SPECTRUM OF PHOTO PROTONS PRODUCED BY γ RAYS IN THE NARROW 82-89 Mev ENERGY RANGE

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Energy spectra were investigated for protons ejected from C^{12} and Al^{27} by γ rays from bremsstrahlung spectra possessing peak energies of 82 and 89 Mev. The experimental data are compared with curves based on Dedrick's data. Although the agreement is not very good it may nevertheless be possible that the quasi-deuteron mechanism contributes significantly to the interaction of γ rays with the nuclei considered.

1. INTRODUCTION

THERE is considerable interest at the present time in the interaction of high energy γ rays with nuclei. From work with γ rays having energies greater than 150 Mev, it can be concluded that at such energies the most important mechanism is the quasi-deuteron one. The results of Odian et al.[1] and of Barton and Smith[2] show that this mechanism can explain almost all the yield of protons having energies greater than 60 Mev. For γ ray energies less than 150 Mev, the picture is not so clear. The work of Gorbunov and Spiridonov[3] on the photodisintegration of He^4 shows that for γ rays having energies in the interval 70 — 170 Mev, the quasi-deuteron interaction amounts to about 30%, and becomes less important at lower energies. Qualitative results obtained by Chuvilo and Shevchenko[4] and also by us[5] indicate that the two-nucleon mechanism can be important at energies less than 100 Mev. Whitehead et al.[7] have recently made a quantitative comparison with the calculations of Dedrick,[6] which were carried out for C^{12} on the basis of the quasi-deuteron interaction. Using γ rays in a narrow energy range (~ 20 Mev) centered on $\overline{E}_\gamma = 96$ Mev, both the excitation function obtained for 37-Mev protons and the energy and angular distribution of the protons agree satisfactorily with Dedrick's calculations.

In the following we present some energy spectra for photo-protons from C^{12} and Al^{27}. They were obtained by a difference method, using γ rays in the narrow energy range bounded by the maximal energies of two bremsstrahlung spectra, the bounds being $E_{\gamma\,max} = 82$ and 89 Mev. The spectra are compared with Dedrick's calculations for the same energy range.

2. BRIEF DESCRIPTION OF THE EXPERIMENT

The method used for getting the energy spectrum of those protons arising from γ rays having energies lying in a certain narrow region of a continuous spectrum depends on the fact that two bremsstrahlung spectra having maximal energies E_1 and E_2 ($E_2 > E_1$) which differ but little from each other (the spectra being normalized to the same number of effective quanta) will then practically coincide at energies less than E_1. Figure 1 shows two spectra with maximal energies $E_{\gamma\,max} = 82$ Mev and $E_{\gamma\,max} = 89$ Mev. The cross-hatched area is their difference.

The proton energy spectra obtained with these two bremsstrahlung spectra were then subtracted, having first been normalized to a γ ray dose corresponding to the passage of one effective quantum through the target. The difference spectrum so

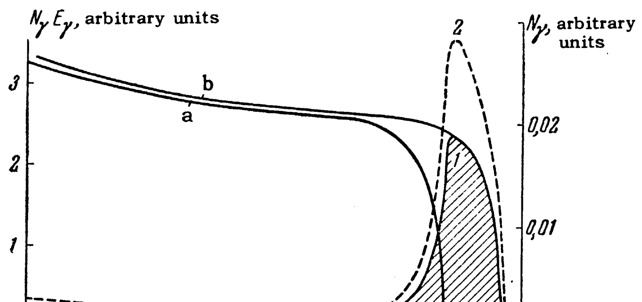

FIG. 1. Bremsstrahlung spectra of γ rays having maximal energies: a) 82 mev, b) 89 Mev. The spectra are normalized to the same total number of effective quanta. Cross hatched area bounded by curve 1 is their difference in units $E_\gamma N_\gamma$. Curve 2 — difference of spectra in units of N_γ, the number of quanta. Scale along ordinate at left is for curves a, b, and 1; along the right, for curve 2.

obtained corresponds to the γ ray spectrum shown by the cross-hatched area in Fig. 1.

The protons were detected by a scintillation telescope, which was described previously.[5] The protons were detected at 90° relative to the γ-ray beam. The targets were oriented at 45° to the direction of the beam. The target thicknesses were C^{12} — 150 mg/cm^2, Al^{27} — 40.5 mg/cm^2. The solid angle of the telescope was 1.08×10^{-2} sterad; its angular resolution function was almost a triangle having a base ±6.0°. Each telescope consisted of two counters. The thickness of the crystal in the back counter NaI(Tl) was 1.8 cm, while the thickness of the crystal in the front counter CsI(Tl) was 0.025 cm. Lead diaphragms defining the telescope solid angle did not allow protons to pass through without traversing the full thickness of the crystal in the back counter. In order to decrease the background, which was due chiefly to the layer of air near the target, the target was placed in an evacuated chamber. As a result, the proton counting rate without the target was less than 1% of the counting rate with the target. Accidental coincidences, as measured by introducing a delay line in one of the telescope channels, accounted for less than 0.1% of the total count.

Since the proton spectrum was obtained by taking the difference between two large almost equal numbers, it was important that the telescopes operate stably. Since the equipment was on round the clock for long periods of time, temperature drifts in the electronics were not important. The gain of each channel was controlled using a Po^{210} source. Measurements at different γ ray energies were continuously alternated. Constant monitoring showed that the stability of the whole setup was satisfactory. More than 80% of the results in all series of measurements lay within the limits of statistical error.

The dose of γ rays passing through the target was measured by the same method as described previously.[5]

With the telescopes it was easy to discriminate between electrons and heavy charged particles. There were few enough deuterons so that these could not have introduced any distortions.[8]

3. RESULTS AND DISCUSSION

The table shows the proton energy spectra from C^{12} and Al^{27}, taken with the continuous bremsstrahlung spectra having maximal energies 82 and 89 Mev. For carbon, our data at $E_{\gamma max}$ = 89 Mev can be compared with the results of Whitehead et al.[7] at $E_{\gamma max}$ = 90 Mev. These spectra are shown in Fig. 2. The yields of protons having energy E_p = 37 Mev agree well (the errors shown are, in both cases, statistical). The cross shows the proton yield quoted in reference 4, and obtained with a bremsstrahlung spectrum having a maximum energy 84 Mev. The energy spectra shown in Fig. 2 disagree somewhat in their decreasing portions. The discrepancy does not disappear completely if one takes into account the finite resolution of the second counter in the telescope and errors in the telescope's energy calibration. The error bars parallel to the abscissa take these two effects into account. Errors connected with corrections for finite target thickness are small at such high proton energies and cannot change the positions of the experimental points very much.

Figures 3 and 4 show the energy distribution of protons from C^{12} and Al^{27} obtained in the manner described above for a narrow range of γ ray energies. Only statistical errors are shown. On both figures, curve 1 is calculated from Dedrick's data. The experimental results represent the difference in proton yields per effective quantum, so in comparing with Dedrick's data it is convenient to place it on the same footing, especially as this takes into account the contribution of low energy quanta (see Fig. 1) almost completely. Dedrick's calculations were for only four γ-ray energies in the interval 50 — 125 Mev, so the theoretical yields were calculated by first interpolating the cross section to intermediate γ-ray energies, then subtracting the results for the two energy intervals:

Target	Mean proton energy E_p, Mev	Proton yield, $\frac{cm^2 10^{-30}}{sterad \cdot Mev \cdot Q}$ $E_{\gamma max}$=82 Mev	Proton yield, $\frac{cm^2 10^{-30}}{sterad \cdot Mev \cdot Q}$ $E_{\gamma max}$=89 Mev	Target	Mean proton energy E_p, Mev	Proton yield, $\frac{cm^2 10^{-30}}{sterad \cdot Mev \cdot Q}$ $E_{\gamma max}$=82 Mev	Proton yield, $\frac{cm^2 10^{-30}}{sterad \cdot Mev \cdot Q}$ $E_{\gamma max}$=89 Mev
					15.4	18.63 ±0.18	18.98 ±0.19
	17.8	4,028±0.040	4,120±0,042		19.1	11,01 ±0.22	11.90 ±0.28
	21.4	2,841±0,052	3.134±0,055		24.0	5,71 ±0.13	6.38 ±0.16
	26.0	1.882±0.034	2.044±0,036		27.7	4.07 ±0.12	4.70 ±0.12
C^{12}	31.4	0.961±0.028	1,127±0.030	Al^{27}	29.8	2.59 ±0.08	3.01 ±0.11
	36.8	0.443±0.010	0,573±0.011		33.6	1.85 ±0.08	2,06 ±0.08
	44.0	0.113±0,004	0.196±0.005		36.7	0.82 ±0.40	1.06 ±0.06
	52.2	0.003±0.0005	0.020±0.002		41.0	0.523±0.035	0.764±0.038
					49.9	0.078±0.013	0.127±0.016

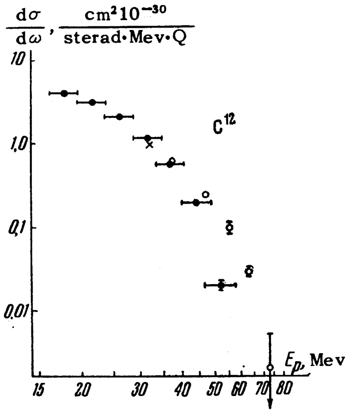

FIG. 2. Energy spectrum of protons ejected from C^{12} when this nucleus is irradiated by the full bremsstrahlung spectrum having $E_{\gamma\,max} = 89$ Mev. Protons observed at 90°. ● — our data, ○ — data of Whitehead et al.,[7] × — data of Chuvilo and Shevchenko.[4] Errors shown are statistical.

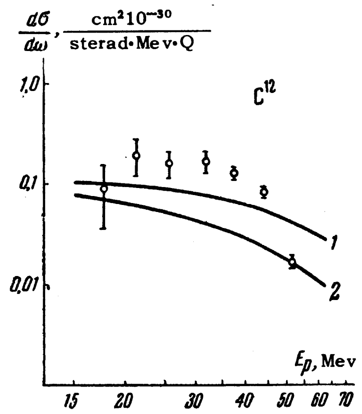

FIG. 3. Energy spectrum for protons from C^{12} for rays in a narrow energy range; $\theta = 90°$. Curves calculated from data of Dedrick;[6] 1 — without taking into account scattering of protons in the nucleus, 2 — taking scattering into account. The errors shown are statistical.

50 — 89 Mev and 50 — 82 Mev in units $cm^2 \cdot 10^{-30}$/sterad-Mev-Q. The contribution of quanta having energies less than 50 Mev is not included, but taking reaction thresholds into account it can be shown that for protons with energy $E_p = 15$ Mev coming from the nucleus C^{12}, this contribution to the theoretically calculated yield is less than 10%. This estimate also holds essentially for Al^{27}.

Curve 1 neglects barrier penetration effects, since at these high proton energies such effects are small. On the other hand, an exact treatment of barrier effects is difficult because the distribution of the orbital angular momenta l of the emitted protons is not known.

In the following we make an approximate estimate of the effect of nucleon scattering in the nucleus. If we assume that nucleon scattering inside the nucleus can be considered as a direct interaction with individual nucleons in the nucleus (which assumption is supported by a number of investigations on the inelastic scattering of nucleons from nuclei), we can expect the total number of protons leaving the nucleus to decrease, and the relative number of low energy protons to increase. This will make the spectrum drop off more sharply. Calculations on the mean free path λ[9] show that for light nuclei this is comparable with nuclear dimensions. For C^{12}, $R = 2.3 \times 10^{-13}$ cm, while $\lambda = 3.4 \times 10^{-13}$ cm for $r_0 = 1.4 \times 10^{-13}$ cm. Hence one need consider only protons which are not scattered at all or only once; it is further assumed that all singly scattered protons having an energy greater than 10 Mev leave the nucleus without experiencing another collision. It is interesting to consider protons traveling at an angle θ with the direction of the γ-ray beam, but leaving the nucleus after scattering at an angle 90°. To simplify the integration, it was assumed that the angular distribution of the scattered protons was a straight line, falling to zero at an angle of 90° with the direction of travel before the collision. This agrees in its general features with the angular distribution of protons scattered from nuclei.[10] The energy distribution of the scattered protons was taken to be isotropic between the limits $E_{p\,min} = E_F$ and $E_{p\,max} = E_p - \frac{2}{5} E_F$ (E_F being the Fermi energy and E_p the proton energy before the collision relative to the bottom of the potential well). Such an energy distribution does not differ too much from the experimentally observed one, especially at large scattering angles.[10,11]

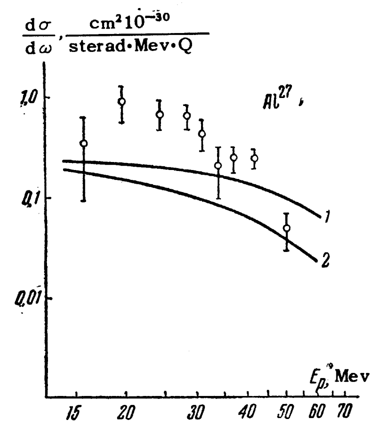

FIG. 4. Same as Fig. 3, but for protons from Al^{27}.

Curves 2 in Figs. 3 and 4 show the energy spectrum calculated from Dedrick's data but taking into account scattering inside the nucleus. The particle yield decreases about the same for both nuclei by $\sim 40\%$. All calculations were carried out for $r_0 = 1.4 \times 10^{-13}$ cm and a potential well of depth 40 Mev.

Comparison of the calculated curves with the experimental data shows that for both elements more protons are observed experimentally than calculated. For carbon, the experimental proton yield in the energy range 15 — 50 Mev is about double the calculated quantity (curve 1). It is not possible to make a more precise statement because the statistical errors of the experimental points are too large.

Whitehead et al.[7] note that for γ-ray energies in the region bounded by the maxima of bremsstrahlung spectra lying at 90 Mev and 110 Mev ($\bar{E}_\gamma = 96$ Mev), and for protons having energies $E_p \geq 37$ Mev, the number of protons at 90° with the direction of the incident beam agrees satisfactorily with Dedrick's calculations, the value of r_0 being taken to be 1.4×10^{-13} cm. In our case most of the protons observed have energies in the range 15 — 40 Mev and are ejected by γ rays of somewhat lower energy ($E_{\gamma \max} = 82 - 89$ Mev). The discrepancy with Dedrick's calculations can be due to several reasons: in the first place, it is possible that with decreasing γ ray energies the relative importance of various mechanisms for the interaction can change and the quasi-deuteron mechanism becomes inadequate, and in the second place it may be that the accuracy of the calculations changes. Simplifying assumptions, defining the model for the interaction, have been made, and the interaction between the emitted nucleons and the nucleus in its final state neglected, so that only approximate agreement with experiment can be expected. Changing r_0 to 1.2×10^{-13} cm increases the theoretical yield by a factor 1.6 and considerably improves agreement with our data. Hence a detailed comparison between the forms of the calculated and experimental spectra is not justified.

For Al^{27}, the experimental yield for protons in the energy interval 15 — 50 Mev is about three times greater than that predicted by Dedrick; however, it is quite likely that the Gaussian distribution of momenta about $E_0 = 16$ Mev, which he has assumed, is not justified for Al^{27}. A distribution corresponding to a smaller value of E_0 could lead to a higher yield of low energy protons and hence to a steeper fall-off in the spectrum, since the total number of protons taking part in the interaction remains the same.

On the whole, however, it cannot be denied that for both of the elements investigated the quasi-deuteron mechanism for the interaction can make a significant contribution.

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