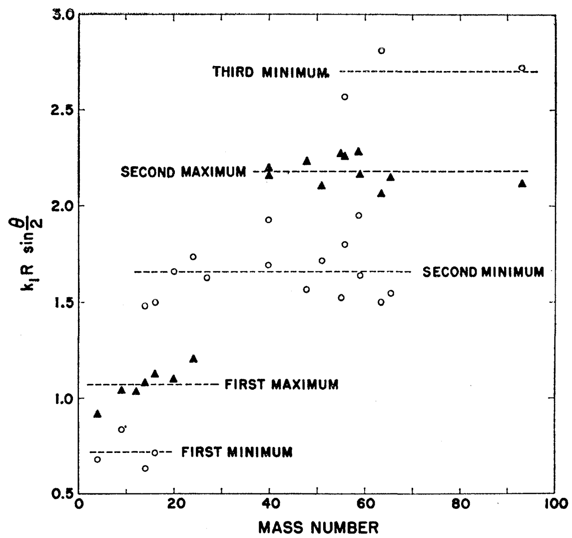

FIG. 3. $k_1R\sin(\theta/2)$ versus A for positions of corresponding maxima and minima in the polarization curves.

through which a compound nucleus, once formed, can decay. This supposition is given credence by the observation that, below 8 Mev, polarization data[7] exhibit fluctuations from one angle to the next for the same element and at the same angle for neighboring elements.

Figure 2 displays the angular dependence of the polarizations and elastic scattering cross sections along with optical model fits to both. Wherever elastic scattering data were available from single-scattering experiments, these were used. Otherwise, the less accurate elastic scattering data which are a by-product of the present polarization measurements are plotted. The dashed and solid curves are theoretical fits to the polarization and elastic scattering data, respectively, using the potential

[7] R. E. Warner and W. P. Alford, Phys. Rev. **114**, 1338 (1959).

$$V(r)=(V+iW)\rho(r)+\frac{\gamma V}{2}\left(\frac{\hbar}{mc}\right)^2\frac{1}{r}\frac{d\rho}{dr}\mathbf{l}\cdot\mathbf{s}$$

and the set of parameters[8]

$$R=1.25A^{\frac{1}{3}}\,\text{f};$$
$$V=-55\text{ Mev},\quad W=-6\text{ Mev};$$
$$\gamma=-23,\quad a=0.50\text{ f}$$

where

$$\rho(r)=\left[1+\exp\left(\frac{r-R}{a}\right)\right]^{-1}.$$

The above parameters are the same as those used to describe the 10-Mev data except that the constant in the radius parameter has been increased by 4%. Again, no attempt was made to carry out a systematic parameter search for a best fit to the data.

As in the case of the higher energy data, extrema in the polarization distributions occur for constant values of the product of target radius and momentum transfer, as predicted by simple diffraction theory. This is shown in Fig. 3. However, the average value of $[k_1R\sin(\theta/2)]$ corresponding to a given extremum point is not the same for the two energies, being as much as 19% lower for the lower energy, if the same radius is used at both energies.

ACKNOWLEDGMENTS

It is desired to acknowledge the large amount of help rendered us by the cyclotron group in providing beams of appropriate energy and intensity. We are also indebted to all of the personnel of the microscopy laboratory for performing the plate analysis work involved in these experiments, and especially to Mrs. May Bergstresser for supervising much of the analysis work and data compilation.

[8] In the paper previously published, reference 1, γ should be negative instead of positive.

PHYSICAL REVIEW VOLUME 124, NUMBER 1 OCTOBER 1, 1961

Momentum and Angular Distribution of Recoil Electrons in Triplet Production*

R. C. MOHANTY, E. H. WEBB, H. S. SANDHU, AND R. R. ROY
Nuclear Physics Laboratory, Department of Physics, The Pennsylvania State University, University Park, Pennsylvania
(Received May 15, 1961)

Ilford G-5 emulsion was bombarded by a hardened bremsstrahlung spectrum of maximum energy of 90 Mev. In 54 433 fields of view of the microscopes 1935 triplets were observed, out of which 1872 triplets were measured in the energy interval of 2 to 90 Mev. Recoil momentum distributions of the low-energy partner of the triplets have been compared with the theory of Suh and Bethe. In addition, the angular distribution of recoil electrons has been presented.

INTRODUCTION

THE cross section for triplet production has been studied[1–3] by absorption method within $10\leq E_\gamma \leq 300$ Mev photon energy range. The absorption technique, however, does not permit such detailed studies as momentum and angular distribution of recoil electrons. Recent theoretical calculations on the momentum

* This work was supported by the Atomic Energy Commission.
[1] John D. Anderson, Robert W. Kenney, and Charles A. McDoland, Phys. Rev. **102**, 1626 and 1632 (1956).
[2] J. Moffatt, J. J. Thresher, G. C. Weeks, and R. Wilson, Proc. Roy. Soc. (London) **A244**, 245 (1958); J. Moffatt and G. C. Weeks, Proc. Phys. Soc. (London) **73**, 114 (1959).
[3] E. Malamud, Phys. Rev. **115**, 687 (1959).

distribution by Suh and Bethe[4] have made such studies significant. During the progress of the present experiments two investigations along this line have been reported.[5,6]

Hart, Cocconi, Cocconi, and Sellen, using a hydrogen-filled diffusion chamber and photons of energy 10 Mev to 1 Bev, showed that the experimental recoil momentum distribution curves above 100 Mev incident photon energy agreed well with the theoretical curves as predicted by Suh and Bethe. Below 100 Mev, however, the experimental results differed from those of the theory and the difference increased with the increase of the recoil momentum. More statistically accurate results published recently by Gates using a hydrogen bubble chamber and photons of energy between 2 Mev and 323 Mev essentially confirmed the above observations.

Both Hart, Cocconi, Cocconi, and Sellen and Gates also studied the angular distribution of recoil electrons. At present there are no theoretical calculations for angular distribution available for comparison with experiments.

The present experiment on triplet production was performed with photon energy between 2 and 90 Mev, the region in which the two previous workers reported disagreement with the theory.

EXPERIMENTAL ARRANGEMENT

The electron-sensitive 1 in.×2 in.×400 μ Ilford G-5 plates were bombarded by a hardened continuous bremsstrahlung spectrum of maximum energy 90 Mev at the National Bureau of Standards electron synchroton, Washington, D. C. The hardening of the beam was achieved by placing carbon absorbers of thickness 496.43 g/cm^2 in the path of the beam. These absorbers were used to eliminate the low energy photons for which the Compton and photoelectric cross sections were high. The background noise was thus appreciably reduced in nuclear emulsions, thereby making studies of triplets possible.

A series of exposures of the plates were made to ascertain the optimum exposure. This was needed to obtain a suitable number of triplets per field of view of the microscope, and at the same time to maintain the signal to noise ratio at such a level as to make the events easily distinguishable for observations. The plates were developed by temperature development technique[7] and were examined by using Leitz Ortholux microscopes. Energy of a photon producing a triplet was determined by estimating the kinetic energy of the tracks by Fowler's coordinate method,[8] taking into account the energy needed for the threshold of triplet production. By convention, the smallest energy of the three partners of a triplet was taken to be the recoil electron. Mostly, the energy of the recoil electron was small and its energy was determined from the range energy relationship.[9] Only in a few cases, the energy of the recoil electron was ascertained from the multiple scattering measurements. For studies of angular distribution between the direction of incident photon and the direction of emission of recoil electron, the angle could be read off with the help of the goniometer attached to the microscope. The estimated total error on the angle was $\pm 5°$.

Typical examples of some triplets are reproduced in Fig. 1.

RESULTS AND DISCUSSIONS

54 433 fields of view of the microscopes were examined. The volume of each field of view was 120 μ ×150 μ×220 μ, yielding a total of 1935 triplets. 1872 triplets were measured. The remaining 63 triplets could not be measured because of their being scattered out of the emulsion.

The theoretical expression for the recoil momentum distribution function for triplet production, as derived by Suh and Bethe in formula (9) of their paper, was used for comparison with our experimental results.[10] The recoil momentum distribution has been calculated from the above theory by evaluating the various expressions with the help of the IBM 650 computer for four intervals of photon energy (i) $E_\gamma = 10$–30 Mev, $k = 39.14$, (ii) $E_\gamma = 30$–50 Mev, $k = 78.28$, (iii) $E_\gamma = 50$–90 Mev, $k = 137$, and (iv) $E_\gamma = 10$–90 Mev, $k = 100$, where k is the energy chosen for the theoretical curve in that interval.

Four graphs are presented in Fig. 2(a)–(d) for the intervals of photon energies mentioned above. The abscissa represents the recoil momentum in dimensionless units whereas the ordinate is the number of events in arbitrary units. The momentum distribution of recoil electron is practically independent of photon energy; for this reason, the number of events observed between the limits 10–90 Mev have been plotted along with the theoretical curve for $k = 100$. Because of the small number of events observed below 10 Mev photon energy no curve has been plotted. Also the number of events for $q > 0.75$ for all energies were too few; for this reason they were not included in the curves.

It can be noted from the four curves that the agreement between the theory and experiment for all intervals of photon energies are satisfactory within experimental error for small values of recoil momentum. However, when the recoil momentum increased, the theoretical distribution curve lies above the experimental points. In this respect our experiment which has been performed with G-5 emulsion is in qualitative agreement with

[4] K. S. Suh and H. A. Bethe, Phys. Rev. **115**, 672 (1959).
[5] E. L. Hart, G. Cocconi, V. T. Cocconi, and J. M. Sellen, Phys. Rev. **115**, 678 (1959).
[6] D. C. Gates, University of California Radiation Laboratory Report UCRL-9390, 1960 (unpublished).
[7] C. Dilworth, G. P. S. Occhialini, and G. Vermaesen, Bull. Univ. Bruxelles, No 13a, (1950).
[8] P. H. Fowler, Phil. Mag. **41**, 169 (1950).
[9] M. A. S. Ross and B. Zajac, Nature **162**, 923 (1948).
[10] We are indebted to C. H. Blanchard for pointing out that the correct expression for $q_{\min}$ should be $[(k+1)/k](Wq_{\min}-1)+2/k$ rather than $Wq_{\min}-1+2/k$ as given by Suh and Bethe.

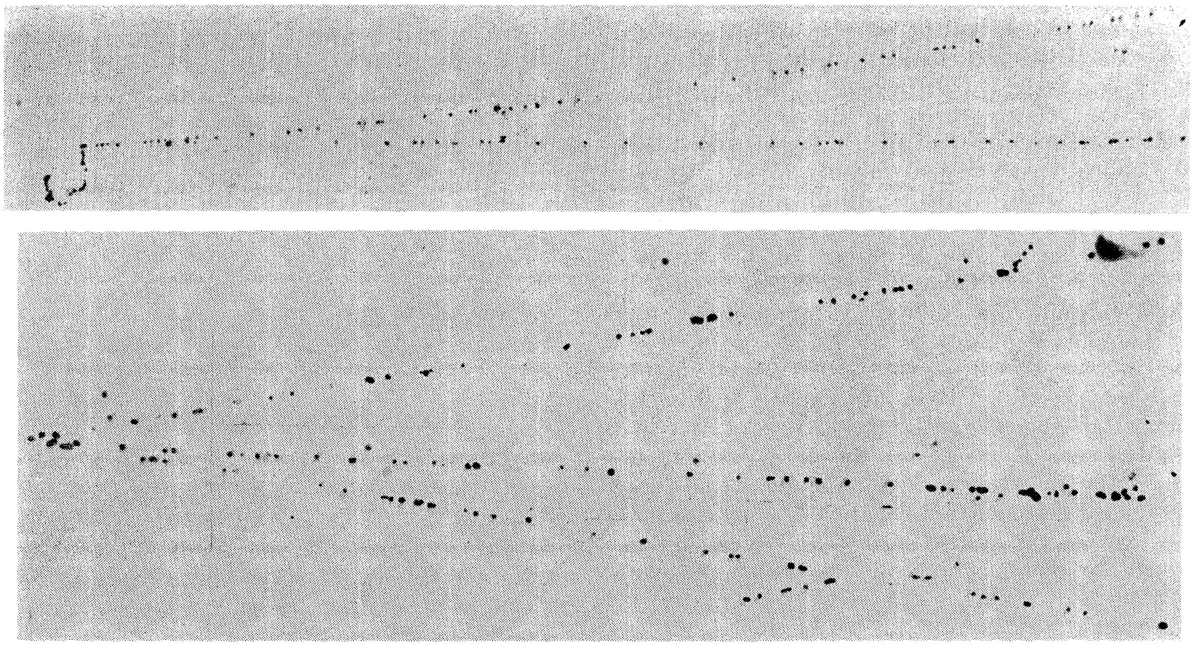

FIG. 1. Typical examples of some triplets.

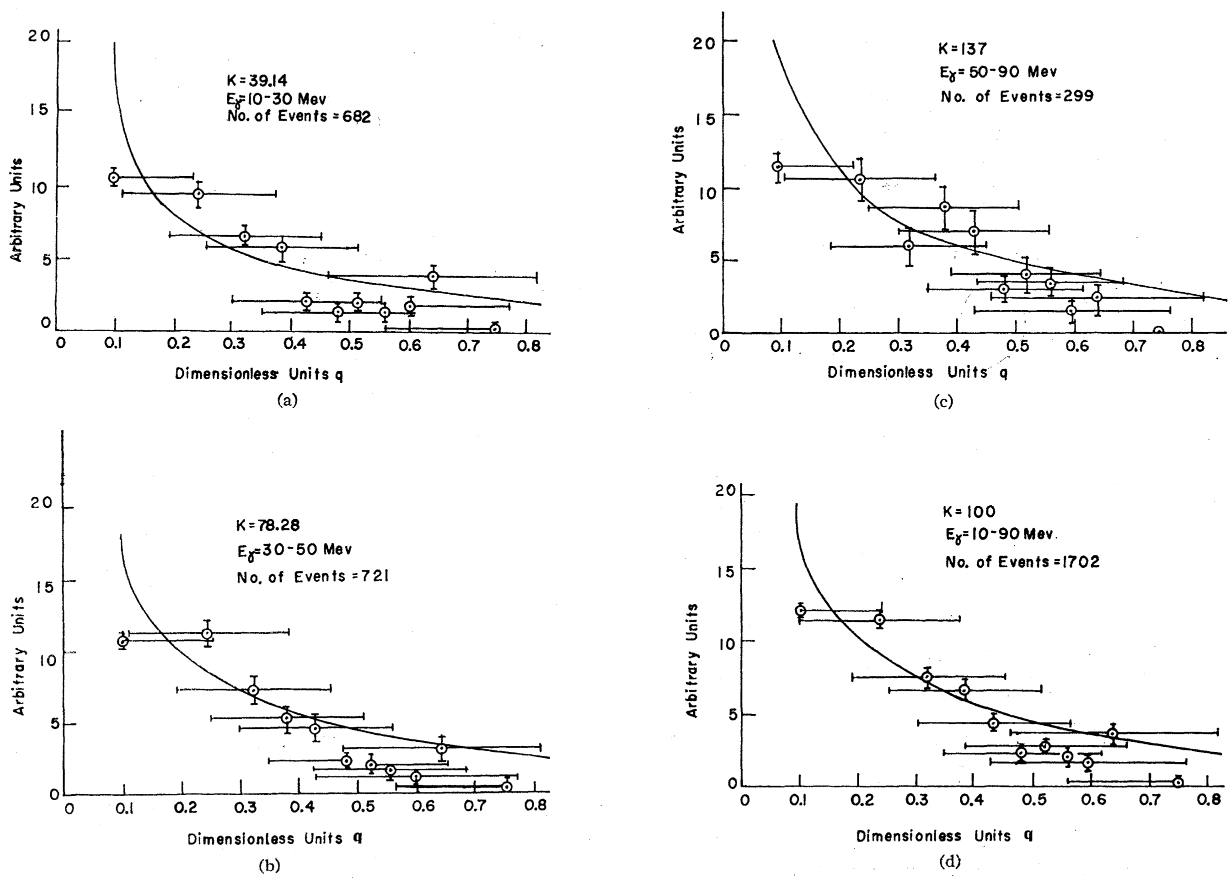

FIG. 2. Energy distributions of recoil electrons. The abscissa represents the recoil momentum in dimensionless units q, whereas the ordinate is the number of events in arbitrary units. The experimental points have been plotted after proper normalization over the whole area with respect to the theoretical curves given by the solid line.

the results obtained by Hart *et al.*, and Gates in hydrogen. One of the possible reasons for this discrepancy with the theory below 100 Mev, as has been pointed out by Hart and co-workers, is due to the exchange effect which has been neglected in the theory. However, it is not certain whether the consideration of exchange effect alone can explain the discrepancy observed at higher recoil momentum.

The angular distribution of recoil electrons is shown in Fig. 3. From the measurement of the projected angle γ and calculating the dip angle from measured range and depth of the track, the cosine of the space angle has been determined from the relation $\cos\delta = \cos\gamma \cos\beta$, where δ and β are, respectively, the space and the dip angle of the recoil electron. Figure 3 gives the curve of number versus space angle δ.

All the events which have been observed for photon energy between 10 and 90 Mev have been combined to plot the curves. This is admissible because the angular distribution is practically independent of photon energy.

If the triplets are produced in the field of free electrons, then from the consideration of kinematics, the recoil electrons must be emitted at angles less than 90°. However, the experimental curve shows nearly equal concentration of points in the forward as well as in the backward direction. This may be due to two factors: (a) scattering of recoil electrons in the emulsion and (b) the effect of binding energy of the recoil electron. It is extremely difficult if not impossible to correct the data taking into account the effect of scattering of very low-energy recoil electrons in the composite elements of the emulsion. The effect of binding energy of the recoil electron on its direction of emission was pointed out by Hart and co-workers. If the energy of the recoil electron is much greater than the binding energy of the atomic electron in whose field the triplets were produced, then the electrons can be considered free in which case most of the recoil electrons should be emitted in the forward direction. These conditions were realized in the experiments of Hart *et al.* and Gates, and also approximately in the present experiment if the recoil electrons of energies ≥ 15 kev are rejected in the plot. A curve was plotted but not reproduced here taking into consideration only those recoil electrons whose energies were ≥ 15 kev. The curve showed that about 77% of the recoil electrons were emitted in the forward direction. However, if the triplets are produced in the field of bound electrons, as would be the case in the present experiment if very low energy recoil electrons are included, then one may expect backward emission.

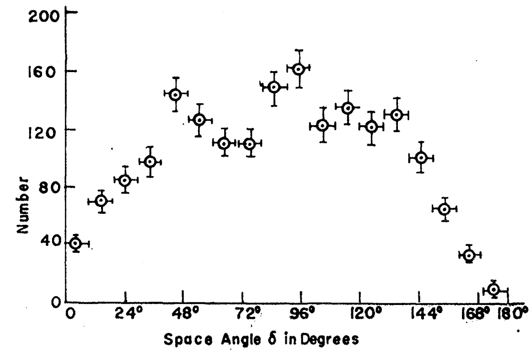

FIG. 3. Angular distribution of recoil electrons. The space angle δ between the direction of emission of recoil electron and incident photon is represented in the abscissa whereas the ordinate gives the number of events.

ACKNOWLEDGMENTS

The authors would like to express their sincere thanks to H. W. Koch and J. M. Wyckoff of the National Bureau of Standards for giving us the facilities for exposures of the nuclear plates and for many discussions. We are indebted to C. H. Blanchard for many helpful discussions. Our thanks are also due to the microscopists, Dorothy Groner, Marie Ventrice, Judy Loftin, Beverly Wilson, Sylvia Levenson, Shashi Krishan, and Olga Kasapyr, for their aid in scanning and in measuring the events.

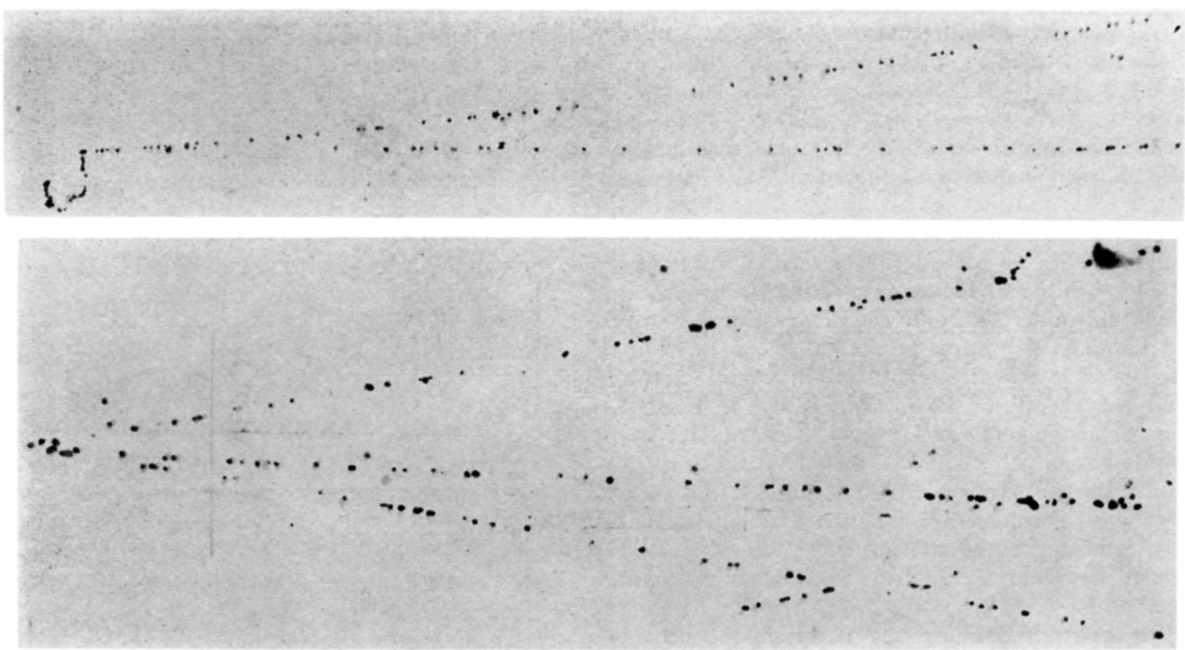

FIG. 1. Typical examples of some triplets.