Update on the study of the $^{14}C+n\leftrightarrow{}^{15}C$ system

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The $^{14}C+n\leftrightarrow{}^{15}C$ system has been used to evaluate a new method [1] to obtain spectroscopic factors (SFs). As part of this investigation, the ANC was determined which was then used to calculate the astrophysically important $^{14}C(n,\gamma)^{15}C$ rate. All of the experiments were conducted at Texas A&M Cyclotron Institute (TAMU-CI) and have been described in previous reports ([2],[3]). The analysis and results were presented in [4] and this report covers new calculations that have been performed, specifically the utilization of the Koning-Delaroche (KD03, [5]) global optical potential parameterization. This parameterization has the advantage of having been fit to scattering data over a larger energy range than CH89. In the case of the 60 MeV $^{14}C(d,p)^{15}C$ reaction, the neutron energy range of CH89 was exceeded, and thus KD03 should be much more reliable for that reaction. Also, an examination of ^{15}C via its mirror, ^{15}F is presented.

Inverse kinematic $d(^{14}C,p)^{15}C$ reaction

The $d(^{14}C,p)^{15}C$ reaction with a ^{14}C energy of 11.7 MeV/u was measured using the TECSA [6] silicon detector array and was described in previous reports. The angular distribution was calculated using the adiabatic distorted wave approximation (ADWA, [7]) and the normalization at forward angles used to extract the ANC. In the ADWA single nucleon potentials are used for the incoming proton and neutron evaluated at half the deuteron energy. This calculation with CH89 potentials was described previously [4] but has since been performed using potentials from the KD03 parameterization. The results for these new

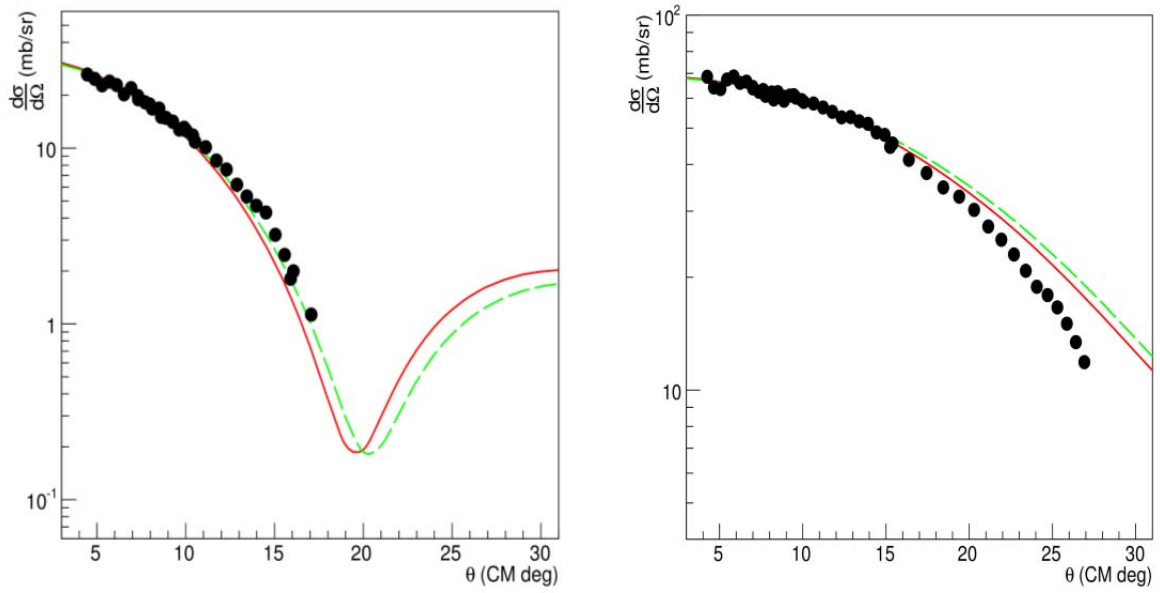

FIG. 1. On the left is the transfer to the $2s_{1/2}$ ground state. Black dots mark the experimental data points and the red and green lines are the ADWA calculation using CH89 and KD03 respectively. On the right is the same plotted for the 740 keV $1d_{5/2}$ first excited state.

calculations are shown in Fig. 1. The new ANC values are $C^2_{2s1/2} = 1.77 \pm .21$ fm^{-1} for the ground state and $C^S_{1d5/2} = (4.08 \pm .49) \cdot 10^{-3}$ fm^{-1} for the first excited state. The final results for the ANCs of the ground state and first excited state including these new calculations are presented in Table I.

Table I. Summary of ANCs found in the different measurements presented in this work.

experiment	$C^2_{2s1/2}$ (fm^{-1})	$C^2_{1d5/2}$ (fm^{-1})
HI transfer	2.09±0.29	$(4.48\pm0.58)\cdot10^{-3}$
$d(^{14}C,p)^{15}C$	1.77±0.21	$(4.08\pm0.49)\cdot10^{-3}$
average	**1.88±0.18**	$\mathbf{(4.25\pm0.38)\cdot10^{-3}}$

60 MeV ^{14}C(d,p)^{15}C reaction

The forward kinematic ^{14}C(d,p)^{15}C reaction was measured with a deuteron energy of 60 MeV. At this energy it was expected that this reaction cross section would have a strong dependence on the interior portion of the DWBA transfer matrix element. In [4] it was found to be almost completely peripheral for the ground state and only slightly non-peripheral for the $d_{5/2}$ first excited state. This analysis was based on calculations using CH89 potentials. These calculations have been repeated using KD03 potentials which should be more valid at this higher energy. The results show a stronger dependence on the interior, however, this reaction is still dominated by the exterior and surface contributions to the reaction rate, limiting the information that can be obtained about the ^{15}C SF. The results of the new calculations are shown in Fig. 2.

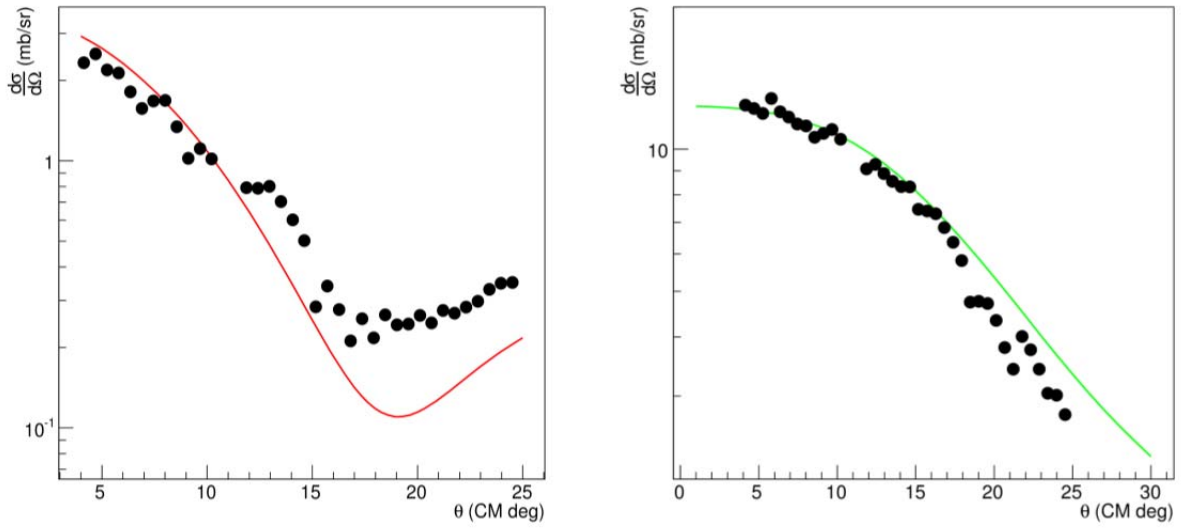

FIG. 2. On the left is the angular distribution for ^{14}C(d,p)^{15}C transfer to the ground state (black dots) and the ADWA calculation (red), the same is shown on the right for transfer to the $d_{5/2}$ excited state (black dots- experiment, green line ADWA).

As described in [1] and [4], a function

$$R^{DW}(b_{nlj}) = |\frac{\tilde{T}_{int}}{b_{nlj}} + \tilde{T}_{ext}|$$

was defined where *T* stands for the transfer matrix element, and *b* is the single particle ANC. The transfer matrix element has been split into two parts, one which is integrated over the interior region ($\tilde{T_{int}}$) and is dependent on the SPANC and another ($\tilde{T_{ext}}$) which is integrated over the exterior and is not dependent on the SPANC. For a peripheral reaction, $\tilde{T_{int}}$ is, by definition, negligibly small and *R* and thus the cross section is determined by $\tilde{T_{ext}}$. However, if a reaction has a non-negligible interior contribution, comparison of the above equation to its experimental counterpart

$$R^{\exp} = \frac{\frac{d\sigma}{d\Omega}^{\exp}}{C_{lj}^2}$$

will fix the single particle ANC. This can then be used to calculate the SF using the relation

$$SF_{nlj} = \frac{C_{nlj}^2}{b_{nlj}^2}.$$

The result of these calculations performed using the KD03 parameterization is shown in Fig. 3.

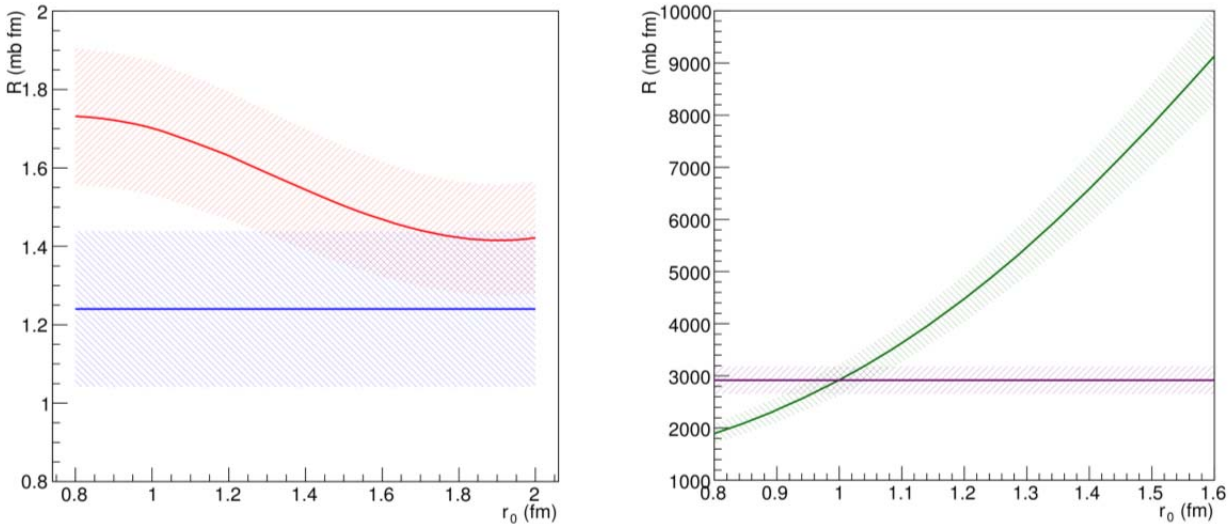

FIG. 3. R_{DW} (red) and R_{exp} (blue) for transfer to the ground state (left) and the $d_{5/2}$ first excited state (R_{DW} green, R_{exp} purple) (right). The uncertainties are shown by the hatched areas. In the calculation this is taken to be 10% and reflects the systematic uncertainty.

The ground state shows a relatively weak dependence on the choice of binding potential geometry and thus on the SPANC. This is a sign that the contribution to the transfer from the interior of the target nucleus is small and cannot be reliably determined. Based on the divergence around r_0=1.25 fm, this gives an upper limit for the SF for transfer to the ground state of ~0.93.

While Fig. 3 shows the ground state dependence of the calculated cross section on the binding potential geometry is weak, a stronger dependence on the binding potential geometry is observed for the transfer to the first excited state. As seen on the right in Fig. 3, R_{calc} overlaps with R_{exp} over the range r_0 from around 0.91 to 1.08 fm, which corresponds to SF values from 1.62 to 1.18. These values are considerably higher than expected, which indicates that the interior contribution to the transfer matrix element is not being correctly calculated and that a more sophisticated microscopic approach needs to be developed. The difficulty in correctly calculating this interior portion combined with the fact that most transfer reactions are dominated by peripheral and surface components highlights the difficulty in determining spectroscopic factors by means of transfer reactions.

Study of ^{15}C via its mirror, ^{15}F

In this section we will use the ^{15}C-^{15}F mirror symmetry to obtain a restriction on the SF of the two lowest states in these nuclei. To do this we examine experimental data on the levels in question with the aim to fix the potential parameters, which then can be used further to obtain SF and ANC. The *n* binding energies (BE) for the ground ($1/2^+$) and for the first excited ($5/2^+$) of ^{15}C are well known to be 1.218 and 0.478 MeV respectively. The compilation of the data for the two lowest states in ^{15}F can be found in [8]. We averaged these data to obtain the B.E. of the proton for the ground state in ^{15}F as – 1370 ± 70 keV with the width of 750 ± 100 keV, and for the first excited $5/2^+$ state: -2780 ± 40 keV with the width of 275 ± 40 keV [9, 10, 11, 12]. Assuming a Coulomb potential of a uniformly charged sphere of radius parameter R_{c0}=1.45 fm, r_0 and a were varied for the real binding potential which was taken to be of the Woods-Saxon shape. For each pair of r_0 and a the real depth was adjusted to reproduce the correct neutron binding energy for ^{15}C. Taking into account the proton's effect on the Coulomb potential in ^{15}F, these parameters were then used to calculate the binding energy of the corresponding proton in the mirror system. The results of these calculations are presented in Fig. 4.

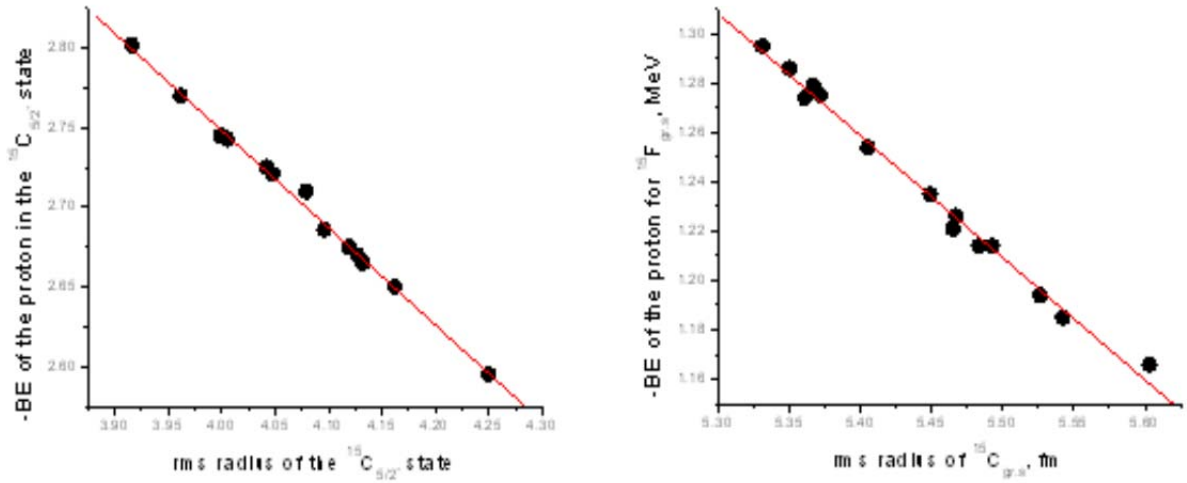

FIG. 4. Calculation of the binding energy of the proton in the ground state and first excited of ^{15}F as a function of binding potential geometry.

As seen on the left in Fig. 4, the experimental BE for the $d_{5/2}$ state corresponds to the rms radius of 3.97 fm in ^{15}C. From these considerations one can then obtain a restriction on the SF, which is defined as

$$SF = \frac{\Gamma}{\Gamma_{sp}}$$

the ratio of the width of the state to the calculated one using shell model wave functions. It is known that that the most sophisticated way to calculate widths of the broad states is to consider a pole in a complex plane [9]. Here we used the dependence of the maximum of the wave function upon the BE, as the method also gives close results [9]. Moreover, this approach was used to fit the data by the experimentalists in the works [10,11]. The calculated widths with parameters r_0=*1.18* and a=*0.6* are 0.590 MeV (for the ground state) and 230 keV (for the $5/2^+$ state in ^{15}F). After correction of the width calculated for the ground state for the experimental B.E, it becomes 720 keV. The calculated values are still smaller than the experimental ones. Taking into account the experimental uncertainties in the widths and the excitation energies, we obtain $SF_{gr.s.} \geq 0.90$ and for the first excited state, $SF_{\text{first ex.s.}} \geq 0.93$. We tested and neglected the weak dependence (~15 keV for the excited state) of the penetrability on the specific values of r_0 and a.

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