PROCEEDINGS OF SCIENCE

Investigation of nucleosynthesis neutron capture reactions using transfer reactions induced by ^{8}Li beam.

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From angular distribution and DWBA analysis of one nucleon transfer reactions it is possible to obtain spectroscopic factors of bound systems. Angular distributions for peripheral transfer reactions can alternately be used to determine the asymptotic normalization coefficient (ANC). ANC coefficients specify the normalization of the tail of the ovelap function, and consequently can be used to normalize astrophysical S-factors for direct capture reactions at stellar energies. Angular distributions for the elastic scattering ^{9}Be(^{8}Li,^{8}Li)^{9}Be and neutron transfer reactions ^{9}Be(^{8}Li,^{7}Li)^{10}Be and ^{9}Be(^{8}Li,^{9}Li)^{8}Be have been measured with a 27 MeV ^{8}Li radioactive nuclear beam. Spectroscopic factors and the corresponding Asymptotic Normalization Coefficients (ANC) for ^{8}Li$\otimes$n=^{9}Li and ^{7}Li$\otimes$n=^{8}Li bound system were obtained from the comparison between the experimental differential cross section and FR-DWBA (Finite Range Distorted Wave Born Approximation) calculations with the code FRESCO. The ANCs obtained can be used to normalize the direct capture cross section of the ^{8}Li(n,γ)^{9}Li and ^{7}Li(n,γ)^{8}Li capture reactions cross section at low energy.

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

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1. Introduction

Reactions induced by short-lived nuclei are of intrinsic interest in nuclear physics as well as in nuclear astrophysics. Light radioactive nuclei are present and play important role in many astrophysical environments. In the inhomogeneous models [1], reactions with ^{8}Li can bridge the A=8 mass gap and heavier elements would then be synthetized in the early universe. In the Type-II supernovae and in massive stars [2], reactions with unstable nuclei could produce seed nuclei for the r-process. Recently, binary neutron star mergers also have been proposed as possible sites for r-process [3], in which similar a situation is found. In a high-neutron-abundance environment, once ^{7}Li nucleus is produced, the chain of reactions $^7Li(n,\gamma)^8Li(\alpha,n)^{11}B(n,\gamma)^{12}B(^+\beta)^{12}C$ takes place and ^{12}C and subsequent heavier elements can be synthetized. The competing chain reaction is $^7Li(n,\gamma)^8Li(n,\gamma)^9Li(\alpha,n)^{12}B(^+\beta)^{12}C$. The key reaction in this chain is the ^{8}Li(n,γ)^{9}Li reaction. Experimental direct measurement of this reaction is impossible because no neutron target exists and the half-live of ^{8}Li is too short (838 ms) to be used as a target. Microscopic calculations have been performed to obtain the reaction rate [4, 5, 6], but the results deviate by an order of magnitude among these works. Recently, some experimental efforts have been devoted to the investigation of the ^{8}Li(n,γ)^{9}Li reaction by using indirect approaches; Coulomb Dissociation [7] and (d,p) transfer reaction [8].

The idea of using transfer reaction to investigate capture reactions is based in the fact that at low energies, the amplitude for the radiative capture cross section is dominated by contributions from large relative distances of the participating nuclei, and, by determining the reduced width or alternately the asymptotic normalization coefficient (ANC) one can normalize the non-resonant part of capture reaction. This ANC can be obtained from peripheral transfer reactions whose amplitudes contain the same overlap function as the amplitude of the corresponding capture reaction of interest [9]. Here, we report on the use of neutron transfer reactions ^{9}Be(^{8}Li,^{9}Li)^{8}Be and ^{9}Be(^{8}Li,^{7}Li)^{10}Be to obtain information on the spectroscopic factor for the ^{7}Li$\otimes$n=^{8}Li and ^{8}Li$\otimes$n=^{9}Li bound systems and consequently, the ANC coefficient which normalizes the non-resonant part of the corresponding ^{7}Li(n,γ)^{8}Li and ^{8}Li(n,γ)^{9}Li, capture reactions.

2. The experiment

The angular distributions for the elastic scattering reaction ^{9}Be(^{8}Li,^{8}Li)^{9}Be, and neutron transfer reactions ^{9}Be(^{8}Li,^{9}Li)^{8}Be and ^{9}Be(^{8}Li,^{7}Li)^{10}Be have been measured at Nuclear Structure Laboratory of the University of Notre Dame, USA. The 27 MeV secondary ^{8}Li radioactive beam was obtained from the TWINSOL system [10]. In this system, the ^{8}Li radioactive beam is produced in a primary target with the ^{9}Be(^{7}Li,^{8}Li) reaction, where the 30 MeV primary ^{7}Li beam up to 1μA was obtained from a 9.5 MeV Tandem Accelerator. The two superconducting solenoids in the TWINSOL system act as thick lenses to collect and focus the secondary beam onto the scattering chamber. The 27 MeV ^{8}Li beam with an average intensity of 5.0 × 10^5 particles per second per 1μA of primary beam and energy resolution of 0.3 MeV full width at half maximum was selected and transported through the solenoids and focused onto a 1.44 mg/cm^2 thick ^{9}Be secondary target. Some beam contaminants, ^{4}He, ^{6}He and ^{7}Li, with the same magnet rigidity, were also present but

Table 1: Optical potential parameters. Radii are given by $R_x = r_x \times A_T^{1/3}$.

SET	V (MeV)	r_R (fm)	a_R (fm)	W_V (MeV)	r_I (fm)	a_I (fm)	r_C (fm)	references
1	173.1	1.19	0.78	8.90	2.52	0.924	1.78	^{7}Li+^{9}Be at 34 MeV [14]
2	234.4	1.21	0.76	8.90	2.43	1.020	1.78	^{7}Li+^{9}Be at 34 MeV [14]
3	152.0	1.38	0.75	6.72	2.72	0.900	1.20	^{7}Li+^{9}Be at 24 MeV [19]

did not produce elements with mass A=8 or A=9 in the same range of energy as the particles from the neutron transfer reaction induced by the ^{8}Li beam.

The scattered ^{8}Li particles and ^{7}Li, ^{9}Li reaction products were detected by an array of ΔE-E silicon detectors. The measurements were performed with two setups where a combination of 3 telescopes covered the laboratory angles of 15, 18, 20, 25, 30, 35 and 40 degrees. Overlap of angles in these setup was usefull for normalization purposes. The telescopes consisted of 20 to 25 μm Si ΔE detectors, backed by 300 μm thick Si E detectors. The detector telescopes had circular apertures which subtended a solid angle of 4 msr for the most forward-angle measurements and 8 to 15 msr for the backward angles. The simultaneous measurement of the transfer particles and elastic scattering was very useful to check the consistency of the overall normalization and to select good set of optical potential parameters. The latter is very important in the transfer FRDWBA calculations. Also during the experiment sporadic runs with ^{8}Li elastic scattering on a gold target were measured to check the normalization of the data (solid angle and ^{8}Li particles in the beam).

3. Results and discussions

The ^{7}Li, ^{8}Li and ^{9}Li particles were easily identified in the ΔE-E two dimensional plot. The angular distribution for the differential cross section of ^{9}Be(^{8}Li,^{8}Li)^{9}Be elastic scattering reaction can be seen in Figures 1a and 1b. The optical parameters used to describe the angular distribution of the ^{9}Be(^{8}Li,^{8}Li) elastic scattering reaction are from ref. [14] and [19] and they are listed in Table-1. The results from the optical model calculation using these set of potential parameters can be seen in Figures 1-a and 1-b. The curve indicated as SP-Potential in Figure 1-b corresponds to the optical model calculations using the Sao Paulo Potential [11], which is a double folding potential with energy dependence and non locality correction. Despite the fact that there was no attempt to adjust the parameters to fit the data, the calculations with these set of potentials parameters give a good description of the elastic scattering data. The SP-Potential also reproduces quite well the phase of the oscillations and absolute normalization, which is quite good considering that this folding potential has no free parameters.

The angular distribution for the ^{9}Be(^{8}Li,^{9}Li)^{8}Be and ^{9}Be(^{8}Li,^{7}Li)^{10}Be reactions can be seen in Figures 2a-d. In the present analysis only the transitions to the ground-states have been considered. As one can see, the differential cross section for the transfer process are very small, being in the range of less than 1 mb/sr, which made these measurements quite difficult at the backward angles due to the limited secondary beam intensity. The FR-DWBA transfer calculations for the (^{8}Li,^{7}Li)

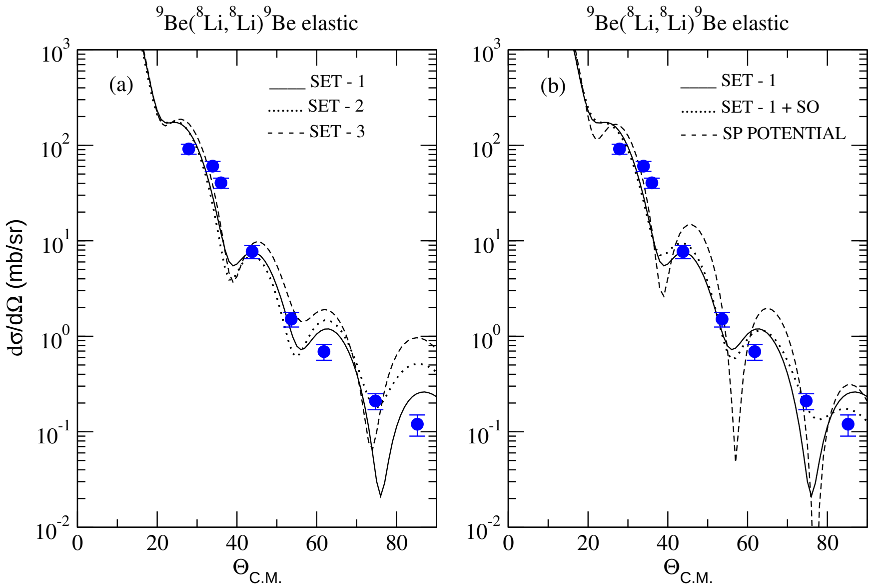

Figure 1: *The differential cross sections of elastic scattering* ^{9}*Be(*^{8}*Li,*^{8}*Li)*^{9}*Be at 27 MeV incident energy. The curves are optical potential calculations with the indicated parameters.*

and (^{8}Li,^{9}Li) neutron transfer reactions have been performed using the Code FRESCO. The same optical potential parameters in Table-1 were used for the entrance and exit channel. One nucleon transfer reactions can provide spectroscopic factor for one vertex once the other vertex is known by comparing the experimental angular distribution with DWBA transfer calculation. In these calculations, bound state wave functions were generated with Woods-Saxon potentials that have geometry parameters $r = 1.25$ fm and $a = 0.65$ fm and the depths of the potentials adjusted to give the correct separation energies.

In the DWBA calculation for the ^{9}Be(^{8}Li,^{7}Li)^{10}Be neutron transfer reaction the spectroscopic factor for the ^{10}Be=^{9}Be$\otimes$n bound system was taken from Cohen and Kurath (C.K.) [13]. By normalizing the calculation to the experimental data (see Figures 2a and 2b), a spectroscopic factor of $S = 0.980$, see Table-2, was obtained for the ^{8}Li=^{7}Li$\otimes$n vertex. This value is also compatible with the value obtained from C.K. calculations. A similar situation where all the spectroscopic factors involved in the transfer agree with values from C.K. calculations has been found in the analysis of the ^{9}Be(^{7}Li,^{6}Li)^{10}Be [14] and ^{9}Be(^{6}Li,^{7}Li)^{8}Be [15] reactions. These results indicate that Cohen-Kurath wave functions are quite good to describe stable nuclei in the mass range A=6 to A=10.

The ^{9}Be(^{8}Li,^{9}Li)^{8}Be neutron transfer reaction proceeds by two possible contributions leaving the ^{9}Li in the ground-state. These two contributions correspond to a neutron transfer to $1p1/2$ or $1p3/2$ orbit in ^{9}Li. Here only the transfer to $1p3/2$ orbit was considered because the contribution

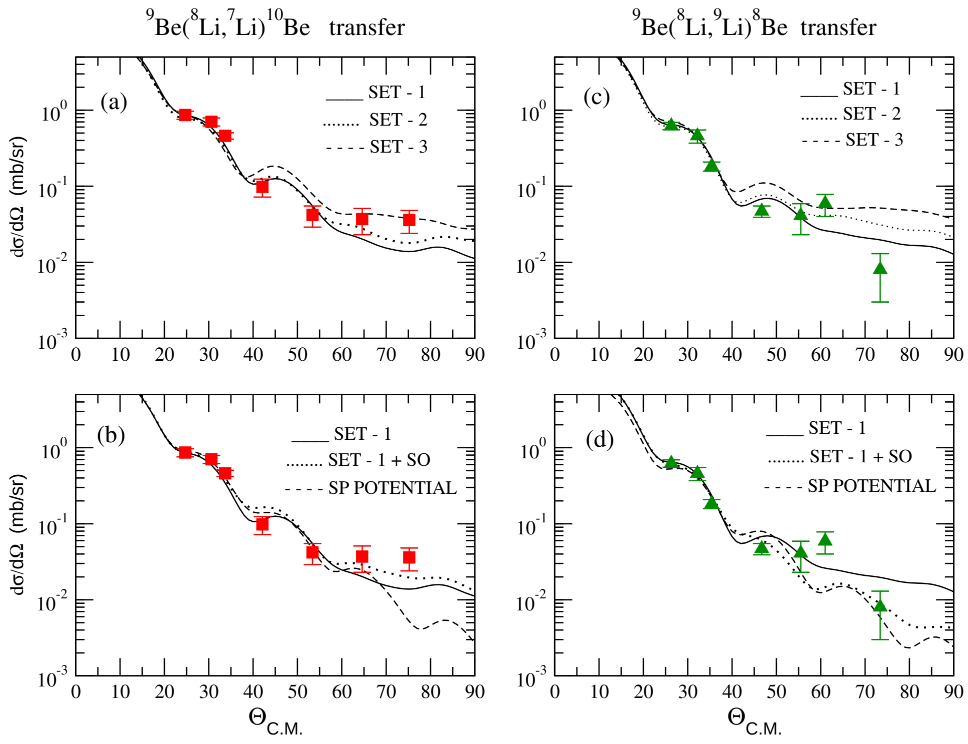

Figure 2: *The differential cross sections of neutron transfer reactions* ^{9}*Be(*^{8}*Li,*^{7}*Li)*^{10}*Be and* ^{9}*Be(*^{8}*Li,*^{9}*Li)*^{8}*Be at 27 MeV incident energy. The curves are FR-DWBA calculations using the code FRESCO with indicated potentials, as explained in the text.*

of the transfer to $1p1/2$ orbit has been found to be less than 5% [16]. For this reaction also, a spectroscopic factor from C.K. was used for the ^{9}Be=^{8}Be⊗n vertex, and by normalizing the FR-DWBA calculation to experimental data a spectroscopic factor of $S = 0.470$ was obtained for the ^{8}Li⊗n=^{9}Li bound system. The results of these FR-DWBA calculations with different sets of parameters are shown in Figures 2-c and 2-d. As one can see, the forward-angle data agree extremely well with calculations. The spectroscopic factor obtained for the ^{8}Li⊗n=^{9}Li bound system is lower than the ones obtained in the two previous investigations using (d,p) reactions [17] and [18]. Part of this difference can be attributed to contributions from compound-nucleus which has to be considered in (d,p) reactions but are small for heavier nuclei transfer reactions. The analysis with SP-Potential gave spectroscopic factors 50% lower than the ones obtained with the SET 1,2 and 3 for both (^{8}Li,^{7}Li) and (^{8}Li,^{9}Li) transfer reactions, probably related to no-locality effects in the folding potential not present in the optical model potentials.

When the reaction is peripheral, transfer cross section can be factorized in terms of a reduced width or ANC instead of spectroscopic factors. The ANC coefficient is given by $ANC^2 = S \times b^2$, where S is the spectroscopic factor and b is the normalization of the bound wave function to a known Whittaker or Hankel function, depending if it is a proton ou neutron capture reaction. The

Table 2: Spectroscopic factors S.

	J^π	Theo. Cohen-Kurath (C.K.) [13]	Other exp. (d,p)	This work SET 1-2-3	This work SP-Potential
^{8}Li⊗n=^{9}Li	3/2-		0.68 (14) Ref.[18] 0.90 Ref.[17]	0.47 (7)	0.30 (5)
^{7}Li⊗n=^{8}Li	2+	0.977		0.98 (15)	0.65 (10)
^{8}Be⊗n=^{9}Be	3/2-	0.580		C.K.	C.K.
^{9}Be⊗n=^{10}Be	0+	2.357		C.K.	C.K.

Table 3: ANC^2=S$\times$b^2.

	J^π	ref. [18]	this work
^{8}Li⊗n=^{9}Li	3/2-	1.33±0.33	0.92±0.14
^{7}Li⊗n=^{8}Li	2+		0.57±0.09

ANC can thus be obtained without the large uncertainties inherent to spectroscopic factor due to the ambiguities on the potential parameters used to calculate the form factor. The ANCs obtained from the present transfer reactions are listed in Table 3. With these ANCs one can calculate the no-resonant part of the corresponding capture reaction.

The author wishes to thank FAPESP (2001/06676-9 and 2006/00629-2) and CNPq (450452/2006-9) for financial support.

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