The Capture and Decay of Mesons in Photographic Emulsions*

W. F. FRY
Department of Physics, Iowa State College, Ames, Iowa
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Meson events have been studied in Eastman NTB-3 plates which were exposed to cosmic radiation in the stratosphere by means of balloons. It is found that 68±7 percent of the mesons ending in the emulsion which do not produce stars or without associated secondary mesons decay with the emission of a high energy electron. Of these mesons, 11.6±1.5 percent (presumably 23.2 percent of the negative mesons) have associated electrons with energies in the interval from 15 to 70 kev. The energy distribution of these electrons is well represented by a simple exponential with a mean energy of 17 kev. Electrons with energies in the interval from 15 to 70 kev are observed from 19.6±4.0 percent of the stars caused by negative π-mesons.

INTRODUCTION

IN the electron sensitive emulsions recently available, even the minimum ionizing tracks due to charged particles traveling with relativistic velocities can be seen. Because of the high stopping power, comparatively large thicknesses, and the long sensitive time, very infrequent events can be studied. These characteristics make nuclear emulsions very suitable for the study of phenomena associated with mesons. However, the high stopping power has a disadvantage, in that particles of very low energies do not produce a well defined track. The practical lower energy limit for electrons in Eastman NTB-3 plates is about 15 kev. Electrons of energy less than 15 kev occasionally produce a clump of silver grains in these emulsions.

The emulsion consists of a group of heavy elements, mainly silver and bromine in the form of crystals, and a group of lighter elements, principally hydrogen, oxygen, nitrogen, and carbon in the form of gelatin. It is evident that photographic emulsions are not suitable for the detailed study of the capture of negative mesons by any one particular element.

This paper describes the study of certain phenomena associated with the decay and capture of mesons in photographic emulsions.

PROCEDURE

Eastman NTB-3 plates of 200-micron thickness, were exposed in the stratosphere by means of meteorological balloons. Since the sensitivity of nuclear emulsions is reduced at low temperatures, the plates were enclosed in Dewar flasks in order to maintain the maximum sensitivity of the plates. The plates were developed by the temperature method devised by Dilworth, Occhialini, and Payne.[1] A systematic search was made for meson tracks ending in the emulsion. Meson tracks were distinguished from proton tracks by two characteristics. Meson tracks have a greater rate of change of grain density with residual range, and a larger amount of small angle scattering. Tracks shorter than 200 microns were not considered.

On searching 47 plates, containing some 10^7 tracks mainly protons and alpha-particles, 659 tracks which stopped in the emulsion were identified as meson tracks. Of these mesons, 500 are presumably μ-mesons, 118 are negative π-mesons causing stars, and 41 are π-mesons which decay into μ mesons.

μ-MESONS

All mesons ending in the emulsion, without associated particles other than electrons, are classified as μ-mesons. Using this criterion, some negative π-mesons are included as μ-mesons. It has been shown that 26.8 percent of the negative π-mesons ending in the emulsion do not produce stars.[2] Since only 118 negative π-mesons were found in the same plates as the 500 μ-mesons, then approximately 43 of the 500 mesons, classified as μ-mesons, are negative π-mesons.

Of the 500 μ-mesons, only 462 μ-mesons were found in plates which were suitable for observing the decay electrons. The decay electron was observed from 122 μ-mesons out of the 462 μ-mesons. The grain density is very low along the tracks of the decay electrons. Tracks of those electrons which make a large angle with the plane of the emulsion will not be seen. The angles made by the observed decay electrons with the plane of the emulsion were measured. The number of decay electrons which were not seen due to their large angle with the plane of the emulsion, can be estimated from the angular distribution of the observed electrons. A histogram was made of the number of observed decay electrons in a given angular interval, as a function of the angle made with the plane of the emulsion. A calculated curve based on an equal number of electrons per unit solid angle and having the same height as the experimental curve, was superimposed on the experimental histogram. The area between the two curves indicated that about 166 electrons should not have been seen. Thus out of $462-43(462/500)=423$ actual μ-mesons a total of $122+166=288$ decayed in the emulsion (68±7 percent). This result is in agreement with the work of Cosyns, Dilworth, Occhialini, and Schoenberg[3] and

* Supported in part by grants from the Research Corporation and the Iowa State College Research Foundation.
[1] Dilworth, Occhialini, and Payne, Nature **162**, 102 (1948).
[2] F. L. Adelman and S. B. Jones, Phys. Rev. **75**, 1468A (1949).
[3] Cosyns, Dilworth, Occhialini, and Schoenberg, Proc. Phil. Soc. A **62**, 801 (1949).

Bonetti,[4] who found 63±4 percent and 68 percent, respectively. These percentages include as μ-mesons the negative π-mesons which did not produce stars in their plates.

The result is also in agreement with crude theoretical predictions based on the following arguments. Assuming that the stopping power of the various constituents of the emulsion for low energy mesons is proportional to the atomic number, it is estimated that 81 percent of the mesons stopped in silver bromide crystals and that 19 percent stopped in gelatin. It has been shown that negative mesons stopped in a material of $Z=10$ have about equal probability of capture and decay.[5] If it is also assumed[6] that the probability of capture of negative mesons is proportional to Z^4, then nearly all of the negative μ-mesons which end in silver bromide crystals will not decay, while essentially all of those ending in the gelatin will decay. If it is further assumed that there are equal numbers of positive and negative μ-mesons in the low energy spectrum from cosmic rays,[7] then of the 423 μ-mesons considered, 212 are negative, of which $(212)(0.19)=40$ should give rise to a decay electron. From these considerations, $212+40=252$ (60 percent) of the mesons decayed. A total of 288 (68 percent) is observed.

A careful search was made for low energy electrons at the end of the μ-meson tracks. All of the plates were suitable for the study of low energy electrons. In these plates 500 μ-mesons were found, of which 46 (9.2 percent) have one associated low energy electron in the energy interval between 15 and 70 kev. Ten (2 percent) have two low energy electrons. Two mesons (0.4 percent) give rise to three low energy electrons. In only one case were a high energy and a low energy electron observed from the same meson. These results are corrected for the contribution of the negative π-mesons in the following section. A study of low energy electrons from μ-mesons has been made by Cosyns *et al*,[3] who found 7.2±1.3 percent of the μ-mesons give rise to one or more electrons of energy greater than 20 kev. A similar study was made by Bonetti[4] who found that 7.2 percent of the μ-mesons give rise to a low energy electron.

It is difficult to estimate the number of electrons in the interval from 15 to 70 kev that were not seen. Many background electrons of energies less than 100 kev were observed in the plates. Many of these tracks were nearly perpendicular to the plane of the emulsion. From this study, it seems that very few electrons in the interval from 15 to 70 kev were missed.

A typical example of an electron originating from a μ-meson is shown in Fig. 1.

[4] A. Bonetti, University of Genoa, Genoa, Italy, private communication.
[5] T. Sigurgeirsson and K. A. Yamakawa, Revs. Modern Phys. **21**, 124 (1949).
[6] J. Wheeler, Phys. Rev. **71**, 462 A (1947).
[7] C. Franzinetti, Phil. Mag. **41**, 86 (1950).

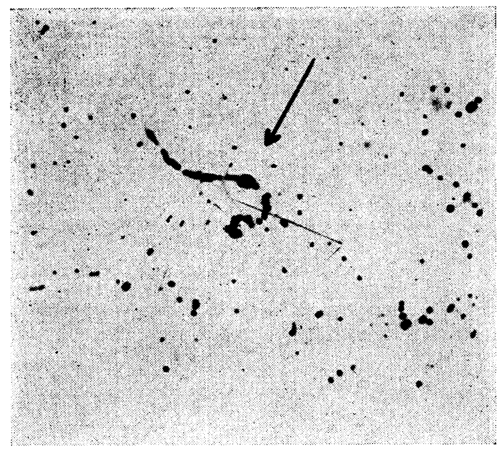

FIG. 1. Mosaic of a μ-meson and an associated low energy electron. The meson track goes to the right and down. A clump of silver grains can be seen at the end of the meson track which is indicated by an arrow. The track of a 45 kev electron can be seen below the meson track.

The energy distribution of the low energy electrons from μ mesons is shown in Fig. 2. There is no evidence of line structure. The spectral energy distribution of these electrons can be approximated by the equation; $N(E)\sim\exp(-E/E_a)$, where E_a is a mean energy and has a value of about 17 kev.

A low energy electron is considered as being associated with a meson only if it originates within two microns from the end of the meson track. Using this criterion, the number of background electrons erroneously counted as being associated with the mesons, can be estimated in the following way. A total of 300 proton tracks were found which stopped in the emulsions. Using the aforementioned criterion, only two cases were found where a low energy electron would have erroneously been considered as having originated from the proton; hence the background can be neglected.

At the end of 32 μ-meson tracks, a clump of silver grains was observed. These "blobs" are not observed

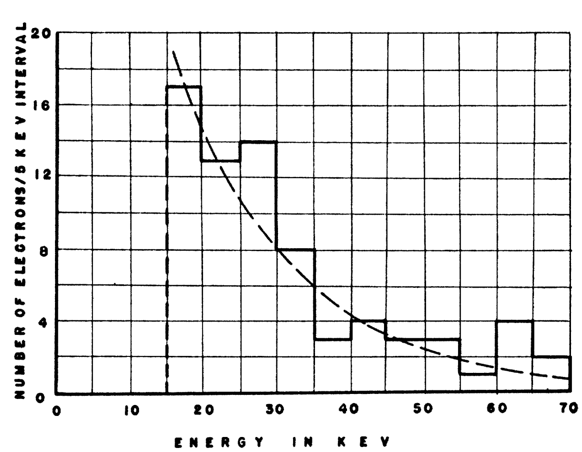

FIG. 2. Energy histogram of 72 electrons from μ-mesons.

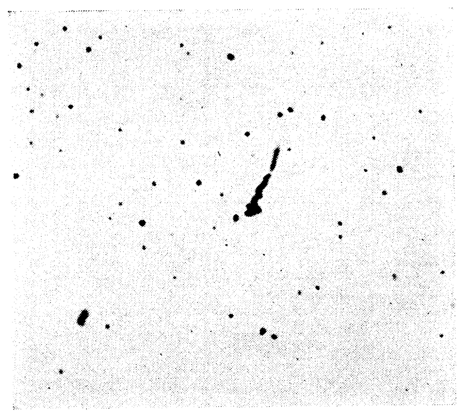

FIG. 3. Photomicrograph of a meson track which has a clump of silver grains at the end.

at the end of the 122 μ-mesons which decay, nor at the end of the 41 π-mesons which decay into μ-mesons. From this, one concludes that the "blobs" are associated only with the capture of negative mesons, rather than with large angle scattering near the end of the meson tracks.[7,8] The "blobs" are thought to be due to one or more electrons of energy below 15 kev. A typical meson track with a clump of grains at the end is shown in Fig. 3.

σ-STARS

Meson tracks were found to end in stars in 118 cases. One or more low energy electrons are observed to originate from 22 stars (18.6 percent). In 4 cases, two low energy electrons are observed from the same star. A typical star with a low energy electron is shown in Fig. 4. The energy distribution of the electrons from meson stars is given in Fig. 5. No correlation was found between the number of low energy electrons and the number of prongs in a star. No minimum ionizing tracks were observed from meson stars. The probability of observing these tracks can be estimated from the study of the number of electrons from μ-meson decays. Since 122 decay electrons were observed out of a total of 288, the probability of observing a minimum ionizing track is about 0.4. Since no minimum ionizing tracks were seen from negative π-stars, the β-activity of the residual nuclei which result in high energy electrons ($E>0.2$ Mev) must be small.

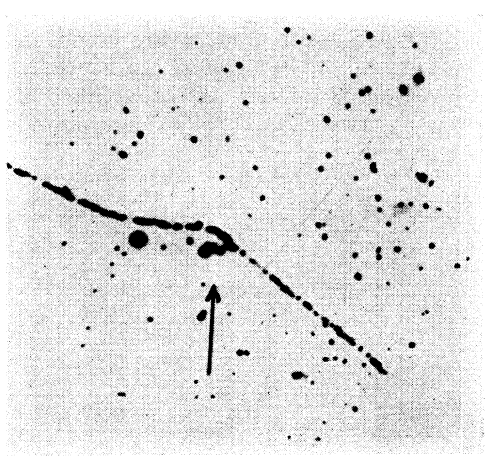

FIG. 4. A mosaic of a one-prong star due to the nuclear capture of a negative π-meson. The meson track is to the left of the mosaic and a proton track to the lower right. A track of a low energy electron, indicated by an arrow, can be seen below the end of the meson track.

An estimate of the contribution to the number of low energy electrons from negative π-mesons classified as μ-mesons can now be made. Since 18.6 percent of the negative π-mesons have an associated low energy electron, of the estimated 43 π-mesons classified as μ-mesons, on the average only $(43)(0.18)=8$ cases of ejection of low energy electrons are due to negative π-mesons. Of the 58 mesons classified as μ-mesons which have an associated low energy electron, on the average only 50 are actually μ-mesons.

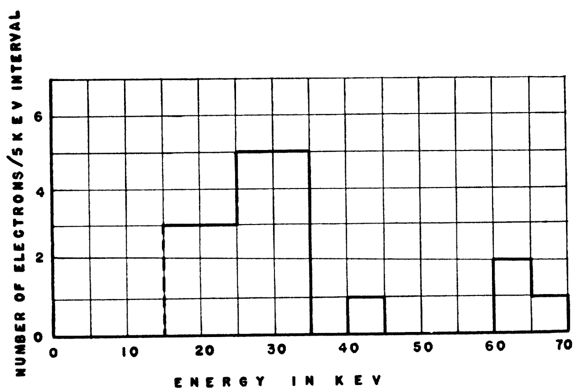

FIG. 5. Energy histogram of electrons from negative meson stars.

Since 118 meson induced stars were found in the same plates along with 41 π–μ-decays, it would appear that the ratio of low energy negative to positive π-mesons in the cosmic radiation is $(118)/(41)(0.73)=4$.

RANGE-ENERGY RELATIONSHIP

Electron sensitive NTB-3 plates were exposed to monoenergetic electrons in an electron microscope and an instrument built by General Electric for electron diffraction studies. The ranges of groups of monoenergetic electrons were determined. The results are shown in Table I.

The numbers listed under the last column are estimates of the probable error in energy of a single electron from a measurement of its range.

The ranges of the individual tracks were measured. The average range was then found. A range energy curve was then made. The apparent energy of each electron was then determined from this curve and a

[8] H. Bradner, Univ. of Calif. Rad. Lab. Report No. 486 (1949).

TABLE I. Mean range of electrons in electron sensitive NTB-3 plates.

Energy in kev	Number of tracks measured	Mean range in microns	Spread in energy
50	35	17.5	±6 kev
30	50	7.0	±4 kev
20	50	3.7	±4 kev

histogram drawn. The results are shown in Fig. 6. It is apparent that detailed line structure could not be detected by range measurements for electrons of energy less than 30 kev.

CONCLUSIONS

Since essentially all of the low energy electrons are associated with μ-mesons which do not decay, it is reasonable to assume that these mesons are negative. It also seems reasonable to assume from energy and radiation considerations that the low energy electrons are not due to atomic capture of the mesons in the lighter elements in the emulsion. Of the 457 μ-mesons, on the average 228 are negative, of which 185 were presumably captured by silver and bromine atoms. Thus the probability is 0.20 ± 0.04 that a negative μ-meson eject one electron in the energy interval from 15 to 70 kev upon capture by an atom of silver or bromine. The probability that two electrons in this energy range are ejected is 0.054 ± 0.015. For three electrons, the probability is about 0.01.

The probability of ejection of low energy electrons by negative π-mesons upon capture by silver or bromine is, within the statistical limits, the same as for negative μ-mesons; namely, 0.19 ± 0.04 for one electron and about 0.04 for two electrons. Also the energy distribution of the low energy electrons from negative μ-mesons and negative π-stars seems to be the same. These facts indicate that the low energy electrons are probably due to some type of interaction of the meson with the electronic shell, such as Auger transitions, rather than a nuclear phenomenon.

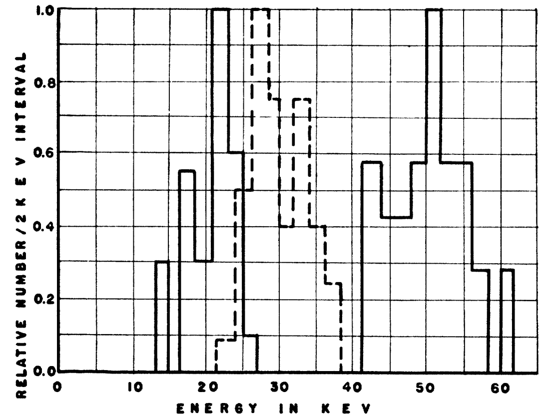

FIG. 6. Apparent energy distribution of three groups of monoenergetic electrons.

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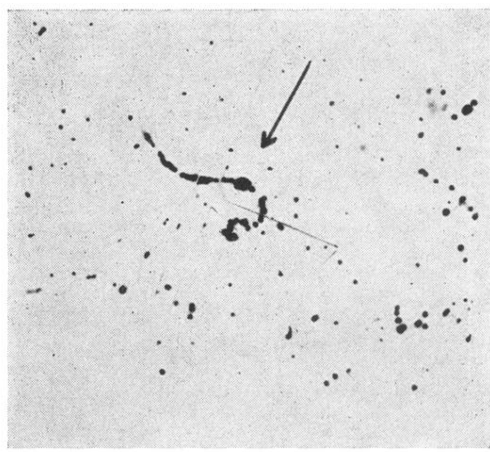

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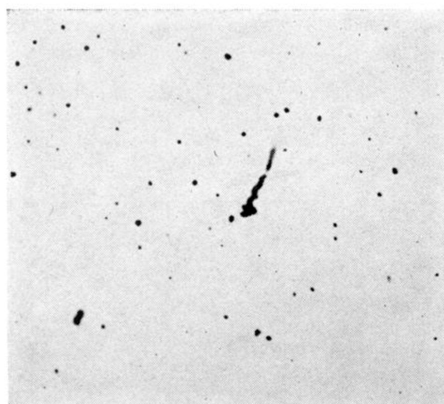
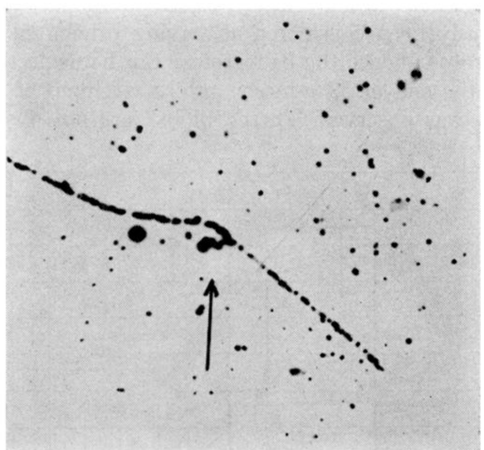


Fig. 3. Photomicrograph of a meson track which has a clump of silver grains at the end.



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