vacuum; then heat the remaining metal so that electrons can flow across the vacuum.

These electrons in the vacuum must be slow. If they were moving fast enough for the Lorentz factor in their mass to be significant, the additional mass thus carried in the vacuum would accumulate, where they strike the metal, as relativistic mass of heat. The basic assumption does not, therefore, classify metals with electrons in vacuum unless the latter are slow.

Even if they are very slow, there is a little accumulation of heat where they strike the metal. The ratio of its mass to that of the electrons, however, is only the ratio of the work function of the metal to the half-million-volt energy equivalent of the electronic rest mass. So the basic assumption, though not strictly exact, is a very good approximation; and the effective m/e for the metal seems practically sure to equal the m/e for slow electrons in vacuum to within a few parts in 10^5.

Paradoxically, this accumulation of heat indicates that the little difference in these m/e values is as if the carriers in the metal were slightly lighter than slow electrons in vacuum, whereas we should expect them to be slightly heavier because of their kinetic energy. Therefore, it should be noted here that both this kinetic energy and the heat come from potential energy released where the electrons enter the metal. If this release is by a fall through an electrostatic potential barrier, and if this barrier exists all over the surface of the incomplete ring of metal, then in considering such small masses as these differences from the vacuum rest mass we must not neglect the mass transported in this surface barrier by the Poynting vector made up out of its electric field and the magnetic field of the current in the ring. The direction of this Poynting vector is opposite to that of the flow of electrons. In short, its relation to the main mass current is that of a back-water. It is very weak; but if the pd in the barrier is uniform over the whole surface, it is just strong enough to resolve the paradox.

This view of it, however, may be far too simple, especially if the metal is not all at the same temperature. The discrepancy is so small that no detailed analysis of it will be attempted here, but we should note that it is likely to have different values for different metals.

In short, the main conclusion here is that, while the effective values of m/e for carriers in metals are probably not perfectly equal, they must all equal the m/e of slow electrons in vacuum to within a few parts in a hundred thousand.

PHYSICAL REVIEW VOLUME 82, NUMBER 6 JUNE 15, 1951

The Transmutation of N^{14} by Protons*

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(Received March 9, 1951)

The reaction $N^{14}(p,\gamma)O^{15}$ has been studied experimentally in the energy range 0.25 to 2.6 Mev, using protons accelerated by an electrostatic generator and observing the induced O^{15} positron activity. Excitation curves have been obtained from Be_3N_2 targets, nitrogen gas targets, and a thin target formed by proton bombardment of a copper foil in a nitrogen atmosphere. The experimental cross section can be described by nine resonances, whose parameters are given. The bearing of these results on the yield of this reaction at stellar temperatures is discussed.

I. INTRODUCTION

By observing the cross section for the $N^{14}(p,\gamma)O^{15}$ reaction, the only transmutation energetically possible when protons of energy less than 3.2 Mev are incident on N^{14}, it is possible to study the properties of certain of the excited states of O^{15}. This particular reaction is also of interest as the slowest of the reactions occurring in the production of stellar energy through the carbon-nitrogen cycle. Previous studies[1–4] had been either of a qualitative nature or confined to proton energies of less than 1 Mev. The completion of an electrostatic generator capable of attaining voltages somewhat above 2.5 Mev permitted the investigation of a large, unexplored energy range.

II. EXPERIMENTAL TECHNIQUE

The protons were accelerated by the $8' \times 22'$ electrostatic generator of this laboratory and were analyzed by a 90° double focusing magnetic analyzer.[5] The

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[1] DuBridge, Barnes, Buck, and Strain, Phys. Rev. **53**, 447 (1938).
[2] Curran and Strothers, Nature **145**, 224 (1940).
[3] R. Tangen, Kgl. Norske Videnskab. Selskabs. Skrafter No. 1 (1946).
[4] Woodbury, Hall, and Fowler, Phys. Rev. **75**, 1462A (1949).
[5] D. B. Duncan, Phys. Rev. **76**, 587A (1949).

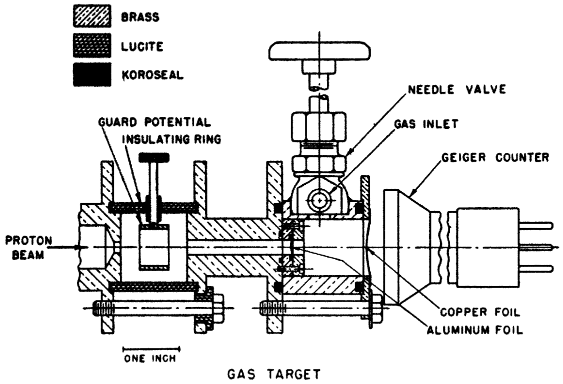

FIG. 1. Nitrogen gas target assembly.

strength of the field in the analyzer was determined by means of a null-reading fluxmeter.[6]

No attempt was made to determine absolute energy, the Al(p,γ) and F($p,\alpha\gamma$) resonances at 0.9933 and 0.8735 Mev being used as calibration standards.[7] Thick target aluminum excitation curves were obtained immediately before and after any nitrogen bombardments, where accurate energy values were needed. A procedure of checking the zero of the fluxmeter at short time intervals was adopted, limiting drifts in energy measurements to less than 0.1 percent. The linearity of the fluxmeter was checked by studying the excitation curves for F($p,\alpha\gamma$) in some detail and by determining the resonance energy in Al(p,γ), using protons and singly charged hydrogen molecules. No detectable dependence of the fluxmeter constant on energy was observed.

The reaction was detected by observing, with a Geiger-Müller counter, the positrons emitted when O^{15} decays to N^{15}, a technique having numerous advantages over that of observing the immediate γ-radiation. It was realized that the choice of target material would be particularly critical. To eliminate errors caused by possible escape of O^{15} from the target before decay and by chemical decomposition of the target, a gas target was used. The gas chamber was separated from the evacuated accelerating system by a thin foil. Absolute yield determinations were based on results obtained with these gas targets. However, because of the straggling in proton energy produced by passage through the entrance foil, solid targets were necessary to investigate the details of sharp resonance structure. Beryllium nitride and a thin nitrogen layer absorbed on a copper foil were used. It is to be noted that no loss of activity through escape of the O^{15} was detected in extensive use of these targets. Many other compounds of nitrogen are definitely not satisfactory in this regard nor in their ability to withstand decomposition under bombardment.

The procedure followed was to bombard the target for a time t_1 (usually 2 minutes), to count the activity for a time t_2 (usually 3 minutes) with high voltage off to reduce background, and to begin bombardment again after a definite time. Under these conditions, the yield in transmutations per proton is a function of the number of counts observed corrected for previous activity and background, the integrated proton current, the half-life of O^{15}, the times t_1 and t_2, and the counting efficiency.[8]

The proton current was measured by charging the condenser in an integrator of standard design. The time was controlled automatically from a synchronous motor. The half-life of O^{15} has been measured previously by many observers. A determination was also made in the course of this work giving a value of 127 ± 2 sec. A value of 126 sec was used in calculations.[9]

The counting efficiency is the most difficult quantity to measure, and a determination was made only for the gas target. The target chamber is pictured in Fig. 1. The proton beam was defined by the aperture stop $\frac{3}{16}''$ in diameter; the aluminum foil at the entrance was placed over a hole $\frac{1}{4}''$ in diameter. With foils 0.00015″ thick, seals which would stand a pressure differential of half an atmosphere were made. The foil was "sandwiched" between two brass disks, as indicated on the drawing, the seals being made with O-rings.

Copper foil 0.001″ thick was used between the counter and the target. Standard needle valves were modified and used as the chamber valves, the valve seat being made flush with the inside bore. The counter was mounted on a lead block and held a fixed distance from the target. The entire assembly was surrounded by lead.

Neglecting absorption of the positrons in the copper foil, the counting efficiency can be expressed as an integral over the volume of the target chamber and the surface of the counter, involving the dimensions of the apparatus and the variation of counter efficiency over

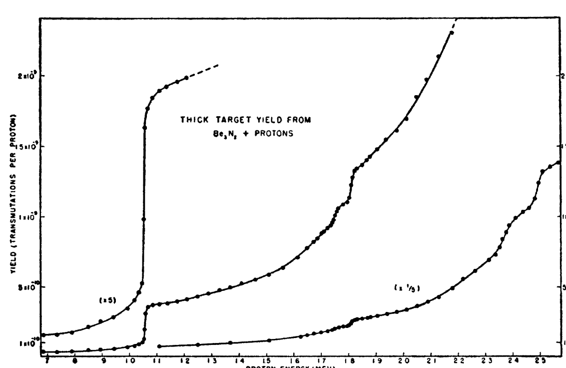

FIG. 2. Thick target yield of positrons from $N^{14}(p,\gamma)O^{15}$. The target material was Be_3N_2. However, the yield calibration shown is that of a pure nitrogen target.

[6] C. C. Lauritsen and T. Lauritsen, Rev. Sci. Instr. **19**, 916 (1948).
[7] Herb, Snowdon, and Sala, Phys. Rev. **75**, 346 (1949).
[8] R. N. Hall and W. A. Fowler, Phys. Rev. **77**, 197 (1950).
[9] G. T. Seaborg and I. Perlman, Revs. Modern Phys. **20**, 585 (1948).

the surface of the counter. The latter was determined empirically using collimated natural beta-particles. The integration was then carried out numerically. The correction for positron absorption was studied experimentally by determining the yield as a function of absorber thickness for otherwise identical conditions of bombardment. The linear relationship obtained was extrapolated to zero-absorber thickness. The over-all determination of counting efficiency made in this way is believed to be accurate to 10 percent.

If the variation in the cross section for a nuclear reaction is small over the energy range corresponding to target thickness and dispersion in proton energy, a condition often satisfied in this experiment, the yield is given by $y=\sigma n t$.[10] Thus with a gas target, where it is possible to measure the thickness (t) and the density (n) by measuring pressure and temperature, the cross section can be directly determined.

After bombarding for several days, two-minute activity was observed to come from the spot on the copper foil which had been hit by the proton beam in a nitrogen atmosphere. Hence to obtain cross-section values it was necessary to obtain plots of yield against target pressure. Linear relationships were obtained at several energies and the correction for the foil activity determined. This thin layer of nitrogen necessitated a correction to the gas target data, but it furnished a remarkably stable thin target for investigation the details of resonant structure.[10a] The method of obtaining it would seem to form a useful technique for making thin targets whenever the target element is a gas. For thick target data, pressed Be_3N_2 was used. This compound was chosen because of its chemical stability, because beryllium does not give a radioactive product upon proton bombardment, and because a large proportion of the total stopping power is attributable to the nitrogen.

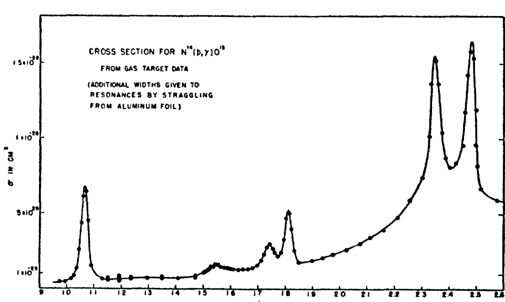

FIG. 3. Thin gas target yield of positrons from $N^{14}(p,\gamma)O^{15}$. The target length along the beam was approximately 1¼″, pressure approximately 1.6 cm Hg, thickness 16 kev at 1 Mev. The energy scale has been corrected to the mean energy of the protons after penetrating the target entrance foil.

[10] Fowler, Lauritsen, and Lauritsen, Revs. Modern Phys. **20**, 236 (1948).

[10a] This absorbed target was formed by bombarding the copper foil with 1.5×10^{4}-Mev coulomb of protons in the energy range 0.7 Mev to 2.6 Mev through a nitrogen atmosphere whose pressure was 1.6 cm of Hg. No deterioration of the target was observed during its subsequent use.

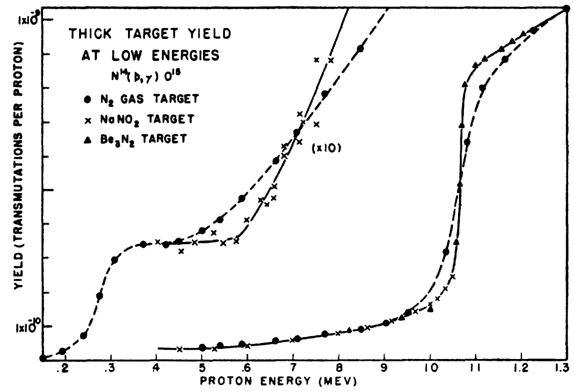

FIG. 4. Thick target yield at low energy.

III. EXPERIMENTAL RESULTS

The thick target curve from bombarding Be_3N_2 is given in Fig. 2. The ordinate has been normalized to give yield in transmutations per proton from gas target data as described below. The data from thin gas targets is given in Fig. 3. The yield has been plotted against mean proton energy after passing through the foil. This was determined by plotting the measured energy at the resonances against resonance energy as determined from the Be_3N_2 curve and extrapolating between these points using the known energy dependence of proton range in aluminum.[11]

As indicated above, the ordinate can be normalized to give the cross section directly. This will not be valid near the resonances where the simple form $y=\sigma n t$ does not hold. The half-life of the activity at each of the resonances was checked to have the correct value. Particular care was used near the peak at 1.55 Mev to show that it was not due to carbon on the front of the entrance foil.

A thick target excitation curve obtained at low energies, using a one-atmosphere nitrogen gas target, is given in Fig. 4. The yield, calibrated by comparison with the Be_3N_2 target, is plotted against mean proton energy. Professor W. A. Fowler also kindly made available data obtained from a thick $NaNO_2$ target bombarded at energies between 300 and 1300 kev by the 8′×13′ electrostatic generator of this laboratory. These data are included in Fig. 4. The thin layer of nitrogen absorbed on the copper foil was also used as a target. Excitation curves for various resonances were obtained. The two highest energy resonances are given in Fig. 5.

DISCUSSION AND CONCLUSION

The experimental data indicate five resonances whose energy can be determined from the midpoints of the steps in the thick target Be_3N_2 curve. Such a determination can be made quite accurately, to within 0.1 percent to 0.4 percent, depending on the width and on the ratio of resonant to nonresonant yield. Data

[11] H. A. Bethe, Brookhaven Publication BNL T-7 (1950) (unpublished).

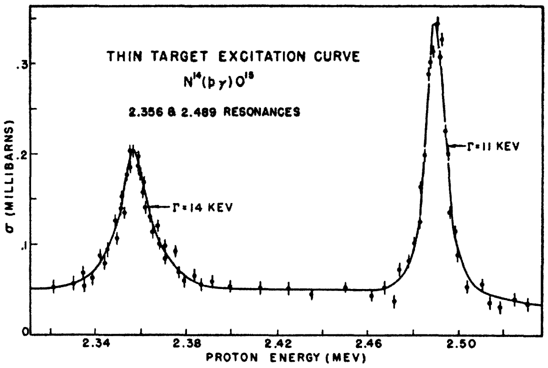

FIG. 5. Thin target curve of the two highest resonances found. The target consisted of nitrogen driven into the copper window of the gas target during the period when the data of Fig. 3 were taken. For the above curves, the entrance foil of the gas chamber was removed and the chamber evacuated.

from the solid thin target curve was used to give the most accurate values of the widths of the resonances. The uncertainties arise primarily from statistical deviations of the data.

Relative values of the thick target step in yield $Y_{\max}(\infty)$ were obtained from the Be_3N_2 target curve. An absolute value for the 1-Mev resonance can be accurately obtained from the thin gas target, using the relationship $\xi Y_{\max}(\infty)=A(\xi)$, where ξ is the target thickness and $A(\xi)$ is the area under the yield curve.[10] The value of $Y_{\max}(\infty)$ obtained in this way serves to normalize the ordinates of thick target curves.

Two additional resonances are immediately indicated which cannot be handled this way. The 277-kev resonance of Fig. 4 could not be studied with solid targets because the generator would not operate successfully at this energy. The yield was measured, but values of resonance energy and width were not obtained. The resonance at 1.5 Mev on Fig. 3 was too broad and weak to be observed with other targets. It was necessary to estimate the parameters from this curve alone with a corresponding decrease in accuracy.

Finally, it is possible to subtract out the yield of these resonances in both thick and thin target curves to look for an adequate description of the remaining

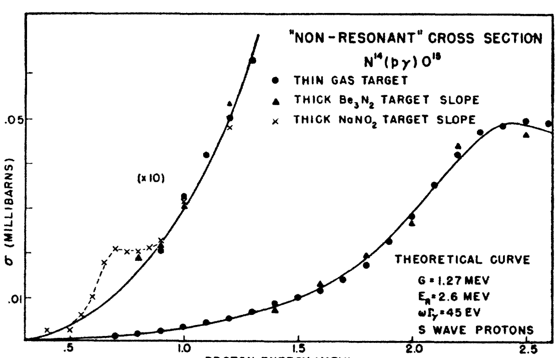

FIG. 6. Thin target curve with sharp resonances omitted.

yield. The experimental values for this cross section are given in Fig. 6. The gas target data represents merely a replotting of previous data with the points near resonances omitted. The points from the thick targets are obtained from the relationship[10] $\sigma=\epsilon(dY/dE)$. Such an evaluation is less accurate than direct measurement. At higher energies, the points are given merely to indicate the degree of consistency between the thick and thin targets. However, the values at low energies could only be obtained in this way.

An attempt was made to fit these data to a resonance of the form[10]

$$\sigma=\pi\lambdabar^2\frac{\Gamma_p\Gamma_\gamma}{(E-E_R)^2+\frac{1}{4}(\Gamma_p+\Gamma_\gamma)^2},$$

where $\Gamma_p=E^{\frac{1}{2}}P(E)G$. The function $E^{\frac{1}{2}}P$ has been tabulated by Christy and Latter.[12] For *s*-wave protons, it was possible to construct a curve which quite adequately described the data. For other than *s*-wave protons, even an approximate fit was found to be impossible. The continuous background can thus be explained in terms of a very broad *s*-wave excited resonance.

A second feature of the cross section as presented in Fig. 6 is the anomaly at 700 kev. This can most reasonably be explained by assuming a small resonance in this region. The energy and width of this resonance were estimated from the dashed curve of Fig. 6.

A complete description of the experimental cross section from 0.25 to 2.6 Mev is given by tabulating values of E_R, Γ, and $Y_{\max}(\infty)$ for the nine resonances that were found. These values and the cross section at resonance, as determined from the relationship[10] $\sigma_R=2\epsilon Y_{\max}(\infty)/(\pi\Gamma)$, are tabulated in Table I.

Various other quantities which are of interest can now be calculated. The quantity $\omega\gamma$ defined[10] as $\omega\Gamma_\gamma\Gamma_p(\Gamma_\gamma+\Gamma_p)^{-1}$, which is approximately equal to $\omega\Gamma_\gamma$, can be calculated for each of the resonances. The width for proton emission at 1 Mev without barrier G, can be calculated.[12] The value obtained will depend on the angular momentum of the protons, which is not known in general. It is necessary, therefore, to give values corresponding to *s*, *p*, and *d*-waves.

In this way, values are obtained for each of the quantities entering the dispersion formula. It is of considerable interest to know the value of the cross section at very low energies, since this reaction forms a part of the carbon-nitrogen cycle. For this reason extrapolated values at 128 kev and 28 kev, for each of the resonances, were calculated. The value at 128 kev is given because the yield has been measured independently at this energy;[4] the value at 28 kev because this is the approximate energy of interest in stellar calculations. In each case, the resonance has been assumed to be caused by *s*-wave protons which give the largest extrapolated

[12] R. F. Christy and R. Latter, Revs. Modern Phys. **20**, 185 (1948).

TABLE I. Resonance characteristics for $N^{14}(p,\gamma)O^{15}$.

E_R (Mev)	Γ (kev)	$Y_{max}(\infty)$ (β^+/proton)	σ_R (millibarns)
0.277[a]	<2[a]	$0.35\pm0.03\times10^{-10}$	>0.15
0.70 ±0.03	100 ±30	0.2 ±0.07	0.001
1.064±0.002	4.8±1	5.5 ±0.1	0.37
1.55 ±0.02	50 ±20	1.2 ±0.2	0.006
1.748±0.005	11 ±3	1.5 ±0.3	0.03
1.815±0.004	7 ±1.5	3.7 ±0.3	0.11
2.356±0.008	14 ±4	15 ±2	0.21
2.489±0.007	11 ±3	21 ±1	0.35
2.60 ±0.05	1270 ±50	300 ±50	0.05

[a] See reference 3.

TABLE II. Computed resonance characteristics and extrapolated low energy cross sections for $N^{14}(p,\gamma)O^{15}$.

E_R (Mev)	$\omega\Gamma_\gamma$ (ev)	$G(s)$ (kev)	$G(p)$ (kev)	$G(d)$ (kev)	σ (128 kev) (10^{-11} barn)	σ (28 kev) (10^{-21} barn)
0.277	0.02	<3000	<20,000	<70,000	<2.5	<1.5
0.70	0.02	1700	8000	15,000	1.1	1.5
1.064	0.63	24	80	960	0.02	0.03
1.55	0.16	110	250	2000	0.01	0.02
1.748	0.21	20	44	280	0.0015	0.003
1.815	0.52	12	27	170	0.002	0.004
2.356	2.4	17	28	140	0.007	0.015
2.489	3.3	12	20	85	0.007	0.015
2.60	46	1250	——	——	8.7	15.0

yield values. The resonances that make appreciable contributions do seem to be *s*-wave. A tabulation of these values is given in Table II.

The arithmetic sum of the contributions of the cross sections at 128 kev is 1.24×10^{-10} barn. The value computed from the thick target yield measured at this energy is 7×10^{-10} barn.[4] The discrepancy in these values can be explained in terms of constructive interference effects between the contributions of the numerous resonances, by the existence of additional low energy resonances, or in part at least by experimental errors. The best extrapolation to stellar energies is made, using the experimental data at 128 kev and assuming no low lying resonances, and gives $\sigma=0.025E^{-1}\exp(-6.95E^{-\frac{1}{2}})$ barns for the proton energy in Mev. At 28 kev this yields σ (28 kev)$=0.9\times10^{-18}$ barn. It must be emphasized that this extrapolation will be meaningless if low energy resonances actually exist. These can be investigated at the present time only by the study of the excited states of O^{15} occurring in other reactions, such as $N^{14}(dn')O^{15*}$. Studies of this nature are underway in this laboratory at the present time.

The widths for γ-ray emission for each of the levels having been measured, the associated oscillator strengths could be calculated if the γ-ray energy were known. A determination of these energies was not attempted. The problems which present experimental difficulties are the low yield of the reaction studied, the high yield of the $N^{15}(p,\gamma)$ reaction even from a non-enriched target, and the high yield from aluminum and beryllium reactions from any of the solid targets found satisfactory. Values have been calculated assuming the transitions are to the ground state. Even if this is correct, the usefulness in determining the multipole order of γ-rays present is quite limited. About all that can be said is that the strong, broad resonance at 2.6 Mev appears to be electric dipole although magnetic dipole cannot be excluded. The other transitions seem to be quite weak for electric dipole.

The values of G permit some few conclusions concerning the angular momentum of the protons. The 2.6-Mev resonance is definitely *s*-wave, the 0.277- and 0.700-Mev resonances are probably *s*-wave, and the others give unusually small values if they are ascribed to *s*-wave.

The yield data presented here are sufficient to describe the observed cross section in the energy range 270 kev to 2.6 Mev and to determine certain of the properties of the excited levels of O^{15}. It does not seem to be possible to obtain a complete description of these levels, including their angular momentum and parity, from these yield measurements alone.

The authors wish to thank the staff of the Kellogg Radiation Laboratory and in particular Professor C. C. Lauritsen, Professor W. A. Fowler, and Professor R. F. Christy for their guidance during the progress of this research.