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Photo-Production of N^{17}

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The delayed neutron activity associated with N^{17} has been produced by the x-ray irradiation of oxygen, the reaction being identified as $O^{18}(\gamma,p)N^{17}$. The threshold for this transmutation has been observed as 16.35±0.2 Mev, and the integrated cross section calculated to be 0.15±0.1 Mev-barn. The N^{17} produced was identified by measuring the neutron activity half-life as 4.15±0.1 sec.

I. INTRODUCTION

THE first light element delayed neutron activity was observed following the bombardment of fluorine with high energy deuterons.[1] The neutron activity was found to result from the beta-decay[2] of N^{17} with a half-life[1] of 4.14±0.04 sec and a beta-ray maximum energy[3] of 3.7±0.2 Mev. This leads to an excited state of O^{17} about 5 Mev above the ground state. This broad excited state of O^{17} breaks up into O^{16} and a neutron of approximately 0.9 Mev energy.[3,4] Many spallation reactions have been observed[5] to produce N^{17}, and it has been produced by[6] $C^{14}(\alpha,p)N^{17}$ and[7] $O^{17}(n,p)N^{17}$. Another possible reaction leading to N^{17} is $O^{18}(\gamma,p)N^{17}$. Despite the natural low abundance of O^{18}, the unique neutron activity makes it possible to detect this (γ,p) reaction with betatron x-rays. This paper reports measurements of the yield curve of this reaction determined by flow methods. Preliminary results were reported earlier.[8]

II. EXPERIMENT

In the initial experiments a 250-cc beaker of ordinary water was placed one foot from the target of a 25-Mev betatron. An enriched[9] BF_3 proportional counter, six inches behind the water, was used to detect the neutrons slowed down by the water plus several inches of paraffin. The water was irradiated at the rate of 15 roentgen units per second with the bremsstrahlung x-rays from the betatron run at 25 Mev for 15 sec. When the betatron was turned off, the counter was turned on and the neutron counts recorded by photographing the scalar with a movie camera. The initial neutron activity of about 30 counts/sec decayed with a half-life of approximately 4 sec. Water enriched in[9] O^{18} showed an increased delayed neutron activity consistent with its enrichment. These tests indicated that the transmutation involved is $O^{18}(\gamma,p)N^{17}$. It was checked that no appreciable amount of this activity was induced by the background neutrons through $O^{17}(n,p)N^{17}$ by activation in and out of the x-ray beam. No activity above background was observed when the water was out of the beam, although the number of neutrons should be about the same. By varying the betatron energy, the yield was observed to appear at about 18 Mev and keep rising up to 25 Mev.

In order to increase the sensitivity of detection, a flow method of irradiation was set up. Water was flowed through a Lucite container of approximately conical shape placed in the x-ray beam about 16 cm from the betatron target. The irradiated water was carried through a $\frac{1}{4}$-in. tube, about 864 cm long, to the neutron detector outside the betatron room. By varying the water pressure from 3 to 30 lb/in.^{2}, the flow rate could be varied from 0.35 to 1.5 liters/min, which corresponded to flow times of from 25 to 6 sec. The flow rate was measured by a flow meter and kept constant by a water pressure reducing valve. The flow tube was coupled to an equally long copper tube coiled around an enriched BF_3 proportional counter[9] immersed in water. This region was enclosed in cadmium and shielded by additional water. This detector had an efficiency of approximately 0.02 for radium-beryllium neutrons. This arrangement was considerably more sensitive than the initial setup, and counts could be continued for times long compared to the half-life under constant conditions of flow and irradiation. The yield curve measured under these conditions is shown in Fig. 1. In this curve the abscissa gives the maximum betatron energy, which was changed by varying the betatron magnet current when expanding at the peak of the magnetic field. The ordinate gives the observed neutron counts for 10 ionization chamber monitor integrator counts. The integrator was calibrated against a Victoreen r-meter, and it was found that 10 counts were equivalent to 140 r-units at three feet. The flow rate was kept at 1.44 liters/min, and several runs were made.

In order to investigate the threshold more carefully, extended observations (up to half an hour) were made in the threshold region, using a "variable" expander on the betatron so that the maximum energy of the x-rays

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* This research was supported by the joint program of the ONR and AEC.

[1] Knable, Lawrence, Leith, Mayer, and Thornton, Phys. Rev. 74, 1217 (1948).

[2] L. W. Alvarez, Phys. Rev. 74, 1217 (1948).

[3] L. W. Alvarez, Phys. Rev. 75, 1127 (1949).

[4] E. Hayward, Phys. Rev. 75, 917 (1949).

[5] W. W. Chupp and E. M. McMillan, Phys. Rev. 74, 1217 (1948).

[6] Sun, Jennings, Shoupp, and Allen, Phys. Rev. 75, 1302 (1949).

[7] Charpie, Sun, Jennings, and Nechaj, Phys. Rev. 76, 1255 (1949).

[8] Sher, Halpern, and Stephens, Phys. Rev. 79, 241 (1950).

[9] Allocated by the Isotopes Division of the AEC.

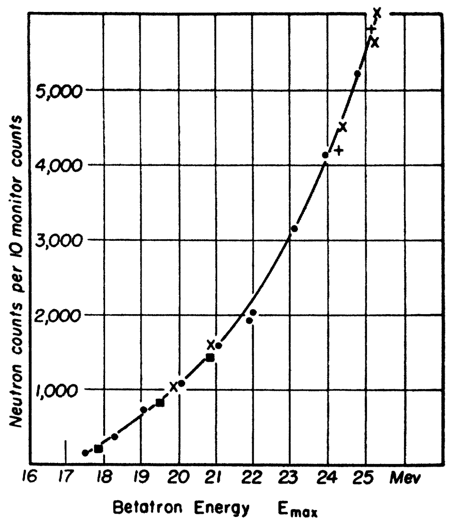

FIG. 1. Neutron counts as a function of betatron energy.

could be changed in small steps and held more constant during a run. A typical curve is shown in Fig. 2. In this curve is shown the delayed neutron activity associated with the production of N^{17} by $O^{18}(\gamma,p)N^{17}$ and, also, the O^{15} positron activity produced by $O^{16}(\gamma,n)O^{15}$. This O^{15} activity was observed in the same run with the N^{17} counts by inserting a thin-wall Geiger counter in the water outlet pipe. The O^{15} activity took longer to build up to equilibrium, since its half-life is 2 min, but the equilibrium activity was quite strong.

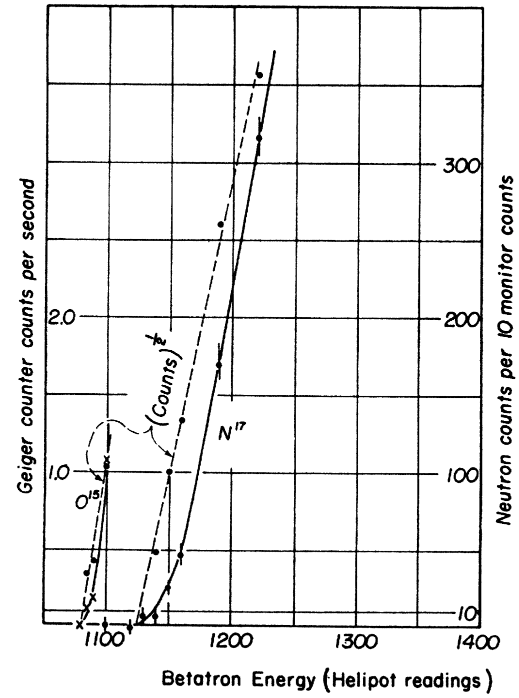

FIG. 2. Neutron counts on right, and O^{15} activity on left as a function of the betatron energy.

The variable expander was calibrated against the assumed known values of the photo-neutron thresholds of deuterium (2.23 Mev), copper (10.9 Mev), and carbon (18.7 Mev). The threshold is at least as low as 16.6 Mev, with an uncertainty of ±0.2 Mev due to the calibration. When the square roots of the counts are plotted (this gives a straight line near (γ,n) thresholds),[10] a straight line extrapolates to 16.35 Mev. Since it might be expected that the (γ,p) yield curve tails off differently than the (γ,n), owing to the coulomb penetration factor, there is still a slight uncertainty in what should be called the threshold. The N^{17} extrapolated threshold relative to that of O^{16} has a smaller calibration uncertainty and is 1.048.

In order to check the half-life and determine the cross section, several corrections have to be applied to the data. The number of neutron counts of the detector during 10 monitor counts (equivalent to 140 roentgen units at three feet) can be expressed as

$$y=\epsilon \exp(-t_f/t_m)[1-\exp(-t_d/t_m)]\pi\alpha^2 RN\cdot YS,$$

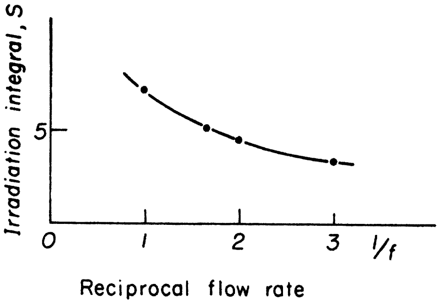

FIG. 3. Irradiation integral S as a function of reciprocal flow rate.

where

$$Y=\int_0^{E_{\max}} n(E, E_{\max})\sigma(E)dE,$$

and

$$S=\int_{x_{\max}}^{x_{\min}} \exp\left[\frac{\pi\alpha^2(x_{\min}{}^3-x^3)}{3ft_m}\right]dx,$$

where

ϵ is the detector efficiency;
t_f is the flow time $=A_f l_f/f$;
A_f is the area of the flow tube;
l_f is the length of the flow tube;
f is the flow rate;
t_m is the mean life of the N^{17} activity;
t_d is the time spent by the water near the detector $=A_d l_d/f$;
α is the approximate angle of the cone of the irradiation box and is the same as the angle of divergence of the x-ray beam;
R is the number of roentgen units/cm^2 at 1 cm for 10 monitor counts;
N is the number of O^{18} nuclei per cc;
$n(E, E_{\max})$ is the number of photons per cm^2 of energy E per roentgen unit per Mev interval when the betatron energy is $E_{\max}$;

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[10] McIlhinney, Hanson, Becker, Duffield, and Diven, Phys. Rev. 75, 542 (1949).

$\sigma(E)$ is the $O^{18}(\gamma,p)N^{17}$ cross section; and
x is the distance from the betatron target, $x_{\max}$ and $x_{\min}$ being the maximum and minimum distances the water occupies.

The first exponential gives the decay during the flow time. The brackets give the fraction of decays occurring while the irradiated water is near the detector. Y gives the bremsstrahlung photon energy distribution times the cross section, and S is an approximate expression of the irradiation process which estimates the fraction of saturation irradiation that is produced. This irradiation integral, S, was evaluated graphically and its value as a function of $1/f$ is given in Fig. 3. The other constants used are, $x_{\min}=16$ cm, $x_{\max}=40$ cm, $N=0.68\cdot10^{20}$ nuclei/cc, $t_m=6$ sec, $\epsilon=0.02$, $\alpha=0.1$, $t_d=9.18/f$. Holding the flow and irradiation conditions constant and varying $E_{\max}$ gives the yield curve of Fig. 1. Since under these conditions

$$y=c\int_0^{E_{\max}} n(E,\,E_{\max})\sigma(E)dE,$$

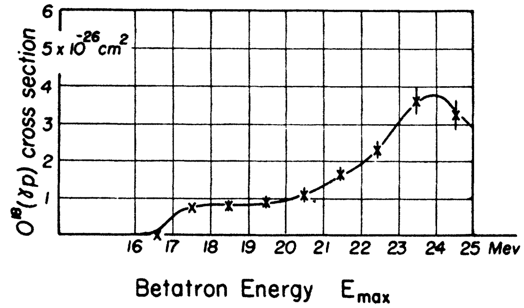

FIG. 4. Calculated cross-section curve for $O^{18}(\gamma,p)$ as a function of betatron energy.

it is possible to find $c\sigma(E)$, knowing n and y. The n values were taken from a set of curves calculated by Katz,[11] who kindly supplied us with copies. The cross-section curve calculated in this fashion is shown in Fig. 4. Keeping $E_{\max}$ constant and varying f should allow t_m to be determined. Since the expected value of t_m is known, we can insert $t_m=6$ sec in the correction terms and evaluate t_m, for this experiment, from the flow time exponential. Under these conditions,

$$\Omega\equiv y/[1-\exp(-t_d/t_m)]Y=c\exp(-t_f/t_m)$$

so that plotting Ω against t_f should give a regular decay curve. This has been done for several different flow tubes, and the resulting curves are shown in Fig. 5. A long Tygon tube, $A=0.1808$ cm^2, $l=888$ cm; a short Tygon tube, $A=0.1808$ cm^2, $l=435$ cm; and a long copper tube, $A=0.1808$ cm^2, $l=864$ cm were each used. These runs were all corrected to $E_{\max}=22.8$ Mev and 10 monitor counts. These curves give half-lives of about 4 sec. A more reliable method for determining the half-life is one in which the correction for irradiation drops out, since this is the least reliable and most approximate correction. At the same flow rate, the counts for the long and short Tygon tube differ only in the flow time. Hence,

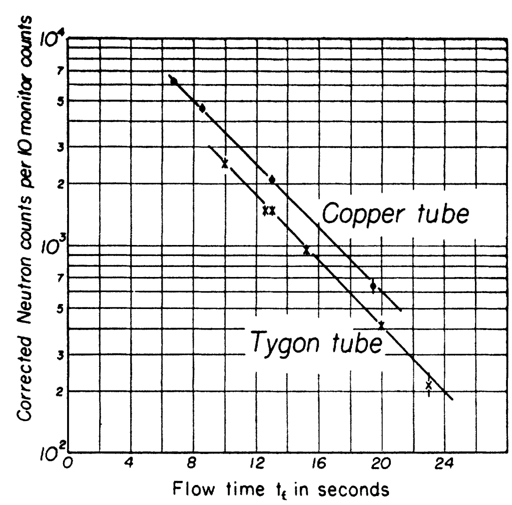

FIG. 5. Corrected neutron counts as a function of flow time.

$$\frac{y_{\text{short}}}{y_{\text{long}}}=\exp\frac{(t_{f\,\text{long}}-t_{f\,\text{short}})}{t_m}$$

$$=\exp\frac{(l_{\text{long}}-l_{\text{short}})A_f}{ft_m}=\exp\frac{4.72}{ft_m}.$$

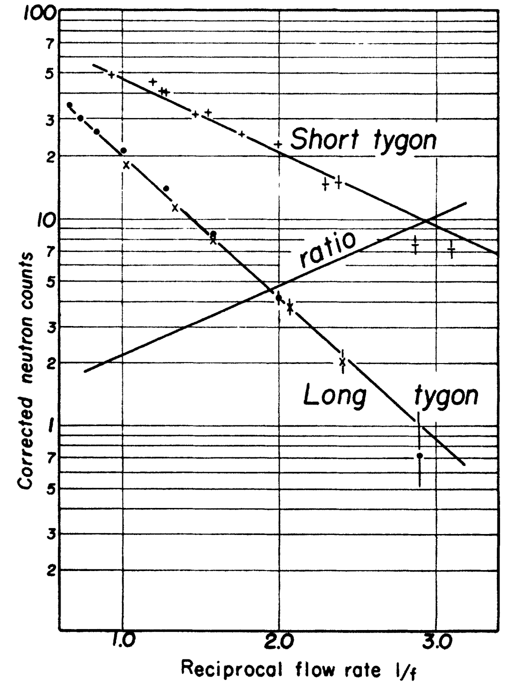

FIG. 6. Corrected neutron counts as a function of reciprocal flow for different length flow tubes. Also shown is the ratio of these two smoothed curves.

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[11] Katz, Johns, Douglas, and Haslam, Phys. Rev. 80, 131 (1950).

Figure 6 shows y_s/y_l as a function of $1/f$ as obtained from smoothed curves of the long and short tygon tube. This curve is consistent with a half-life of 4.15 sec, but the uncertainty due to statistics and other variations is about ±0.1 sec. The factor c can now be evaluated for typical conditions of flow and irradiation and the absolute cross section determined. It will be uncertain, because of the irradiation correction term, the difficulty of determining the absorption in the water and holder, the uncertainty in the actual efficiency of the neutron counter, and the uncertainty in the derivation of the cross-section curve from the yield curve. We have neglected those N^{17} nuclei which decay to the ground state of O^{17} and, hence, give no delayed neutrons. Alvarez[3] estimates these to be less than 5 percent of the total. The peak cross section appears to be 0.037×10^{-24} cm^2 at 24 Mev, as indicated in Fig. 4. The integrated cross section is about 0.15 Mev-barn. The relative uncertainties in the cross section curve due to statistics in the yield curve data are indicated in Fig. 4. The absolute uncertainty is estimated at ±50 percent. The integrated cross section has an additional uncertainty because of the assumed shape of the high energy part of the cross-section curve of ±0.1 Mev-barn.

III. DISCUSSION

The threshold values of $O^{16}(\gamma,n)O^{15}$, 15.6±0.2 Mev and of $O^{18}(\gamma,p)N^{17}$, 16.35±0.2 Mev can be compared with the values calculated from the nuclear masses. Using Rosenfeld's masses[12] and the N^{17} beta-ray and neutron energy, we calculate values of 15.58±0.08 and 16.01±0.3 Mev, respectively. The agreement in the case of O^{16} is quite good, although a previous measurement gave a somewhat higher value.[13] We would expect the observed O^{18} threshold to be greater than the value calculated from the masses by the effective barrier height. The N^{17} coulomb barrier for protons is about 3 Mev. The height of the barrier for 0.1 penetration can be estimated[14] to be 0.8 Mev, while for 0.01 penetration it drops to 0.4 Mev. The observed difference, 0.34±0.36 Mev, then seems reasonable for the extrapolated threshold.

Since O^{18} is such a light nucleus, its photo-disintegration can probably not be discussed reasonably in terms of the statistical theories. The (γ,n) threshold is calculated to be 8.0 Mev, so it can be assumed that the photo-neutron emission is the predominant reaction and that the photo-proton cross section is only a fraction of the photon absorption. The resonance energy and the integrated cross section are comparable with those measured on other light nuclei.[15, 16] It is reassuring to note that a (γ,p) reaction observed with this somewhat different technique (i.e., delayed neutrons) exhibits a cross-section curve similar to those measured by radioactivity and proton scintillations.

The value of the energy at the peak cross section, 24±2 Mev, and the integrated cross section, 0.15±0.1 Mev-barn, observed in the $O^{18}(\gamma,p)N^{17}$ reaction, are consistent with values calculated on the dipole interaction theories. Levinger and Bethe[17] predict an average energy of photon absorption of 29 Mev (Yukawa well, $r_0=1.5\cdot10^{-13}$ cm, and $x=\frac{1}{2}$) and an integrated absorption cross section of 0.38 Mev-barn. Goldhaber and Teller[18] calculate a resonance energy of 25 Mev and an integrated absorption cross section of 0.26 Mev-barn. In either case, the absorption cross section, which includes $(\gamma,n)(\gamma,2n)$, $(\gamma n,p)$ etc., would be expected to be several times the (γ,p) cross section.

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[12] L. Rosenfeld, *Nuclear Forces II* (Interscience Publishers, New York, 1949).

[13] G. C. Baldwin and H. W. Koch, Phys. Rev. **67**, 1 (1945) give 16.3±0.4 Mev.

[14] We are indebted to Professor V. Weisskopf for sending us his latest barrier penetration tables.

[15] A. K. Mann and J. Halpern, Phys. Rev. **80**, 470 (1950).

[16] H. Waffler and S. Younis, Helv. Phys. Acta **22**, 614 (1949).

[17] J. S. Levinger and H. A. Bethe, Phys. Rev. **78**, 115 (1950).

[18] M. Goldhaber and E. Teller, Phys. Rev. **74**, 1046 (1948).