Unusual $\pi-\mu$ Decays in Photographic Emulsions*

W. F. Fry†
Department of Physics, University of Chicago, Chicago, Illinois, and Department of Physics, Iowa State College, Ames, Iowa

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A total of 11 841 π-μ decays has been studied in Ilford C-2 and G-5 photographic plates, where both the π- and μ-meson tracks stopped in the emulsion. In 12 cases the range of the μ-meson track from the π-meson decay is less than 480 microns and in 2 cases the range is greater than 720 microns. The ranges of the μ-meson tracks of the 14 unusual π-μ decays are: 120, 185, 258, 260, 290, 416, 430, 441, 444, 470, 470, 476, 828, and 1035 microns. The normal range of the μ-meson from π-meson decays is about 600 microns. A study of the grain density in C-2 plates, gap density in G-5 plates, and the number and energy of the δ-rays along the short μ-meson tracks indicates that the μ-mesons were ejected from the π-decays with a lower velocity than from normal π-μ decays. It is possible to explain the short range of the μ-meson in 4 of the events and the long range of the μ-meson in the 2 events by assuming that the π-meson decayed in flight. The grain density or gap density along the μ- and π-meson tracks in the remaining 8 events is inconsistent with the assumption that the short range of the μ-meson is due to the decay in flight of the π-meson. If a correction is made for the thickness of the emulsion, the probability that a μ-meson from a stopped π-meson decay will have a range less than 480 microns is found to be $3.3\pm1.3\times10^{-4}$. This probability is in general agreement with theoretical predictions based upon the assumption that a soft photon is occasionally emitted from the π-μ decay resulting from the charge acceleration of the μ-meson.

I. INTRODUCTION

ONE of the striking characteristics of the π-meson decays in photographic emulsions that were first observed by Lattes, Occhialini, and Powell[1] was the length of the μ-meson tracks. The lengths of the μ-meson tracks from π-meson decays were found to be nearly constant. This fact suggested the possibility that the π-meson decays into a μ-meson plus one additional particle, presumably a neutrino,[2]

$$\pi\rightarrow\mu+\nu. \tag{1}$$

The range distribution of 1000 μ-mesons from π-meson decays in two Ilford C-2 plates has been obtained.[3] The range distribution is Gaussian within the statistical limits; it has a mean of 597 ± 1 microns and a standard deviation of 29.1 ± 0.7 microns. The results of this study are in general agreement with the earlier results of Barkas.[4]

A π-μ decay was found by Powell[5] where the range of the μ-meson was estimated to be less than 350 microns. The π-meson was ejected from a cosmic-ray star. The short range of the μ-meson was ascribed to the decay of a negative π-meson from a mesonic "Bohr" orbit of an atom. A short μ-track from a positive π-meson decay was found by Smith.[6] It was possible to explain the short range of the μ-meson by assuming that the π-meson decayed in flight.

Recently, several positive π-μ decays have been observed by the author[7] where the short range of the μ-meson cannot be explained by the decay in flight of the π-meson. The analysis of the π-μ decays, where the range of the μ-meson is abnormal, is reported in this paper.

II. PROCEDURE

A study of π-μ decays has been made in both Ilford C-2 and G-5 photographic emulsions. C-2 plates of 200 microns in thickness which had been exposed in the spiral orbit spectrometer to the Berkeley cyclotron, were made available to the author by Dr. R. Sagane. Ilford G-5 plates of 400 microns in thickness were exposed to the University of Chicago cyclotron. The G-5 plates were so arranged that the tracks of the π-mesons are about 1000 microns long. It is desirable to have the π-meson tracks long and nearly in the plane of the emulsion in order that the π-μ junction can be easily identified. Both the C-2 and G-5 plates were searched for π-μ decays with a total magnification of about 250×. Only those decays were studied where the π- and μ-meson tracks stopped in the emulsion. The horizontal projected length of each μ-meson track was estimated by a calibrated scale in the eyepiece of the microscope, with a total magnification of 250×. If the length of the μ-meson track in the plane of the emulsion was found to be less than 520 microns, the true length was determined by successive measurements of small sections of the track with a total magnification of 1000×. The largest uncertainty in the measurement of the length of a track was found to be due to the measurement of the vertical component of the track. Nevertheless the uncertainty in the length of the μ-meson track from a normal π-μ decay is estimated to be no greater than 20 microns for an extreme case in 400-micron thick plates. For a μ-meson track which does not make a

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† Present address, Department of Physics, University of Wisconsin, Madison, Wisconsin. A portion of the work was undertaken while the author was a U. S. Atomic Energy Commission Postdoctoral Fellow (1951–1952) at the University of Chicago.

1 Lattes, Occhialini, and Powell, Nature **160**, 453 (1947).
2 C. O'Ceallaigh, Phil. Mag. **41**, 838 (1950).
3 W. F. Fry and George R. White, Phys. Rev. **90**, 207 (1953).
4 W. H. Barkas, Am. J. Phys. **20**, 5 (1952).
5 C. F. Powell in "Cosmic Radiation," *Calston Papers* (Butterworth Scientific Publications, London, 1949).
6 F. M. Smith, reported in reference 4.
7 W. F. Fry, Nuovo cimento **8**, 590 (1951); Phys. Rev. **83**, 1268 (1951); Phys. Rev. **86**, 418 (1952).

large angle with the plane of the emulsion, the true range can be estimated to within about 5 microns. Since the distortion of the emulsion usually increases with increasing emulsion thickness, and since the largest error in the measurement of the range is introduced by the vertical sections of the track, it is advantageous to use relatively thin emulsions for this study.

Two types of plates, the relatively insensitive C-2 and electron sensitive G-5 plates, were used for this study because of the many desirable characteristics of each type. In C-2 plates the individual grains along the track can be counted, except for the region near the very end of the track. The relatively large variation in grain density with velocity, for slow mesons in C-2 plates, can frequently be used to an advantage. For example, the change in grain density between the π- and μ-meson tracks usually makes it possible to distinguish visually a π-μ decay fron a scattered μ-meson without counting the number of grains along the two tracks. The velocity of a π- or μ-meson can be estimated from the grain density for meson energies as low as 1.5 to 2 Mev. The estimation of the π-meson velocity was found to be important in connection with the possibility of decay in flight of the π-meson. On the other hand, the ability of G-5 plates to record minimum ionizing particles is of considerable importance in the study of the δ-rays along the μ-meson tracks and the decay electrons from the μ-mesons.

III. RESULTS

A total of 3922 π-μ decays, where both the π- and μ-mesons stopped in the emulsion has been studied in C-2 plates. Similarly, 7919 decays have been studied in G-5 plates. Among these 11 841 π-μ decays, 13 unusual π-μ decays are observed where both meson tracks stop in the emulsion and where the range of the μ-meson track is less then 480 microns or greater than 720 microns. In one additional case a π-μ decay is observed

TABLE I. Characteristics of unusual π-μ decays.

Event	Type of emulsion	Range of μ-meson track in microns	Energy of μ-meson in Mev	Measured angle between directions of π- and μ-meson tracks	Energy in Mev of π-meson assuming decay in flight
1[a]	C-2	120	1.6	73	5.0
2[a]	C-2	185	2.1	20	16.6
3[a]	G-5	290	2.7	59	6.6
4[a]	G-5	416	3.3	51	8.3
5[a]	G-5	430	3.35	26	15.4
6[a]	G-5	441	3.4	56	5.1
7[a]	G-5	470	3.5	28	15.4
8[a]	G-5	470	3.5	36	11.9
9	C-2	258	2.5	93	1.7
10	C-2	260	2.5	113	0.7
11	C-2	444	3.4	160	0.03
12	G-5	476	3.5	117	0.09
13[b]	C-2	828	4.8	10	0.05
14	G-5	1035	5.5	55	0.5

[a] Events which do not appear to be decay in flight of the mesons.
[b] Interpreted as a flight of a negative π-meson. See reference 12.

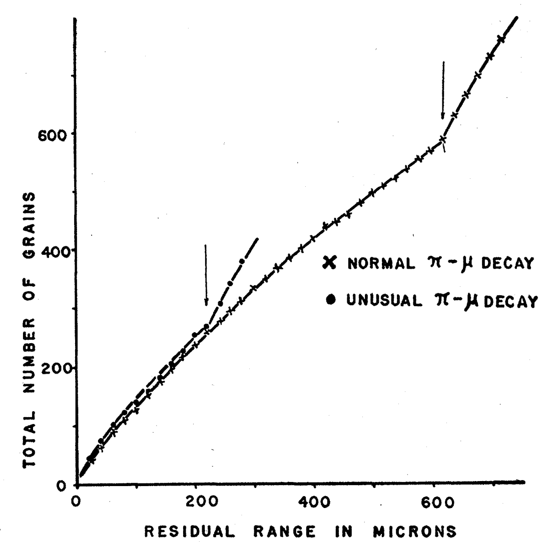

FIG. 1. The integral number of grains, starting at the end of the μ-meson track, as a function of the residual range is shown for the unusual π-μ decay which is listed as event 9, and for a normal π-μ decay. The π-μ junction is indicated by the arrow.

where the μ-meson track leaves the emulsion after 975 microns. The residual range has been estimated to be 60 microns by a comparison of the gap density with the gap density along a μ-meson track of a normal decay which occured within 100 microns of the unusual event. A decay electron track is observed from each of the 7 μ-meson tracks of the unusual π-μ decays which are in G-5 plates. The characteristics of the 14 unusual π-μ decays are given in Table I.

The probability that a μ-meson from a π-decay at rest will have a range less than 480 microns can be estimated from the standard deviation of the previously measured range distribution, assuming that the events are distributed according to the Gaussian distribution. This probability is about 6×10^{-5}. Since the probability is very low that the range will be less than 480 microns resulting only from straggling, all π-μ decays where the length of the μ-meson track is less than 480 microns have been carefully studied.

Tracks of μ-mesons as well as π-mesons are observed to enter the surfaces of the emulsions in both the C-2 and G-5 plates. The μ- mesons were probably due to the decay in flight of π-mesons before they entered the emulsion. Occasionally a slow μ-meson was scattered through a large angle in the emulsion and subsequently stopped in the emulsion after traveling several hundred microns from the scattering point. It is necessary to be able to distinguish this type of event from a π-μ decay. If the range of the μ-meson, from the π-decay or the scattering point, is greater than about 400 microns, the two types of events can be readily disinguished by a visual comparison of the grain densities in C-2 plates or gap densities in G-5 plates along the two tracks at the junction. For events where the length of the μ-meson track is less than about 400 microns, the two

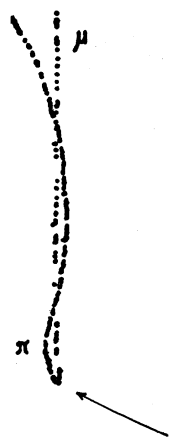

FIG. 2. A portion of the π- and μ-meson tracks of event 9 is shown in the drawing. The event was found in a C-2 plate. The range of the μ-meson is 258 microns. The difference in the grain density along the π- and μ-meson tracks can be seen, indicating that the event is a π-μ decay and not a scattered μ-meson.

types of events can be distinguished by grain counting or gap counting. The total number of grains has been counted along the π- and μ-meson tracks starting from the end of the μ-meson track, for the π-μ decay which is listed as event 9 in Table I. The results are shown in Fig. 1 as well as the results of a similar count in the same plate of a normal π-μ decay. A comparison of the integral number of grains as a function of the residual range of the μ-meson for the unusual decay and for the normal π-μ decay indicates that the μ-meson was ejected with a lower velocity in the unusual decay than in the normal decay. There is no evidence for an abrupt change in the velocity of the μ-meson along the track as has been recently reported by Riezler and Rudloff.[8] A projection drawing of a portion of the π-μ decay which is listed as event 9 is shown in Fig. 2. The difference in the gap densities in a G-5 plate along the end of a π-meson track and the beginning of a μ-meson track is illustrated in Fig. 3(a) and Fig. 3(b) by the projection drawing of the unusual π-μ decay which is listed as event 3 in Table I. The total number of gaps along the π- and μ-meson tracks starting at the end of the μ-meson track has been counted in event 4. The results are shown in Fig. 4. The π-μ junction is clearly evident by the abrupt change in the slope of the curve at the π-μ junction.

In general, it is easier to distinguish visually π-μ decays from scattered μ-meson tracks in C-2 than in G-5 plates. However, the δ-rays which are observed along the tracks of particles in G-5 plates can be used in some cases to distinguish the two types of events. The maximum velocity that a meson can give to an electron in a collision is twice the velocity of the meson. The maximum energy of a δ-ray is then $E_e = 4E_m m_e/M$ where E_m is the kinetic energy of the meson and m_e and M are the mass of the electron and the meson, respectively. If δ-rays are observed along a meson track, a lower limit of the kinetic energy of the meson can be determined from the energy of the δ-rays. A few events have been observed in G-5 plates which would appear upon casual inspection to be π-μ decays but which are shown to be scattered μ-mesons by the presence of one or more δ-rays near the scattering point, along the portion of the track which was assumed to be the

[8] W. Riezler and A. Rudloff, Z. Naturforsch. **7a**, 570 (1952) and private communications.

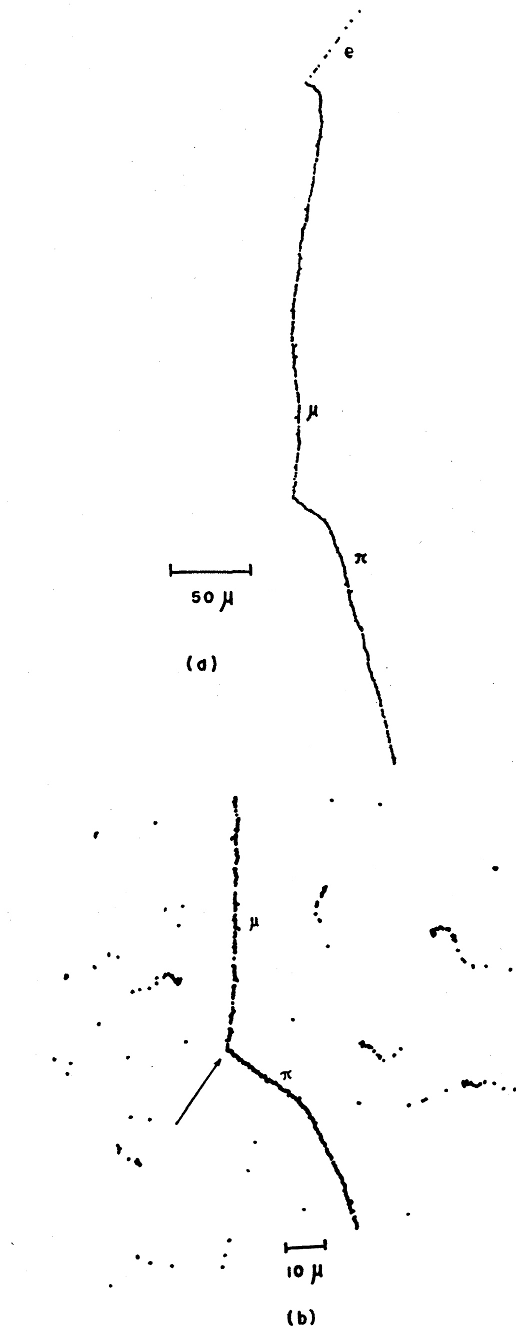

FIG. 3. (a) A projection drawing of a π-μ decay in a G-5 plate, which is listed as event 3, is shown above. The range of the μ-meson is 290 microns. (b) A projection drawing of a π-μ decay in a G-5 plate listed as event 3. Only a portion of the π- and μ-meson tracks is shown. The range of the μ-meson is 290 microns. The difference in the number of gaps along the π- and μ-meson tracks can be seen.

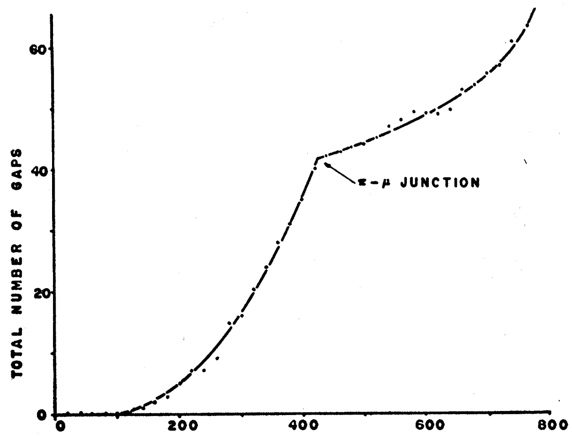

FIG. 4. The total number of gaps up to a range R beginning at the end of the μ-meson track for event 4 is shown in the above curve. The unusual π-μ decay was found in a G-5 plate. The π-μ junction can be clearly disinguished by the abrupt change in the slope of the curve. The range of the μ-meson is 416 microns.

π-meson track. The assumption that these events were not π-μ decays was subsequently verified by gap counting along both tracks near the scattering point.

The total energy of the δ-rays along the μ-meson tracks of the unusual π-μ decays has been obtained. The measurements were undertaken to see if the short range is due to a statistical fluctuation in the total energy given to the high energy δ-rays for the events where the μ-meson range is around 450 microns. The energy of the electrons was estimated by measuring their range and utilizing the range-energy relationship of Zajac and Ross.[9] The total energy of the δ-rays ($E>12$ kev) along the last 450 microns of the μ-meson tracks from normal π-μ decays has been obtained for 25 events. The results are summarized by the histogram in Fig. 5. The total energy of the δ-rays ($E>12$ kev) along the μ-meson tracks of 7 unusual π-μ decays is listed in Table II. The estimation of the total energy of the δ-rays is crude, mainly for two reasons. Some of the "knock-on" electron tracks or δ-rays are masked by the heavy μ-meson track and are not observed. Also the estimation of the energy of an electron from the length of the track is poor for electrons of energy below 20 kev. Nevertheless, if the short range of the μ-mesons is due to an increased number of high energy δ-rays, the excess energy should be observable. About 500 kev will change the mean range of a μ-meson from 450 microns to 600 microns. A comparison of the energy of the δ-rays along the μ-meson tracks from the unusual decays (Table II) with the total energy of the δ-rays along the μ-meson tracks from normal π-μ decays (Fig. 5) strongly indicates that the short range in these events is not due to an abnormally high energy loss to energetic δ-rays.

It may be possible in certain cases to explain the

[9] B. Zajac and M. Ross, Nature **164**, 311 (1949).

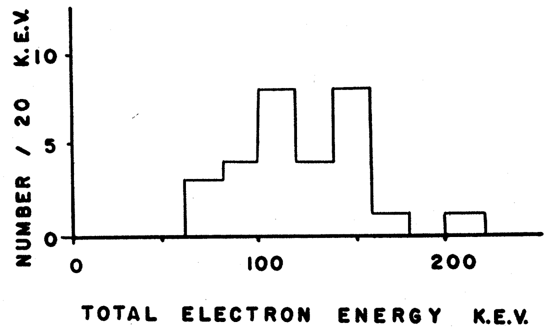

FIG. 5. The distribution of the total energy of the δ-rays ($E>12$ kev) along the last 450 microns of the μ-meson track from normal π-μ decays is shown in the histogram.

abnormal range of the μ-meson from a π-meson decay by assuming that the π-meson decayed while still in motion. This mechanism would be expected to produce abnormally long μ-meson tracks as well as short μ-meson tracks. If the abnormal range of a μ-meson from a π-meson decay is due to the decay in flight of the π-meson there should be a correlation of the angle between the directions of the π- and μ-meson tracks, the energy of the π-meson at the time it decayed and the energy of the μ-meson. Assuming that the abnormal ranges of the μ-mesons that are listed in Table I are due to the decay in flight of the π-mesons, the energy of the π-meson at the time of decay can be calculated for each event. It is assumed that the direction of the π-meson at the time of decay is the same as the direction of the last few microns of the π-meson track. The calculated energy of the π-meson at the time of decay is shown in the last column of Table I. In events 1 through 8 the grain density in C-2 plates and the gap density in G-5 plates along the π-meson track near the π-μ junction is definitely inconsistent with the estimated energy of the π-meson assuming that the π-meson decayed in flight. It is possible that the π-meson was scattered in the backward direction while still in motion. In order to estimate this probability the number of large angle scatterings along π-meson tracks of normal π-μ decays, in the interval from 4 to 8 microns from the junction, has been measured. The range-energy relationship for very low energy mesons is not accurately known, but the energy of a π-meson which as a range of 6 microns is estimated to be 0.3 Mev. The range of a μ-meson

TABLE II. δ-rays along μ-meson tracks.

Event	Range of μ-track in microns	Total energy in kev of δ-rays with $E>12$ kev
4	416	75
5	430	80
6	441	167
7	470	88
8	470	166
11	444	134
12	476	145

would be 250 microns from the decay in the backward direction of a π-meson of 0.3 Mev. The scattering in the 4-micron interval along the π-meson track in each of the 100 normal π-μ decays has been measured. Only in 5 cases was the π-meson scattered through an angle larger than 60 degrees. Thus, the probability that a π-meson of 0.3 Mev will be scattered through an angle greater than 60 degrees, per micron length of track, is about one percent. The probability that a π-meson in a given energy interval will decay in flight can be calculated from an estimate of the time spent in the energy interval and the probability of decay per unit time.[10,11] The upper limit of the π-meson energy that must be considered is determined by the requirement that the π-meson track must appear heavier than the μ-meson track in order that the event will be recognized as a π-μ decay. The lower limit to the energy interval is determined by the condition that the range of the μ-meson must be less than 480 microns. These conditions fix the energy interval from about 2 Mev to 20 kev. The time spent in this energy interval is approximately 4×10^{-12} sec. The meson spends nearly all of this time near the high energy portion of the interval where the probability of large angle scattering is small. The probability that a π-meson will decay in flight in a photographic emulsion in the energy interval from 2 Mev to 20 kev is 1.7×10^{-4}. The probability that a π-meson will be scattered through a large angle in the last micron of track (in the energy interval from 20 kev to 2 Mev) and subsequently decay in flight is less than 1.7×10^{-6}. This probability is considerably lower than the occurrence of short μ-meson tracks from π-meson decays. Therefore the short range of the μ-meson tracks in events 1 through 8 do not appear to be due to the decay in flight of the π-mesons.

In the events 9 through 12 the angle between the π- and μ-meson tracks is such that the possibility cannot be excluded that the short range of the μ-meson is due to the decay in flight of the π-meson. In fact, the long range of the μ-meson tracks in events 13 and 14 is thought to be due to the decay in flight of the π-mesons.[7,12] If the events (9 through 12) which can be explained by decay in flight of the π-meson are excluded and if a correction is made for the thickness of the emulsions, the probability that a μ-meson from a π-meson decay will have a range less than 480 microns is found to be $3.3\pm 1.3\times 10^{-4}$.‡

An explanation for the unusual π-μ decays has been given independently by several investigators, namely, Nakano *et al.*,[13] Primakoff,[14] Eguchi,[15] Fialho and Tiomno,[16] and Fialho.[17] It has been proposed that a soft photon may accompany the π-μ decay due to the charge acceleration of the μ-meson at the time of decay:

$$\pi\rightarrow\mu+\nu+\gamma. \qquad (2)$$

The theoretical predictions are in general agreement with the experimental results for the ratio of "radiative" to normal decays. The theoretical value for this ratio is 1.3×10^{-4} which is to be compared with the experimental value of $3.3\pm 1.3\times 10^{-4}$. Fialho[17] has considered the effect of the magnetic moment of the μ-meson on the probability of emission of the γ-ray. Unfortunately, no definite conclusions can be drawn concerning the magnetic moment of the μ-meson from the comparison of the experimental results with the theoretical predictions because of the relatively small number of radiative decays that have been observed.

Short μ-meson tracks from π-meson decays have been observed by Powell,[5] Smith,[6] Bramson *et al.*,[18] George,[19] and Riezler and Rudloff.[8]

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[10] E. A. Martinelli and W. K. H. Panofsky, Phys. Rev. **77**, 465 (1950).
[11] Durbin, Loar, and Havens, Phys. Rev. **88**, 179 (1952).
[12] W. F. Fry, Phys. Rev. **84**, 385 (1951).

‡ *Note added in proof*.—This value is slightly higher than previously reported (see reference 7) due to the inclusion of an additional event (event 8 in Table I).
[13] Nakano, Nishimura, and Yamaguchi, Prog. Theoret. Phys. **6**, 1028 (1951).
[14] H. Primakoff, Phys. Rev. **84**, 1255 (1951).
[15] T. Eguchi, Phys. Rev. **85**, 943 (1952) and private communications.
[16] G. E. A. Fialho and J. Tiomno, Anais acad. brasil. cienc. **24**, 245 (1952).
[17] G. E. A. Fialho, Notas De Fisica No. 1, 1952 (unpublished).
[18] H. J. Bramson and W. W. Havens, Jr., Phys. Rev. **83**, 861 (1951); Seifert, Bramson, and Havens, Phys. Rev. **86**, 603 (1952); Seifert, Bramson, and Havens, Bull. Am. Phys. Soc. **28**, No. 1, 20 (1953).
[19] E. P. George (private communications).