PHYSICAL REVIEW A VOLUME 15, NUMBER 3 MARCH 1977

Differential and cumulative integral cross sections of electron-field pair production: Experimental study at 2.614 MeV using a streamer chamber*

J. Augerat, M. Avan, M. J. Parizet, G. Roche, J. Arnold, J. Fargeix, and A. Fleury†
Laboratoire de Physique Nucléaire, Université de Clermont, Bôite Postale 45, 63170 Aubière, France
(Received 8 June 1976)

The cross sections for electron-field pair production by photons (triplets) are studied in helium and in two helium-neon mixtures with a streamer chamber at an incident photon energy of 2.614 MeV. The streamer chamber is triggered by the coincidence between the electron and the positron detectors. The chamber is located between two Helmholtz coils giving a magnetic field of 300 G. A detailed analysis of the false triplet events is performed by using new kinematical criteria. The results are the following: (1) Experimental differential energetic distributions for the two electrons and the positron are consistent with those recently calculated by Mork and Haug. (2) These cross sections are very different for pair and triplet production. (3) Differential angular cross sections agree with the distribution predicted by Mork and Haug. (4) The measured cumulative integral cross sections in helium and in the helium-neon mixtures, compared with Mork and Jarp's theoretical predictions and within experimental uncertainties, are consistent with the total cross section of 12.8 μb/electron predicted by Mork and Haug. (5) An upper limit for the total multiplet cross section in Ne was determined to be 10^{-8} b/electron.

I. INTRODUCTION

The theory of electron pair production (e^+, e^-) by unpolarized photons incident on free electrons or a charged particle is completely developed in quantum electrodynamics. However, the formal complexity of the equations has led theorists to make simplifying assumptions which limit the validity of the results. Moreover, experimental studies are always performed with atomic electrons. Exact calculations must take into account the following effects: (1) The γ-e interaction between the photon and the electron, in the field of which the pair is created, (2) an exchange effect due to the presence of two identical electrons in the final state, (3) atomic binding of the electron in the target atom, (4) the Coulomb correction and screening effect of the nucleus and the other electrons, (5) radiative corrections.

Theoretical and experimental works on this subject are presented in detail by Mork,[1(a)] Motz, Olsen, and Koch,[2] and Joseph and Rohrlich.[3]

In the recent theoretical calculations by Mork[1(b)] and Haug[4] for free electrons, the γ-e interaction and exchange effect are taken into account; binding and screening can be evaluated in our experimental conditions by a study of the minimum recoil momentum and the impact parameter. Mork[1(b)] gives exact total cross section near threshold and also differential cross sections on all parameters for photon energies (in units of mc^2, m being the electron rest mass) of 4.4, 5.12 (2.614 MeV), 7.0, and 10.

For low photon energies, the minimum recoil momentum is close to mc and the impact parameter is very small, of order λ_0 (the Compton wavelength). The interaction area is very near the initial electron, where its field is dominating. In this case, the screening effect of the nucleus and the effect of the other electrons can be neglected for the triplet process at 2.614 MeV, and Mork's calculations are valid. Two other effects should be considered: the Coulomb corrections are not important for triplets at all energies, and radiative corrections[1] are expected to be small.

Only one experiment using a visual detector has been performed near threshold[21]; the two analyzed events cannot allow a detailed analysis of the cross sections. The lack of experiment near threshold is due to the difficulties in detecting and analyzing the low-energy electrons and also because the triplet cross section is small compared to the other interaction cross sections.

The aim of the present experiment is to investigate the energy range near the threshold where γ-e and exchange effects are important.

The crucial point of an experiment with a visual detector is the distinction between pairs and triplets, which depends upon the detection of the three electrons of the triplets at low photon energies and essentially the recoil at high energy. Generally at high energy only a fraction of the triplets can be detected. In our streamer chamber (helium at normal conditions), an electron with the minimum recoil momentum (kinetic energy $T = 77.8$ keV) gives a track length of 52 cm which is large enough to allow a good momentum measurement. Hence in our case (a photon energy k of 2.614 MeV and helium gas) all triplets are measurable.

We introduce a new method for the analysis of individual triplet events. Kinematical relationships reported by Motz, Olsen, Koch, and Mork applied to our experimental conditions have been used to establish discrimination criteria of real and false triplet events. These criteria are necessary for a fine study of the experimental differential cross sections if the number of triplets is small compared with the number of pairs (if the photon energy is small and close to threshold or the atomic charge Z large). In our experiment, kinematical criteria can be applied to each individual event.

In Sec. II of this paper, we present a brief description of the apparatus–the streamer chamber, trigger, and driving system. In Sec. III, we give the new method of analysis for real and false triplet events and the experimental use of it. Section IV contains the experimental differential and cumulative cross sections and their comparison with the theory.

II. APPARATUS

Figure 1 shows the general arrangement of this experiment: pairs and triplets are produced in the helium gas of the streamer chamber. The electronic driving system associated with the chamber has been previously described by Roche *et al.*[5]

Most triplet experimental studies use a bremsstrahlung spectrum; for more accurate studies a monochromatic photon beam is necessary. Near

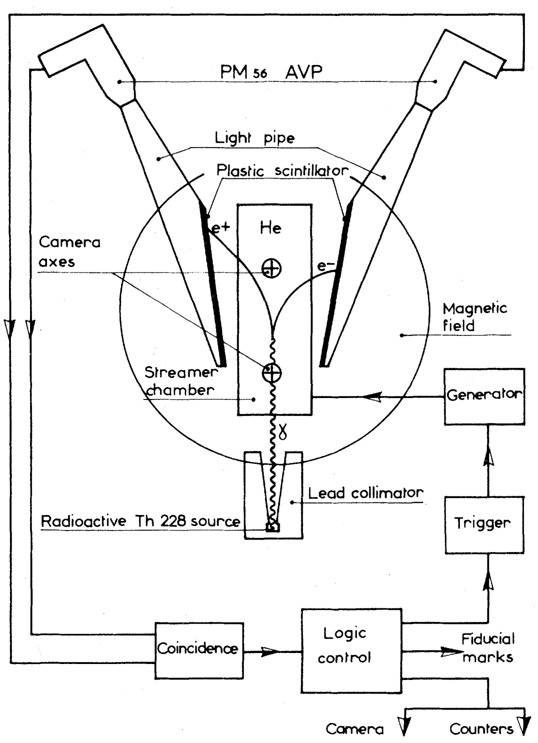

FIG. 1. General experimental setup.

threshold, radioactive sources give γ rays of well-known energy; we have chosen a thorium 228 source of 200 mCi with γ rays of maximum energy 2.614 MeV (Tl 208) and intensity of 35.9%, the other γ lines are under the triplet threshold.

A lead collimator with a conical drilled hole determines the photon beam and attenuates by a factor 10^6 the photons emitted toward the plastic scintillator detectors, the electrodes and the walls of the chamber. After passing through the hole, the γ spectrum contains only one line above 2.04 MeV. Outside the beam, no pair or triplet event was found, hence the shielding given by the collimator was deemed adequate.

A gaseous target is necessary for low momentum analysis; we selected pure helium or a mixture of helium (95%) and neon (5%) (called neogal 5). The use of neogal 5 minimizes the corrections due to impurities, and with this type of gas bright, good-quality (small length parallel to the electric field, small diameter) streamers can be obtained more easily for a given electric field and pulse than in pure helium. Because the electron-field pair production cross section per atom is proportional to Z, while nuclear-field pair production is proportional to Z^2, the gas purity inside the chamber is essential. In the working conditions, the results of the gas analysis with a mass spectrometer are given in a previous paper by Roche *et al.*[6] With the results of the gas analysis we found a correction of 3% for the triplet total cross section and 9% for total pair cross section in helium. In neogal 5, the results are 2% and 4%. In the study of differential cross sections, it is not possible to differentiate the triplets caused by electrons from impurities (oxygen or nitrogen) from the triplet events in the field of electrons in helium. This is not important because these electrons can be considered as free at 2.614 MeV photon energy. For the calculation of the experimental total cross section the impurities in the gas are taken into account.

Impurities are principally due to the outgassing of the Lucite walls of the chamber, very small holes in the Mylar windows (10 μm thick) and diffusion of gases through the Mylar. The chamber operates at atmospheric pressure, and in our case a continuous purging of the chamber is required (0.1 to 0.2 liter per minute).

The detection system has been previously described[6]; some improvements have been added since this reference was published.[8] We may trigger on specific events such as annihilation of the positron and detection of the two 511-keV γ rays, or a double coincidence between the positron and the electron. A triple coincidence between the three particles of the triplet seems to be very difficult to work out. We have choosen a double coincidence (e^+, e^-); in this case pair events (e^+, e^-) and triplet events $(e^+, 2e^-)$ are photographed.

Good accuracy and precision in momentum and angular measurements requires a high streamer density along the track, streamers with small diameter, and a length along the electric field which is not too large. The brightness of streamers is also important for the photography.

Photographs are taken by two cameras through the high-voltage electrode. The optical axes are parallel, in the same plane and normal to the photon beam; the cameras are located at 134 cm from the mass electrode, the stereo-angle is 18°. We use Nikkon lenses of 55-mm focal length and $f/2$ relative aperture for the photography. The demagnification number between the real space and film is 26. For our experiment the background is very weak and the scanning of films very easy.

III. NEW CRITERIA FOR TRIPLET-EVENTS ANALYSIS–EXPERIMENTAL RESULTS

A. Measurement of energies and angles–data analysis

The geometrical reconstitution of an event in space is obtained from the two views of the cameras. The method and the program are described in detail by Parizet.[8] We neglect the energy loss in the helium gas (0.3 keV cm^{-1} for 1-MeV kinetic energy electrons). The error distribution in spatial real coordinates of the vertex of triplet events is shown in Fig. 2. We notice that the mean accuracy of the x coordinate (0.04 cm) is good; on the y coordinate the mean accuracy is only 0.2 cm; these values allow accurate spatial reconstitution of points.

Several tests have been carried out to determine the accuracy of the optical system, the measuring table of film coordinates, and the error of the reconstitution method.[7] For a triplet event, the spatial reconstitution method gives energies and angles of the three particles and the errors on these values.

B. Kinematical relations for the triplet process

As it has been shown in a preliminary experiment (Bonnet[9] and Augerat[10]), it is imperative to use kinematical relations in order to separate real triplets from false ones. We use the following notations. $T_1, T_2; E_1, E_2; \vec{p}_1, \vec{p}_2$: the kinetic and total energies and momenta of the electrons in the final state. $T_3, E_3, \vec{p}_3$: the kinetic and total energy and momentum of the positron. $k, \vec{k}$: the photon energy and momentum. θ_1, θ_2, θ_3: the angles between $\vec{k}$ and $\vec{p}_1, \vec{p}_2, \vec{p}_3$, respectively. θ_{12}, θ_{13}, θ_{23}: the angles between $\vec{p}_1, \vec{p}_2; \vec{p}_1, \vec{p}_3$, and $\vec{p}_2, \vec{p}_3$, respectively.

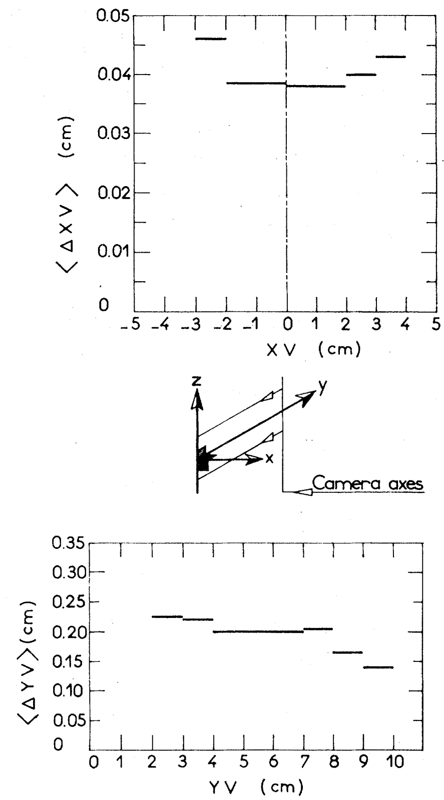

FIG. 2. Mean error for the vertex coordinates versus these coordinates. XV, YV, ZV are the spatial coordinates of the vertex of the event. ΔXV is the error on the x coordinate perpendicular to the optical axes of the cameras and nearly perpendicular to the photon beam. ΔYV is the error on the y coordinate parallel to the optical axes and perpendicular to the photon beam. Due to the configuration, the ΔZV error on Z coordinate which is parallel to the photon beam is equal to ΔXV.

Because of the interchangeability of each of the three particles in triplet production (charge excepted), kinematical limits are the same for the three particles. For a free target electron, limits for θ_i and E_i $(i = 1, 2, 3)$ for a given k have been given previously.[1,2] For $k = 2.614$ MeV, the maximum and minimum values of the kinetic energy and emission angle are the following $(i = 1, 2, 3)$:

$$T_{i,\max} = 1190 \text{ keV},$$

$$T_{i,\min} = 77.8 \text{ keV},$$

$$\theta_{i,\max} = 27.8^\circ,$$

$$\theta_{i,\min} = 0^\circ.$$

For k decreasing, $\theta_{i,\max}$ decreases, this result is characteristic of the triplet process near threshold, it is opposite to that of pair production in the nucleus field where the mean emission angle increases when k decreases (because of the mass of the nucleus, there are not limits to emission angles of electrons in pair production). We note that at threshold for $k=4m_0c^2$ $\theta_{i,\max}=0°$. For high photon energies the two processes are very similar for the two created particles.

(a) For a given energy E_j the limits for E_i are

$$E_i=A^{-1}[B\pm(B^2-AC)^{1/2}]\,,\qquad i\neq j,\ \ j=1,2,3,\ \ i=1,2,3,\quad (1)$$

where the plus sign gives the maximum value of E_i and the minus sign the minimum value; and

$$A=(E-E_j)^2-(p_j-k)^2\,,$$
$$B=(E-E_j)[kp_j-E(E_j-m)]\,,$$
$$C=m^2(p_j-k)^2+[kp_j-E(E_j-m)]^2\,,$$
$$E=E_1+E_2+E_3=k+m\,,$$

m being the rest mass of the electron. We can deduce corresponding relations between T_i versus T_j $(T_i=E_i-m)$. Relations (1) give the limits for T_1 versus T_2, T_1 versus T_3, and T_3 versus T_2.

(b) For a given emission angle θ_i the limits for E_i are

$$E_i=m\{[(k^2-m^2)\pm k\cos\theta_i\,(k^2\cos^2\theta_i-4mk)^{1/2}]\times[(k+m)^2-k^2\cos^2\theta_i]^{-1}\}\quad (2)$$

[same notations as for $\theta_i=\theta_{i,\max}$, $E_{i,\max}=E_{i,\min}=(k+m)/(k-m)$.

(c) The limits of the opening angle θ_{ij} versus the kinetic energy T_i for a given T_j are

$$\cos\theta_{ij}=[b-ac\pm(a^2+b^2+a^2b^2-2abc)^{1/2}]a^{-2}\,.\quad (3)$$

The notations are the same as for Eqs. (1) and (2), and

$$a=\frac{p_j}{k}\,,\quad b=-\frac{p_j}{p_i}\,,\quad c=\frac{E(E_i+E_j-m)-E_iE_j}{kp_i}\,.$$

At $k=2.614$ MeV, the maximum value of θ_{ij} is 41° and the minimum value 0°.

All these relations are valid only if binding and screening effects are negligible or very small compared with the minimum kinetic energy of the three particles of the triplet. For $k=2.614$ MeV, $T_{1,\min}=T_{2,\min}=T_{3,\min}=77.8$ keV. This value is larger than the binding energy of the K electrons of helium (25 eV) or K and L electron in the neon atom (874 eV).

Now it is necessary to analyze the possible sources of errors which can lead to a "false" triplet and the use of relations (1) to (3) given above.

The curves representing all these kinematical criteria are given in Refs. 8–10 for $k=2.614$ MeV.

C. Statistical analysis of false events

In three runs, we have taken 357 000 photographs; only the two last runs have been used for the analysis. The Table I gives the results.

All the experimentalists using a visual detector use the following criterion in order to define a triplet: three electron tracks of the same age must start from the same point after spatial reconstitution, the curvature of the tracks being such that one may be a positive electron and the others two negative electrons. Taking into account only this criterion, we found 378 triplet events, but with this method all the following events are called triplets: (i) real triplet events corresponding to the reaction $\gamma+e^-\to(e^++e^-)+e^-$; (ii) spatial coincidence between a pair events $\gamma+\mathrm{N}\to(e^++e^-)+\mathrm{N}$ and a Compton e^- electron from another photon at the vertex of the pair of near the vertex (depending on the spatial accuracy of the spatial reconsitution)—this type of false event is called $(p+c)$; (iii) emission of a delta ray near the vertex of a nucleus pair event. This event will be noted $(p+\delta)$ in the following.

The number of events of type (ii) and (iii) can be computed by a statistical method using the results of Table I.

We have found 66 δ rays of length greater than 2 cm (61 on the tracks, 5 at the vertex), with a 10-cm mean track length; this leads to 9×10^{-4} $\delta\,\mathrm{cm}^{-1}$ in helium. We can suppose that if a δ ray occurs at a smaller distance than 1 cm from the vertex of a pair, it gives a false triplet. We found six events of type $(p+\delta)$ in helium; it is only an evaluation, the same calculation in neogal leads to 22 $(p+\delta)$ false events.

For the case (ii) the number of false events is given by the probability for a Compton track to occur in a small volume surrounding the vertex. We found less than one $(p+c)$ event in helium and two in neogal.[11]

The upper statistical analysis is sufficient for a total cross-section study, as made by Hart *et al.*[12] for δ rays and Phillips *et al.*[13] for false events due to Compton tracks; but for an energetic or an angular differential cross-section study it is not possible to subtract individually the false triplet contribution. We introduce a new method for event analysis with the new criteria using the kinematical relations described above.

D. Triplet analysis with kinematical criteria

Criterion (A) follows from Eq. (1): the three tracks of real triplets must agree with (1).

TABLE I. Scanning results of the last run. Line 3 gives the total number of photographs with a pair event: (i) pair alone; (ii) pair and a Compton track inside the chamber, the origin of it cannot be confused with the pair vertex; (iii) pair with a δ ray produced by the electron or the positron. Line 5 gives the number of events of type (iii); the kinematical criteria are applied on the events of line 7 only.

	Gas	He(100%) (impurities less than 1%)	He(94.6%) Ne(5.4%)	He(70%) Ne(30%)	Total
1	Total number of photographs taken by the two cameras	72 400	40 600	22 500	136 500
2	Number of photographs with tracks	25 878	12 007	9333	52 224
3	Total number of pairs	3527	3932	4358	11 817
4	Pair events + Compton tracks with origin inside the chamber	46	73	82	201
5	Pair events with a δ ray on one of the tracks	61	90	110	261
6	Compton events	6228	4489	2052	12 769
7	Events with three tracks of same origin	177	135	66	378

Criterion (B) follows from Eq. (2): emission angles must agree with (2). The two criteria (A) and (B) are used as elimination criteria; (A) and (B) are applied successively at each event having three tracks of same origin. Criterion (C) corresponding to Eq. (3) is used as a check of $(p+\delta)$ events.

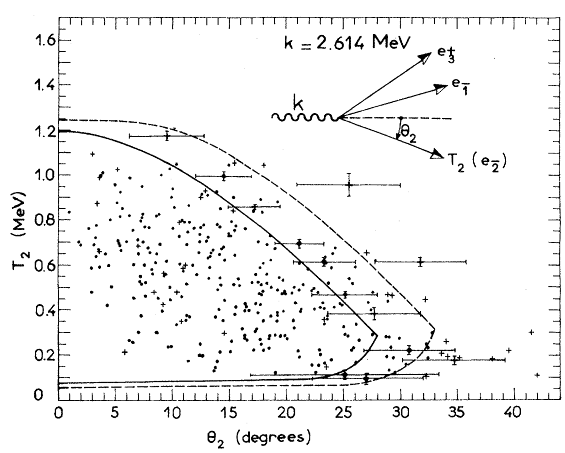

FIG. 3. Application of the kinematical criteria (A) for the positron (T_3) and the negaton 1 (T_1) and for k =2.614 MeV. The crosses represent the events rejected by (A) or (B) or (C). Note that there are three diagrams of this type for (A) criteria: (T_1, T_3), (T_1, T_2), (T_2, T_3). On some events we have reproduced the experimental errors on T_1 and T_3. The events which are not rejected (real triplets) are represented by a point.

During the photograph scanning we have eliminated some false triplet events of type $(p+\delta)$: these events have a special configuration due to the kinematics; the δ electron is emitted with an angle to the electron or the positron greater than 60°. This δ track is generally different from the two others due to the fact that its angle with the electric field of the chamber is small. This track appears to be continuous with no separable streamers and can be visually differentiated from the other tracks. Twenty-five events of this type have been found; all are false events $(p+\delta)$.

Among the events with three tracks of same origin, 34 are not measurable for several reasons: bad development of film, only one view can be used, or one of the tracks is too short (less than 2 cm). However, these events are accounted for in the total triplet cross section.

For the events with measurable momentum we have applied successively (A) and (B). In Fig. 3, the result of the application of (A) is given for all triplet events.

In our experiment, the kinetic energy of one particle is given with an accuracy of 5 to 12%

as function of this energy. This error contains implicity the multiple scattering errors, which are not small for low energy electrons. The dashed-line limit curve takes into account experimental errors on T. All the events with one (or two, or three) representative points outside of the area of the dashed curve are rejected by (A). We give in the figure 3 only T_3 versus T_1; two other similar limit curves are used for T_1, T_2, and T_3, T_2. We have found 28 events rejected by (A).

Criterion (B) introduces a selection on emission angles: Fig. 4 is an example of application of (B) for the negaton 2 (T_2 versus θ_2). Two analogous curves for particles 1 (T_1 versus θ_1) and 3 (T_3 versus θ_3) are also used. As in the (A) criterion, it is necessary to take into account experimental errors of angle and kinetic energy. The new limit area is given by the dashed line in Fig. 4. This criterion is applied to all events rejected or not rejected by (A). (B) rejects some of $(p+\delta)$ events, some $(p+c)$ events, and also events with a simple diffusion at large angle or multiple scattering. This criterion is not sufficient for an identification of the type of false event.

The application of (B) resulted in the rejection of 26 events. The use of (C) and the comparison with the δ or Compton kinematics gives a check and an identification of the type of false event. The opening angles θ_{ij} ($i=1,2,3$; $j=1,2,3$; $i\neq j$) are taken into account; a graphical representation of (C) is not possible.

For each event, we consider the θ_{ij} measured value and we compare it to the kinematical limit $\theta_{ij,\max}$ given by the T_j and T_j experimental values from the Eq. (1): If $\theta_{ij}<\theta_{ij,\max}$, the event can be a real triplet. If $\theta_{ij}>\theta_{ij,\max}$ but less than 60°, the event can be a $(p+c)$ event or a large multiple scattering angle event. If $\theta_{ij}>60°$ with a high probability, the event is of the type $(p+\delta)$ (δ ray closed to the vertex).

The comparison between the triplet and δ-ray

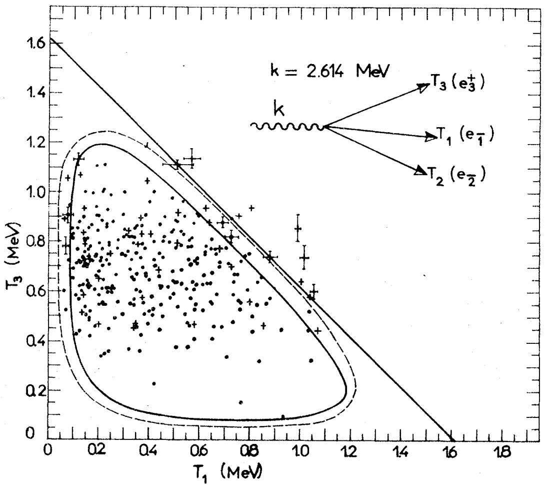

FIG. 4. Application of the kinematical criteria (B) on the negaton 2 (T_2 versus θ_2), there are also two identical curves for T_1, θ_1 and T_3, θ_3. The notations are the same that for the Fig. 3.

kinematics is given in Fig. 2 of Ref. 14 using the results of the second run.

The results of the application of (A) and (B) and the check with (C) are given in Table II. They are in good agreement with the statistical evaluation of the false events, but it can be applied to each event, and the corrections for the differential cross section are possible in this case. False events are essentially due to the $(p+\delta)$ events in our experiment. With the small memory time of the streamer chamber (of order of 10 μ sec), the $(p+c)$ false events are very rare.

With that kinematical analysis, we can eliminate individually each false event before studying the differential cross sections.

E. Application of our method for previous triplet experiments with visual detectors

Kinematical relations had been reported on the results of Hart *et al.*[12] by Augerat[10]; the agree-

TABLE II. Results of the event analysis.

Gas inside the chamber	He	He(94.6%) Ne(5.4%)	He(70%) Ne(30%)
Number of events with three tracks with the same origin	182	140	80
Unmeasurable events	23	14	21
Pair $+\delta$ electron	5	6	15
Pair + Compton electron	1	2	1
Events perturbed by multiple scattering	12	11	11
Triplets	141	107	32

ment is satisfactory. The 5% of false events due to δ rays reported by Hart can explain the events outside the limit curve for $k = 1000$ MeV.

In the study of Benaksas and Morrison[15] with a streamer chamber and atomic electrons of neon, 50% of the events do not agree with criterion (B)[10]; this cannot be explained by experimental errors of energy and angle. The use of our analysis method seems to be necessary in this case for $Z = 10$ where the number of detectable triplets is small compared with the number of pairs (2% for $k = 600$ MeV and $Z = 10$).

If we apply the limit values of angles for the photon energy of the experiment of Mohanty *et al.*,[16] we find a number of false events larger than 50%. The study of Castor[17] shows that if the nuclear G5 emulsion is used as a detector, the number of false triplet events is large and the distinction between false and real events very difficult.

In the two type of gas (helium and neogal 5) we have never found events with more than three tracks of same origin.

We think that the analysis of events of this type (materialization in the field of more than one electron, or multiple pair production) is very difficult. For this type of study[18] a kinematical analysis is necessary and requires the use of a magnetic field for momentum and charge measurement.

The application of our analysis method is therefore difficult to apply to earlier experiments, because all authors do not give for each individual event the photon energy and the momentum of the three particles after interaction.

IV. EXPERIMENTAL DIFFERENTIAL CROSS SECTIONS

Experimental cross sections are given for 314 events obtained according to the above analysis. Near threshold the atomic electron cannot be differentiated from the created electron. In all cases, we sum the results for the negatons 1 and 2.

A. Differential energetic cross sections

The differential cross section $d\sigma/dT_3$ of the positron is given in Fig. 5; the theoretical cross section from Mork and Jarp is normalized to the experimental histogram.

The cross section for the two negatons, $d\sigma/dT_1 + d\sigma/dT_2$, is presented in Fig. 6; the theoretical cross section of Mork is also normalized to the same area. The two theoretical curves are corrected with our energetic resolution on T [19]; with our experimental errors the correction is small. The experimental histogram for negatons is in good agreement with the Mork and Jarp results. On the same figure, we have also plotted the differential pair cross section (Bethe-Heitler results). We remark that the shape of the cross section is very different for pairs and triplets at our energy. The agreement is not so good for the positron case; this can be explained by the experimental detection threshold of 350 keV on the positron.

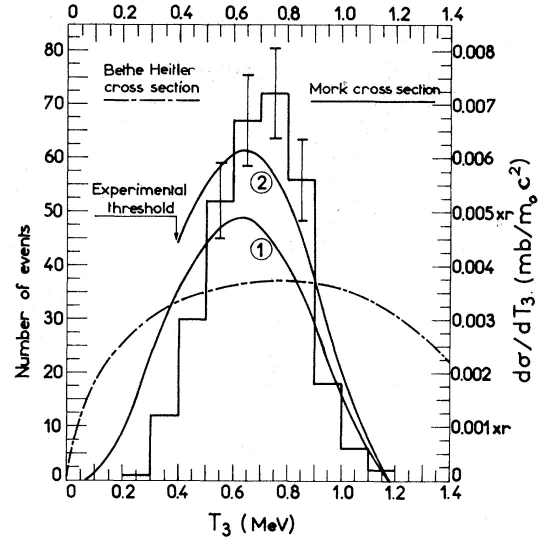

FIG. 5. Differential cross section $d\sigma/dT_3$ for the positron. Theoretical curve from Mork and Jarp (Ref. 2); the curve (1) is normalized for $T_3^m < T_3 < T_3^M$, the curve (2) for $T_s < T_3 < T_3^M$ where T_s is the experimental detection threshold, $T_s = 400$ keV. T_3^m and T_3^M are the minimum and maximum value of T_3. We have also reported, but without normalization, the Bethe-Heitler cross section $d\sigma/dT_+$ for the pair production process in the nuclear field where T_+ is the kinetic energy of the positron. The correction of the theoretical cross section due to the accuracy on energy measurement is very small compared to the statistical errors. r is a normalization coefficient: $r = 0.48$ for the curve 1 and 0.59 for the curve 2.

B. Differential angular cross section

Figures 7, 8, and 9 show the experimental angular cross section $d\sigma/d\theta_3$, $d\sigma/d\theta_1 + d\sigma/d\theta_2$, and $d\sigma/d\theta_{13} + d\sigma/d\theta_{23}$, respectively. The theoretical results given by Jarp and Mork are also reported (continuous line). Both experimental and theoretical distributions are normalized in area. We have corrected the theoretical results with our experimental angular resolution. The agreement between experimental and theoretical distributions is good in the case of θ_3 (the discrepancy for the negaton angles can be explained by the multiple scattering errors on the low-energy electrons).

We also give the cross section $d\sigma/d\theta_{12}$ in Fig. 10. No theoretical curve exists for this angle.

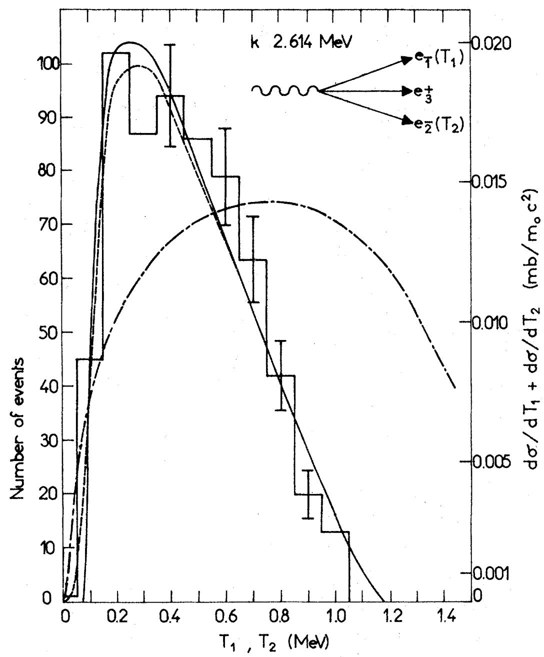

FIG. 6. Differential cross section $(d\sigma/dT_1+d\sigma/dT_2)$ for the two negatons. The theoretical cross section from Mork and Jarp (Ref. 2) (solid line) is normalized. The experimental accuracy on the kinetic energy is folded into the theoretical curve given by Mork and Jarp (dashed line). The dot-dashed line is the Bethe-Heitler cross section $d\sigma/dT$ for $k=2.614$ MeV and without normalization. The electron spectrum for the triplet process is totally different from the Bethe-Heitler spectrum at $k=2.614$ MeV.

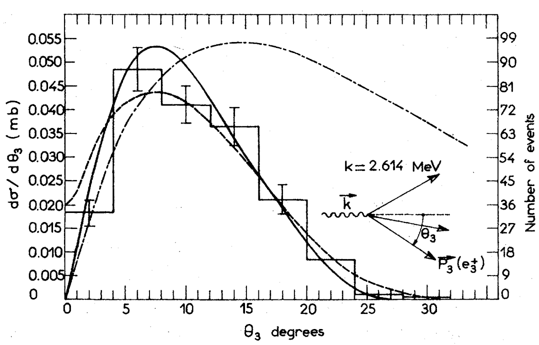

FIG. 7. Differential cross section $d\sigma/d\theta_3$ for the emission angle of the positron. The solid line is the theoretical cross section from Mork and Jarp. The experimental accuracy on the kinetic energy is folded into the theoretical curve given by Mork and Jarp (dashed line). The histogram corresponds to experimental results with the statistical errors. The dot-dashed line is the theoretical Bethe-Heitler cross section without normalization $d\sigma/d\theta_+$ where θ_+ is the angle $(\vec{k},\vec{p}_+)$.

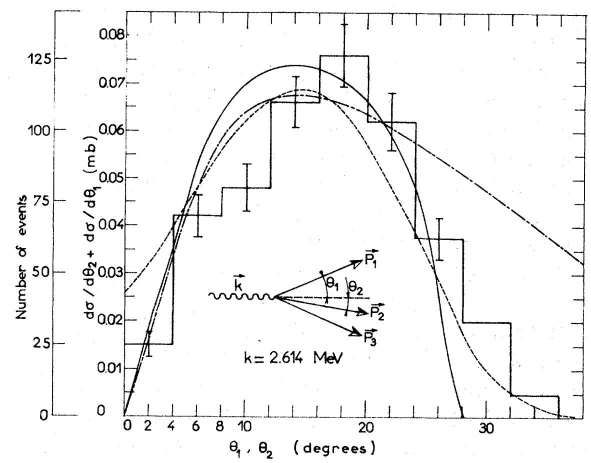

FIG. 8. Differential cross section $(d\sigma/d\theta_1+d\sigma/d\theta_2)$ for the two negatons 1 and 2. The experimental accuracy on emission angles is folded into the theoretical curve (dashed line). The solid line is the theoretical cross section from Mork and Jarp. The dot-dashed line is the Bethe-Heitler cross section $d\sigma/d\theta_-$ where θ_- is the angle $(\vec{k},\vec{p}_-)$ (identical to $d\sigma/d\theta_+$).

In Fig. 7, we have reported the pair cross-section emission angle $d\sigma/d\theta_+$ given by Bethe-Heitler (θ_+ is the angle between $\vec{k}$ and the positron $\vec{p}_+$). This distribution is completely different from that of triplets at 2.614 MeV.

V. CUMULATIVE TRIPLET CROSS SECTION AT 2.614 MeV–MULTIPLET CROSS SECTION

A direct and absolute measurement of the total triplet cross section is not possible because we do not know with sufficient accuracy the number of photons of the beam. A calculation of the detection

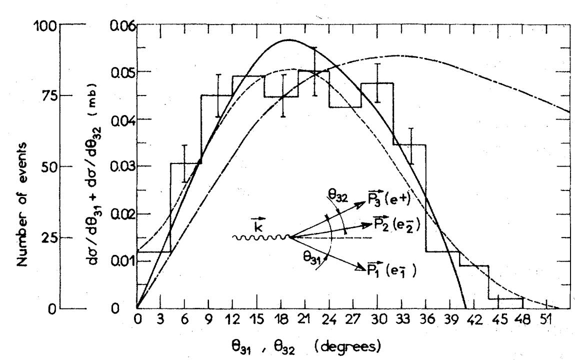

FIG. 9. Distribution of opening angles $(d\sigma/\theta_{31}+d\sigma/d\theta_{32})$. The solid line is the theoretical Mork cross section, normalized to the experimental histogram. The dashed line is the same theoretical cross section but corrected by the experimental accuracy on θ_{31} and θ_{32}. The dot-dashed curve is the Bethe-Heitler cross section $d\sigma/d\theta$ where θ is the $(\vec{p}_+,\vec{p}_-)$ angle, without normalization.

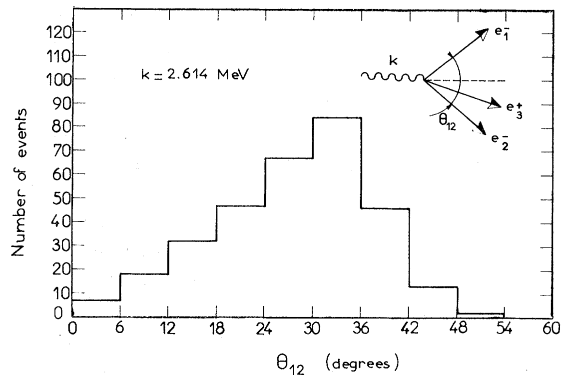

FIG. 10. Experimental angular distribution $d\sigma/d\theta_{12}$ where θ_{12} is the angle between the momenta of the electrons 1 and 2.

efficiencies e_1, e_2, e_3 for the three particles of the triplet is also necessary for absolute cross-section determination; in the present experiment e_1, e_2, e_3 depend on the emission angles, the azimuthal angles, the kinetic energies, and the vertex coordinates.

We calculate a relative cross section by comparison with the pair production cross section given by Bethe and Heitler. For helium, $Z=2$, and $k=2.614$ MeV the Bethe-Heitler result is correct and gives a right value of the total pair cross section. We use for the total pair cross section at 2.614 MeV and for helium, 1.48 mb/atom.

The conditions are the following: (i) We consider the events occurring in the same useful volume inside the chamber. (ii) We evaluate the cumulative triplet cross section for each type of gas separately. (iii) We suppose that the detection efficiencies for the positron of the triplet, e_3, and the positron of a nucleus pair, e_+, are identical for small emission angles and kinetic energies greater than 400 keV:

$$\theta_3 < \theta_0, \quad 400 < T_3 < 1200 \text{ keV}$$

$$\theta_+ < \theta_0, \quad 400 < T_+ < 1200 \text{ keV}.$$

(iv) We correct the results by taking into account the impurities in the chamber (essentially nitrogen and oxygen). The corrections are more important in helium than in neogal 5. (v) The photon spectrum after passing through the hole in the lead collimator has only one γ line at 2.614 MeV above the triplet threshold photon energy.

Condition (iii) is well fulfilled for θ_0 values less than 16°. Figure 11 shows the validity of (v), the sum of the kinetic energies for the three particles of the triplets gives only one line at $\langle T_1+T_2+T_3\rangle = 1.594$ MeV corresponding to $k = 2.614$ MeV $- 1.022$ MeV.

We call σ_p^l the pair cross section given by

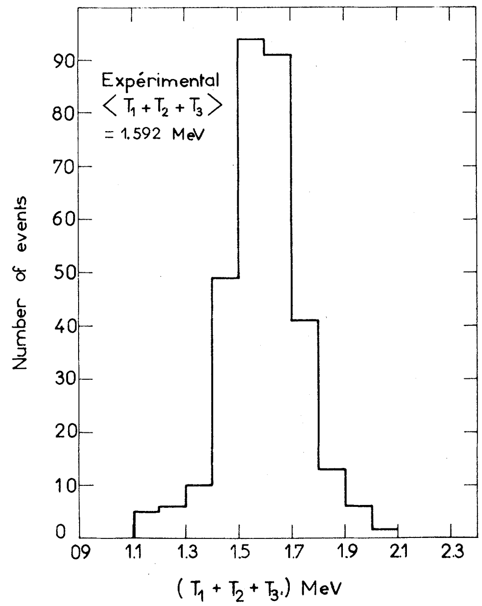

FIG. 11. Distribution of the sum of the kinetic energies of the three particles $(T_1+T_2+T_3)$ for all events, after application of the kinematical criteria. It appears that there is one γ-ray line at $k=(1.594+2m_0c^2)$ MeV.

numerical integration of $d^2\sigma/dT_+\,d\theta_+$:

$$\sigma_p^l = \int_{0,\,T_+=400\text{ keV}}^{\theta_0,\,T_+=1200\text{ keV}} \frac{d^2\sigma}{dT_+ d\theta_+}\, dT_+\, d\theta_+ .$$

We obtained a total number N_p of pairs produced in the chamber and N_t total number of triplets. Then we measured a number of pairs N_p^m and the number N_t^m of triplets (for a given gas).

If n_p and n_t are the numbers of pair and triplet

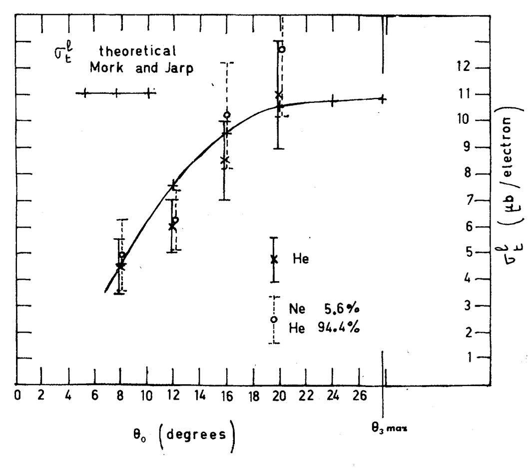

FIG. 12. Experimental cross section σ_t^l (the definition of σ_t^l is given in the text) versus angle θ_3 between $\vec{k}$ and $\vec{p}_3$ for small angles θ_3 where detection efficiency for the three particles is the same. We give the results separately for helium and the mixture helium 95%, neon 5%.

events corresponding to the limit conditions (iii); the total cross section σ_t^l is given by

$$\sigma_t^l(0<\theta_3<\theta_0, 400<T_3<1200 \text{ keV}) = \sigma_p^l \frac{N_t}{N_p}\frac{n_t^l}{n_p^l}\frac{N_p^m}{N_t^m}.$$

After elimination of the false events and taking in account the impurities corrections we have experimentally for helium: $N_t = 165$ and $N_p = 3177$; for neogal 5: $N_t = 123$ and $N_p = 3768$.

In Fig. 12, we present the results of this calculation for $\theta_0 = 8°$, $12°$, and $16°$. The theoretical values σ_t^l had been calculated by Mork and Jarp[20] by integration of $d^2\sigma/dE_3\,d\theta_3$ with the same limits as in the experimental case. In spite of the small amount of statistics for each point, the agreement with the Mork result is satisfactory.

Finally, information is provided on possible multiplet production in the field of neon atomic electrons (materialization in the field of more than one electron). We have never observed a type of event with four tracks (3 negatons, 1 positron) with the same origin. The multiplet cross section at $k = 2.614$ MeV is very small in our experimental conditions, less than 10^{-8} b/electron in neon.

VI. CONCLUSION

Our results may be summarized as follows.

(a) First it has been shown that the streamer chamber is particularly well adapted to this type of experiment because it allows low-energy measurements in 4π sr as in a bubble chamber. The apparatus can be triggered on special types of events; studies of small cross sections are possible and generally the background is very low on photographs; in this case the scanning is very easy. Near threshold and for low photon energies, below 20 MeV, the efficiency for detecting the three tracks of the events is very close to 100%.

(b) A detailed analysis of the false triplet events had been done; the number of these events found experimentally is in good agreement with statistical calculation. The elimination of false triplets individually is necessary if one wants to study differential cross sections (particularly when the number of triplets is small compared to that of pairs).

(c) If we apply the kinematical criteria to previous experiments the number of events outside the limit curves is important in many cases.

(d) The differential energetic cross sections of the two negatons is in quite good agreement with the theoretical result of Mork and Jarp. The agreement is not so good for the positron, this can be explained by the detection threshold energy (350 keV). The shape of the energetic triplet cross section is very different from those of the pair production process.

(e) The angular triplet cross sections (on emission angles of the three particles or on opening angle between two of them) are in good agreement with the theoretical results of Mork and Jarp; the effect of multiple scattering is not negligible on electrons of small energies. At our energy, the angular distributions are very different for pairs and triplets.

(f) The experimental cross section $\sigma_t^l(\theta_3 < \theta_0;$ $400 < T_3 < 1200$ keV) is consistent with Mork's results.

(g) No event had been found positively indentifiable as a multiplet (one positron, three electrons) in neon.

ACKNOWLEDGMENTS

We wish to thank Professors H. A. Olsen, K. J. Mork and S. Jarp, University of Trondheim; R. H. Pratt, University of Pittsburgh, and Dr. L. C. Maximon for their helpful discussions and advice concerning the theory. We are indebted to Professor L. Avan and Professor D. B. Isabelle for their encouragement. We are very grateful to Dr. F. Schneider and E. Gygi, for their interest and help in technical problems. We wish to thank Dr. Di Lullo and the NATO Science Committee for their support.

*Work supported in part by the NATO Science Committee Research Grants, No. 738 and 828.

†Present address: Conservatoire National des Arts et Métiers 292, rue Saint Martin-75003, Paris, France.

[1](a) K. J. Mork, Proc. Phys. Seminar Trondheim No. 7 (1965); K. J. Mork, Phys. Rev. 160, 1065 (1967); (b) S. Jarp and K. J. Mork, Phys. Rev. D 8, 159 (1973).

[2]J. W. Motz, H. A. Olsen, and H. W. Koch, Rev. Mod. Phys. 41, 581 (1969).

[3]J. Joseph and R. Rohrlich, Rev. Mod. Phys. 30, 354 (1968).

[4]E. Haug, Z. Naturforsch. 30A, 1099 (1975).

[5]G. Roche, J. Fargeix, G. Girard, and F. Ramos, Nucl. Inst. Meth. 86, 61 (1970).

[6]G. Roche, J. Arnold, J. Augerat, L. et M. Avan, J. Bonnet, J. Fargeix, A. Fleury, J. Jousset, M. J. Parizet, and M. Vialle, Nucl. Inst. Meth. 103, 533 (1972).

[7]M. J. Parizet, Thèse de Doctorat d'Etat, No. 203 (Université de Clermont, 1975) (unpublished).

[8]M. J. Parizet *et al*. (unpublished).

[9]J. J. Bonnet, Thèse de Doctorat de Spécialité, No. 260 (Clermont-Ferrand, 1971) (unpublished).

[10]J. Augerat, Thèse de Doctorat-ès-Sciences Série E,

No. 169 (1972) (unpublished).

[11]This volume surrounding the vertex depends on the number of streamers on each track and the shape of the event.

[12]E. L. Hart, G. Cocconi, V. T. Cocconi, and J. M. Sellen, Phys. Rev. 115, 678 (1959).

[13]J. A. Phillips and P. G. Kruger, Phys. Rev. 76, 1471 (1949).

[14]J. Augerat, M. Avan, M. Ballet, J. Jousset, M. J. Parizet, and G. Roche, Lett. Nuov. Cim 11, 685 (1974).

[15]D. Benaksas and R. Morrison, Phys. Rev. 160, 1245 (1967).

[16]R. C. Mohanty, E. H. Webb, H. S. Sandhu, and R. R. Roy, Phys. Rev. 124, 1017 (1961). This paper contains a misprint on page 1019. The authors take the value $\sigma_p/\overline{Z}$ for the triplet cross section, where σ_p is the total cross section and $\overline{Z}$ the average value of Z in emulsion, instead of $\sigma_p/(\overline{Z^2}/\overline{Z})$. The authors found a number of triplet events in agreement with the erroneous value $\sigma_p/\overline{Z}$ larger by a factor 3 ($\overline{Z}=13.6$ and $\overline{Z^2}/\overline{Z}=34$ for emulsion G5).

[17]J. Castor, Thèse de Doctorat de spécialité, No. 162 (1969) and Thèse de Doctorat d'Etat, No. 208 (1975) (unpublished).

[18]R. R. Roy, C. H. Blanchard, E. H. Webb, H. S. Sandhu, and R. C. Mohanty, Proc. Phys. Soc. 78, 1301 (1961).

[19]The experimental errors in T are given approximately by the formula. $\Delta T_i(\text{keV}) = \pm (23 + 24\times 10^{-3} T_i)$ (keV) where $i=1,2,3$. The corrections are negligible for $d\sigma/dT_1 + d\sigma/dT_2$ the corrections are of the order of a few percent for T_1 and T_2 near the minimum value.

[20]K. J. Mork and S. Jarp (private communication).

[21]W. E. Ogle and P. G. Kruger, Phys. Rev. 67, 282 (1945).