Measurement of the $^{14}C(d,p)^{15}C$ reaction at E_d=60 MeV

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

This reaction has recently been measured at Texas A&M University Cyclotron Institute using a 60 MeV total energy deuteron beam from the K500 super-conducting cyclotron. The deuteron beam impinged on a thin (~335 μg/cm^2), high-purity, self-supporting ^{14}C target and reaction products were measured using the MDM spectrometer and the Oxford ionization chamber detector. This measurement was previously attempted in February 2008, however the available solid angle defining slit proved to be too big (4°x2°) for the acceptance of the Oxford detector. Typically a 4°x1° slit is used with this detector, however no slit of adequate thickness for deuterons of this energy was available, and while a raytrace calculation indicated that the larger slit would be acceptable, this proved not to be the case. A good particle identification was obtained from the 2008 experiment, however, the measurement had to be repeated to obtain the angular distribution needed.

This measurement is part of an ongoing project [1] to investigate the use of the asymptotic normalization coefficient (ANC) to fix the external contribution to the DWBA transition matrix element and thereby experimentally determine the single particle ANC (SPANC) in order to remove this otherwise arbitrary and potentially significant parameter dependence in the determination of the spectroscopic factor [2]. The relatively high energy deuteron beam was selected to maximize the interior contribution to the reaction while at the same time being a decent compromise for both cross section and description within the DWBA.

The beam accelerated by the K500 was 30 MeV/nucleon HD+, which was then stripped after the machine to give the 60 MeV deuterons. This beam was taken through the beam analysis system (BAS) [3] in order to improve the momentum and position resolution of the beam at the target. After the ^{14}C target a new, thicker 4°x1° acceptance slit defined that acceptance of the spectrometer. Elastic scattering and (d,p) were both measured. These were also measured on a ^{12}C target with the same spectrometer settings in order to subtract contributions from ^{12}C impurity in the ^{14}C target. The ^{14}C target was found to have approximately 1.6x10^{18} atoms/cm^2 ^{12}C, or about 11% by number. Elastic scattering on the ^{12}C target was also measured and this was used to correct the elastic angular distribution for scattering on ^{14}C. Thickness of the ^{14}C target was measured in beam using a ^{20}Ne beam at 15 MeV/nucleon. A gold foil was placed behind the ^{14}C target and elastic scattering was measured at small angles using a single, narrow acceptance slit. After the position in the focal plane was measured for the combined ^{14}C + Au target, the ^{14}C target was removed and the difference in position in the focal plane was measured. Using the programs RAYTRACE [4] and LISE [5] the thickness of the ^{14}C target was then determined.

Particle identification for this run was also improved over the measurement made in 2008 by using a thicker scintillator. Because of the high energy and low Z of the reaction products very little energy was deposited in the Oxford detector ionization chamber (used to measure ΔE for the ΔE-E_{res} particle ID) and the products were not stopped in the ¼" scintillator. For this new measurement a new 1.5" thick scintillator and associated light guides were fabricated and installed. Both deuterons and protons stop in the new scintillator, and the light output is roughly proportional to their distance traveled (much longer for the highly penetrating protons). The resulting improvement in particle identification is shown in Fig. 1. In addition to this, an updated electronics scheme using all in-cave electronics was utilized.

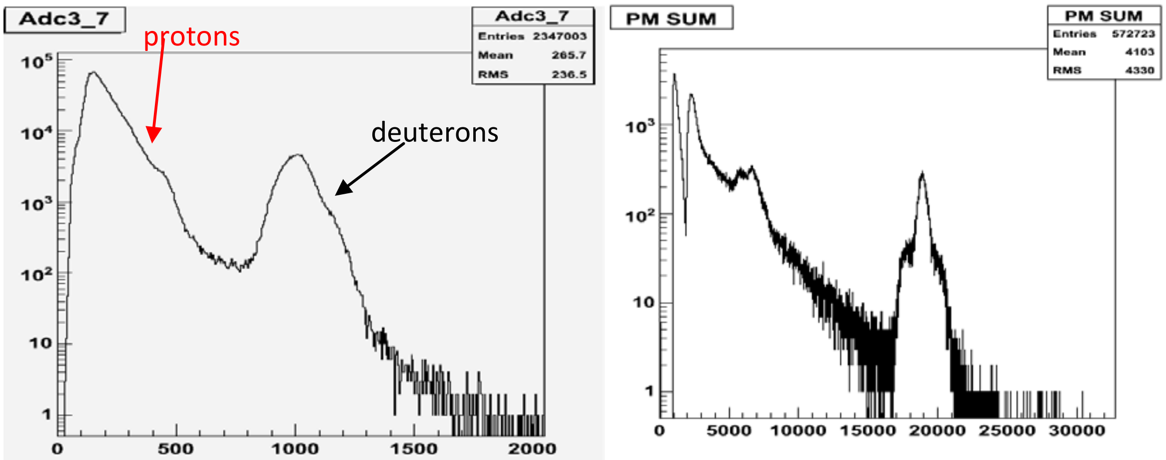

FIG. 1. On the left, particle identification in 2008 using a 0.25” thick scintillator and on the right particle identification from the most recent experiment using a new, 1.5” thick scintillator.

The elastic scattering was fit using an OMP of the WS form. The global potential parameterization of Ref. [6] was used as a seed. To improve the fit, spin orbit coupling and the surface imaginary terms were neglected. A grid search for values of the real volume potential was performed to find local χ^2 minima (Fig. 2). The local minima were then used for a further fit over all six optical model parameters. The three fits are shown in Fig. 3. The potential parameters are given in Table I.

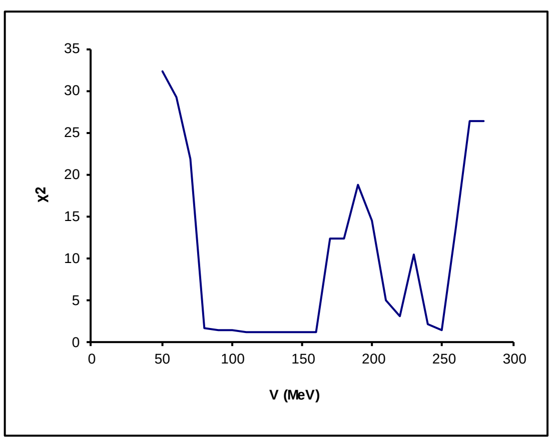

FIG. 2. Grid search in V.

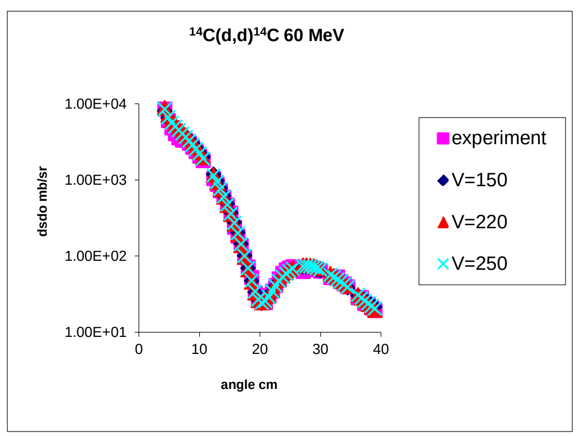

FIG. 3. Elastic scattering of 60 MeV deuterons on ^{14}C shown with optical model fits.

Table I. Summary of optical potentials for elastic scattering of 60 MeV deuterons on ^{14}C.

	V (MeV)	W (MeV)	r_v (fm)	r_w (fm)	a_v (fm)	a_w (fm)	χ^2
WS1	274	17.3	1.79	2.54	0.729	1.30	1.437
WS2	151	8.05	1.36	4.59	0.920	0.913	1.19
WS3	376	3.88	1.24	5.56	0.739	0.861	0.871

An adiabatic distorted wave approximation calculation (ADWA) was made using potentials taken from the CH89 [7] parameterization. In the ADWA the breakup of the deuteron in the entrance channel is handled explicitly and the transition matrix for a (d,p) reaction

$$\tilde{T} = \langle \chi^{(-)} \phi_{nA} \,|\, V_{np} \,|\, \Psi^{(+)} \rangle \tag{1}$$

reduces to [8]

$$\tilde{T}_{ADW} = \langle \chi^{(-)} \phi_{pA} \,|\, V_{pn} \,|\, \tilde{\chi} \phi_{pn} \rangle \tag{2}$$

where the n-p effective interaction, V_{pn}, is taken to be zero range and

$$[E + \epsilon_0 - T_R - \bar{V}]\tilde{\chi} = 0 . \tag{3}$$

Here ϵ_0 is the deuteron binding energy and

$$\bar{V} = V_n + V_p + V_C \tag{4}$$

where V_n and V_p are, respectively, the neutron and proton optical potentials evaluated at half of the deuteron energy. V_C is the Coulomb potential. Finite range effects on the deuteron potential can be approximated by [9]

$$U_{FR} \approx \frac{\langle \phi_d \,|\, V_{np} (V_n + V_p) \,|\, \phi_d \rangle}{\langle \phi_d \,|\, V_{pn} \,|\, \phi_d \rangle} . \tag{5}$$

This potential still contains the proton- and neutron-target optical potentials evaluated at half the deuteron energy, but the evaluation is significantly more complex, requiring integration over the deuteron wave function along with the n-p interaction. A simple approximation of the finite range effect was given by Ref. [10] and this, along with the formulation of ref. [9], were examined for several cases in Ref. [11]. For both approximations an increase in real and imaginary diffuseness and real and imaginary depths was observed, though the two approximations differed in amount. For all ADWA calculations performed here the Wales-Johnson approximation of Ref. [10] was used for simplicity of calculation.

The ADWA has the advantage that only nucleon optical potentials are required, for which CH89 was utilized. The Reid soft core potential [12] was used for the n-p interaction. The calculations were made using the code FRESCO [13]. The experimental angular distribution and calculation for the transfer to the ground state and first excited state is shown in Fig. 4. Both show a good match to the data at forward angles, while the calculation deviates from the experiment at larger angles.

Analysis of this experiment is ongoing.

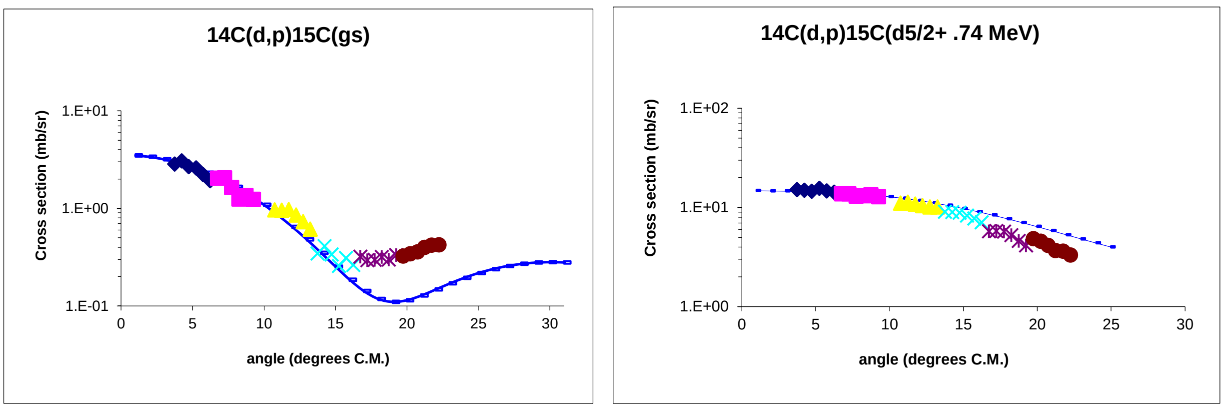

FIG. 4. On the left is (d,p) going to the ground state of ^{15}C and on the right is transfer to the 1st excited state. In both the blue line is the ADWA calculation, in the case of the transfer to the excited state there is a renormalization factor of 0.8 and for the ground state the calculation was not renormalized.

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