ANGULAR DISTRIBUTION OF PHOTOPROTONS FROM NITROGEN

By B. M. Spicer*

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Summary

The energy distribution and angular distributions of protons ejected from nitrogen by 11·5 MeV bremsstrahlung have been measured. From the results obtained, it is concluded that the (γ,p) reaction in nitrogen is due to magnetic dipole and electric quadrupole transitions for photon energies of 7·6–11 MeV.

I. Introduction

The most general feature of photodisintegration experiments is the existence of the so-called " giant resonance " (Baldwin and Klaiber 1948; Johns *et al.* 1950). This resonance occurs in the cross section *v.* energy curve of every photonuclear reaction. The mechanism of this reaction was described by Goldhaber and Teller (1948) in terms of electric dipole absorption of γ-rays exciting counter-current motion of proton and neutron " fluids " in the nucleus.

Considerable interest was shown in the (γ,n) reactions in nitrogen, oxygen, and fluorine when the Saskatchewan group showed that, as well as the giant resonance, there was also a smaller resonance on the low energy side of the giant one (Johns *et al.* 1951; Horsley, Haslam, and Johns 1952*a*, 1952*b*). It is the nature of the photodisintegration reaction causing this smaller resonance which is of interest here.

Blatt and Weisskopf (1952) support the Goldhaber-Teller postulates regarding the giant resonance, and suggest that the smaller resonance is due to a combination of magnetic dipole and electric quadrupole transitions. They calculate that the relative importance of electric quadrupole to magnetic dipole transitions increases as the square of the quantum energy for the case of a middle-weight element. On this picture, electric dipole absorption becomes important at about 15 MeV, but is negligible at lower energies.

Peaslee (1952) has derived the Breit-Wigner formula for the case where the incident particle is a photon. On the basis of this derivation, he notes that, to produce the large maximum of the giant resonance, electric dipole matrix elements in which the overlap between initial and final states is almost complete are required. Further, he considers that the excited compound state must have a particular structure that corresponds to coherent excitation of the neutrons and protons into counter-current oscillation, in agreement with the Goldhaber-Teller model. The smaller resonance is then assumed to arise from " incoherent " electric dipole excitation—where all neutrons do not move against all protons.

* Physics Department, University of Melbourne.

Electric dipole excitation postulated by Peaslee for the low energy resonance must produce an angular distribution of the form $a+b\sin^2\theta$, where θ is the angle between the photon beam and direction of the proton. A combination of magnetic dipole and electric quadrupole excitations should give an angular distribution of the form $a+b\sin^2\theta\cos^2\theta$.

The present experiment is an attempt to determine the mechanism of the reaction in the energy region up to 11·5 MeV, by observing the energy distribution and angular distributions of the protons emitted in the $^{14}N(\gamma,p)^{13}C$ reaction. Since the nature of the (γ,p) and (γ,n) reactions is the same, a subsidiary resonance is expected in the cross section *v.* energy curve of the (γ,p) reaction. It will be more completely separated from the giant resonance in the case of the (γ,p) reaction as the threshold is 3 MeV lower.

The energy distribution and angular distributions of the photoprotons from nitrogen have been measured with accuracy sufficient to discriminate between the two hypotheses mentioned above.

II. Experimental Arrangement

The source of X-rays was the Melbourne synchrotron, which was operated at 11·5 MeV throughout this work. The energy scale of the machine was calibrated at the thresholds of the photoneutron reactions in ^{109}Ag and ^{63}Cu, which were measured to be $9\cdot2\pm0\cdot2$ and $10\cdot8\pm0\cdot2$ MeV respectively, in agreement with other observations (Baldwin and Koch 1945; McElhinney *et al.* 1949).

The X-rays were collimated into a beam of total angular width of 55 min by a lead collimator, and the X-ray intensity was monitored with an aluminium-walled ionization chamber.

A scattering chamber, similar to that described by Diven and Almy (1950), contained nitrogen at a pressure of 1 atm. The gas served as the target for the X-rays. The protons from the $^{14}N(\gamma,p)$ reaction were detected in Ilford C2 nuclear emulsions (50μ thick), which were placed in the scattering chamber parallel to, and to one side of, the X-ray beam. The 1 atm of nitrogen in the scattering chamber will stop particles from the reactions $^{14}N(\gamma,d)^{12}C$, $^{14}N(\gamma,\alpha)^{10}B$, $^{14}N(\gamma,np)^{12}C$ before they reach the plates. Their thresholds are respectively 10·26, 11·7, and 12·5 MeV.

To make a background run, the X-ray beam was excluded by blocking the collimator opening with a lead plug, all other experimental arrangements remaining unchanged. In this way the effect of neutrons produced in the collimator was estimated. The actual distributions of protons were then found by subtracting the result of the background run from that of the actual run.

A source of background not eliminated by this means is that due to neutrons produced at the synchrotron itself. These neutrons will come almost entirely from the platinum target, for the energy region considered. The number of these neutrons was estimated using the result given by Edwards and MacMillan (1952) for the integrated cross section of the $Pt(\gamma,n)$ reaction. The protons produced in the $^{14}N(n,p)$ reaction induced by these neutrons contribute less than 3 per cent. of the total protons observed.

III. Measurement of Tracks and Treatment of Data

Measurements made on the proton tracks were the projection of the range on to the plane of the plate, the angle to the beam direction, and the final depth in the emulsion reached by the track. To be accepted a track was required to start at the surface of the emulsion and have direction compatible with origin in the irradiated part of the target. The acceptable angular range was 40–140°. Background plates were analysed in the same way as the plates exposed in the actual run.

The energy of the protons at the surface of the emulsion was obtained from the range-energy relation for Ilford C2 emulsions given by El Bedewi (1951). The energy lost by the proton in the gas between target and plate was calculated using the energy loss results given by Aron, Hoffman, and Williams (1949).

$$-\frac{\mathrm{d}E}{\mathrm{d}x}=\frac{4\pi^2e^4z^2}{mv^2}NZ\left[\ln\frac{mv^2}{I}-\ln(1-\beta^2)-\beta^2\right]$$

was approximated by

$$-\frac{\mathrm{d}E}{\mathrm{d}x}=\frac{A}{E}[\ln E+B],$$

where $A=0\cdot0866$, $B=3\cdot253$. This gave a maximum error of less than $\frac{1}{3}$ per cent. for the range of proton energies considered. To obtain the energy of ejection of the proton from the nitrogen nucleus, the following procedure was adopted. If E_1 and E_2 are the energy of ejection from the nitrogen nucleus and the energy of the proton at the surface of the emulsion respectively, the distance travelled in the gas may be obtained from

$$x=\int_{E_1}^{E_2}\frac{\mathrm{d}E}{-\mathrm{d}E/\mathrm{d}x},$$

giving

$$x=\frac{1}{A\mathrm{e}^{2B}}[\mathrm{Ei}\{2(\ln E_1+B)\}-\mathrm{Ei}\{2(\ln E_2+B)\}],$$

where

$$\mathrm{Ei}(y)=\int_{-\infty}^{y}\frac{\mathrm{e}^y\mathrm{d}y}{y}.$$

The distance travelled in the gas may also be calculated from the angle of the track to the beam and the known position of the track in the plate. Using these two equations for the distance and knowing the energy of the proton at the surface of the emulsion, the initial proton energy may be calculated.

The uncertainty in energy due to the finite thickness of the target ranged from $\pm0\cdot06$ MeV for protons of 5 MeV emitted at 90° to the X-ray beam, to $\pm0\cdot25$ MeV for $1\cdot5$ MeV protons emitted at 45° to the beam.

To plot angular distributions, the data were grouped into three energy intervals (2·2–2·6, 2·6–3·0, 3·0–4·0 MeV) and the tracks were grouped into 10° angular intervals, according to the angle they made with the X-ray beam in the laboratory system. The mean differential cross section over the 10°

interval was calculated from the number of tracks per 10° interval, by making a correction for the solid angle subtended by each interval at the position of the track. The number of tracks, $N(\theta)$ in a given angular range, found in an area ΔA is given by

$$N(\theta)=\text{const. } \mathrm{d}\sigma(\theta)\int_{\text{vol.}}\frac{z}{R}\cdot\frac{\Delta A}{R^2}\mathrm{d}V,$$

where z is the height of the centre of the beam above the plate, R is the distance from ΔA to target, and the integration is performed over the volume of gas-target subtending the angle of 10° at ΔA. Carrying through this integration, we find that, in the first approximation,

$$N(\theta)=\text{const. } \mathrm{d}\sigma(\theta)\ .\ \overline{\sin\theta},$$

where $\overline{\sin\theta}$ is the average value of $\sin\theta$ over the 10° interval.

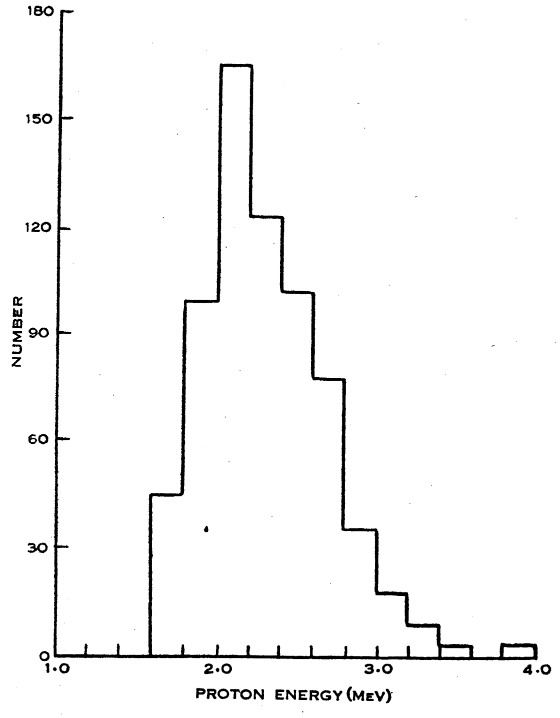

Fig. 1.—Energy distribution of photoprotons from nitrogen.

IV. Results

The results obtained from the measurements are shown in Figures 1 and 2. Measurements were made of 650 tracks.

The energy distribution of protons with energies greater than 2·2 MeV is shown in Figure 1. The lower limit of 2·2 MeV is set because protons of energy less than 2·2 MeV may be stopped in the gas before they reach the plates.

Figure 2 shows the angular distributions plotted for the three energy intervals mentioned above. The angular distribution for the interval 2·2–2·6 MeV may not be correct as even some of these protons could have been stopped before they reached the emulsion surface, if their angles were less than 60 or greater than 120°. The other two energy intervals provide angular distributions which can be fitted by curves of the form $a+b \sin^2\theta \cos^2\theta$.

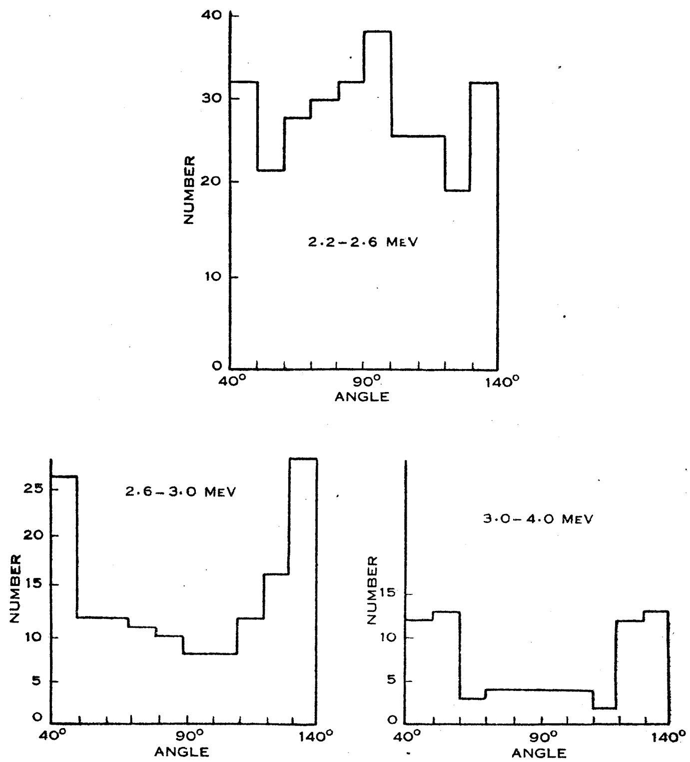

Fig. 2.—Angular distribution of photoprotons.

V. Discussion

The threshold for the reaction $^{14}N(\gamma,p)^{13}C$ was calculated from mass tables given by Bethe (1949), Ewald (1951), Li *et al.* (1951), and Ogata and Matsuda (1953). The mean value found was $7\cdot56\pm0\cdot02$ MeV. Using this value and 11·5 MeV for the bremsstrahlung peak energy, the maximum proton energy expected was 3·6 MeV, calculated from $E_p=13/14\ .\ (h\nu-E_b)$, where E_b is the threshold for the reaction.

The angular distributions for the proton energy ranges 2·6–3·0, 3·0–4·0 MeV can be fitted by curves of the form $a+b \sin^2\theta \cos^2\theta$, where the ratio b/a is greater for the latter case than the former. It is not possible to interpret the angular distribution for protons less than 2·6 MeV in energy. This distribution appears to approach isotropy, when allowance is made for the loss of protons due to their complete stopping in the gas.

The angular distributions for protons in the energy range $2 \cdot 6$–$4 \cdot 0$ MeV are compatible with those expected from a combination of magnetic dipole and electric quadrupole transitions. In this energy range, there is no evidence whatever for the $a+b\sin^2\theta$ distribution expected from the electric dipole absorption postulated by Peaslee (1952).

VI. Conclusion

From the evidence given above the photoprotons from nitrogen are produced by a combination of magnetic dipole and electric quadrupole transitions for quantum energies up to 11 MeV. The magnetic dipole transitions predominate at lower energy, but fall off rapidly in importance. The relative importance of electric quadrupole to magnetic dipole absorption increases with increasing photon energy. Thus, the postulates of Blatt and Weisskopf (1952) are at least qualitatively substantiated.

VII. Acknowledgments

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