The Decay and Capture of μ-Mesons in Photographic Emulsions

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ABSTRACT. Observations on the decay and capture of μ-mesons in Kodak NT4 and Ilford G5 photographic emulsions are described. It is found, in agreement with other workers, that $63 \pm 4\%$ of all μ-mesons stopping in the emulsion decay with the emission of a fast electron, a result which is shown to be in reasonable agreement with theoretical predictions. The emission of *slow* electrons is observed from $7 \cdot 2 \pm 1 \cdot 3\%$ of all slow mesons, and these are ascribed mainly to an Auger effect accompanying the capture of μ-mesons.

§1. INTRODUCTION

IT has already been shown that it is possible to detect the decay electron of the μ-meson in the new highly sensitive emulsions (Brown, Camerini, Fowler, Muirhead, Powell and Ritson 1949). In this paper the results of an investigation of the mechanism of stopping and capture or decay of these mesons in the various elements of the emulsion is described. The photographic emulsion is not a very suitable medium for this purpose since it is composed partly of heavy elements, silver and bromine, combined in the form of dielectric crystals, and partly of an amorphous mixture of light elements, carbon, hydrogen, nitrogen and oxygen. Moreover, it has a high stopping power which prevents the recognition of electrons of energy less than 20 kev.

Exposures have been made at the Pic du Midi of batches of plates of the Kodak NT4 and Ilford G5 emulsions, of thicknesses 200, 400 and 600 microns, for 6 days and 12 days. All mesons entering the plate from outside and ending in the emulsion without giving rise to a star or to a secondary meson have been classified as positive or negative μ-mesons (formerly designated as ρ-mesons).

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§2. OBSERVATIONS AND FRACTION OF μ-MESONS WHICH DECAY

In Table 1 are given the observed numbers of mesons in the various exposures, separated into mesons which stop giving rise to no observable electron (μ), those which give a fast electron only ($\mu + e$), those giving a fast electron and one or more slow electrons ($\mu + e + A$), and those giving rise only to slow electrons ($\mu + A$).

Table 1

Exposure (days)	Plates	Thickness (microns)	Area (cm²)	Total No.	μ	$\mu+e$	$\mu+e+A$	$\mu+A$
6	Kodak NT4	400	100	65	18	40	1	6
12	Kodak NT4	400	131	205	78	114	0	13
12	Kodak NT4	200	109	61	24	31	1	5
6	Ilford G5	600	50	82	32	45	0	5

A decay electron will be observed only if it is emitted at a sufficiently small angle to the plane of the emulsion. In order to determine the fraction of decay of electrons which have been missed, the lengths of the tracks of all the decay electrons in plates of the same thickness have been measured. Using the usual geometrical argument, the distribution so obtained has been fitted to the calculated distribution. The correction made in this way shows that failure to observe dipping electrons causes a loss of 10% of the observed number in a 400 micron emulsion. The number of tracks available in the other plates is not sufficient to repeat the measurements for 200 and 600 micron plates, but it is assumed that the loss is approximately inversely proportional to the thickness, i.e. 7% for 600 microns and 20% for 200 microns.

In order to find the fraction of mesons giving rise to decay electrons, all mesons giving a fast electron have been put in one group ($\mu + e$) and all without a fast electron in the other group (μ), regardless of the presence or absence of slow electrons. The results after making the geometrical correction are given in Table 2.

Table 2

Plate	Thickness (microns)	Total No. of mesons	$\mu+e$	μ	% of mesons which decay
Kodak NT4	400	270	171	99	63 ± 5
Kodak NT4	200	61	38	23	62 ± 10
Ilford G5	600	82	48	34	59 ± 9

The percentage of decay in the different groups of plates is consistent within the experimental errors, and the results, combined for all the plates, give a total number of 413 mesons, of which 257 decay (i.e. 62 ± 4%) and 156 are captured.

Approximately 2·5% of these particles will be negative π-mesons which are captured by the nucleus and give rise to no visible star. This is deduced from the fact that the number of negative π-mesons giving stars is 10% of the number of ρ-mesons, and the results of experiments at Berkeley which show that 25% of the negative π-mesons ending in emulsions insensitive to electrons give no ionizing particles. Thus of the 413 mesons which stop in the emulsion, 409 will be μ-mesons; of these, 257 decay (i.e. 63 ± 4%) and 152 are captured, a result in good agreement with the Bristol group (Brown *et al.* 1949).

The existence of a positive excess of slow mesons is not definitely established for energies of the order of 10 Mev. which are important in the photographic plate.

Preliminary reports from Franzinetti on the magnetic sandwich method indicate that positive and negative μ-mesons are present in approximately equal numbers. Thus, in the absence of evidence to the contrary, it will be assumed that the numbers are equal. Then of the 409 μ-mesons the 204 ± 14 which are positive must all decay, so that of the negatives 53 ± 7 ($26 \pm 3\%$) decay and 74% are captured. If it is assumed that among the various elements of the gelatine the probability of stopping a meson is proportional to Z, and the probability of capture is proportional to Z^4 (Wheeler 1947), the fraction of negative mesons stopped in gelatine which decay is about 80%. On the same reasoning all the negative mesons stopped in AgBr will be captured. Thus the decay of the negative mesons requires that 30% are stopped in the gelatine. A rough calculation of the relative number stopped, assuming that the stopping power at low energies is still proportional to the number of electrons per unit path, gives a value of 33% for gelatine. This agreement may be considered satisfactory.

§3. MESONS WHICH ARE CAPTURED WITH EMISSION OF SLOW ELECTRONS

As indicated in Table 1, the emission of slow electrons has been observed from the ends of $7 \cdot 2 \pm 1 \cdot 3\%$ of the meson tracks, and these are ascribed mainly to an Auger effect accompanying the capture of μ-mesons. A detailed analysis shows that this proportion implies an actual occurrence of more than 20% in the cases in which a negative meson stops in the heavy elements of the emulsion.

Although all the slow electrons are ascribed in this paper to μ-mesons, it is possible that an appreciable fraction could be due to negative π-mesons which are captured without producing visible stars. Only experiments with artificially produced mesons can give the exact value of this fraction, but certainly not more than one-third of the effect we have observed could be ascribed to this cause. The actual proportion is, in fact, probably much smaller than one-third because this value has been obtained on the assumption that *all* the captured negative π-mesons emit slow electrons. If the emission of slow electrons by these negative π-mesons is the same as for star-producing σ-mesons, the contribution would fall from one-third to one-seventh.

The extent of the loss of slow electrons emitted due to the failure to recognize them as such is very difficult to estimate. These electrons are highly scattered and, therefore, it is not possible to determine their point of origin unless the density of grains in the vicinity of the end of the meson track is high and even. When of very low energy (20–30 kev.) they can easily be obscured by the track of the meson. When of higher energy (50–150 kev.), the beginning of the electron track is frequently well defined, but it is difficult to follow it to the end if the general density of slow electrons in the neighbourhood is high. Electrons of less than 20 kev. will never be recognized, since their range is too short.

It is essential to establish a rigorous criterion for the admission of a slow electron as originating from the end of a meson, since the probability of a chance juxtaposition of the end of the meson track with the beginning of the track of one of the numerous electrons of the background is appreciable. The criterion adopted is that slow electrons should be admitted as Auger electrons only if the beginning of the track can be certainly identified within 1 micron of the end of the meson. The probability of a chance effect has then to be determined. This is done in two ways. First, the number of slow electron tracks on 6,360 microns of

meson track and 6,700 microns of proton tracks are counted. A total of 90 slow electrons is found, giving a frequency of 1·5% for the chance effect. It is realized that some of these slow electrons may be genuine delta rays ejected by the fast particle, and an attempt has been made to repeat the measurement using the image of a fine wire superposed on that of the emulsion. This gives a frequency of slow electrons of the order of 0·2%. A more direct approach has therefore been adopted. Among the protons ejected from the stars, search has been made for those giving an apparent Auger effect, which in this case must certainly have been spurious. In the exposure of 6 days one such effect has been found in 270 protons and in the 12-day exposure one in 220 protons. The probability of a chance effect can therefore be estimated as not more than 0·5% even in a 12-day exposure.

The results given in Table 1 show a frequency of the Auger effect of 7% of the total number of mesons, i.e. 14% of all negative μ-mesons (neglecting the contribution from negative π-mesons). This figure is certainly a lower limit since the rigorous criterion excludes possibly as many Auger effects as have been accepted. Of these 7%, less than 1% are associated with a fast electron, which strongly

Table 3. Energy of Observable Auger Electrons in the Chief Components of the Emulsion

Element	Energy of Auger Electrons (kev.) Transitions							
	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9
Carbon	78	14·5						
Nitrogen	106	19·7						
Oxygen	139	25·8						
Bromine	2650	494	173	80	43·5	26·1	17·0	
Silver	4780	890	311	144	78·4	47·1	30·7	21·4

indicates that practically all the Auger electrons are produced in AgBr. From the above estimate of 30% of mesons stopping in gelatine, it follows that of negative mesons stopped in AgBr at least 20% give rise to an observable Auger electron.

The energy of the electrons that should be expected from the Auger effect can be deduced from the position of the orbits of a meson of mass 214 round the nuclei of the various elements of the emulsion. These are given in Table 3. It will be seen that in the gelatine only the last transitions of the meson will give rise to Auger effects observable in the photographic plate (i.e. of energy greater than 20 kev.). According to the theory of Fermi and Teller (1947) it is in the last transitions that the emission of radiation rather than Auger effects become predominant. In the case of AgBr there are several possible transitions before the meson arrives in the region of loss by radiation (for these elements the loss by radiation becomes important for meson orbits whose radii are of the order of Zr_K, r_K being the radius of the meson K orbit corresponding to the atomic number Z). The exact values of the relative probabilities of Auger effect and of radiation on this theory have not, to our knowledge, been calculated.

The observed distribution in range of the Auger electrons is given in Figure 1 (a). The range–energy relation of slow energy electrons in these emulsions is not yet known with precision and may possibly depend somewhat on the batch, but some idea of the corresponding energies can be obtained from the curve given for Kodak NT2a emulsions. The distribution in energy of the Auger
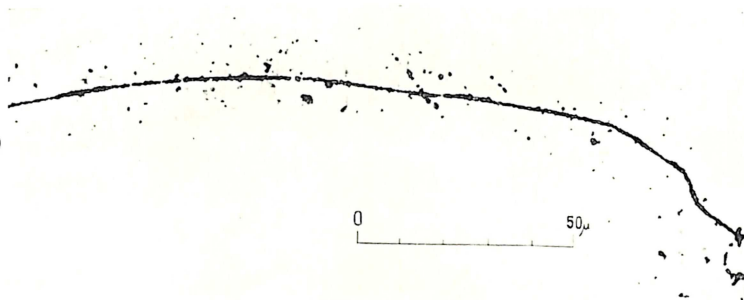
(a)
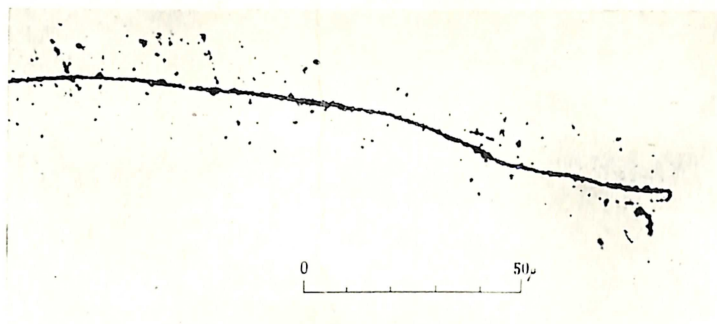
Single slow electron.
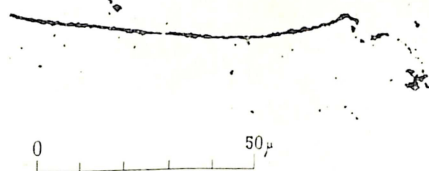Plate: Kodak NT4, 400 μ.
Exposure: 6 days.
Obs.: Eric Shramm.

(b)
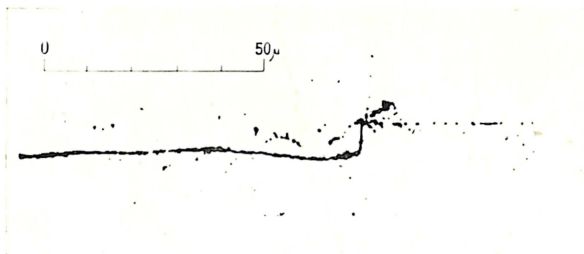
Several slow electrons
and single fast electron.
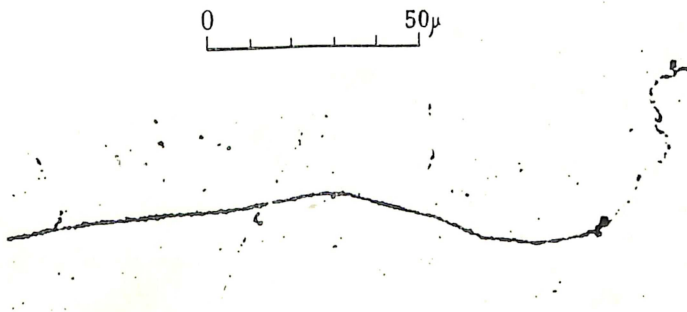Plate: Kodak NT4, 400 μ.
Exposure: 6 days.
Observer: Mme Hubert.

(c)

Two slow electrons.
Plate: Kodak NT4, 400 μ.
Exposure: 6 days.
Observer: Mme Hubert.

(d)

Single slow electron.
Plate: Ilford G5, 600 μ.
Exposure: 6 days.
Observer: Mme Hubert.

(e)

Three slow electrons.
Plate: Kodak NT4, 400 μ.
Exposure: 12 days.
Observer: Mme Hubert.

Slow electrons observed at the end of meson tracks.

electrons is given in Figure 1 (*b*) and the spectrum calculated for silver and bromine in Figure 1 (*c*). Taking into account the difficulties in recognition and measurement of these tracks and the uncertainty of the range–energy curve, there is reasonable agreement. The absence of well-defined lines in the experimental spectrum can be easily explained by the overlapping of the lines of the various elements; moreover, these lines have probably been broadened by the errors of observation and straggling.
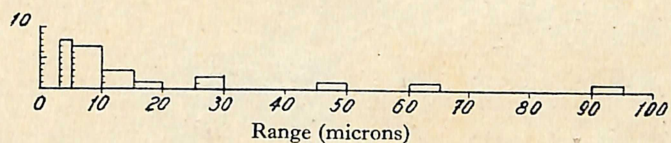
(*a*) Observed number of Auger electrons.
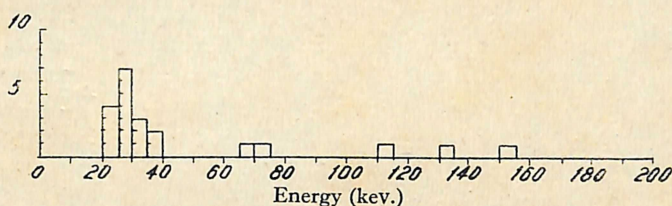
(*b*) Observed number of Auger electrons.
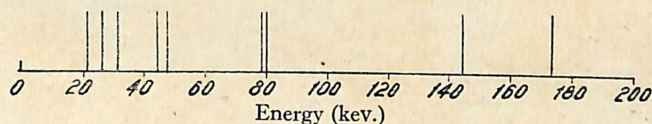
(*c*) Calculated spectrum for silver and bromine.

Figure 1.

The conclusions which can be drawn from these measurements seem to be that the existence of the Auger effect—which should more properly be called internal-conversion effect since the transfers of energy correspond to meson orbits well within the electron cloud—has been demonstrated, and its frequency is not large. This indicates that it is largely suppressed by a more probable competing process such as radiation.

ACKNOWLEDGMENTS

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