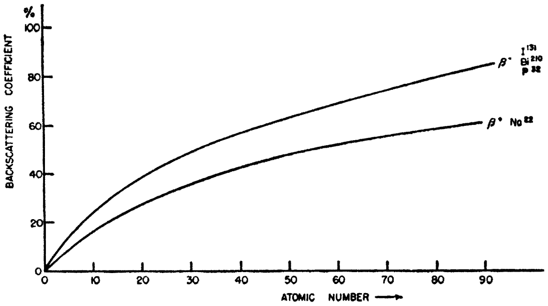

FIG. 2. Experimentally determined curves for the percentage of the backward radiation reflected into the counter as a function of the atomic number of the backing material.

The results of these experiments for I^{131}, RaE, P^{32}, and Na^{22} are shown in Fig. 2. The curve for percentage backscattering of negative electrons as a function of Z indicates that the backscattering is energy independent within the experimental accuracy, and is in good agreement with results obtained by Burtt[1] and by Engelkemeir.[2] This energy independence for negative electrons was indicated in a paper by Schonland,[3] although his quantitative results were lower, probably due to differences in geometry.

It is a little surprising to note the lower values of backscattering found for the positrons of Na^{22} as compared to the electrons of I^{131}, although the maximum energies of the β^+-particles and of the β^--particles are nearly equal.

Annihilation of positrons should account for a reduction of backscattering by only a few percent according to theoretical data.[4] However, the relativistic treatment of Coulomb scattering shows a marked increase of β^--scattering and a reduction of β^+-scattering as compared with the Rutherford formula.[5] This effect tends to explain our results, except that it ought to increase with atomic number, while the two curves in Fig. 2 indicate approximately a constant ratio.

A detailed interpretation of the present experiments seems to require additional theoretical and experimental work.

[1] B. P. Burtt, Nucleonics **5**, No. 2, 28 (1949).
[2] D. W. Engelkemeir, Plutonium Project Memorandum MUC-NS 312.
[3] B. F. S. Schonland, Proc. Roy. Soc. **A108**, 187 (1925).
[4] W. Heitler, *Quantum Theory of Radiation* (Clarendon Press, Oxford, 1936), p. 231.
[5] N. F. Mott and H. S. W. Massey, *The Theory of Atomic Collisions* (Clarendon Press, Oxford, 1933), pp. 80–85.

Dissociative Recombination

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BY the successful exploitation of microwave techniques several groups of workers[1] have recently derived interesting information on the decay of ionization. In most of the gases used there could be no complications due to negative ion formation, and the decay could apparently be attributed to electron recombination. The measured rate coefficients, α, were very high, ranging from about 10^{-8} cm³/sec. to about 10^{-6} cm³/sec. for the various gases investigated. In an earlier letter[2] it was shown that atomic ions could scarcely be involved since radiative recombination, and the few other processes available to these, seem much too slow. Consideration was therefore given to molecular ions and the suggestion was made that dissociative recombination, $XY^+ + e \rightarrow X' + Y'$, might be very effective. This possibility will now be examined in greater detail.

The reaction can be treated as taking place in two stages. As a result of a radiationless transition an excited molecule, XY' is formed. If this is unstable its constituents may move apart under the influence of their mutual repulsion thereby preventing auto-ionization. A quantal expression is available for the rate at which electrons of energy ϵ enter the excited state. It can be written in terms of $f(\epsilon)$, the familiar Franck-Condon factor measuring the degree of overlap between the nuclear wave functions concerned in the initial transition, and of $t_A(\epsilon)$, the time associated with the auto-ionization process. To determine the fraction of excited molecules that dissociate, $t_S(\epsilon)$, the time for effective separation to occur, must also be introduced. From the product of the rate and the fraction the following approximate formula for the recombination coefficient is obtained:

$$\alpha(\epsilon)=\{rh^3f(\epsilon)/8\pi(2m^3\epsilon)^{\frac{1}{2}}(t_A(\epsilon)+t_S(\epsilon))\}, \qquad (1)$$

where r is the ratio of the statistical weight of XY' to that of XY^+, h is Planck's constant and m is the electronic mass. As usual $f(\epsilon)$ is such that $\int_\epsilon f(\epsilon)d\epsilon$ is unity. If the electrons have an energy distribution corresponding to a temperature T then

$$\alpha(T)=\{rh^3/2(2\pi mkT)^{\frac{3}{2}}\}\times\int_\epsilon\{\exp(-\epsilon/kT)f(\epsilon)/(t_A(\epsilon)+t_S(\epsilon))\}d\epsilon. \qquad (2)$$

k being Boltzmann's constant. Numerical substitution, and the adoption of mean values t_A and t_S for $t_A(\epsilon)$ and $t_S(\epsilon)$ respectively, yields

$$\alpha(T)=2\cdot1\times10^{-16}\{r/T^{\frac{3}{2}}(t_A+t_S)\}\times\int_\epsilon\exp(-\epsilon/kT)f(\epsilon)d\epsilon \text{ cm}^3/\text{sec.} \qquad (3)$$

Accurate computations for any specific ion would be extremely difficult to perform, but by making estimates of the permissible magnitudes of the various quantities appearing in the formula some indication of the potentialities of the recombination mechanism under consideration can be obtained. Clearly r can be appreciably greater than unity; a figure as high as 10 is not impossible, especially if a number of excited states are included. It is not easy to assess t_A; for many transitions it must certainly be long, but judging from the theoretical and spectroscopic evidence available[3] it may actually be of the order of 10^{-13} sec. in some instances, and even shorter times have been reported. The value of t_S may also be of this order since the relative velocity is perhaps 10^5 cm/sec. and since a movement of less than 10^{-8} cm will often be sufficient to ensure the permanence of the neutralization.[4] The integral in (3) depends on details of the potential curves which in general are unknown; it will be very small unless $f(\epsilon)$ is appreciable for low ϵ, but in favorable circumstances it can equal the numerical value of $2kT$ when expressed in electron-volts. If these tentative estimates of the *possibilities* are accepted, and if (for the sake of definiteness) T is taken to be 250°K a recombination coefficient of some 10^{-7} cm³/sec. is obtained. As need scarcely be stressed, little significance should be attached to this figure which is given merely to demonstrate that *in certain by no means exceptional cases* dissociative recombination can be extremely rapid.

The assumption has hitherto been made that the ions studied by Brown, Holt and their associates were diatomic. This is not necessarily true. In some instances they may conceivably have been complex and the fragments may have been in part molecular. It is most important to determine the nature of the ions by means of optical or mass spectrographs. For until this is done the results obtained cannot be extrapolated to the low pressures and comparatively high temperatures that are of interest for many geophysical and astrophysical applications. In this connection it may be noted that even in the E layer the value of α found by radio-workers[5] is only 10^{-8} cm³/sec. which is more than an order smaller than the higher values obtained in the laboratory.

Finally, attention may be drawn to the fact that much might be learned from a supplementary experimental investigation of the closely analogous process of dissociative attachment (e.g., $XY + e \rightarrow X' + Y^-$) in both di- and polyatomic gases. The coefficients so far obtained are of order 10^{-10} cm³/sec. or smaller.[6] In view of effects due to the absence of an attractive Coulomb field, and to the restricted number of excited states, etc., it would be expected that they would in general be less than those for recombination. Further data on them would be useful.

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[1] M. A. Biondi and S. C. Brown, Phys. Rev. **75**, 1700 (1949) and **76**, 1697 (1949); Holt, Richardson, Howland, and McClure, Phys. Rev. **77**, 239 (1950). I wish to take this opportunity of thanking Professors Brown and Holt and their associates for a helpful discussion of their experiments.

[2] D. R. Bates, Phys. Rev. **77**, 718 (1950).

[3] Ta-You Wu, Phys. Rev. **66**, 291 (1944); A. G. Shenstone, Phil. Trans. Roy. Soc. **A241**, 297 (1948).

[4] It is apparent that "stabilization" by the emission of radiation or by collisions of the second kind, are very inefficient by comparison. Thus the time associated with the former cannot be much less than 10^{-8} sec.: and at a pressure of, say, 25 mm Hg, that associated with the latter would still be as long as 10^{-10} sec. even if the deactivation cross section were several orders greater than the gas kinetic.

[5] S. K. Mitra, *The Upper Atmosphere* (Royal Asiatic Society of Bengal, Calcutta, 1948).

[6] H. S. W. Massey, *Negative Ions* (Cambridge University Press, London, 1938).

The Detection of Artificially Produced Photo-Mesons with Counters*

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DELAYED coincidences between mesons and their decay electrons, as first observed by Rasetti,[1] have been widely used in cosmic-ray research as a means of counting mesons. A closely related technique in which the delay is timed from a very short proton pulse, has been used by Alvarez *et al.*[2] in the first electronic detection of artificially produced mesons. With the synchrotron the x-ray pulses are not short enough for the use of the latter method; therefore that of Rasetti has been used, with the x-ray pulse widened to about 2 msec. in order to reduce random coincidences.

When a positive π-meson comes to rest, it disintegrates very quickly into a μ-meson, and this in turn into an electron, with the well-known 2.1×10^{-6}-sec. mean-life. The range of the μ-meson is only $\sim$0.2 g, so that when this process takes place in a scintillation crystal with linear dimensions of the order of several centimeters, a large fraction of the decay electrons will also appear in the crystal. The $\pi\rightarrow\mu$-decay is too rapid to be resolved in the electronics of the experiment; instead, the characteristic half-life of the $\mu\rightarrow e$ decay is used to identify the meson. Negative mesons coming to rest in condensed matter do not produce decay electrons and therefore are not counted.

The apparatus is sketched in Fig. 1. The 330-Mev (max.) x-ray beam is collimated to $1\frac{1}{2}$ in. diameter and allowed to strike a target. The mesons produced at the target are detected in a telescope of three anthracene scintillation crystals after traversing variable amounts of aluminum absorber. The telescope can be rotated about the target in the plane of the beam. A meson is counted if it comes to rest in crystal II and its decay electron appears in the same crystal. That is, we require a pulse simultaneously in crystals I and II, but no pulse in crystal III. This coincidence starts several successive delay gates of two microsecond time width and if a pulse appears in crystal II during the gate time, it is recorded in that channel. There is an appreciable number of accidental delayed coincidences. These can be calculated from the known single counting rates, gate width, and duty cycle, and are then subtracted. The accidental rate is usually about 10 to 20 percent of the counting rate in the first channel. When the target is removed, both accidental and real coincidences are smaller by a factor of several hundred.

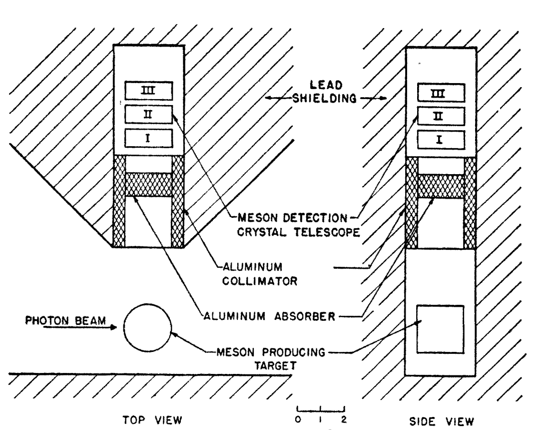

Fig. 1. Arrangement of target, absorbers, and meson detection scintillation counter telescope.

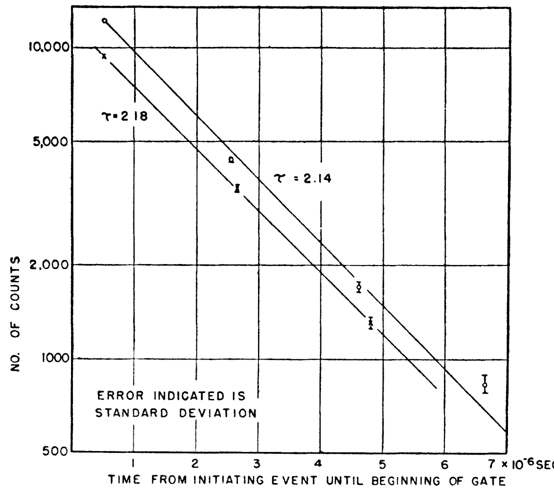

Fig. 2. Relative counting rates in the delayed channels. Two sets of data are shown because three channels were used at first, later four.

After the background subtraction the counting rates in the several delay channels should reproduce the exponential $\mu\rightarrow e$ decay. The lifetime data so far obtained are plotted in Fig. 2. When the x-ray energy is reduced below threshold no mesons are observed.

Since the crystals are proportional counting devices, the counting rates are functions of the amplitudes required for those pulses

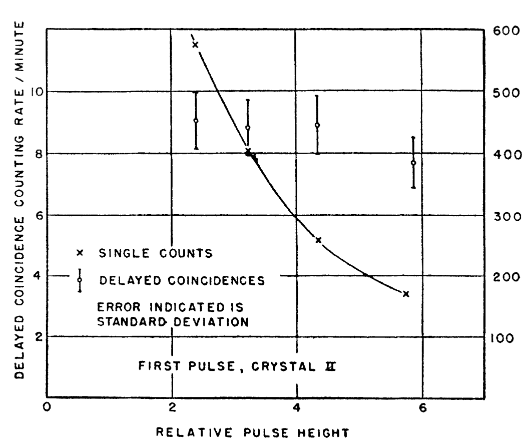

Fig. 3. Counting rate in crystal II (points without statistical error) and meson counting rate (with mean statistical error indicated) as a function of the minimum voltage required of the first pulse in crystal II.