On the Production of Electron Pairs in the Field of an Electron*,**

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The ratio, $R=\sigma\text{-pairs}/\sigma\text{-triplets}=C(Z^2)_{ef}/Z_{ef}$ for three gases, CH_4, air, and argon, has been studied and C found to be 3.63, 3.97, and 4.11, respectively. The average value of C from these data is 3.92±0.26. The gamma-rays from $F^{19}(p, \alpha)\gamma O^{16}$ were used in this experiment. The measured energies of the gamma-rays as deduced from pairs formed in CH_4 are 6.13±0.06 and 7.12±0.07 Mev. Data on the energy distribution of the low energy negative electron of the triplet are included.

INTRODUCTION

THE production of an electron pair by a gamma-ray has been known for some time. In order that both energy and momentum be conserved, a third particle must be present in this process.

It is known that the threshold energy for pair production is

$$h\nu=2mc^2(1+m/M),$$

where $h\nu$ is the threshold energy, m the rest mass of the electron, and M the rest mass of the particle in whose field the pair is created.

In general, the formation of an electron pair takes place in the field of the nucleus of the absorbing atom. The threshold energy is then approximately $2mc^2$ and the cross section is proportional to Z^2 where Z is the atomic number of the absorbing medium.

Perrin[1] in 1933 suggested the possibility of the formation of an electron pair in the field of an electron. The threshold energy for this case is $4mc^2$. The cross section should be proportional to Z, there being Z electrons about a nucleus of charge Z.

One of the significant differences between these two cases of pair production is that in the former, although the nucleus may take considerable momentum, the energy it receives is small, whereas in the case of pair formation in the field of an electron, the energy of the recoil electrons may be appreciable. In a Wilson cloud chamber the latter process will give rise to a "triplet"—three electron tracks starting at one apex, one positive and two negative (one of the two negative electrons being the electron about which the electron pair was formed).

In 1938 da Silva[2] reported finding one triplet starting in a lead foil. In 1941 Shinohara and Hatoyama[3] observed one triplet which occurred in the gas of a cloud chamber. Groshev[4] looked for triplets while examining pairs produced in nitrogen, krypton, and xenon. While observing 435 pairs, no triplets were found. K. Zuber[5] also looked for triplets in argon and although 142 pairs were found, no triplets were observed.

Ogle and Kruger[6] in 1945 obtained two triplets in a cloud chamber using the gamma-rays from radioactive sodium. Momentum and energy were found to be conserved in both triplets within experimental error.

It was the purpose of this investigation to determine as accurately as possible the ratio of the cross section for pair production in the field of a nucleus to that for triplet production at one gamma-ray energy. Examples of electron pairs and triplets are shown in Figs. 1, 2, and 3.

SOURCE OF GAMMA-RAYS

The source of gamma-rays was obtained by bombarding crystals of CaF_2 by protons accelerated in the cyclotron of thè University of Illinois. The reaction that is believed to occur is as follows:

$$
\begin{array}{l}
{}_9F^{19}+{}_1H^1\rightarrow[{}_{10}Ne^{20}]\rightarrow{}_8O^{16*}+{}_2He^4,\\
\qquad\qquad\qquad\qquad\qquad\downarrow\\
\qquad\qquad\qquad\qquad\quad {}_8O^{16}+h\nu.
\end{array}
$$

The above scheme is necessary since it has been found that the gamma-ray energy is independent of the bombarding energy of the protons.

For some time the gamma-ray spectrum was thought to consist of a single line at 6.4 Mev.[7] Recently, Walker and McDaniel[8] and Rasmussen, Hornyak, and Lauritsen[9] have reported two lines. The reported values including those from this study are given in Table I.

Protons are accelerated in the cyclotron to an energy of 5 Mev. A molecular hydrogen beam could be obtained with the same cyclotron adjustments as for deuterons. During the greater part of the experiment, a 4 μa molecular hydrogen beam, equivalent to 8 μa of atomic hydrogen, was used.

* Assisted by the joint program of the ONR and the AEC.
** Preliminary reports on these data have been given, (a) J. A. Phillips and P. Gerald Kruger, Phys. Rev. **72**, 164 (1947); (b) J. A. Phillips and P. Gerald Kruger, Phys. Rev. **74**, 1259 (1948); (c) J. A. Phillips and P. Gerald Kruger, Phys. Rev. **75**, 1289 (1949).
*** This report is part of a thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy at the University of Illinois, 1949.
[1] F. Perrin, Comptes Rendus **197**, 1100 (1933).
[2] A. M. da Silva, Ann. d. Physik **11**, 504 (1939).
[3] K. Shinohara and M. Hatoyama, Phys. Rev. **59**, 461 (1941).
[4] L. V. Groshev, J. Phys. Acad. Sci. U.S.S.R. **5**, 135 (1941).
[5] K. Zuber, Helv. Phys. Acta **15**, 38 (1942).
[6] W. E. Ogle and P. Gerald Kruger, Phys. Rev. **67**, 282 (1945).
[7] Fowler, Lauritsen, and Lauritsen, Rev. Mod. Phys. **20**, 236 (1948).
[8] R. L. Walker and B. D. McDaniel, Phys. Rev. **74**, 315 (1948).
[9] Rasmussen, Hornyak, and Lauritsen, Phys. Rev. **75**, 1462 (1949).

Large pieces of natural CaF_2 crystals were used as the target. Six inches in front of the CaF_2 target was a "beam shutter" made of copper which normally kept the beam from striking the CaF_2 target. Immediately before an expansion of the cloud chamber this shutter was pulled aside by an air ram.

THE APPARATUS

A 12-in. Wilson cloud chamber operating at a pressure of 1.75 atmos. was used. Since the cyclotron was to be used with the cloud chamber, it was desirable to decrease the cycle time of the chamber as much as possible. James L. Lawson[10] has pointed out that the cycle time of a cloud chamber can be reduced by overcompression. Following his suggestion a second piston was installed, designed so as to allow an overcompression of the main chamber (for a few seconds immediately after an expansion) before coming back to the normal compressed position. This allows the chamber to come to thermal equilibrium earlier than would otherwise occur, and old tracks evaporate faster. Thus, not only has the cycle time of the chamber been reduced but more radiation can be allowed to enter the chamber during each expanison. It has been found that with a normal expansion ratio of 1.19 for methane the overcompression ratio (i.e., normally compressed volume to overcompressed volume) was 1.03 for best performance. This resulted in a decrease of the cycle time of the cloud chamber, methane-filled, from 36 sec. to 23 sec. and permitted operation with twice the gamma-radiation entering the chamber as compared to non-overcompression.

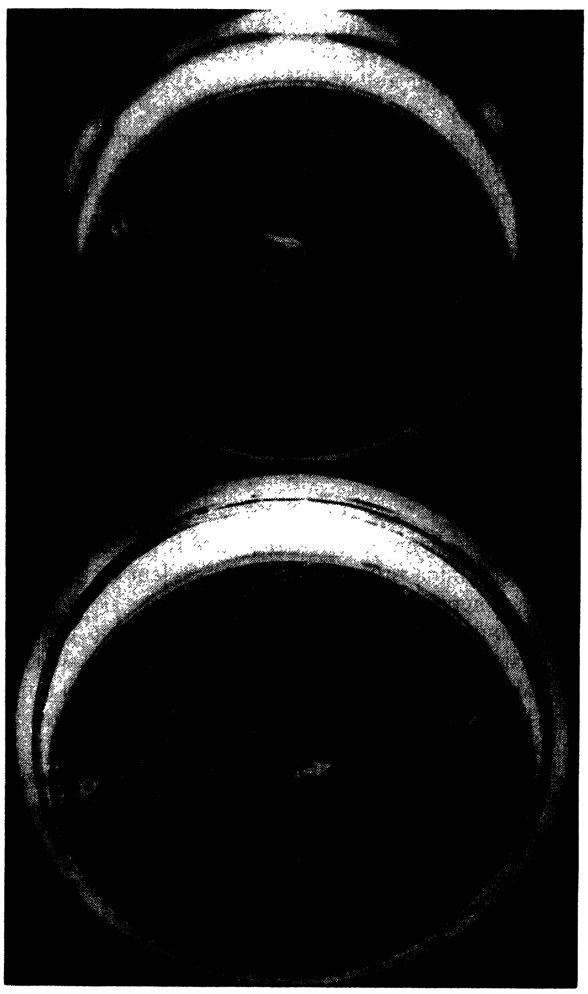

FIG. 1. Two stereoscopic views obtained in a cloud chamber filled with air of an electron pair created in the field of a nucleus. The gamma-rays are incident in the direction of the arrow.

The cloud chamber is provided with two field coils, placed one above the other so as to give a uniform field in the usuable portion of the chamber. A current regulator kept the current (for a few seconds before and during the expansion of the cloud chamber) to within ± 0.5 percent and usually to within ± 0.25 percent of a predetermined value.

The magnetic field was measured by two different methods. Using a super-regenerative detector method of Roberts[11] of measuring a magnetic field with the magnetic moment of the proton, a resonant frequency of 6.895 ± 0.011 mc/sec. was obtained. Using a value for the gyromagnetic ratio of the proton of 2.675×10^4 radians/sec. gauss, the calculated magnetic field was 1619.6 ± 9.1 gauss. Also, a separate determination was made using flip coils and a standard mutual inductance. Averaging the results of the latter method where three coils were used gives 1623 ± 11 gauss. An average value of the two methods (1621.5 ± 7.3 gauss) was used throughout the experiment.

The camera, which was automatic, was provided with an Eastman Kodak Ektar $f/2$ coated lens. Eastman Kodak Super XX 35-mm film was used with an exposure of 1/20 sec. The film gate of the camera was so designed that the film could be repositioned accurately after an exposure in the camera.

A mirror box, between the camera and cloud chamber, allowed stereoscopic pictures of the chamber to be taken during each expansion. Thus, when an exposure is reprojected through the optical system it is possible to determine accurately the position of any track in the cloud chamber.

COLLIMATION OF THE GAMMA-RAYS AND SHIELDING OF THE CHAMBER

The cloud chamber is located outside of the 4-ft. thick water tanks which completely surround the cyclotron as shown in Fig. 4. A 6-in. I.D. pipe extends through the water tank on a line between the target and the cloud chamber. A paraffin plug 3 ft-long and 6 in. O.D. lies inside this pipe at either end of which is a 6-in. long lead plug. Extending through these plugs and

[10] James L. Lawson, private communication.

[11] A. Roberts, Rev. Sci. Inst. 18, 845 (1947).

lined up between the target and the cloud chamber is a 1-in. diameter hole. The 7-in. long target is so tilted that the front faces of the crystals are exposed to this 1-in. hole. A 1-in. diameter hole was machined in the side of the target box in line with the collimator and covered with a 0.005-in. aluminum foil. As neutrons caused a number of recoil protons which badly fogged the chamber, a 4-in. block of paraffin was placed immediately in front of the collimator passing through the water tanks on the cyclotron side.

Appreciable gamma-ray shielding around the chamber was necessary. A partial shield from general radiation from the cyclotron is afforded by the 4-ft. thick water tank in front of the chamber. Two and one-half tons of lead has been placed around the cloud chamber most of which has been concentrated between the water tanks and the cloud chamber with only a small fraction around the sides and backs of the chamber. Satisfactory shielding has been achieved, since, of the several thousand electron pairs observed in the chamber, none were found to lie outside the collimated region.

MEASUREMENT OF GAMMA-RAY ENERGIES

Gamma-ray energies were determined by measuring the energies of electron pairs which were formed in the gas of the cloud chamber. A set of criteria were established and if a pair could satisfy these, measurements of the radii of the electron tracks were made. The criteria to be satisfied for the acceptance of a measurable pair were as follows:

(a) Both electron tracks, one positive and the other negative, must be of the same age and density and have a sharp and clearly defined apex.

(b) Both electron tracks had to lie within 10° of the plane of the cloud chamber which is perpendicular to the magnetic field.

(c) Each track of the pair must have no obvious large angle single scattering unless the track was long enough to obtain a good measurement without including the scattered region.

The measurement of a pair consisted in reprojecting the photograph through the camera and mirror system used to take the picture. The two stereoscopic images (one the direct view and the other the reflected view from the mirror) were observed through a ground glass screen. By manipulating the ground glass screen the two images could be made to coincide and thus, if no errors were present in the system, the original position and shape of the track in the cloud chamber could be determined.

Several tests have been carried out to determine with what accuracy the optical system could reproduce a given set of circles. A system of circles was photographed, reprojected, and measured. Measurements made a few weeks after processing, when the film was completely dry, showed that the optical system could reproduce a circle to within an accuracy of ± 0.5 percent.

A measuring engine has been used by which the sagitta for a given cord of a circle can be measured. These data are then sufficient to determine the radius of curvature. The practice which has been followed in measuring the energies of electron tracks is to measure the sagitta of each track five times for each of 2 cords. These measurements are repeated several days later. Thus four values for the radius of curvature of each track are obtained. If a measurement cannot be repeated to within at least 3 percent, the pair has been discarded. Pairs will then be discarded if the film cannot be repositioned in the camera or if large angle single scattering is treated differently in the two sets of measurements.

A serious limitation to this method of gamma-ray energy determinations is the small angle scattering which occurs in the gas of the cloud chamber. To obtain an estimate of the probable error introduced by scattering the treatment of Rossi and Greisen[12] has been used

FIG. 2. A photograph of an electron pair created in the field of an electron. The direction of the gamma-ray is shown by the arrow and one of the two negative electrons is the electron in whose field the pair was formed.

[12] B. Rossi and K. Greisen, Rev. Mod. Phys. 13, 268 (1941).

TABLE I. Gamma-ray energies from $F^{19}(p, \alpha)\gamma O^{16}$.

Walker and McDaniel	6.13±0.06 Mev	6.98±0.07 Mev
Rasmussen, Hornyak, and Lauritsen	6.16±0.04 Mev	7.06±0.06 Mev
Authors	6.13±0.06 Mev	7.12±0.07 Mev

Their results have been verified by Smith and Kruger[13] within experimental error.

MEASURED ENERGIES OF THE GAMMA-RAYS

Eighty-seven electron pairs in CH_4 were found to satisfy the above selection criteria. Each pair was measured as has been described. A histogram of the distribution of energies of the pairs is shown in Fig. 5. It appears that there are two gamma-ray lines. Averaging the energies of the individual pairs in each peak, the energies 6.13±0.06 and 7.12±0.07 Mev are obtained. The assigned errors have been determined by considering the probable error in the magnetic field measurement, non-uniformity of the magnetic field in the plane of the chamber, reproducibility of tracks by the optical system, and the probable error from the mean of the energies of the individual electron pairs.

The number of pairs under the 6.13-Mev peak is 30 and under the 7.12-Mev peak there are 57 pairs. The cross section[14] for pair production at 6.13 Mev is $1.37\times10^{-27} Z^2$ and at 7.12 Mev is $1.57\times10^{-27} Z^2$. Thus, correcting for the cross sections at these energies, the 7.12-Mev line is about 1.7±0.4 times as intense as the 6.13-Mev line at a bombarding energy of 5 Mev.

Early in this investigation**[(a)] two strong lines with some evidence for three weaker lines were reported from measurements of 40 electron pairs formed in air. Subsequently, the magnetic field was remeasured as described above and found to be higher than had been previously determined.

Two of these lines, when corrected by use of the more accurate magnetic field value, agree with the data here presented, but it appears that small angle scattering in air is sufficient to make this gas unreliable for electron energy determinations.

DETERMINATION OF THE RATIO OF PAIR TO TRIPLET PRODUCTION

From the present experiment, in agreement with others, the gamma-ray energies from $F(p, \alpha)\gamma O$ lie between 6 and 7 Mev. Since the ratio of the cross sections for pair and triplet production is not expected to vary widely over this interval, the energy of each pair and triplet has not been measured. Thus only the total number of pairs and triplets observed are considered sufficient to determine the ratio of the cross sections for a gamma-ray energy of about 6.5 Mev.

The criteria for a countable pair were as follows:

(a) Two electron tracks of the same age appear to start at a single point in both stereoscopic views, the curvature of the tracks being such that one would have been made by a positron and the other by a negative electron.

(b) The density of the two electron tracks must be constant along the tracks near the apex.

(c) The region immediately about the apex must be free of other tracks such that if there were another electron track leaving the apex it would of a certainty be observed.

The criteria for a countable triplet were similar:

(a) Three electron tracks of the same age must start from a single point, the curvature of the tracks being such that if all three tracks originated at the apex one would be a positive electron and the other two negative electrons.

(b) The density and sharpness of the three electron tracks must be the same and constant along the track near the apex in so far as the relative energies of the three electrons allow.

(c) When reprojected through the camera and mirror system and observed by means of a ground glass screen the three tracks must be seen to converge and meet at a single point.

FIG. 3. An example of an electron pair created in the field of an electron in which one of the negative electrons had low energy. The gas of the cloud chamber is air and the magnetic field is 1622 gauss.

[13] L. W. Smith and P. Gerald Kruger, Phys. Rev. **72**, 357 (1947).
[14] W. Heitler, *The Quantum Theory of Radiation* (Oxford University Press, London, 1936), p. 200.

The pictures were all examined twice by means of a Spencer delineascope. Any doubtful pair was examined by a magnifying lens or reprojected through the camera and mirror system and examined more critically.

DETERMINATION OF $(Z^2)_{ef}/Z_{ef}$

Three gases (methane, air, and argon) were used in the present experiment. The ratio $(Z^2)_{ef}/Z_{ef}$ for each gas was calculated per molecule of the gas; for example, in methane the effective Z^2 for the production of pairs per molecule will be 40 (36 for the carbon atom and 1 for each of the four hydrogen atoms). The total number of electrons in each molecule is ten. Hence, if the cross section for pair production is purely additive, the ratio of $(Z^2)_{ef}$ to Z_{ef} for methane will be 40/10 or 4. Throughout the experiment a 50:50 mixture by volume of alcohol and water was used. At 20°C the vapor pressure[15] of alcohol is 2.19 cm Hg and of water 1.46 cm Hg. When the presence of these vapors are included the effective Z^2/Z for each gas was calculated to be as shown in Table II.

RESULTS FOR THE RATIO OF PAIR TO TRIPLET PRODUCTION

The data that were obtained for the three gases are shown in Table III.

From these data a weighted average of 3.92 ± 0.26 Z^2/Z is obtained for the ratio of pair production in the field of a nucleus to pair production in the field of an electron.

Six hundred and sixteen pictures were taken with hydrogen in the cloud chamber and 728 pictures with helium. The sensitive time of the chamber when filled with these gases was found to be so short that the number of pictures necessary to obtain enough triplets to determine the cross section for triplet production with some accuracy was so large as to make the use of these gases impractical.

SOURCES OF ERROR

(1) There was some concern as to whether a few triplets would be missed and counted as pairs owing to the low energy negative electron having such a small energy that its range would not be long enough to be detected in the cloud chamber. A simple calculation, however, from the conservation of energy and momentum shows that the minimum energy this electron may have is $2\ mc^2(mc^2/h\nu)^2$. At a gamma-ray energy of 6.5 Mev this corresponds to an energy of about 6 kev which will have a range of about 0.2 cm in the cloud chamber. An electron of this range is probably just too short to be observable. The lowest energy negative electron of a triplet observed had an energy of about 20 kev with a range of 0.65 cm. As triplets having a track of 0.5 cm in length should be easily seen it is believed that there is not an appreciable number of triplets having a track too short to be seen.

[15] N. Das Gupta and S. K. Ghosh, Rev. Mod. Phys. 18, 280 (1946).

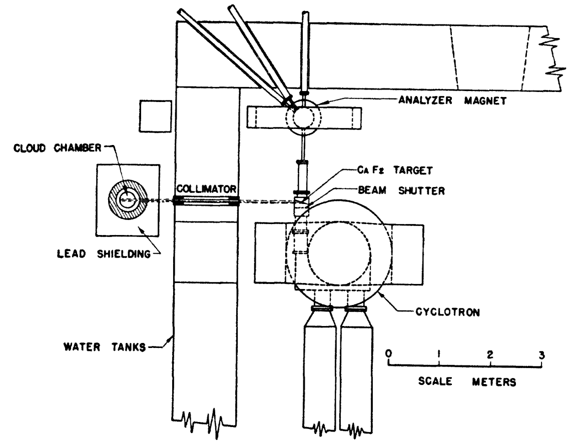

FIG. 4. A schematic diagram showing the location of the cloud chamber with respect to the cyclotron. A 1-in. hole through lead plugs in the water tanks surrounding the cyclotron collimates the radiation from the target.

(2) Selections of triplets are based only on observations made on the projected image of the triplet by the optical system. To satisfy the selective criteria the tracks would have to be sharp and distinct, especially near the apex with the region immediately about the apex free from all other tracks. With so many variables affecting the operation of a cloud chamber it is difficult to keep the quality of tracks unchanged over long periods of time. There may have been a few real triplets which were rejected as there was some doubt as to whether the tracks met at a point or crossed due to fuzzy broad tracks. Since any doubtful triplet was discarded, the number of triplets accepted is probably too small rather than too large. The number of triplets about which there was some doubt was about 1 percent of the total number of triplets.

(3) There is a possibility that a pair and a photoelectric or Compton electron may start so close together that they might appear to form a triplet. In order to estimate the probability of this happening, the number of photoelectric and Compton electrons in each of several expansions were counted. A cylindrical volume about the apex of a pair 1 mm in diameter and 2 mm long was defined as that volume such that if a photoelectric or Compton electron started in this region a possible "confusable" triplet would result. The data on this point for the three different gases is shown in Table IV.

The probability of a "confusable" triplet is still smaller than that shown in Table IV. Here the average total number of photoelectric and Compton electrons appearing per picture were used. Many of the photoelectric and Compton electrons are of so high an energy that if one such electron appeared in a "confusable" region the triplet would be discarded since it would obviously have too high a total energy. Again, the

TABLE II. Calculated $(Z^2)_{ef}/Z_{ef}$ for the gases used in the cloud chamber corrected for alcohol and water vapors.

Gas	$(Z^2)_{ef}/Z_{ef}$
Methane	4.07
Air	7.35
Argon	17.7

TABLE III. Data obtained for the determination of the ratio of pair to triplet production.

Gas in cloud chamber	CH_4	Air	Argon
Total number of pictures	13,362	19,295	11,672
Total number of pairs	1,430	3,441	6,484
Total number of triplets	97	118	89
$(Z^2)_{ef}/Z_{ef}$	4.07	7.35	17.7
$\frac{\sigma\text{-pairs}}{\sigma\text{-triplets}}\left(\frac{Z_{ef}}{(Z^2)_{ef}}\right)=C$	3.63±0.41	3.97±0.41	4.11±0.53

TABLE IV. Data for the determination of the possible number of "confusable" triplets.

Gas in cloud chamber	CH_4	Air	Argon
Number of photoelectric or Compton electrons per picture	7.0	9.22	16.2
Percent of total pairs that might form a confusable triplet	0.012	0.016	0.028
Percent of triplets which might be a confusable triplet	0.18	0.46	2.0

photoelectric and Compton electrons were of all ages and densities while in an acceptable triplet the ages and densities of all three tracks must be the same. Therefore, the probable number of "confusable" triplets in air and methane are negligible and in argon might be as high as 1 percent of the total triplets observed.

ENERGY DISTRIBUTION OF THE RECOIL ELECTRON

Measurements have been made on the energy of all the low energy negative electrons of the triplets observed in CH_4 and air. This proved difficult since only a small fraction of these tracks can be expected to lie in the plane of the chamber perpendicular to the magnetic field. Also, these tracks, caused by slow electrons, will suffer appreciable scattering in the gas of the chamber. In general, the energy was determined by measuring the radius of the track in the plane of the track which approximated its curvature most closely. The angle of the plane of the track with the direction of the magnetic field was measured and the component of the magnetic field perpendicular to this plane calculated. (This is an approximation since such a track in reality is a helix. A detailed analysis, however, was impossible since most tracks were short—the usable portion of the chamber being only $1\frac{1}{4}$ in. high.) The lowest energy electrons were measured by range if it was certain that the entire track could be seen. Range energy relationships of Das Gupta and Ghosh[16] were used. It is estimated that the measured energies are correct to within about 50 percent for electrons having energies between 20 and 500 kev and about 30 percent for those electrons having energies above 500 kev. The results of these measurements are shown in Table V and Figs. 6 and 7.

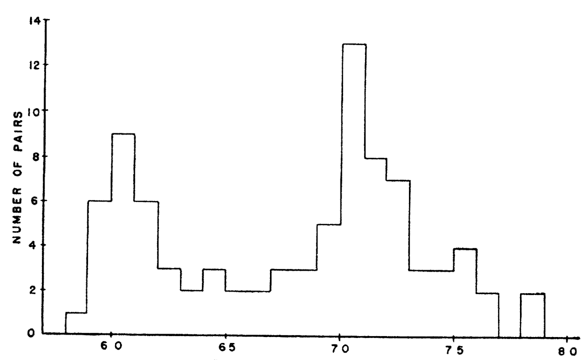

FIG. 5. A histogram of the distribution of energies of electron pairs formed in the gas of the cloud chamber.

CONSERVATION OF MOMENTUM

Since it is possible to observe all the particles taking part in the formation of a triplet (the direction and energy of the gamma-ray known from the collimation of the radiation and measurements of the energies of the three electrons), it should be possible to show that momentum is conserved in the process. There were 25 cases in which this measurement was attempted. A life-size enlargement was made of the triplet through the original optical system. From this enlargement the centers of the circles which most closely approximated the tracks of the electrons were determined. Then the angles at which the electrons left the apex were measured.

Since in most cases the energy of the low energy electron is small and the effects of scattering on angles and energy measurements so large the results are not very significant. The triplets measured show a large spread in energies, and in many cases just as good agreement could be made with the known gamma-ray energies if the energy of the low energy negative electron were ignored. About the most that can be said is that momentum is conserved within experimental error, but as a criterion for the selection of triplets formed in a cloud chamber, conservation of momentum is impossible.

DISCUSSION OF RESULTS

1. Energy and Intensity of the Gamma-Rays

There seem to be two gamma-ray energy lines when CaF_2 is bombarded with 5-Mev protons—one at 6.13 ±0.06 Mev and the other at 7.12±0.07 Mev. The ratio of the intensities of these lines from these data is about

[16] N. R. Das Gupta and S. K. Ghosh, Rev. Mod. Phys. 18, 225 (1946).

TABLE V. Measured energies of the low energy negative electron of triplets formed in methane and air.

(Three triplets have E_{min}^- tracks not measurable.)

		Methane		
0.020 Mev	0.057 Mev	0.15 Mev	0.28 Mev	0.54 Mev
0.027	0.061	0.15	0.29	0.64
0.030	0.062	0.15	0.30	0.68
0.030	0.063	0.15	0.30	0.74
0.031	0.070	0.16	0.30	0.75
0.031	0.074	0.16	0.30	0.81
0.034	0.080	0.16	0.31	0.83
0.034	0.080	0.17	0.32	0.87
0.034	0.083	0.17	0.32	0.95
0.035	0.084	0.17	0.33	0.97
0.036	0.084	0.17	0.38	1.00
0.038	0.098	0.18	0.39	1.11
0.039	0.098	0.18	0.39	1.36
0.040	0.10	0.19	0.39	1.56
0.044	0.11	0.19	0.40	1.59
0.050	0.11	0.20	0.42	1.60
0.052	0.11	0.21	0.42	1.80
0.054	0.11	0.25	0.42	
0.054	0.12	0.26	0.45	
0.056	0.12	0.27	0.50	
		Air		
0.022 Mev	0.073 Mev	0.16 Mev	0.28 Mev	0.49 Mev
0.023	0.087	0.17	0.29	0.49
0.025	0.089	0.18	0.29	0.50
0.027	0.092	0.19	0.29	0.54
0.027	0.093	0.19	0.30	0.58
0.035	0.095	0.19	0.30	0.59
0.037	0.095	0.20	0.30	0.61
0.038	0.099	0.20	0.30	0.62
0.042	0.10	0.20	0.32	0.64
0 044	0.10	0.20	0.33	0.67
0.048	0.11	0.22	0.34	0.68
0.049	0.11	0.22	0.34	0.72
0.049	0.11	0.23	0.34	0.76
0.056	0.12	0.23	0.34	0.77
0.056	0.12	0.23	0.36	0.78
0.059	0.12	0.24	0.37	0.78
0.060	0.12	0.24	0.37	0.81
0.061	0.12	0.24	0.37	0.90
0.066	0.13	0.26	0.38	0.93
0.069	0.14	0.26	0.39	0.99
0.069	0.14	0.26	0.40	1.07
0.069	0.16	0.26	0.40	1.17
0.070	0.16	0.26	0.43	1.92

TABLE VI. The ratio of the intensities of the two gamma-ray lines when CaF_2 is bombarded with protons as a function of the bombarding energy.

Observer	Bombarding energy	$I_{7.1}/I_{6.1}$
Walker and McDaniel	0.45 Mev	0.044
	0.70	0.17
	1.15	0.38
Goldhaber*	2.6	~1.0
Authors	5.0	1.7±0.4

* G. Goldhaber, Phys. Rev. **74**, 1725 (1948).

1.7±0.4 (see above). The ratio of the intensities of the two lines in the present data compared with the results of other observers is shown in Table VI.

2. Cross Section for Triplet Production

At a gamma-ray energy of about 6.5 Mev the ratio of the cross sections for the production of a ± electron

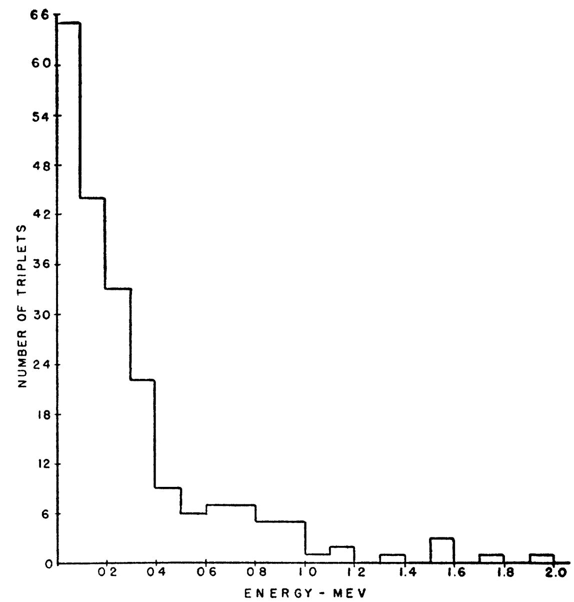

FIG. 6. The distribution of measured values of the kinetic energy of the low energy negative electron of triplets formed in air and methane.

pair in the field of a nucleus to that in the field of an electron from the data here presented is 3.92±0.26. Within statistical limits the ratio of the cross sections is proportional to Z^2/Z of the absorbing medium.

Several calculations[17] have been made of the total cross section for triplet production as a function of energy. The results differ markedly from each other and none are in good agreement with the value obtained in the present experiment. It appears that this experiment

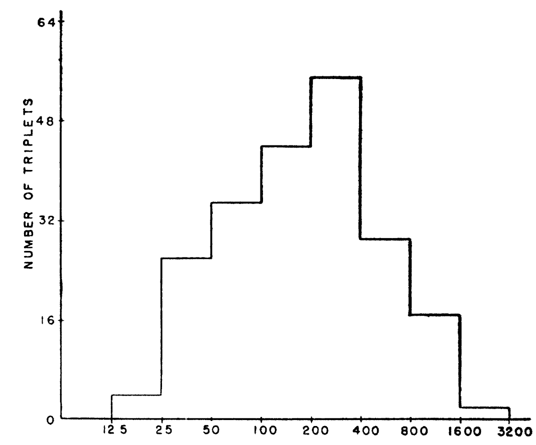

FIG. 7. The distribution of measured values of the kinetic energy of the low energy negative electron of the triplets plotted in equal logarithmic energy intervals.

[17] (a) K. M. Watson, Phys. Rev. **72**, 1060 (1947). (b) A. Borsellino, Nuovo Cimento **IV**, 1 (1947). (c) P. Nemirovsky, J. Phys. Acad. Sci. U.S.S.R. **11**, 94 (1947). (d) V. Votruba, Phys. Rev. **73**, 1468 (1948).

must await further theoretical attention before a valid comparison with theory can be made.

3. Energy Distribution of the Low Energy Negative Electron

It appears from the measurements of the low energy negative electron of the triplet that the main part of this process is connected with small momentum transfer to the recoil electron. This is in agreement with predictions of Bethe,[18] Votruba, and Nemirovsky.

ACKNOWLEDGMENTS

The authors are grateful to Professor H. A. Bethe for valuable discussions during the course of this experiment. They also express their thanks to Mr. E. Hahn for helpful assistance in making the magnetic field measurement.

[18] H. A. Bethe, Proc. Camb. Phil. Soc. **30**, 524 (1934).

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Neutron Production at Mountain Altitudes*

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The rate of production of neutrons by cosmic rays was measured at 3510 meters elevation in lead, aluminum, and paraffin, and in paraffin at 1640 meters elevation by means of an ionization chamber filled with boron trifluoride. The variation with elevation for production in paraffin differs slightly from that in the heavier elements, but agrees well with observations by other observers of the production in air at higher altitudes and with the variation of extensive showers. The neutrons are produced with a larger multiplicity in lead than in paraffin. Comparison with measurements of star production in photographic plates results in the value of 3 to 6 neutrons per star. Bursts of ionization resulting from other cosmic-ray phenomena were also observed.

INTRODUCTION AND APPARATUS

DURING the spring of 1948 measurements were made[1] of the rate of production of cosmic-ray neutrons in several materials at sea level. The experiment was so designed that absolute rates of neutron production could be accurately calculated from known nuclear cross sections, both total and capture, for the elements used. The detector consisted of a cylindrical ionization chamber filled to atmospheric pressure with boron trifluoride gas of standard isotopic composition. Bursts of ionization in the chamber were caused by α-particles produced in the reaction $B^{10}+n=Li^7+\alpha$. The chamber was placed at the center of a pile of material consisting of approximately equal amounts by weight of paraffin and of the element to be investigated, distributed homogeneously. Enough paraffin was used so that only neutrons formed within the pile were able to reach the ionization chamber and be detected. The ionization chamber was furnished with "guard rings" constructed of borax and other chambers filled with boron trifluoride, so that the calculation of the number of neutrons diffusing into the chamber and being captured was reduced to a one-dimensional problem with axial symmetry which could be solved rigorously. The ionization chamber was connected to an electrometer tube with a balanced amplifier. The output voltage was applied to a galvanometer which produced a trace on moving photographic paper. Thus the size of the ionization pulse in the chamber could be measured. The background was determined by surrounding the chamber with a layer of borax within the pile of paraffin. For further details of the experimental arrangement, reference should be made to the thesis mentioned. Since the rates to be reported here depend on the nuclear cross sections chosen, these values are reproduced in Table I.

OBSERVATIONS

During the summer of 1948 the sea level observations were extended by others taken in Colorado at Denver, 1640 meters elevation, atmospheric depth 865 g/cm^2, magnetic latitude 48.5°N and at Climax, 3510 meters elevation, atmospheric depth 675 g/cm^2, magnetic latitude 48.1°N. The experiments were performed in a truck with a light roof of approximately 1.3 g/cm^2 thickness in open areas.

The direct result of the observations is a set of curves giving the rate of occurrence of pulses of a given size in the ionization chamber. Figure 1 shows three such curves taken at Climax. The abscissas are given in arbitrary units (a deflection of $\frac{1}{32}$ inch on the photographic paper) and the ordinates are rates per hour of occurrence of pulses per unit interval of size. The highest curve shows the observations obtained when the pile contained 517

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[1] A. R. Tobey, Ph.D. thesis, Yale University (1948); Phys. Rev. **75**, 894 (1948).

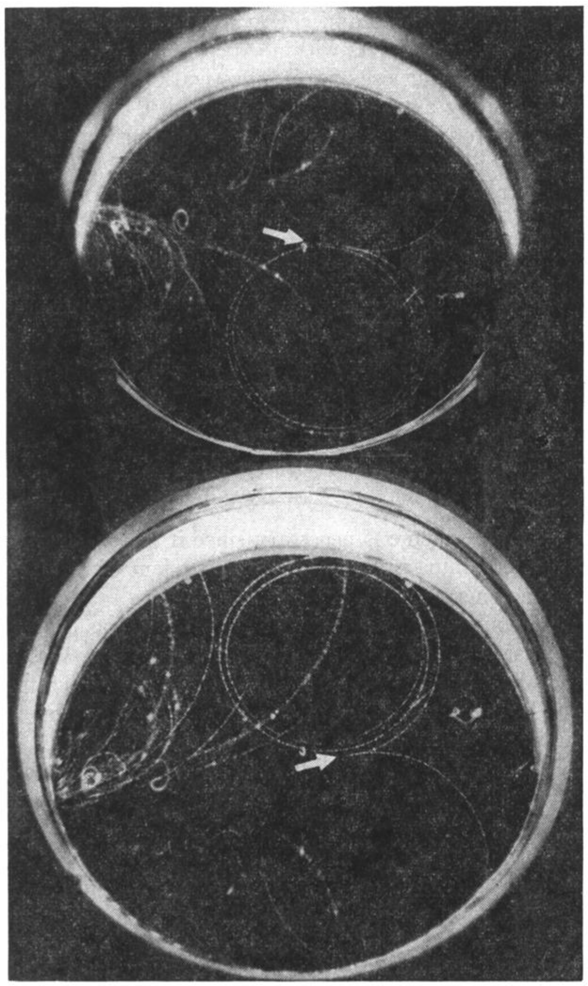

FIG. 1. Two stereoscopic views obtained in a cloud chamber filled with air of an electron pair created in the field of a nucleus. The gamma-rays are incident in the direction of the arrow.

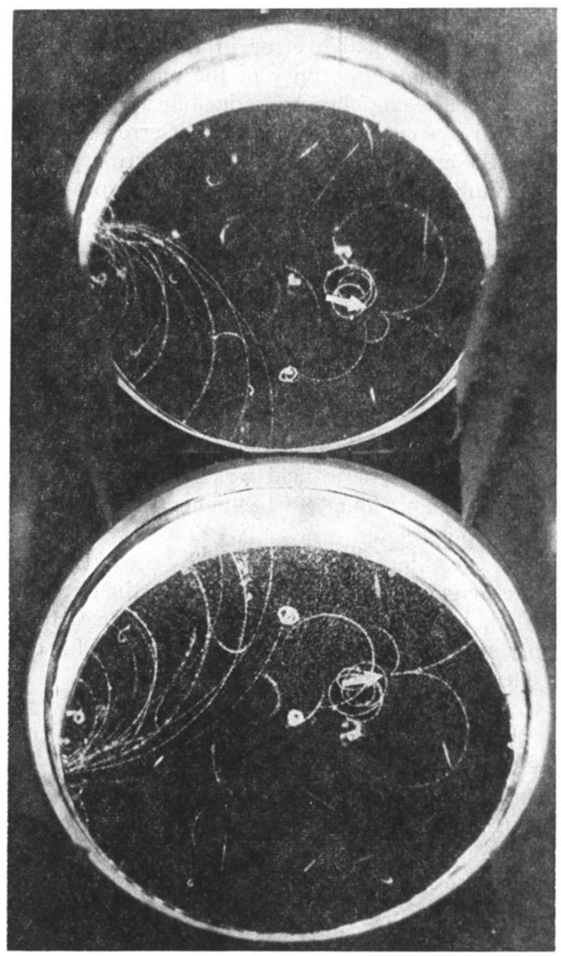

FIG. 2. A photograph of an electron pair created in the field of an electron. The direction of the gamma-ray is shown by the arrow and one of the two negative electrons is the electron in whose field the pair was formed.

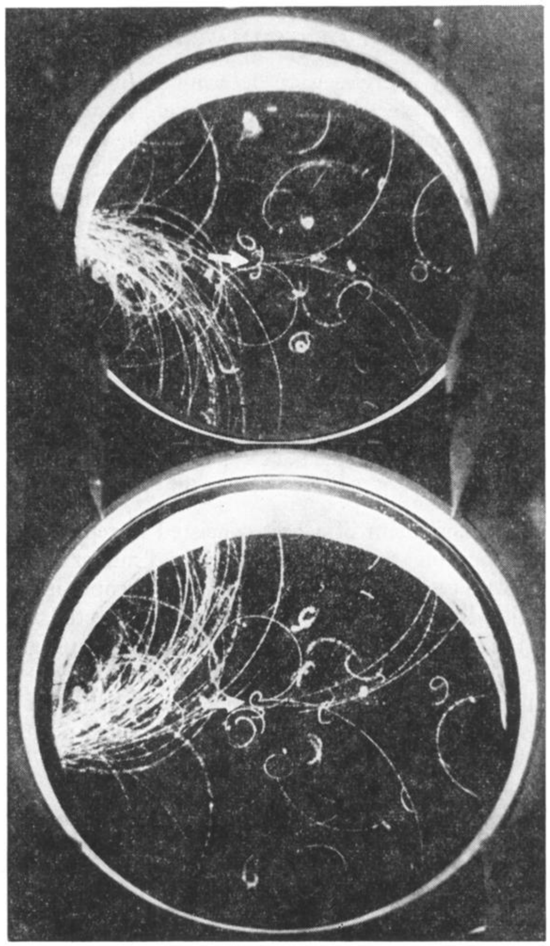

FIG. 3. An example of an electron pair created in the field of an electron in which one of the negative electrons had low energy. The gas of the cloud chamber is air and the magnetic field is 1622 gauss.