

Ejection of Electrons by Ions at High Fields

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IN the accompanying letter by Germer and Haworth, evidence is presented to show that a positive ion in a high field ($\sim 10^7$ volts/cm) must be able to eject several electrons from a metal. On the other hand, present theories of ejection by positive ions in low fields require that the ion be neutralized as the first step in the ejection process and, hence, that an ion be unable to eject more than one electron.¹ If the hypothesis of Germer and Haworth is correct, the mechanism must be qualitatively different at high fields.

A positive ion near the surface of a metal creates a deep well in the potential energy function of an electron, and, if the ion is close to the metal, an electron can readily tunnel from the metal to the ion. At low fields, the electron has no place else to go and either remains on the ion, thus neutralizing it, or returns to the metal.

At high fields the picture is different. One readily sees that the potential energy surface of the electron has a "pass" lying on the opposite side of the ion from the metal. If the field is sufficiently high, the energy at the pass is lower than the Fermi level in the metal. An electron coming from near the Fermi level can then escape to infinity. Thus an electron has become free by tunneling through the barrier between the metal and the ion, which is easier than tunneling through the barrier which exists when the field alone is present.

To get some idea of the emission caused by such a process, we have made some calculations based on a one-dimensional metal. The electrons inside the metal were assumed to occupy the energy levels of an electron in a box, with the highest energy 4.2 volts below vacuum. Letting r be the distance from the metal surface, we took the potential due to the metal to be:

$$\Phi = e/[4r + (e^2/W_0)].$$

W_0 gives the energy at the bottom of the conduction band, which was chosen to be 10 volts below vacuum. The results turn out to be independent of the length of the metal. We assumed a field of 2.5×10^7 volts/cm and made calculations for several values of r . In calculating the potential due to the ion, we included the effects of the image charge.

We then assumed that all electrons with energies above the outer maximum (which the pass becomes in one dimension), which tunnel through the inner barrier become free, and that no other tunnel through the first barrier. Following a well-known method² we computed a transmission coefficient through the first barrier for several energies lying above the outer maximum. This coefficient was multiplied by the number of collisions per second, with one end of the metal, made by electrons with the assumed energy and by the density of energy levels, and the product was integrated numerically over all energies from the height of the outer maximum to the Fermi level. This gives the number of electrons per second ejected from the metal, as shown by Table I.

TABLE I. Ejection of electrons by a proton. Field = 2.5×10^7 volts/cm.

Distance of ion from surface, A.U.	Estimated emission, electrons per second
6	52×10^{12}
8	9×10^{12}
10	10^{12}
∞ (pure field emission)	10^6

The mean value of the emission rate from 10 to 6 A.U., using Simpson's rule, is 15×10^{12} electrons/sec.; if an ion travels from 10 A.U. to 6 and back to 10, with a mean velocity of 10^6 cm/sec., it would eject 1.2 electrons on the average. Since 6 A.U. is probably much too large a distance for reflection, we conclude that an ion may well be able to eject many electrons from the metal.

¹ A. Cobas and W. E. Lamb, *Phys. Rev.* **65**, 327 (1944), (contains further references).

² See, for example, E. C. Kemble, *Fundamental Principles of Quantum Mechanics* (McGraw-Hill Book Company, Inc., New York, 1937), p. 109 ff.

On the Stability of the Neutral Meson

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THE discovery¹ of the disintegration of a heavy (π) meson into a light one (μ meson, most likely the particle constituting the penetrating component of the cosmic radiation) has provided strong evidence² in favor of the existence of neutral mesons of mass about 70 Mev.

In order to explain a photograph of a 24-Mev decay electron, observed by Anderson, Adams, Lloyd, and Rau,³ these authors and later Marshak⁴ have suggested that the μ -meson might decay into an electron and a neutral particle apparently identical with the neutral meson of Lattes, Occhialini, and Powell. Greisen⁵ has recently indicated that several cosmic-ray phenomena "which have defied even qualitative explanation up to the present are made understandable in the light of the neutral meson hypothesis" provided the neutral meson decays immediately into two photons. This γ -instability has been predicted on theoretical grounds by several authors.⁶

We want to point out that we have secured experimental evidence proving an incompatibility between the hypothesis that the 2.2- μ s meson decay into an electron and a neutral meson and the hypothesis that the neutral meson is unstable *versus* emission of two photons with a very short lifetime. The experimental arrangement has been described⁷ in connection with a research—which gave a negative result—to find out whether the decay of the 2.2- μ s meson consists of the emission in opposite directions of one electron and one photon, each of about 50 Mev. Clearly the same arrangement, for the details of which we refer to our previous note, is capable of deciding whether the decay of the 2.2- μ s meson consists of the emission of an electron and a neutral meson unstable *versus* emission of two photons of about 35 Mev. The number of

decay electrons from mesons stopped in graphite was recorded, and at the same time electron-photon coincidences were looked for. While the net number of measured delayed coincidences (observed rate minus casual rate) is $0.01 \begin{cases} +0.06 \\ -0.01 \end{cases}$ per hour, the rate to be expected according to the hypothesis of a neutral meson unstable *versus* emission of two photons of 35 Mev with a mean life $\lesssim 10^{-10}$ sec. is about one per hour.

We conclude that either the neutral meson is not emitted in the 2.2- μ s decay process, or, if it is emitted, it does not decay into two photons with a mean life $\lesssim 10^{-10}$ sec.

It seems that a similar conclusion can be reached from the experiment of Sard and Althaus,⁸ who, by using a method different from ours, failed to observe a γ -radiation in the 2.2- μ s decay of mesons brought to rest in brass. It should be noticed that while our experiment refers to positive and negative mesons, their experiment refers only to positive ones.⁹

There remains, of course, the possibility that there are two distinct types of neutral mesons, one of which is stable and the other unstable *versus* emission of γ -radiation.

A more complete account of this work will be submitted for publication in the near future.

¹ C. M. Lattes, H. Muirhead, G. P. S. Occhialini, and C. F. Powell, *Nature* **159**, 694 (1947).

² C. M. G. Lattes, G. P. S. Occhialini, and C. F. Powell, *Nature* **160**, 453 (1947); **160**, 486 (1947).

³ C. D. Anderson, R. V. Adams, P. E. Lloyd, and R. R. Rau, *Phys. Rev.* **72**, 724 (1947).

⁴ R. E. Marshak, *Bull. Am. Phys. Soc.* **22**, No. 6, p. 14.

⁵ K. I. Greisen, *Phys. Rev.* **73**, 521 (1948).

⁶ J. R. Oppenheimer, *New York Meeting of American Physical Society*, January, 1947; R. J. Finkelstein, *Phys. Rev.* **72**, 415 (1947).

⁷ E. P. Hincks and B. Pontecorvo, *Phys. Rev.* **73**, 257 (1948).

⁸ R. D. Sard and E. J. Althaus, *Bull. Am. Phys. Soc.* **23**, No. 2, p. 20 (1948).

⁹ M. Conversi, E. Pancini, and O. Piccioni, *Phys. Rev.* **71**, 209 (1947).

Polarization Effects in the Ionization Loss of 1-Mev Electrons in Carbon*

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THE possibility that polarization effects might reduce the energy loss by ionization of fast-charged particles was suggested by W. F. G. Swann¹ and investigated theoretically by Fermi² and recently by Halpern and Hall.³ Experimental attempts to verify the effect at high energies ($\geq 20mc^2$) have proved successful in one instance,⁴ inconclusive in another.⁵ At lower energies the correction has not been considered effective and has been neglected in most collision problems.⁶ Halpern and Hall indicate, however, that the effect at low energies is not always appreciable; in fact, it yields an 8 percent reduction in the collision loss of 1-2-Mev electrons in carbon. By measurement of the relative stopping powers of carbon and H₂O at these energies, this prediction has been confirmed.

The success of the method depends heavily upon the discrimination between real absorption in a sample and apparent absorption due to scattering of particles out of the solid angle subtended by the counters. Fortunately,

in the comparison of carbon and H₂O, this discrimination is possible. First, it may be pointed out that for the case under consideration the scattering is predominantly multiple. Williams⁷ has given as the criterion for multiple scattering,

$$M = (2\pi NZ^{4/3}/\beta^2)(h/mc)^2 t \gg 1,$$

where N represents the electron density in a sample of thickness t cm. For the thicknesses of carbon and H₂O employed, $M = 2 \times 10^3$, in satisfactory accordance with the criterion. Furthermore, under these conditions, if thicknesses of different materials are measured in radiation lengths, equal thicknesses yield equal mean square scattering angles.⁸ This, of course, holds only for equivalent energy distributions of particles penetrating the samples. Hence, the ideal situation would prevail if samples of equal thicknesses (in radiation lengths) would also exhibit equal stopping powers on the basis of the Halpern-Hall theory. For then the scattering loss would form the same percentage of the apparent absorption in both substances. The condition which insures this state of affairs is

$$S(\text{H}_2\text{O})/S(\text{C}) = x(\text{C})/x(\text{H}_2\text{O})$$

where x denotes the radiation length, S the stopping power. In the case of carbon and H₂O this condition is satisfied to within a few percent.

In the experiment (Fig. 1) two thin-wall (0.035 g/cm²) argon-ether counters were used. Coincidences were counted by means of a Rossi circuit, the pulses from which were fed into a scale of 64. The resolving time of the circuit as determined by the accidental coincidence rate was 0.45 10^{-6} second. Equal thicknesses (in radiation lengths) of slab carbon and H₂O were inserted alternately into a thin-wall aluminum jacket at position A . Very nearly equal counting rates were observed, the difference being evaluated by reference to an aluminum absorption curve. The stopping power ratio, $S(\text{H}_2\text{O})/S(\text{C})$, was taken as the ratio of the quantities $S(\text{H}_2\text{O})/S(\text{Al})$ and $S(\text{C})/S(\text{Al})$. Table I shows $S(\text{H}_2\text{O})/S(\text{C})$ for two sample thicknesses and the values calculated from theory.

TABLE I. Summary of results.

	Thickness of samples			Effective energy range Mev	Stopping power ratio $S(\text{H}_2\text{O})/S(\text{C})$
	Radiation lengths	g/cm ² carbon	g/cm ² H ₂ O		
Author	0.0055	0.29	0.25	1.2 < E < 2.1	1.16 \pm 0.025 (exp.)
Author	0.0079	0.41	0.36	0.8 < E < 2.0	1.17 \pm 0.02 (exp.)
Halpern-Hall				1 < E < 2	1.16 (calc.)
Bethe-Bloch (neglecting polarization)				1 < E < 2	1.08 (calc.)

The negligibility of scattering errors was verified by shifting each sample to position B and observing the decreased coincident rates due to the increase in the intensity scattered out of the counter train. The decreased rates for carbon and H₂O were equal to within 2 percent. In view of the dependence of the differential scattering probability upon θ^{-4} , the error in the stopping power ratio due to scattering at position A can be shown to be less than 0.2 percent.