^{½}$ (in m). At room temperature (T = 297 K), an atomic density $\rho = 5\text{x}10^{28}$ m^{-3}, and $n_{eff} = 1$ being the number of valence electrons per metallic atom, one finds a radius R_D a factor 10 smaller than the Bohr radius. This in turn leads to a U_e value of 300 eV, consistent with the experimental values. From the experimental U_e values one can deduce n_{eff} and compare it with that obtained from the Hall effect: both values agree within experimental uncertainties [2]. Another sensitive test of the model addresses the temperature dependence of the U_e values $U_e(T) \sim T^{-½}$.

Results

Experimental investigations are currently underway in Bochum and preliminary results confirm also this expectation [3].

In order to further explore the influence of the host material on the screening potential energy, other reactions can be studied in metals. Investigations of the $^{6,7}\text{Li}(d,\alpha)^{4,5}\text{He}$ both in a PdLi_x alloy (x ~ 7%) have recently been reported [4] leading to $U_e = 1500 \pm 310$ eV. By comparison, the screening potential energies of the $^{6}\text{Li}(d,\alpha)^{4}\text{He}$ reaction obtained for a LiF target (i.e. an insulator) was reported to be 380±250 respectively [5], whereas the theoretical adiabatic limit is $U_e^{ad} = 170$ eV.

Based on the above model for metals, the corresponding Debye radius scales as 1/Z (here Z=3) for the d+Li reaction in a pure metallic Li target. When compared with the d+d reaction in Li (U_e ~ 110 eV [6]) a three times higher screening potential energy (U_e ~ 330 eV) can therefore be expected. However, for Li in a metal host an additional contribution arises from the quasi-free electrons n_{eff} of the metal itself ($U_e \sim \sqrt{n_{eff}}$). For Pd (n_{eff} ~ 6.5) a total $U_e \sim U_e^{ad} + U_e^{Debye} \sim 1000\,\text{eV}$ can then be expected, in qualitatively good agreement with recent measurements [4]. In order to confirm these predictions, additional independent data are needed. In Bochum, the d(d,p)t reaction in lithium is now being measured.

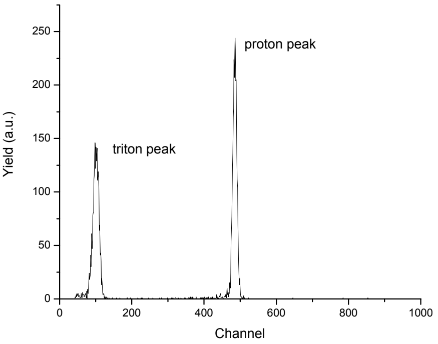

Fig. 1. Spectrum for d(d,p)t reaction in metallic lithium. Deuterium energy = 30 keV. Elastic recoils were stopped by 1 μm Ni foil.

Published, accepted or in press work

1. C.E. Rolfs and W.S. Rodney: *Cauldrons in the Cosmos*, the University of Chicago Press, 1988.
2. F. Raiola,…A.P. Jesus, J.Cruz, J.P. Ribeiro *et al.*, European Physical Journal A13 (2002) 377-382; Physics Letters B547 (2002) 193; *European Physical Journal A* **19** (2004) 283-287
3. F. Raiola…A.P. Jesus, H. Luís, J.Cruz, J.P. Ribeiro, *et al.*, in preparation .
4. J. Kasagi *et al.*, *J. Physical Society of Japan* **73** (2004) 608.

---

[1] Dep. Física da Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa

[2] Centro de Física Nuclear da Universidade de Lisboa

[3] Dep. Física da Faculdade de Ciências da Universidade de Lisboa