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

M. McCleskey, A. M. Mukhamedzhanov, V. Goldberg, R. E. Tribble, E. Simmons, A. Spiridon, A. Banu, B. Roeder, L. Trache, X. Chen,* and Y. -W. Lui

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 proposed was 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 [1].

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/nucleon ^{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 direct radiative capture to the ground state of ^{15}C, 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:

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

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 (Cnlj) 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

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* Present address : Department of Chemistry, Washington University, St. Louis, Missouri

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.

Both $^{13}C(^{14}C,^{15}C)^{12}C$ at 12 MeV/nucleon and $^{14}C(d,p)^{15}C$ at 30 MeV/nucleon have been measured at Texas A&M. The beams were accelerated by the K500 super-conducting cyclotron and reaction products were measured using the MDM high-resolution spectrometer.

THE $^{14}C+^{13}C$ EXPERIMENT

Initially performed in September of 2007, this experiment was done using a thin (100 μg/cm2) ^{13}C target and a ^{14}C beam at 12 MeV/nucleon. Elastic scattering and single neutron transfer $^{13}C(^{14}C,^{15}C)^{12}C$ were measured simultaneously. A significant angular shift was present, however, and this made it impossible to have a meaningful fit to optical model calculation for the elastic scattering at forward angles where the cross section is rapidly changing as a function of the scattering angle. To resolve this and to also improve the angular distribution for the transfer reaction, the experiment was repeated in May of 2009, and the preliminary results of this new experiment are presented here.

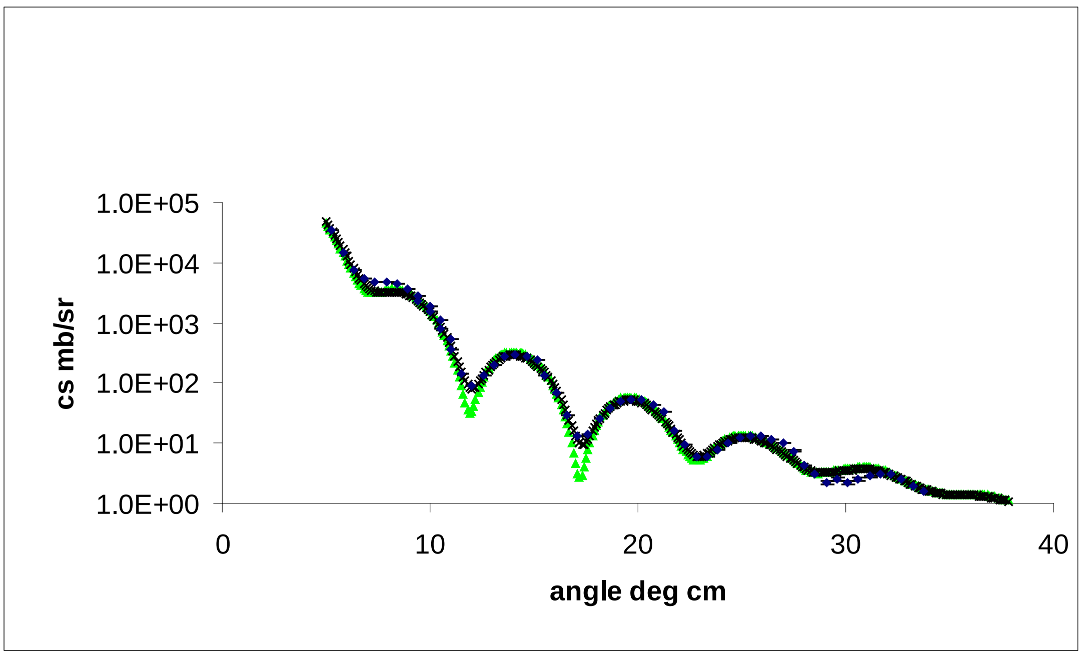

FIG. 1. Elastic scattering angular distribution of 12MeV/nucleon ^{14}C on ^{13}C. The diamonds are the measured elastic scattering with statistical error bars shown; the triangles are the calculation made using an optical model potential and a double folding procedure; the X's are the same calculation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

The elastic scattering cross section is compared in Fig. 1 with that calculated with an optical model potential (OMP) obtained from a semi-microscopic double folding procedure using the JLM effective interaction. The OMP parameters (renormalizations and ranges) N_V=0.45, N_w=0.90, 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 bound p-shell nuclei [2,3]. 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. The normalization of the DWBA calculated cross section to the experimental measurement (Fig. 2) gives the spectroscopic factor which combined with the calculated single particle ANC and the previously measured ANC for ^{13}C [3] will give us the ANC for ^{15}C.

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

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

We found $C^2(2s_{1/2}) = 2.08$ *+/-?* fm^{-1} (this value is still preliminary). The J^π=5/2+ first excited state at E*= 740 keV was also populated, and we could determine the ANC for both states. Analysis of this experiment is ongoing.

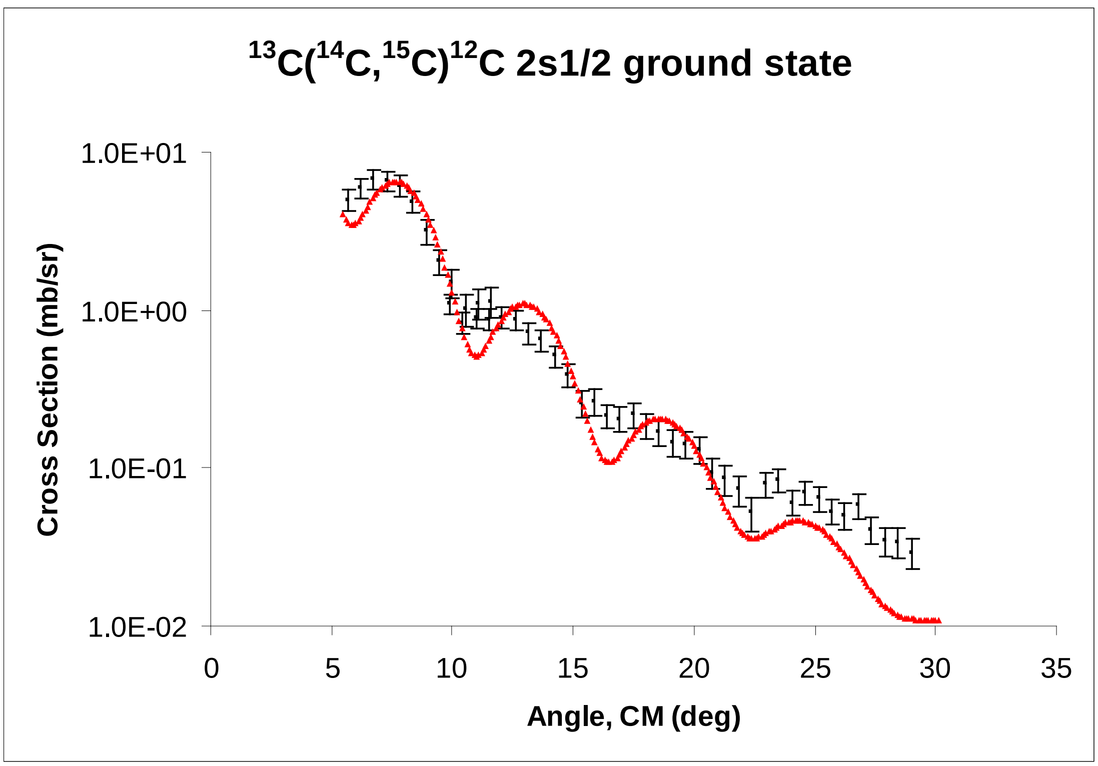

FIG. 2. Neutron transfer of 12MeV/nucleon 14C from 13C forming 15C in the ½+ (2s1/2) ground state. The squares are the experimental results, the triangles are the DWBA calculation using PTOLEMY.

The same states in ^{15}C were also populated using a 60 MeV deuteron beam on a ^{14}C target in February of 2008. The lowest two states were clearly identified and a measurement to obtain the angular distribution is planned for the middle of 2010. At an incident deuteron energy of 60 MeV this reaction has a non-trivial interior contribution. Using the ANC for ^{15}C obtained from the HI neutron transfer experiment to fix the exterior component of the reaction, this will allow us to determine the SF for ^{15}C unambiguously by means of fitting the interior part.

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