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Threshold and Resonances in $C^{14}(p,n)N^{14}$ Reaction and Energy Levels of N^{15} *

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The threshold energy required to induce the (p,n) reaction in C^{14} has been measured to be $E_t=0.664\pm0.009$ Mev or a reaction energy of -0.620 ± 0.009 Mev. This reaction is the inverse of the $N^{14}(n,p)C^{14}$ process studied by Hughes and Eggler and their observed reaction energy $Q_{n,p}=0.597\pm0.009$ Mev can be compared with the negative of the reaction energy observed here. Six resonances have been observed in the process at 1.14, 1.30, 1.47, 2.05, 2.21, and 2.65 Mev, three of which can be correlated with those previously observed in the $N^{14}(n,p)$ reaction. The cross section at the first resonance at 1.14 Mev has been measured to be approximately 0.7 barn.

INTRODUCTION

SINCE the first observation of (p,n) reactions by Du Bridge, Barnes, and Buck,[1] measurements have been made of various (p,n) thresholds with the Westinghouse Van de Graaff type of generator as a source of high energy protons.[2,3] Resonances have been found in the excitation functions above the threshold, particularly for Li^7 and Be^9, yielding information about the compound nuclei involved.[4,5] We have extended work of this type by measuring the threshold of the (p,n) reaction of the radioactive isotope C^{14} and, by using both thick and thin target techniques, several resonances attributable to the excited nucleus of N^{15} have been found. From these data it is also possible to place limits on the mass of the neutrino from the threshold measurement and to determine some of the energy levels of N^{15} from the resonances. Some estimate of the cross section for the first (p,n) resonance level can be given.

EXPERIMENTAL

The Westinghouse Van de Graaff high voltage generator[6] was used as a source of high energy protons. The voltage scale used in these experiments is based on the $Li^7(p,n)$ threshold at 1.883 ±0.006 Mev of Hanson and Benedict,[7] and the voltage extrapolation was carried out by a compensating generating voltmeter whose linearity was known to be better than 0.1 percent.[2]

The proton ion current was measured by a current integrator modified slightly from that of Watt[8] and the reaction was carried out within a Faraday cage arranged as in Fig. 1.

* Assisted by the Joint Program of the Office of Naval Research and the Atomic Energy Commission.

[1] L. A. Du Bridge, S. W. Barnes, and J. H. Buck, Phys. Rev. **51**, 995 (1937).
[2] R. O. Haxby, W. E. Shoupp, W. E. Stephens, and W. H. Wells, Phys. Rev. **58**, 1035 (1940).
[3] W. E. Shoupp, B. Jennings, and W. Jones, Phys. Rev. **73**, 421 (1948).
[4] J. E. Hill, and W. E. Shoupp, Phys. Rev. **73**, 931 (1948).
[5] W. J. Hushley, Phys. Rev. **67**, 34 (1945).
[6] W. H. Wells, R. O. Haxby, W. E. Stephens, and W. E. Shoupp, Phys. Rev. **58**, 162 (1940).
[7] A. O. Hanson and D. L. Benedict, Phys. Rev. **65**, 33 (1944).
[8] B. E. Watt, Rev. Sci. Inst. **17**, 334 (1946).

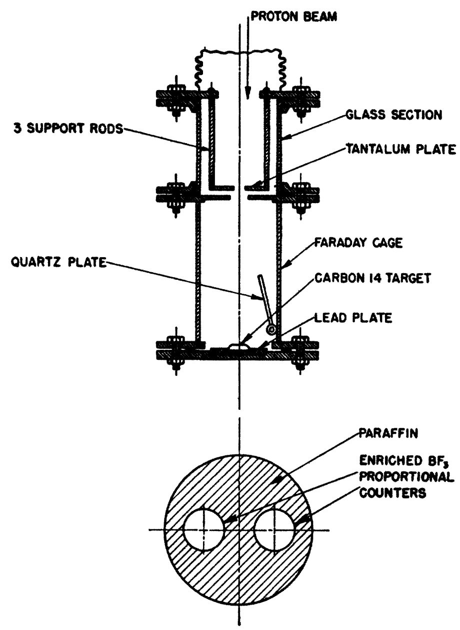

FIG. 1. Arrangement of target, paraffin, and BF_3 proportional counters.

Neutrons produced by this reaction were counted by two large proportional counters filled with boron trifluoride enriched in B^{10} and surrounded by about five centimeters of paraffin. Pulses from the counters were amplified by an Atomic Instrument Company Model 204-A amplifier which operated a pulse discriminator, a scale of 10, and a mechanical recorder.

THICK TARGET RESULTS AND THE THRESHOLD MEASUREMENT

The thick C^{14} target was a one-millimeter layer of $BaCO_3$ powder containing 2.7 percent of the active C^{14}. The thick-target curve (Fig. 2) shows the threshold and resonances up to 3.0 Mev and shows the relative position of threshold and resonance levels. The $C^{14}(p,n)$ reaction energy $Q_{p,n}$ is obtained from the threshold energy E_t since $Q_{p,n}=-(14/15)E_t$. To aid in extrapolating the excitation function to the threshold a method based on a yield equation due to Stephens, Spruch, and Schiff was used.[9] Their work indicates that the neutron yield near the threshold should vary directly with $(E_p-E_t)^{\frac{3}{2}}$, where E_p is the proton energy and E_t the threshold energy.

[9] W. E. Stephens, L. Spruch, and L. I. Schiff, University of Pennsylvania Report, June 1947.

This theoretical relationship involves the assumptions that the capture of a slow neutron by N^{14} (the reverse process) obeys a $1/v$ law and that no resonances exist near the threshold. The latter is justified from the experimental evidence shown in Fig. 3. Plotting the $\frac{2}{3}$ power of the neutron yield against E_p, one obtains a straight line which is extrapolated to the threshold as shown in Fig. 3, apparently justifying the assumptions made. The $C^{14}(p,n)$ threshold obtained in this manner from several thick target runs is 0.664 $\pm$0.009 Mev (see Table I), and the reaction energy $Q_{p,n}$ is -0.620 ± 0.009 Mev.

The energy value for the $C^{14}(p,n)$ reaction $Q_{p,n}$ is equal to the negative of that for the inverse reaction $N^{14}(n,p)$, $Q_{n,p}$. The $Q_{n,p}$ value for this reaction has been measured by a number of investigators with results between 0.55 to 0.71 Mev as summarized by Hornyak and Lauritsen.[10] Recently Huber and Stebler[11] gave a value of 0.63 ± 0.01 Mev from ionization chamber measurements, and Hughes and Eggler[12] have found a value of 0.596 Mev from measuring the length of proton tracks in a cloud chamber. Using the $Q_{p,n}$ value (-0.620 ± 0.009 Mev) obtained in this experiment and taking the value (0.755 $\pm$0.016 Mev) for the neutron-proton mass difference[13] and (14.00751 ± 0.00004 a.m.u.)[14] for the mass of N^{14}, we calculate the mass of C^{14} to be (14.00766 ± 0.00007 a.m.u.). Although this yields practically the same value (14.00767 $\pm$0.00005 a.m.u.)[14] as that derived from the beta-ray energy of C^{14}, it does not involve the assumption of zero neutrino mass.

C^{14} is a neta-emitter and decays according to Eq. (2). Consider then the two reactions,

$$C^{14}+H^1\rightarrow N^{14}+n^1+Q_{p,n}, \quad (1)$$

$$C^{14}\rightarrow N^{14}+Q_{\beta^-}+\nu. \quad (2)$$

Combining these equations we obtain for the neutrino rest mass, ν,

$$\nu=(n^1-H^1)-Q_{\beta^-}+Q_{p,n}. \quad (3)$$

[10] W. F. Hornyak and T. Lauritsen, Rev. Mod. Phys. **20**, 191 (1948).
[11] P. Huber and A. Stebler, Phys. Rev. **73**, 85 (1948).
[12] D. J. Hughes and C. Eggler, Phys. Rev. **73**, 809 (1948).
[13] W. E. Stephens, Rev. Mod. Phys. **19**, 19 (1947).
[14] H. A. Bethe, *Elementary Nuclear Theory* (John Wiley and Sons, Inc., New York, 1947).

Using the value $Q_{\beta^-}=(0.155\pm0.002$ Mev)[15] for the maximum beta-ray energy of C^{14} we obtain from Eq. (3)

$$\nu=(0.755\pm0.016)-(0.155\pm0.002)-(0.620\pm0.009)\text{ Mev},$$

$$\nu=(-0.020\pm0.027)\text{ Mev}$$

or, if one ignores the negative mass deviation, the neutrino mass is about one percent of that of the electron.

THIN TARGET RESULTS

The thin C^{14} target was prepared by allowing CO_2 containing C^{14} (which was produced at *A* in Fig. 4) to react with a very thin layer of $Ba(OH)_2$, *B* which had been sprayed on a

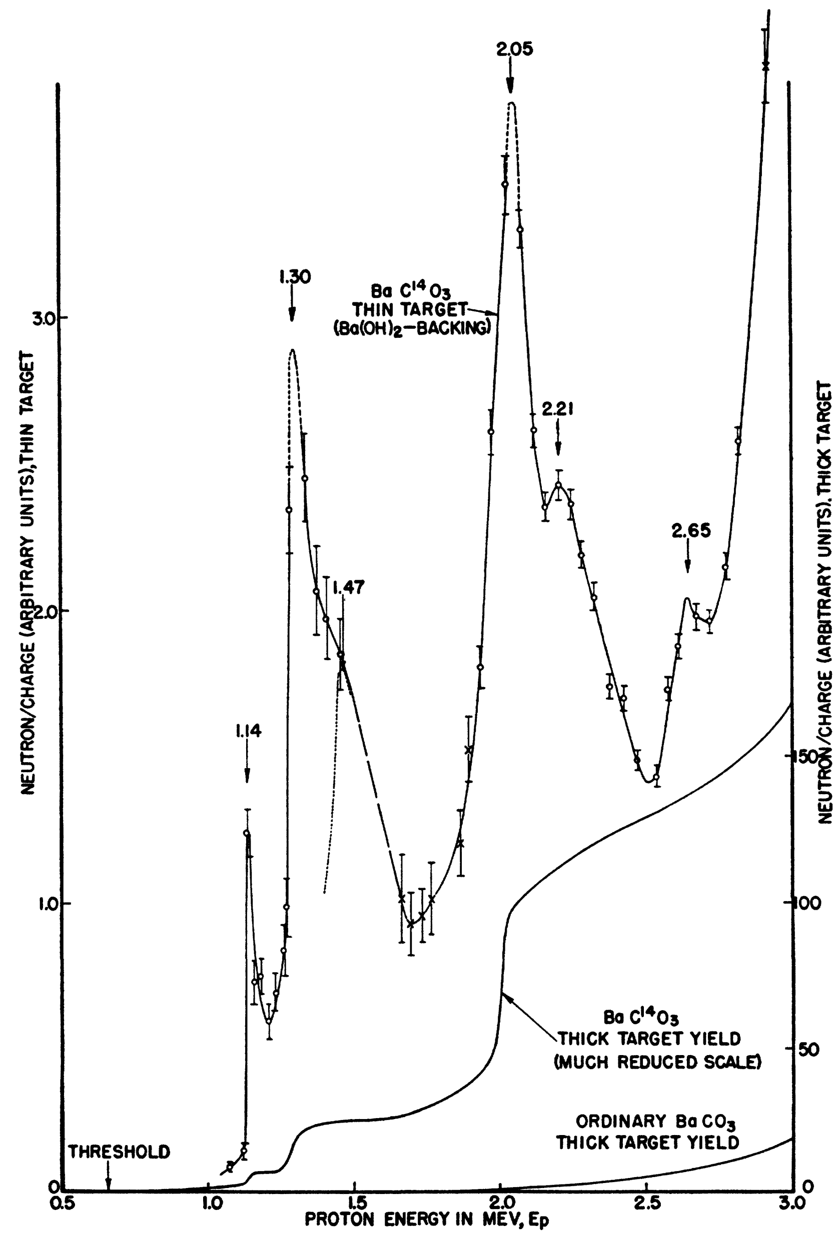

FIG. 2. $C^{14}(p,n)$ resonances.

[15] J. L. Berggren and R. K. Osborn, Bull. Am. Phys. Soc. **23** (2), 46 (1948).

tantalum plate. The reaction at B produces a small amount of $BaCO_3$ containing C^{14}. The amount of C^{14} on the thin target was measured by means of the C^{14} radioactivity with a thin mica window Geiger counter and compared with a $Ra(D+E)$ standard supplied by the National Bureau of Standards. It is found to be 0.26 microcurie per cm^2. This corresponds to about 4.2×10^{-9} mole of C^{14} per cm^2, using 5100 years[16] as its half-life. Since only about 2.7 percent of the carbon atoms in the barium carbonate are C^{14}, the thickness of $BaCO_3$ is about 6×10^{-6} cm. Using data on atomic stopping power and range-energy relationship of proton given by Livingston and Bethe[17] and by interpolating a value of atomic stopping power of barium between silver and gold, we obtain an approximate target thickness of 0.003 Mev for a proton energy of 1.14 Mev.

The $C^{14}(p,n)$ excitation function for the thin

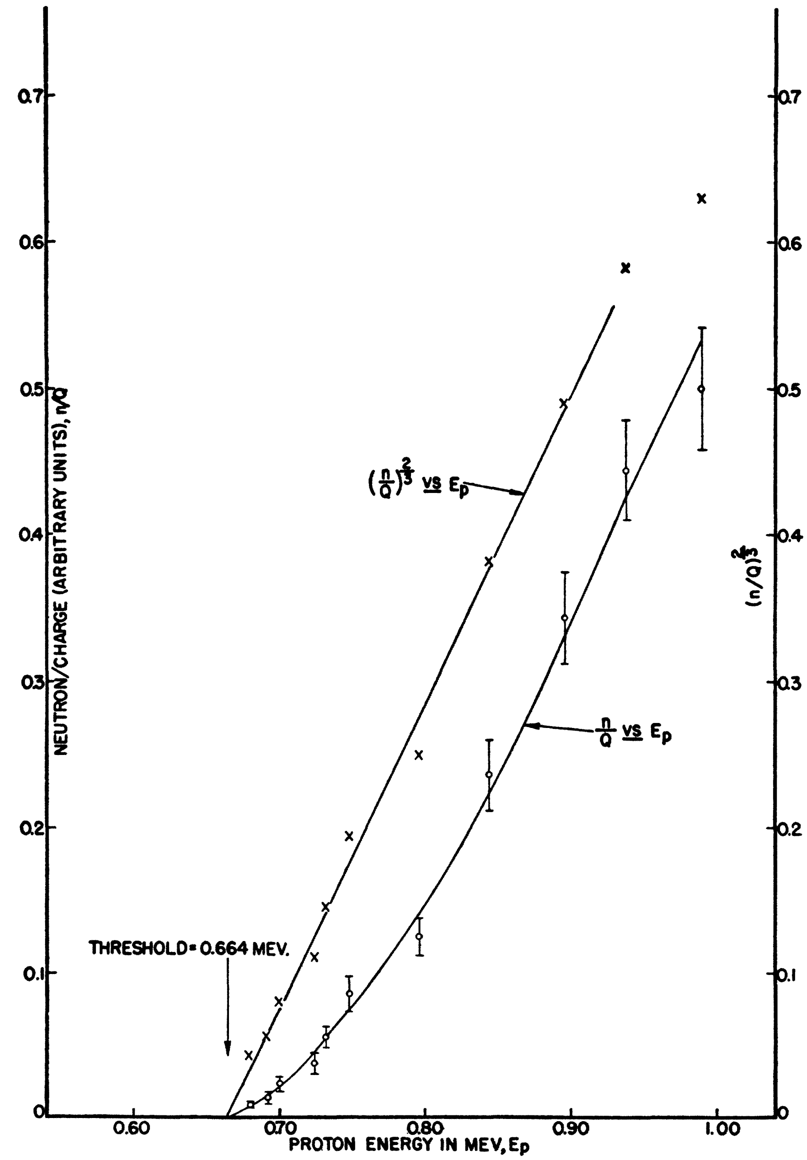

FIG. 3. $C^{14}(p,n)$ threshold ($BaC^{14}O_3$ thick target).

[16] L. D. Norris and M. G. Inghram, Phys. Rev. **73**, 350 (1948).
[17] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 245 (1937).

TABLE I.

	Proton energy Mev	Reaction energy $Q(pn)$ Mev	Energy levels in $H^1+C^{14}\rightarrow N^{15}$ $[10.14+(14/15)E_p]$ Mev	Energy levels in $n^1+N^{14}\rightarrow N^{15}$ $[10.76+(14/15)E_n]$ Mev
C_{14} threshold	0.664 ± 0.009	-0.620 ± 0.009		
Resonance 1	1.14 ± 0.02		11.21 ± 0.29	11.28
Resonance 2	1.30 ± 0.02		11.35 ± 0.29	11.41
Resonance 3	1.47 ± 0.05		11.51 ± 0.32	
Resonance 4	2.05 ± 0.02		12.06 ± 0.29	12.11
Resonance 5	2.21 ± 0.05		12.21 ± 0.32	
Resonance 6	2.65 ± 0.05		12.62 ± 0.32	

target is shown in Fig. 2. Strong resonances are observed at 1.14, 1.30, and 2.05 Mev and doubtful ones at 1.47, 2.21, and 2.65 Mev.

The existence of a resonance of 1.47 Mev is doubtful because the resolution of our experimental method was not high enough to separate it from the nearby resonance at 1.30 Mev. The small peaks at 2.21 and 2.65 Mev were checked by several independent runs across this voltage range. There is no doubt that the general rise in neutron yield above 2 Mev, found in the thin target results, is due to the backing layer of $Ba(OH)_2$. However, the yield at the first resonance is probably due to the C^{14} target alone and therefore can be used to make a cross section estimate. For the same reason, it is possible to estimate the half-widths of only the first resonance, which is about 0.04 ± 0.01 Mev. This corresponds to a life time of 10^{-19} sec. for the compound nucleus at this level. Also shown in Fig. 2 are the thick target yields for $BaC^{14}O_3$ and ordinary $BaCO_3$ in reduced scale.

When a proton enters a C^{14} nucleus, the compound nucleus, N^{15} is formed:

$$C^{14}+H^1\rightarrow N^{15*}+10.14 \text{ Mev.} \qquad (4)$$

An energy of excitation of 10.14 Mev was calculated from the mass data given by Bethe,[14] which are used throughout the paper with the exception that the mass of the neutron and of C^{14} are taken to be 1.00894[13] and 14.00766 a.m.u., respectively. The energy levels of N^{15} corresponding to the resonance energy of the proton E_p in the $C^{14}(p,n)$ reaction may be calculated thus:

$$E_{N^{15}}=10.14+(14/15)E_p \text{ in Mev.} \qquad (5)$$

The N^{15} energy levels so obtained are given in Table I and in Fig. 5. which also shows the levels obtained for the inverse reaction $N^{14}(n,p)$ by Barschall and Battat;[18]

$$E_{N^{15}}=10.76+(14/15)E_n \text{ in Mev.} \qquad (6)$$

Since the voltage calibration used in the two experiments may not be the same the agreement in absolute value may be fortuitous. However, the agreement in level separation is excellent

$C^{14}(p,n)$ CROSS SECTION

To estimate the cross section it is necessary to know the angular distribution $N(\theta)$ of the emitted neutrons in the laboratory system for the reaction $C^{14}(p,n)N^{14}$. This may be calculated from Eq. (7):

$$N(\theta)=N(\varphi)\{2\gamma\cos\theta + [(1+\gamma^2\cos2\theta)/(1-\gamma^2\sin^2\theta)^{\frac{1}{2}}]\}. \qquad (7)^{**}$$

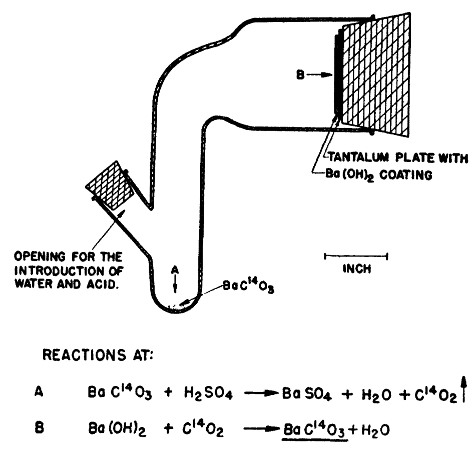

FIG. 4. Simple apparatus for preparing thin $BaC^{14}O_3$ target.

[18] H. H. Barschall and M. E. Battat, Phys. Rev. **70**, 245 (1946).

** A slightly different form of Eq. (7) is given by C. E. Mandeville [J. Franklin Inst. **244**, 385 (1947)] who, however, does not give Eq. (8). The latter was derived following a similar treatment for recoil nucleus after Livingston and Bethe (reference 17).

Here $N(\varphi)$ is the angular distribution in the center of gravity system and may be assumed for the (p,n) type of reaction to be spherically symmetrical. θ is the angle between the incident and ejected particles in the laboratory system, and γ is given by

$$\gamma=\{M_pM_eE_p/M_rM_c[Q+(M_t/M_c)E_p]\}^{\frac{1}{2}}, \quad (8)^{**}$$

where M_p, M_t, M_e, M_r, and M_c are the masses of projectile, target, ejected particle, recoil nucleus, and compound nucleus, respectively, and Q is the reaction energy. We have also $M_c=M_p+M_t=M_e+M_r$. For the $C^{14}(p,n)N^{14}$ reaction

$$\gamma=[E_p/(196E_p-129)]^{\frac{1}{2}}, \quad (9)$$

where E_p is the proton energy in Mev. At $E_p=1.14$ (the first resonance level in Fig. 2 where the background is negligible), the over-all estimated average number of neutrons per unit solid angle in all directions is about 80 percent of that in the forward direction. The average number of neutrons intercepted by the counters (extending over an angle of about 30 degrees from the proton beam) is estimated to be about 99 percent of that in the forward direction. In

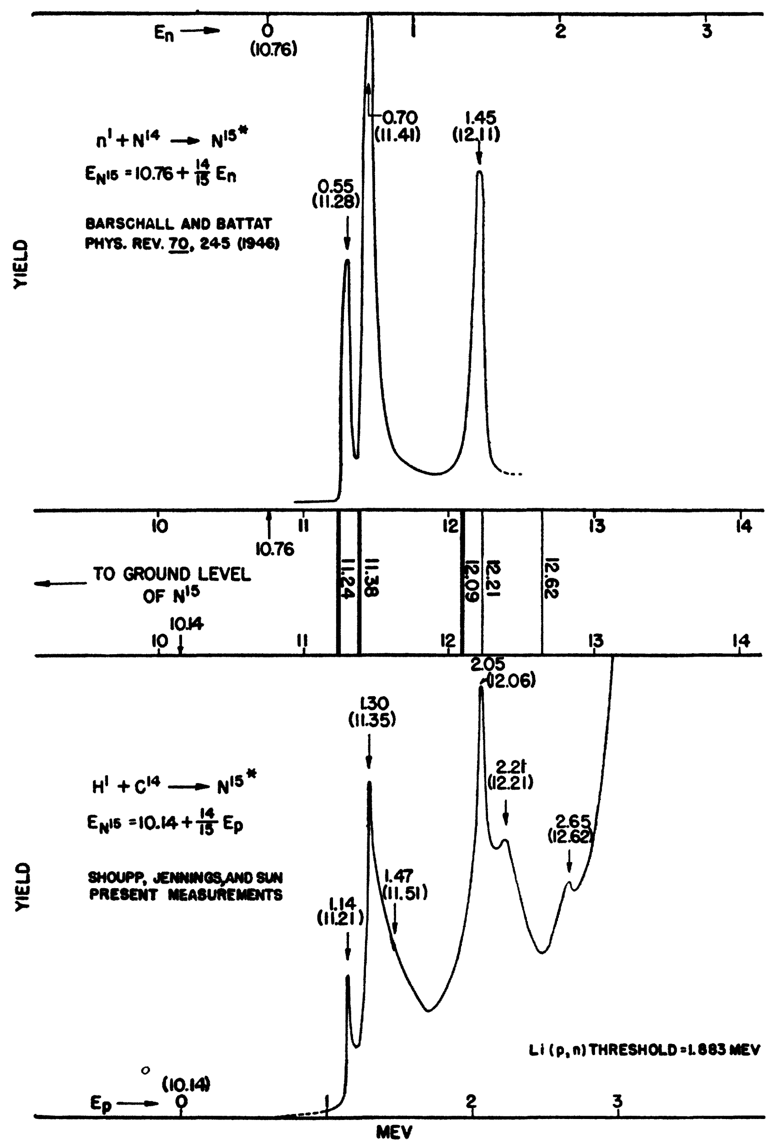

FIG. 5. Energy levels of N^{15}.

order to determine the absolute number of neutrons passing through the proportional counters from the number of recorded counts, spherical neutron sources of known intensity and various energies between 0.03 and 4.25 Mev were placed at the same distance from the counters as was the C^{14} target.[19] In this manner a conversion factor of 0.0028 was estimated and found to be nearly energy independent. The total number of neutrons emitted from the C^{14} target at a given proton voltage and ion current can be determined from the recorded number of neutron counts, the conversion factor, and the angular distribution relationship stated. Knowing the number of C^{14} nuclei in the target area where the beam hits, one calculates the cross section of the process to be about 0.7 barn for the top of the first resonance.

The cross section, $\sigma_{p,n}$, is related to that of the inverse $N^{14}(n,p)C^{14}$ process, $\sigma_{n,p}$, by the principle of detailed balance:[14]

$$\sigma_{p,n}/\sigma_{n,p}=[(2s_n+1)(2s_N+1)/(2s_p+1)(2s_C+1)]\cdot[P_n^2/P_p^2], \quad (10)$$

where s and P denote spin and momentum in the center of gravity system and subscripts denote the individual nuclear particles involved. The spins of n, $p(H^1)$, N^{14}, and C^{14} are known to be $\frac{1}{2}$, $\frac{1}{2}$, 1 and 0,[20] respectively. Since the masses of n and p and of N^{14} and C^{14} are about the same, Eq. (10) becomes

$$\sigma_{p,n}=3[(E_p-E_t)/E_p]\sigma_{n,p}, \quad (11)$$

an equation which involves only quantities measurable in the laboratory system, where E_p and E_t are the proton energy and the threshold energy of the $C^{14}(p,n)N^{14}$ reaction. For E_p at 1.14 Mev and using a vlaue of 0.085 barn for $\sigma_{n,p}$ from Barschall and Battat,[18] $\sigma_{p,n}$ was calculated to be 0.11 barn which is about $\frac{1}{6}$ of that estimated from our experiments.

[19] Boron trifluoride proportional counter calibrated at Argonne National Laboratory by Dr. D. J. Hughes and associates.

[20] F. A. Jenkins, Phys. Rev. 73, 639 (1948).

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Total Cross Sections of Nuclei for 90-Mev Neutrons*

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Total cross sections of H, D, Li, Be, C, N, O, Mg, Al, Cl, Cu, Zn, Sn, Pb, and U for 90-Mev neutrons have been measured, using the 184-inch cyclotron as a source and carbon disks as detectors. Experimental details are described, and a brief discussion of some of the theoretical implications of the results is given.

I. INTRODUCTION

DATA on the total cross sections of nuclei for neutrons are of considerable importance, since they furnish the most direct evidence from which the sizes of nuclei can be computed. If a nucleus is thought of as simply an opaque sphere of collision radius R (which includes an "effective radius" of the incident neutron), then the total cross section σ_t is given by:

$$\sigma_t=2\pi R^2, \quad (1)$$

so long as the de Broglie wave-length of the neutron is not too large compared to the nuclear diameter.** Deviations from this simple law can result from several causes. When the neutron energy is only a few Mev, resonance levels in the compound nucleus produce irregular variations in σ_t. At energies of 25 Mev[1] and 14 Mev,[2] the resonances are not very important, as would be expected from the fact that the excitation ener-

* The results of this work were published in a Letter to the Editor, Phys. Rev. 72, 1264 (1947).

** See the Appendix for fuller discussion.

[1] R. Sherr, Phys. Rev. 68, 240 (1945).

[2] Amaldi, Bocciarelli, Cacciapuoti, and Trabacchi, Nuovo Cimento 3, 203 (1946).