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A HIGH RESOLUTION MEASUREMENT OF THE $^{14}C(d, n)^{15}N$ REACTION

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Abstract: Angular distributions of neutrons from the $^{14}C(d, n)^{15}N$ reaction have been measured at $E_d = 3.09$ MeV using the time-of-flight technique. Transitions to all levels below 9.5 MeV in ^{15}N are observed and spectroscopic factors are extracted for transitions with $l = 0$ and $l = 1$ using DWBA analysis. From these factors, absolute spectroscopic factors are obtained with the aid of two independent sum rules.

The only observed $s_{\frac{1}{2}}$ proton widths belong to the 5.30 and 9.06 MeV states.

E | NUCLEAR REACTION $^{14}C(d, n)$, $E = 3.09$ MeV; measured σ (E_n, θ). ^{15}N levels deduced spectroscopic factors. Enriched target.

1. Introduction

States of the ^{15}N-^{15}O mirror pair may be excited via (d, p) and (d, n) reactions in targets with $(J, T) = (0,1)$ and $(1,0)$. This opportunity is unique and permits a thorough experimental investigation of the wave functions of states in the residual nucleus and of the target ground states. The $^{14}C(d, n)^{15}N$ reaction has been the least used path to the mirror pair. The (d, n) measurement of Imhof *et al.* [1]) dealt only with levels below 7.3 MeV excitation in ^{15}N; the yield functions below $E_d = 3$ MeV showed resonant structure and the deviation of the angular distributions from stripping patterns, identifiable with direct interaction components, prevented any conclusions about l-values and spectroscopic factors. However, Chiba [2]) had previously established the $l = 1$ character of transitions to the ^{15}N ground state and the 6.33 MeV level, but the spectroscopic factors extracted [3]) had large uncertainties.

We measured the $^{14}C(d, n)^{15}N$ reaction with a deuteron beam limited to $E_d = 3.1$ MeV. Compound nucleus formation, while not negligible, may not interfere too drastically with intense $l = 0$ and $l = 1$ stripping angular distributions, especially if the bombarding energy is varied to achieve optimum conditions. Orbitals with $s_{\frac{1}{2}}$ and $p_{\frac{1}{2}}$ are expected to characterize many of the levels below the 9.5 MeV excitation in ^{15}N to which this study is limited.

2. Experimental procedure

A ^{14}C target of unknown thickness was bombarded with deuterons from the 3.1 MeV Harwell IBIS Van de Graaff accelerator [4]). A time-of-flight spectrum at 10 m

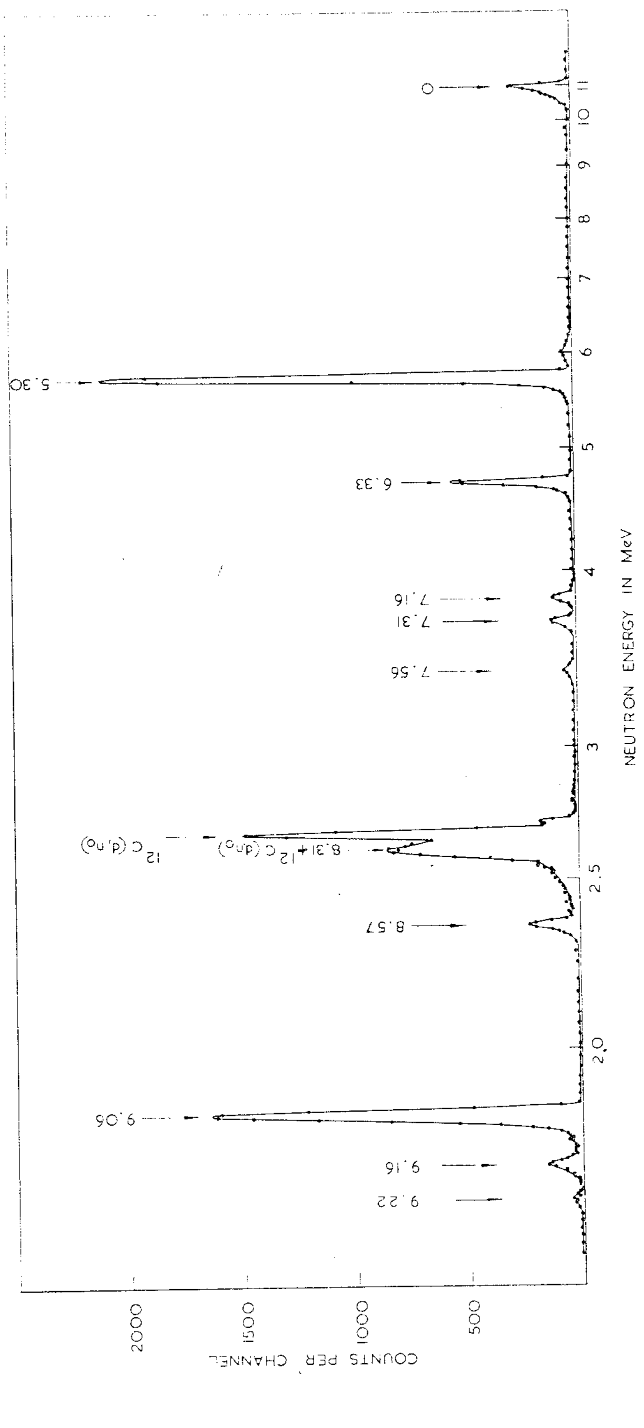

Fig. 1. Neutron spectrum of the $^{14}C(d, n)^{15}N$ reaction at $\theta = 0°$ and $E_d = 3.09$ MeV. The arrows indicate the positions of known levels in ^{15}N.

flight path and with time resolution of 2 ns is shown in fig. 1. Groups corresponding to all known [5]) levels in ^{15}N up to 9.5 MeV are resolved except to the 5.27/5.30 MeV doublet and also to the 8.31 MeV level, which coincides with peaks from two sources of ^{12}C contaminations at the target and at a beam collimator. The weak group with $E_n \approx 6$ MeV most likely arises from an unknown target contaminant.

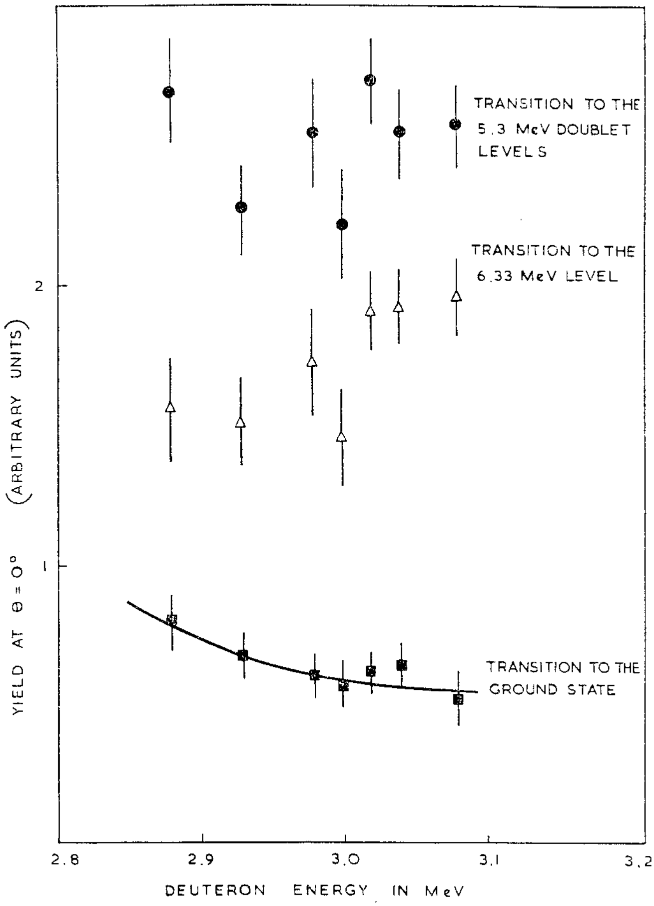

Fig. 2. Yield of the $^{14}C(d, n)^{15}N$ reaction at $\theta = 0°$. The solid line gives the yield of the ground state transition measured in ref. [1]).

The yield (fig. 2) to the ^{15}N ground state, as a function of deuteron energy, agrees with that measured by Imhof *et al.* [1]) and Chiba [2]), who established the existence of a broad maximum at $E_d \approx 2.8$ MeV. The maximum is not evident in the yield to the 5.3 and 6.33 MeV levels. This effect follows from the competition between compound nucleus formation (fluctuating yield functions) and the direct reaction mechanism (smooth yield functions). Compound nucleus formation more easily effects transitions to low-lying states since those channels have larger transmission coefficients

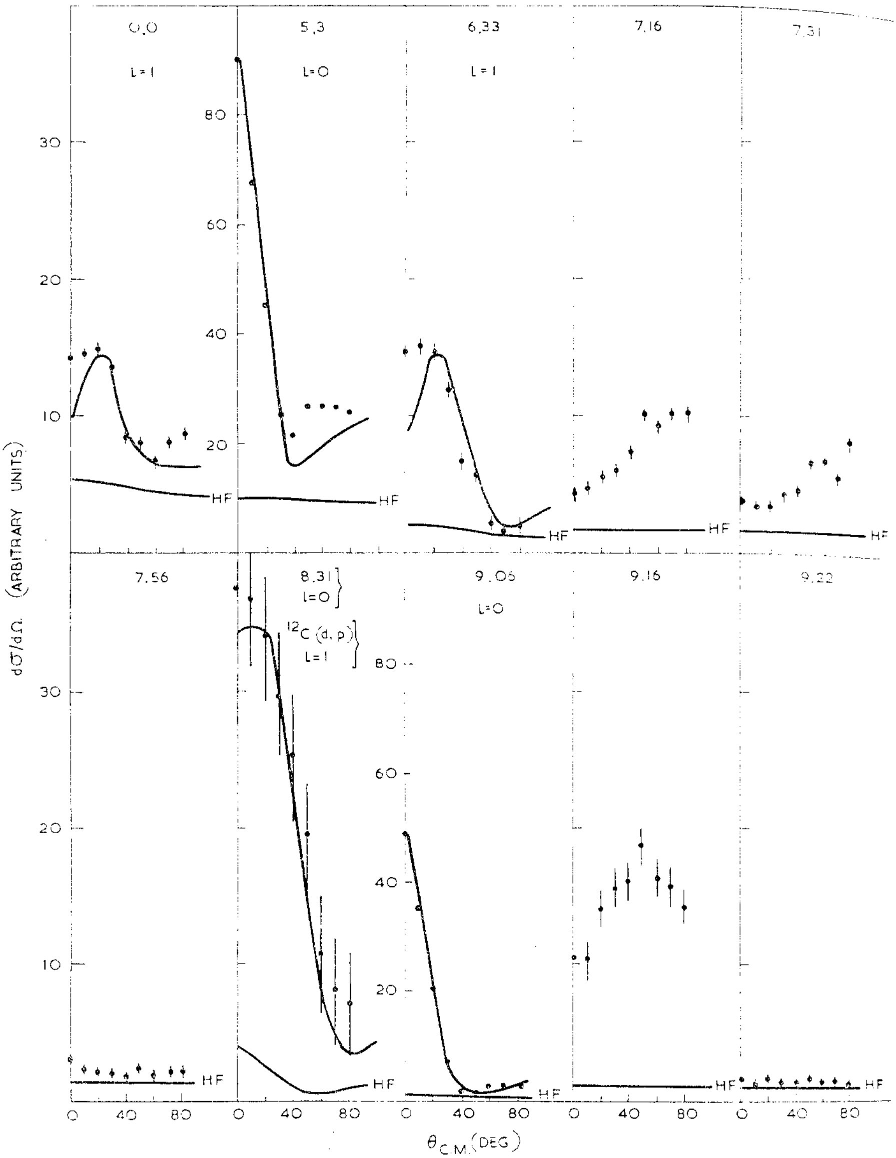

Fig. 3. Angular distributions of the neutron groups from the $^{14}C(d, n)^{15}N$ reaction. The solid lines indicate the distributions predicted by Hauser-Feshbach theory (HF) and by DWBA theory (including the HF contribution).

than those involving high-lying levels, while the reverse argument applies to the direct reaction mechanism. The $l = 0$ transitions, in particular, mainly proceed via direct interaction at this bombarding energy as does the $l = 1$ transition to the 6.33 MeV level. Fig. 3 shows the relative differential cross sections of the neutron groups observed at $E_d = 3.09$ MeV. We notice that the transitions to the 5.3 MeV doublet is predominantly $l = 0$, i.e. the $J^\pi = \frac{1}{2}^+$ level at 5.30 MeV is mainly populated. The ^{12}C(d, n$_0$)^{13}N transitions and the transitions to the 8.31 MeV level of ^{15}N are shown in order to indicate an upper limit of the strength of the $l = 0$ transitions to the 8.31 MeV state.

3. Analysis of the relative differential cross sections

In order to extract useful S-factors from the direct reaction cross sections we decompose the observed cross sections into compound nucleus σ_{CN} and direct reaction σ_{DI} parts and assume that the interference is negligible.

3.1. HAUSER-FESHBACH CALCULATIONS

To determine the amount of compound nucleus formation in the measured angular distributions, we assume that σ_{CN} is given by Hauser-Feshbach theory. It is known [6]) that σ_{HF} over-estimates σ_{CN}. The σ_{HF} are therefore reduced so that they nowhere exceed the measured differential cross sections, while the ratios of σ_{HF} in the different exit channels are left unaltered. The net uncertainty in the extracted value of $d\sigma_{DI}$ at the angle of maximum yield is generally 20 % except for the ground state transition where it is 60 % as a result of the large amount of compound nucleus formation. Because of the relatively low bombarding energy, we are unable to determine precisely σ_{DI} for the ground state transition. On the other hand, the direct interaction part of the $l = 0$ transitions and the $l = 1$ transition to the 6.33 MeV level may be confidently analysed by means of DWBA theory.

3.2. DWBA CALCULATIONS

The available distorted wave Born approximation programme † had the facility to include spin-orbit coupling terms in the local distorting optical potentials. It employed the zero-range approximation. The optical model parameters adopted are summarized in table 1. The real potential was of Saxon-Woods shape; the imaginary potential had a Gaussian shape peaked at the surface.

TABLE 1

Optical-model parameters

Type	U (MeV)	r_u (fm)	a_u (fm)	W (MeV)	r_w (fm)	a_w (fm)	V_s (MeV)
deuteron A	123.6	0.9	0.9	6.36	2.132	1.24	6
deuteron B	131	0.9	0.9	7.5	1.89	1.29	6
neutron	40.3	1.42	0.65	8.0	1.42	0.98	0

All deuteron potentials were taken from Satchler's analysis [7]) of ^{12}C(d, d)^{12}C for deuteron energies between 2.8 and 34.2 MeV. Potential A is appropriate for scattering

† Supplied by Dr. B. Macefield.

at $E_d = 3.23$ MeV; potentials B is an average for scattering at $E_d = 9$ and 10 MeV, i.e. a region which shows the least "resonant" structure in the excitation function of deuteron scattering on ^{12}C [see fig. 1 of ref. [7])].

The captured proton was assumed to move in a Saxon-Woods potential which was determined in the following manner:

The $l = 0$ transitions to the 5.30 *and* 9.06 MeV *states.*

(C′) Both states were given the same potential depth $U = 66$ MeV with $r = 1.15\,A^{\frac{1}{3}}$, $a = 0.6$ and $r_0 = 1.25$; $a = 0.8$ fm, respectively. This gave the empirical Q-values for the two states. The different size parameters of the potentials were introduced to simulate the effect of residual forces not included in the single-particle, shell model having a potential depth U.

(C″) The states were given the same potential ($r_0 = 1.2\,A^{\frac{1}{3}}$; $a = 0.7$ fm) except for the depth parameter U which was determined by the Q-values.

The $l = 1$ transitions to the ground state and the 6.33 MeV *state.*

(D′) The same potential depth ($U = 42$ MeV) was used for both states, while the size parameters were $r_0 = 1.5\,A^{\frac{1}{3}}$; $a = 0.9$ and $1.2\,A^{\frac{1}{3}}$ and $a = 0.7$ fm, respectively, in order to give the proper Q-values of the states.

(D″) The potentials were determined as in case C″.

The alternative potentials are discussed in sect. 4. Deuteron potential B gave the measured angular distribution with zero cut-off radius in the DWBA code, while potential A needed a cut-off of 3.5 to 4.5 fm to give the measured angular distributions. Used in this way, the predicted absolute $d\sigma_{DI}$ (on the stripping peak) differed no more than 15 % between the two deuteron potentials. This error is incorporated in the quoted uncertainty of the measured S-factor. Typical angular distributions are shown in fig. 3.

4. Normalization of the *S*-factors

The absolute value of the extracted S-factors can be normalized by means of sum rules for $l = 0$ and $l = 1$ transitions given by French and Macfarlane [8]). Define the total measured strength of transitions with a particular l-value

$$G_{exp}(T) = C^2 \frac{2J_f+1}{2J_i+1} S_{exp}, \tag{1}$$

where C is the isospin, (T) the vector coupling coefficient, and S_{exp} is measured in the (d, n) reaction. French and Macfarlane [8]) have shown that one expects the following theoretical relationship:

$$G_{theor}(T<) = \langle\text{proton holes}\rangle_j - \frac{\langle\text{neutron holes}\rangle}{N-Z+1}, \tag{2}$$

where ⟨proton holes⟩$_j$ refers to the effective number of hole states in the (lj) shell-model orbit in the wave function of the target nucleus ground state.

The dominant configuration of the ^{14}C ground state is $(1s)^4$ $(1p)^{10}$. From the ^{14}C(d, t)^{13}C reaction, it is known [9]) that this state contains only 0.5 % and 7 % admixtures of 2s and 1d, respectively. As a result, we predict from relation (2)

$$G_{\text{theor}}(l = 0) = 1.3, \tag{3}$$

$$G_{\text{theor}}(l = 1) = 2, \tag{4}$$

for transitions to $T = \frac{1}{2}$ final states in the ^{14}C(d, n)^{15}N reaction.

Using a suitable overall normalization of the extracted S-factors, one has, in fact, from the present experiment

$$G_{\text{exp}}(l = 0) = 1.3 \pm 0.3,$$

$$G_{\text{exp}}(l = 1) = 5 \pm 4,$$

when bound state potentials C′ and D′ were used. It is thus possible to normalize these S-factors consistently, since eqs. (3) and (4) are satisfied simultaneously.

Potential C″ introduced 20 % variation in the value of $G_{\text{exp}}(l = 0)$ while potential D″ gave $G_{\text{exp}}(l = 1) = 11 \pm 8$, i.e. slightly outside the allowed value. Unfortunately, the major contribution to the value of $G_{\text{exp}}(l = 1)$ comes from the ground state transition which was shown above to be particularly hazardous to measure. However, it appears that the bound potential D″ is less satisfactory. (We normalize so that eq. (3) is satisfied since the $l = 0$ transitions are most accurately measured.)

The suitable normalized S-factors are given in table 2. For $l = 0$ transitions, the average of value given by potentials C′ and C″ are quoted and the errors limits encompass these values. For $l = 1$ transitions, only the results of potential D′ are given since potential D″ yields too large ground state spectroscopic factor as discussed above †.

TABLE 2

Summary of absolute S-factors for 2s and 1p nucleon transfer in the ^{14}C(d, n) reaction to levels in ^{15}N with $T = \frac{1}{2}$

E_x (MeV)	$J\pi$	1	S
0	$\frac{1}{2}^-$	1	1.7 ±1.4
5.30	$\frac{1}{2}^+$	0	0.62±0.15
6.33	$\frac{3}{2}^-$	1	0.56±0.14
8.31	$\frac{1}{2}^+$	(0)	< 0.04
9.06	$\frac{1}{2}^+$	0	0.28±0.08

† Both D-potentials give the same S-factor for the 6.33 MeV state.

5. Discussion of results

5.1. THE $l = 1$ TRANSITIONS

The present values of $S = 1.7 \pm 1.4$ and $S = 0.56 \pm 0.14$ for transitions to the ground state and the 6.33 MeV state are in fair agreement with the values $S = 0.91 \pm 0.16$ and $S = 0.30 \pm 0.08$, respectively, deduced in ref. [3]) using PWB analysis. The ground state S-value may also be compared to the S-factor in the inverse analogue reaction ^{15}N(p, d)^{14}N leading to the $T = 1$ state in ^{14}N, i.e. the analogue of the ^{14}C ground state. Bennett's [12]) measurement gave

$$\frac{S[^{15}\mathrm{N}(\mathrm{p}, \mathrm{d}_1)]}{S[^{15}\mathrm{N}(\mathrm{p}, \mathrm{d}_0)]} = 0.23.$$

If one takes $S[^{15}\mathrm{N}(\mathrm{p}, \mathrm{d}_0)]$ equal to the well-established [3]) value $S = 1.1$ for the inverse $^{14}\mathrm{N}(\mathrm{d}, \mathrm{p}_0)^{15}\mathrm{N}$ ground state reaction, the value $S[^{15}\mathrm{N}(\mathrm{p}, \mathrm{d}_1)] = 0.25$ falls at our lower limit. The earlier quoted PWB value disagrees with this low value however.

The plausible values of the S-factor for the ground state transitions are outside the theoretical values $S = 1.3 \pm 0.15$ predicted by various forms of the intermediate coupling shell model. This discrepancy has been extensively discussed by Macfarlane and French [3]).

5.2. THE $l = 0$ TRANSITIONS

A shell-model calculation of even-parity states in ^{15}N has been given by Halbert and French [13]), but no S-factors for proton transfer were given by these authors.

It is interesting to note that the only $T = \frac{1}{2}$ states with observed proton width at 5.30 and 9.06 MeV excitation have zero-neutron width, and that the only states with neutron width at 7.32 and 8.32 MeV excitation have zero-proton width.

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