Note on the Resonance Scattering of High Energy γ-Rays by Nuclei of Carbon and Copper

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A search has been made for the resonance scattering of high energy γ-rays in nuclei of carbon and copper using the 100-Mev betatron to provide the primary radiation. The scattering in carbon and copper is less than 1 percent and 3 percent, respectively, of the total cross section for resonance absorption.

EVIDENCE indicating that there is a resonance absorption of γ-rays at high energies has been obtained by several investigators[1,2] from a study of $\gamma-n$, reactions. Goldhaber and Teller[3] have suggested a nuclear model which may account for this absorption. According to Goldhaber and Teller there may also be a strong scattering of γ-rays at the resonance energy characteristic of each nucleus. The angular distribution of this scattered radiation, following the Goldhaber-Teller argument, is given by the classical Thomson formula

$$I(\theta) \propto (1+\cos^2\theta),$$

where θ is the angle between the primary beam and the scattered radiation. This is believed to hold for cases where the characteristic wave-length is greater than 2π times the nuclear radius.

We have investigated the scattering in copper and carbon, using the 100-Mev betatron for a source of γ-rays and a cloud chamber for a detector of the scattered radiation. Our data indicate the resonance scattering to be small in terms of the total nuclear absorption, and our result is an upper limit for this process.

A measurement of scattered radiation at a mean angle of $\theta=11°$ has afforded a means of making an absolute intensity calibration of the γ-ray beam. This is necessary for evaluating the cross section for resonance scattering. The Compton effect produces a relatively strong spectrum of scattered radiation at this angle. Since this spectrum is readily calculable, the intensity of the observed spectrum is a measure of the beam intensity. Figure 1 shows the pair spectrum obtained from the scattering of γ-rays in carbon, for a peak betatron energy, E_m, of 50 Mev. By pair spectrum is meant the number of pairs produced (in a lead foil 0.5 mm thick) in the chamber as a function of the pair energy. Taking account of the Klein-Nishina differential scattering cross section, the bremsstrahlung produced by secondary electrons in the carbon, the geometry, and the cloud-chamber efficiency, and assuming a primary quantum spectrum of the form $N(E)dE=K(dE/E)$,[4] we have calculated the theoretical pair spectrum in 5-Mev intervals down to 5 Mev. This is normalized to fit the experimental data and plotted in Fig. 1. The fit between the theoretical and experimental curves is satisfactory. The number of observed pairs is small above the "Compton cut-off" energy of 22 Mev, i.e., the maximum energy with which 50-Mev quanta can be scattered at our minimum angle of 9° by the Compton effect. Using the normalizing factor for this curve, we find the average number of quanta at a distance of 3 meters from the betatron target in a 1-Mev interval at 22 Mev (copper resonance energy) to be 1.9×10^3 per cm² per pulse for $E_m=50$ Mev.[5] (This is the greatest intensity, at this energy, which was available from the betatron during the period of the experiment.[6]) The corresponding constant for $E_m=100$ Mev follows from this, if one knows the relative γ-ray intensity for $E_m=50$ Mev and for 100 Mev. This ratio is obtained in a straightforward way by comparing the activation of copper samples placed directly in the beam. The quantum yield per pulse for $E_m=100$ Mev is found to be 6.0 times greater

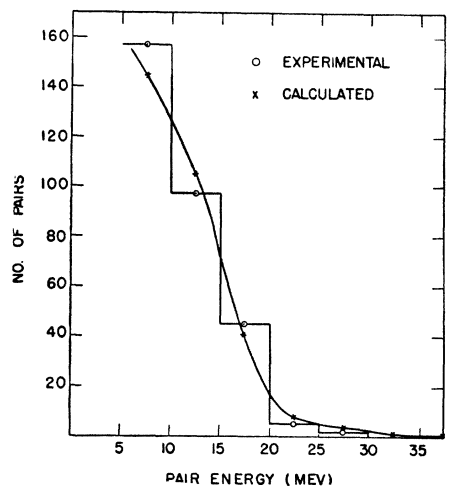

FIG. 1. Pairs observed in cloud chamber from quanta scattered in carbon at $\theta=11°$. The calculated values are for Compton scattering and bremsstrahlung from secondary electrons.

[1] G. C. Baldwin and G. S. Klaiber, Phys. Rev. **71**, 3 (1947); Phys. Rev. **73**, 1156 (1948).
[2] M. L. Perlman and G. Friedlander, Phys. Rev. **74**, 442 (1948).
[3] M. Goldhaber and E. Teller, Phys. Rev. **74**, 1046 (1948).
[4] Early measurements by J. L. Lawson, using the spectrum analyzer recently described, Phys. Rev. **75**, 436 (1949), indicate this spectrum to be approximately correct (private communication).
[5] These results can be shown to agree with those obtained by J. L. Lawson and M. L. Perlman, Phys. Rev. **74**, 1190 (1948), using a different method, when account is taken of the different experimental conditions.
[6] The relative betatron intensity is checked periodically by a Victoreen *R*-thimble placed directly in the beam, and is monitored continuously by an ionization chamber at one side of the beam.

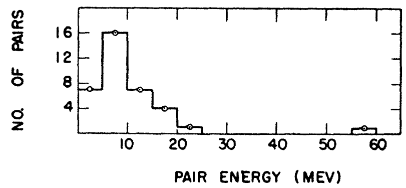

FIG. 2. Pairs observed in cloud chamber from quanta scattered in copper at $\theta=120°$.

than the number quoted above for $E_m=50$ Mev. These absolute intensities are estimated to be accurate within 40 percent.

The measurements at $\theta=11°$ do not constitute a sensitive test for the resonance scattering. The geometry is such that the calculated intensity of the scattered quanta is smaller than the expected bremsstrahlung in the carbon, assuming a scattering cross section equal to the total cross section of Goldhaber and Teller and a $(1+\cos^2\theta)$ distribution.

A value of θ near 90° is more favorable for the detection of resonance scattering because the distance from scatterer to detector is smaller and the contribution from Compton scattering and bremsstrahlung from secondary electrons is less. Scattering measurements in carbon and copper have been made with the following experimental conditions. The γ-rays from the betatron, operated at 100 Mev and maximum intensity, pass through a collimator which defines a beam 1 cm high and 3 cm wide at the scatterer. A magnetic field sweeps out electrons from the beam as it passes through the collimator. Carbon or copper of sufficient thickness to absorb 90 percent of the primary γ-rays is placed in the beam. The cloud chamber is placed at the side of the scatterer so that scattered quanta hitting the pair-forming lead foil in the chamber have a mean angle, with the forward direction of the beam, of 120°, and a spread in angle of 45°. Additional shielding of lead is placed between the betatron and the cloud chamber to absorb stray radiation from the betatron.

In the thick scatterers used, only a fraction of the primary quanta in the resonance energy interval are absorbed or scattered by the nucleus. This fraction is given by the ratio of the nuclear cross section to the sum of all absorption cross sections, including pair production and Compton scattering; these are averaged over the resonance interval. For assumed resonance widths between about 1 and 10 Mev the resonance cross section is expected to be smaller than the sum of the pair and Compton cross sections. For this range of widths, therefore, the number of nuclear resonance processes should be nearly independent of the width. If *all* of the resonance absorption resulted in *scattering* with a $(1+\cos^2\theta)$ distribution, we should expect to observe an average of 0.03 pairs of resonance energy per picture from the copper, and 0.01 resonance pairs per picture from the carbon. This expectation is based on the Goldhaber-Teller values of the total integrated cross section and on our measurement of the absolute beam intensity; it includes corrections for geometry, cloud-chamber detection efficiency, and absorption of the scattered quanta.

From 12,000 pictures taken with the carbon target and 5000 with the copper target, we have obtained no pairs which clearly result from nuclear scattering. From carbon we have observed one pair of energy 18 Mev and no others greater than 13 Mev; the few pairs observed can probably be accounted for as bremsstrahlung from secondary electrons in the carbon. The nuclear scattering in carbon of quanta of about 30 Mev, therefore, cannot amount to more than 1 percent of the total nuclear resonance absorption predicted by Goldhaber and Teller.[7] From copper we have observed the spectrum of pairs shown in Fig. 2. Since the multiple scattering of secondary electrons and the radiation probability are greater in copper than in carbon we should expect to observe a greater number of pairs from bremsstrahlung. It is probable that the observed pairs are of this origin. If one makes the assumption, however, that all five of the pairs lying between 15 and 30 Mev are due to nuclear resonance, this scattering is no greater than 3 percent of the nuclear resonance absorption.

It would be helpful to have a measurement of the total cross section and the total width of the absorption resonance. Early in our investigation we made a tentative measurement of the continuous spectrum of the γ-rays from the betatron transmitted through two feet of carbon, using the cloud chamber to measure the pair spectrum. Our data, although weak statistically so far, suggest a dip in the pair spectrum in the neighborhood of 30 Mev. Measurements of this type may provide information about the total resonance absorption.

We wish to thank Dr. E. E. Charlton and the betatron group for their generous cooperation. Dr. G. C. Baldwin kindly called our attention to this problem in advance of publication of the Goldhaber-Teller paper. We were fortunate in being able to discuss some of the theoretical aspects of the nuclear resonance effect with Professor H. A. Bethe and Dr. H. Hurwitz. Our program is supported by Contract N7 onr 332 with the ONR.

[7] In contrast to this result, the $\gamma-n$ absorption in carbon measured by J. L. Lawson and M. L. Perlman, Phys. Rev. **74**, 1190 (1948), is about equal to the predicted total cross section.