

FIG. 1. Coincidence resolution curves. $P(x)$ is the prompt resolution curve obtained with an Au^{198} source and $F(x)$ is the delayed resolution curve observed with a Tm^{170} source, normalized to equal included areas. The curves intersect at $x=x_0$ where $F(x)$ is a maximum. Positive values of the delay time x correspond to delaying the pulses from the Tm^{170} beta-ray counter behind the source. The standard deviations of the points are indicated by vertical bars.

idence resolution curve was compared in the spectrometer with the resolution curve obtained when hard beta-rays were passed through the anthracene crystals of both counters. The results showed that the half-life of the 411-keV transition in Hg^{198} does not exceed 2×10^{-10} sec.⁵ The Au^{198} coincidences are thus prompt for purposes of this experiment.

Figure 1 shows the prompt resolution curve $P(x)$ observed for Au^{198} and the delayed resolution curve $F(x)$ observed for Tm^{170} , plotted to the same included area. Positive values of the delay, x , correspond to delaying the pulses from the Tm^{170} beta-ray counter behind the source. The areas were determined by numerical integration and the statistical error in equalizing the areas is less than two percent. The two curves obey the criterion² of intersecting at the maximum of $F(x)$.

The mean life $\tau = 1/\lambda$ for the Yb^{170} transition has been evaluated from the curves of Fig. 1 in three ways. Newton's² Eq. (5) applied with $A = -\infty$, $B = x_0$ gives $\tau = (2.34 \pm 0.12) \times 10^{-9}$ sec., and with $A = x_0$ and $B = \infty$ gives $\tau = (2.31 \pm 0.09) \times 10^{-9}$ sec., the average being $\tau = (2.32 \pm 0.07) \times 10^{-9}$ sec. Bay's³ Eq. (4) gives $\tau = (2.28 \pm 0.08) \times 10^{-9}$ sec. The value of τ obtained in the usual way from the slope of $\log F(x)$ at large positive delay is $(2.3 \pm 0.4) \times 10^{-9}$ sec.

The new analyses give much improved statistical accuracy for a case such as this one, where $P(x)$ and $F(x)$ overlap to a large extent. The standard deviations quoted were obtained by carrying the standard deviations of the measured points through the numerical integrations. Averaging the above determinations of τ and making allowance for the fact that the Au^{198} coincidences are only known to be prompt within 2×10^{-10} sec., we get $\tau = (2.3 \pm 0.3) \times 10^{-9}$ sec., or $T_{1/2} = (1.6 \pm 0.2) \times 10^{-9}$ sec. for the 83-keV transition in Yb^{170} .

The new methods of analysis enable the present coincidence apparatus to set upper limits on half-lives of the order of 2×10^{-10} sec., and to measure half-lives of the order of 5×10^{-10} sec. with fair accuracy.

¹ R. E. Bell and H. E. Petch, Phys. Rev. **76**, 1409 (1949).

² T. D. Newton, Phys. Rev. **78**, 490 (1950).

³ Z. Bay, Phys. Rev. **77**, 419 (1950).

⁴ J. S. Fraser, Phys. Rev. **76**, 1540 (1949).

⁵ Bell and Petch (reference 1) showed that this half-life was less than 2.1×10^{-9} sec. The new reduced limit was obtained with the same apparatus but using improved methods of analysis of coincidence resolution curves.

Saturation Backscattering of Positive Electrons

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THE percentage backscattering of positive electrons from a source backing thick enough to ensure complete absorption of the beta-particles (saturation thickness) has been studied under the conditions of geometry shown in Fig. 1. It was found that the backscattering of the positrons of Na^{22} under the same geometrical conditions is consistently 30 to 40 percent lower than the electron backscattering of I^{131} , RaE , and P^{32} .

As a check on the accuracy of the experimental technique, the backscattering of the negative electrons of I^{131} , Bi^{210} , and P^{32} was also investigated. In one set of experiments the weightless deposit approximately 12 mm in diameter was mounted on a thin aluminum leaf (0.22 mg/cm²) and net counting rates were measured with saturation thicknesses of Be, C, Al, Fe, Cu, Ag, and Pb backings placed directly beneath the weightless source. The net counting rate with no backing material beneath the source was assumed to be due only to forward radiation. The ratio of the net counting rate measured with a backing of atomic number Z to the net counting rate due to forward radiation will then indicate the percentage backscattering. In a different set of experiments, aliquots identical in activity and geometric size within one percent were deposited directly on polished faces of disks of saturation thickness again ranging from Be to Pb. The net counting rate in each case was plotted against the atomic number of the backing material and this curve was extrapolated to $Z=0$. The net counting rate extrapolated for $Z=0$ was assumed to be due to forward radiation only. The percentage backscattering was then calculated in the same manner as before.

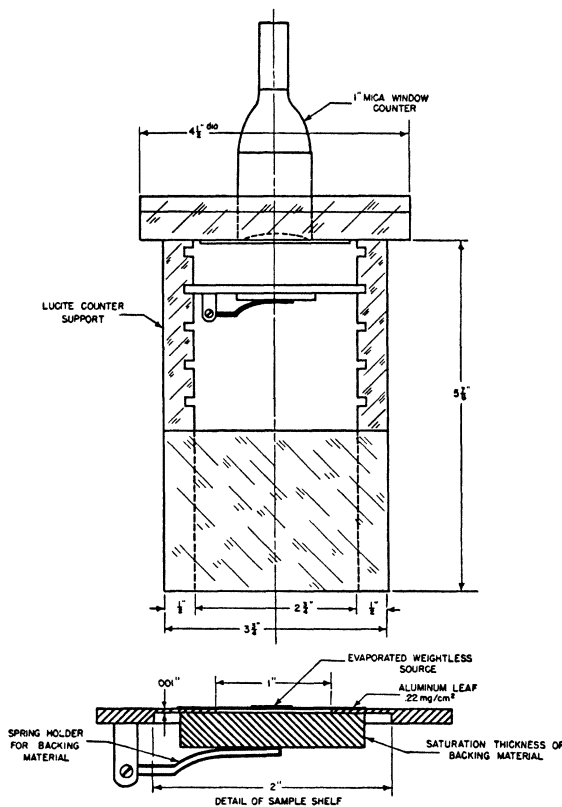


FIG. 1. Diagram showing dimensions of counter and source used in the backscattering experiments.

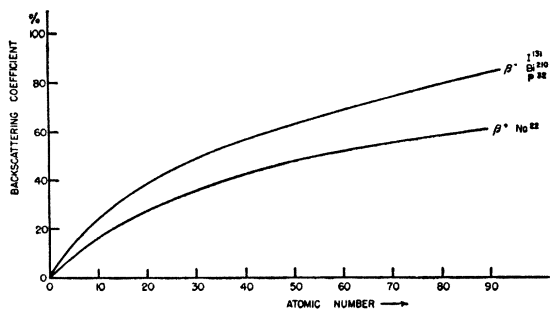


FIG. 2. Experimentally determined curves for the percentage of the backward radiation reflected into the counter as a function of the atomic number of the backing material.

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 Burt¹ 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. Burt, *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 workers¹ 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 letter² 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:

$$\alpha(\epsilon) = \{r h^2 f(\epsilon) / 8\pi (2m^3 \epsilon)^{3/2} (t_A(\epsilon) + t_S(\epsilon))\}, \quad (1)$$

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 $\int_0^\infty f(\epsilon) d\epsilon$ is unity. If the electrons have an energy distribution corresponding to a temperature T then

$$\alpha(T) = \{r h^2 / 2(2\pi m k T)^{3/2}\} \times \int_0^\infty \{\exp(-\epsilon/kT) f(\epsilon) / (t_A(\epsilon) + t_S(\epsilon))\} d\epsilon. \quad (2)$$

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

$$\alpha(T) = 2.1 \times 10^{-16} \{r / T^{3/2} (t_A + t_S)\} \times \int_0^\infty \exp(-\epsilon/kT) f(\epsilon) d\epsilon \text{ cm}^3/\text{sec}. \quad (3)$$

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 available³ it may actually be of the order of 10^{-18} 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-workers⁵ 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