Use of neutron transfer reactions to indirectly determine neutron capture cross sections on neutron-rich nuclei

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Cross sections for the capture of low-energy neutrons on unstable neutron-rich nuclei are important for nuclear science and their reliable knowledge is increasingly requested by nuclear astrophysics to test quantitatively the nucleosynthesis in the r-process, by nuclear engineering for the design of new reactors using novel fuel cycles, and by national security. It is difficult, and in many cases impossible, to make direct measurements for all the reactions for which good cross sections are needed. We must build systematics, make structure and reaction models, and use indirect approaches. One such approach is to combine several neutron transfer reactions at different laboratory energies to extract information that can be used to determine reliably neutron capture cross sections at low energies.

The radiative neutron capture reaction $^{14}C(n,\gamma)^{15}C$ is being used as a test case for such an indirect determination. Our approach intends to combine information from the peripheral reaction of 12 MeV/u ^{14}C on a thin ^{13}C target and the non-peripheral reaction of 60 MeV deuterons on a thin ^{14}C target, both populating the same states in neutron-rich nucleus ^{15}C. From the $^{13}C(^{14}C,^{15}C)^{12}C$ experiment we will determine the asymptotic normalization coefficient (ANC) and we will use the non-peripheral (d,p) reaction on ^{14}C to obtain the spectroscopic factor (SF) which will then be used to calculate the radiative capture at astrophysical energies.

Unlike proton capture at astrophysical energies, neutron capture is not an entirely peripheral process. As such, there will be a contribution from the interior of the nucleus when computing the transition matrix element:

$$\begin{aligned}\sigma_{(n,\gamma)} &= SF\left|\langle\Phi_{B=(An)}\left|O_{elm}\right|\Phi_A\chi_n^{(+)}\rangle\right|^2\\ &= SF\left|M_< + M_>\right|^2 = \left|(SF)^{1/2}M_< + C_{nlj}\left(M_>/b_{nlj}\right)\right|^2 \qquad (1)\end{aligned}$$

The overlap integral $<\Phi_B|\Phi_A>$ in the exterior region behaves as $b_{nlj}h_l(ikr)$ where h_l is a Hankel function and the normalization factor b_{nlj} is the single particle ANC. Therefore,

$$M_> \approx b_{nlj}\langle h_l(i\kappa r)\left|O_{elm}\right|\chi_n^{(+)}\rangle$$

and for the correct evaluation of the second term in Eq. (1), the knowledge of the ANC (C_{nlj}) extracted from peripheral reactions is sufficient, but for the evaluation of the first one an unambiguous determination of the SF and of the overlap integral in the interior of the nucleus are also needed. For a peripheral reaction like (p,γ), the ANC would be all that is needed, however we will also have to consider the contribution from the interior for a (n,γ) reaction. Information to assess it can be extracted from a combination of neutron transfer reactions.

Progress in the analysis of the $^{13}C(^{14}C,^{15}C)^{12}C$ experiment

In September of 2007 we measured neutron transfer and elastic scattering of a 12MeV/u ^{14}C beam on a thin ^{13}C target using the MDM spectrometer and the MDM detector. At 12 MeV/u the transfer of a neutron from the ^{13}C target to the ^{14}C beam is a peripheral process. The goal of that experiment was to determine the ANC for ^{15}C. Elastic scattering was measured to determine the optical model potential (OMP) needed for DWBA calculations.

Position calibration of the detector was achieved through the elastic scattering of the beam off a 200μg/cm^2 Au target, which then passed through a five finger mask. Position at each of the four position sensitive avalanche counters was calculated for the five resulting rays using RAYTRACE code. The calculated positions were compared with those observed and a linear fit was made. RAYTRACE was also used to perform the raytrace reconstruction where the angle and position in the focal plane observed in the detector was related to the scattering angle in the target and the excitation energy. The angular distribution from 2 to 20 degrees in the lab frame was measured for elastic scattering of ^{14}C on ^{13}C and for the neutron transfer reaction $^{13}C(^{14}C,^{15}C)^{12}C$ from 2 to 8 degrees.

The elastic scattering cross section is compared in Fig. 1 with that calculated with an OMP obtained from a semi-microscopic double folding procedure using the JLM effective interaction. The optical model parameters (renormalizations and ranges) N_V=0.37, N_w=0.70, t_V=1.2 fm and t_W=1.75 fm were those from the general procedure established earlier from the study of elastic scattering of loosely

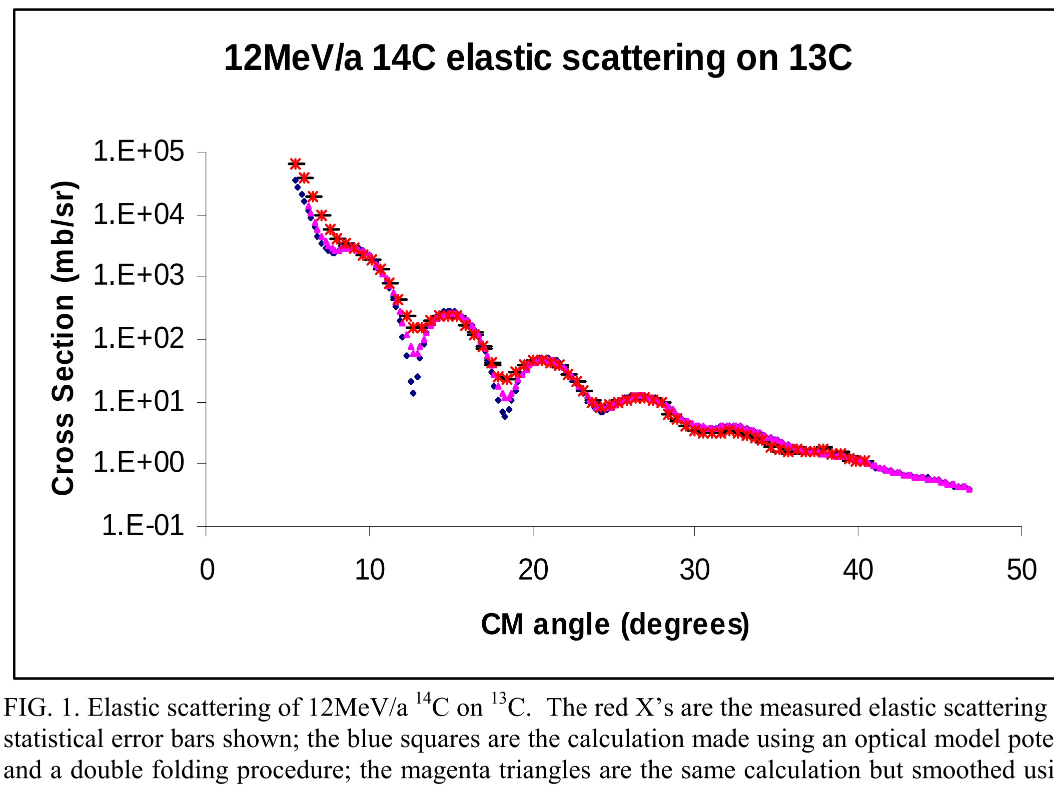

FIG. 1. Elastic scattering of 12MeV/a ^{14}C on ^{13}C. The red X's are the measured elastic scattering with statistical error bars shown; the blue squares are the calculation made using an optical model potential and a double folding procedure; the magenta triangles are the same calculation but smoothed using a Gaussian smearing function.

bound p-shell nuclei [1,2]. The overall agreement is good; in particular, the position of the minima and maxima, the oscillation period and the trend of the absorption are reproduced, therefore no further optimization was attempted at this stage. Then, the surface region of this potential was fitted with a Woods-Saxon potential, which was used to perform a DWBA calculation of the neutron transfer $1p_{1/2} \rightarrow 2s_{1/2}$ using the PTOLEMY code (Fig. 2). The normalization of the DWBA calculated cross section to the

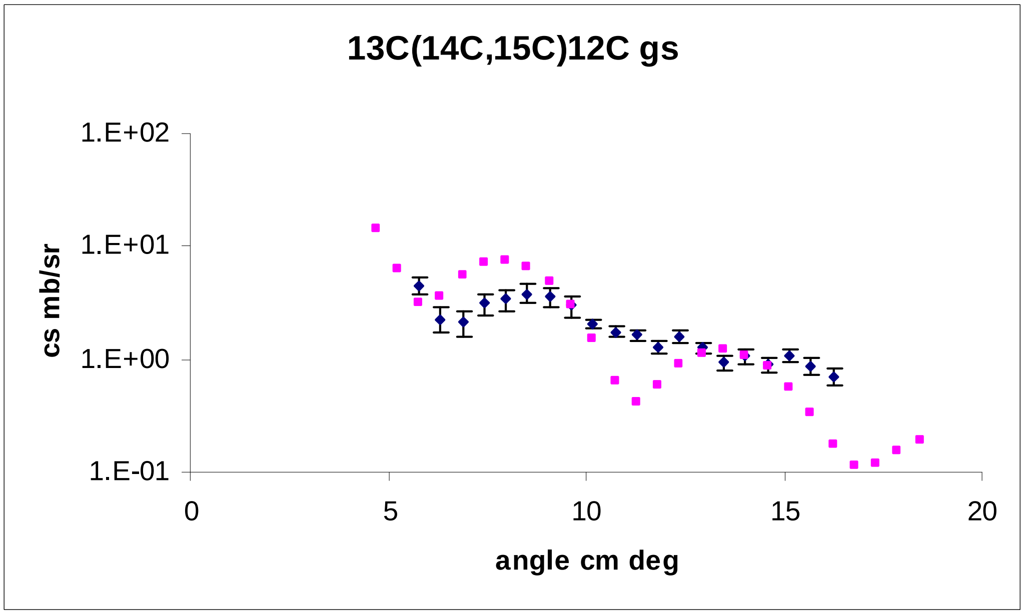

FIG. 2. Neutron transfer of 12MeV/a ^{14}C from ^{13}C forming ^{15}C in the ½$^{+}$ ($2s_{1/2}$) ground state. The blue diamonds are the experimental results, the magenta squares are the DWBA calculation using PTOLEMY.

experimental measurement gives the spectroscopic factor.

$$\frac{d\sigma}{d\Omega}_{\exp} = SF(^{13}C, 1p_{1/2}) \cdot SF(^{15}C, 2s_{1/2}) \frac{d\sigma}{d\Omega}_{DWBA}$$

The single particle ANC, b, is found by taking the ratio of the wave function calculated in the asymptotic region to the Hankel function over the radius. The ANC for ^{13}C(1p1/2) is known to be C^2=2.40 +/- 0.12 fm^{-1} [1]. Finally, this gives us the ANC for ^{15}C using:

$$C^2 = SF \cdot b^2$$

We found $C^2(2s_{1/2}) = 1.91 \pm 0.17$ fm^{-1} (this value is still preliminary).

There is a discrepancy of approximately a factor of two in the measured elastic scattering at small angles (less than 4 degrees lab) compared with the calculated value. Also, the low-lying, first excited $J^{\pi}=5/2^{+}$ state 0.74 MeV in ^{15}C dominated the transfer measurements and the cross section for the ground state was very low. Therefore, in May of 2009, we performed a second experiment with the same beam and target as in 2007; however, we used the Oxford detector, which allowed for a better particle ID. Scattering off the gold target was measured at both +4 and -4 degrees (lab) and the comparison of the cross sections at these angles indicates that the angle measured on MDM was off by approximately 0.3

degrees. Elastics and neutron transfers on ^{13}C were re-measured from 2 to 17 degrees. Particle ID using the energy loss and residual energy signals from the Oxford detector is shown in Fig. 3. Analysis of this experiment is ongoing. The above preliminary results will likely change once the correction for spectrometer angle is made and the additional statistics for the transfer reaction is added.

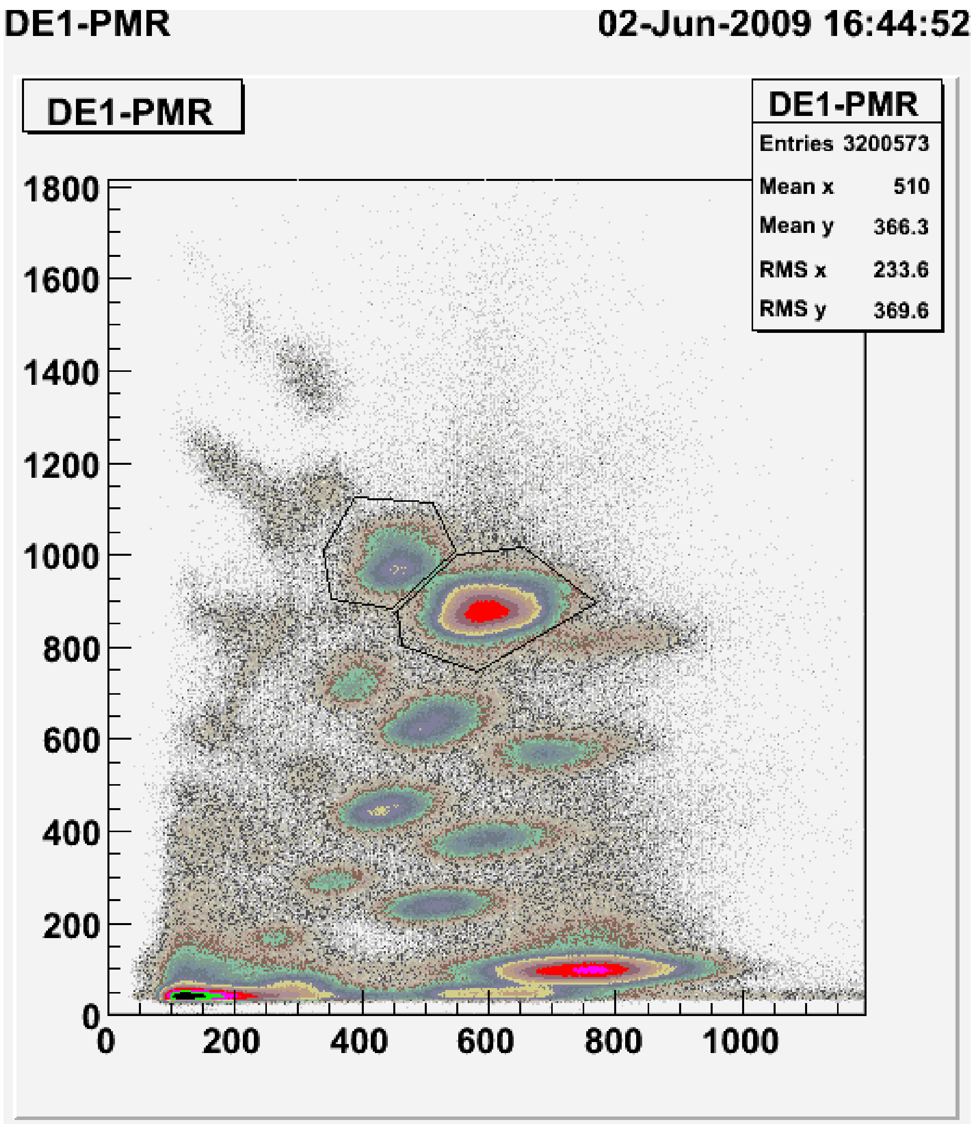

FIG. 3. Particle ID using ΔE-E_{res}

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[2] F. Carstoiu *et al.*, Phys. Rev. C **70**, 054610 (2004).

[3]. T. Al-Abdullah, PhD thesis, Texas A&M University, 2007.