mulas. (The Bothe values for λ_s and R are actually not relevant to 500-kev particles. Nevertheless, Bothe was able to apply his method to 680-kev electrons with success, because, as shown in Table I, the Bothe value for the ratio R/λ_s departs from the improved estimate much less than the separate values of R and λ_s.[4])

Estimates of the back-scattering coefficient β were derived from the various values of R/λ_s according to the Bothe theory. The resulting asymmetry, $\beta^-/\beta^+\sim1.16$, is roughly comparable to the observed effect. This result is taken as an indication that the differences in single scattering alone may well be responsible for the observed differences in back-scattering. Much better agreement with the experimental results should not have been expected in view of the approximations involved. In particular, it should be noted that the observed values of β correspond to an isotropic source at the boundary of the back-scatterer, whereas the values calculated on Bothe's theory do not apply to an isotropic source but rather to one intermediate between that and a normally incident one. For this reason the observed and calculated values of β cannot be expected to agree in an absolute sense.

I would like to thank Dr. U. Fano for suggesting this investigation and for many helpful discussions.

[1] H. H. Seliger, Phys. Rev. **78**, 491 (1950).
[2] See, e.g., N. F. Mott and H. S. W. Massey, *The Theory of Atomic Collisions* (Oxford University Press, New York, 1945), p. 81ff.
[3] W. Bothe, Ann. Physik **6**, 44 (1949).
[4] See also C. H. Blanchard and U. Fano, Bull. Am. Phys. Soc. **26**, No. 2, G10(A) (1951).

Concerning Certain Anomalous Small Angle Diffraction Effects

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HALPERN and Gerjuoy[1] have pointed out that radiation scattered from a parallelopiped will (on the basis of the usual theory) extend to anomalously large angles when the incident beam is very nearly parallel to any face. Recently, Forrester and Mittenthal[2] have attempted to observe this effect in the diffraction of light by a glass cube immersed in a liquid of nearly equal index. They show that extremely large intensities at these angles should be expected, providing the optical path length through the glass cube is many wavelengths larger than in the surrounding medium. Their experiments fail to reveal this intense scattering, and they suggest several explanations, one of them being that the Born approximation (single scattering) underlying Halpern and Gerjuoy's formulas is inapplicable here.

We wish to point out that smallness of the phase shift through the scatterer is a common criterion for the validity of the Born approximation,[3] and that, further, for the case in which the refractive index of the scatterer differs from the surrounding index by much less than unity, a different type of approximate calculation can be made which is valid for both large and small phase shifts and which reduces to the Born approximation in the latter case. In this method, the radiation field is calculated on a plane situated just beyond the scatterer and perpendicular to the incident beam; from this, the far-field is found by the Kirchhoff form of Huygen's principle. The field on this intermediate plane is approximated sufficiently well by (a) the undisturbed incident field at all points outside the geometrical shadow of the scatterer, and (b) a field inside the shadow having the same amplitude but with its phase modified at each point according to the optical path length on a line straight through the scatterer and reaching that point. These approximations seem rather drastic at first sight, but their validity is demonstrated by work of van de Hulst,[4] who considers spherical scatterers and shows that the rigorous Mie solution for electromagnetic radiation agrees with such computations under similar limitations. It is also easy to show directly that the Born approximation emerges (for scattering angles small compared with 1 radian) when the phase shift is small. This can be shown for any shape of scatterer.

We have carried through such a calculation for the case of a cube with two opposite faces parallel to the incident beam, and we have calculated the differential cross section for scattering in a plane perpendicular to these faces. When the phase shift through the center of the cube is large compared with unity, the differential cross section never exceeds that of an equal sized rectangular aperture by more than a factor of 4. Also, at intermediate values of the phase shift, the cross section is always of the same order of magnitude as that of an equal sized aperture. These results can be readily understood on the basis of a physical interpretation of this mode of calculation, also owing to van de Hulst.[4] The contribution from the radiation in the geometrical shadow corresponds closely, for large cubes, to rays refracted by geometrical optics; the remainder correspond to radiation diffracted around the cube. Here, the field arising from the "ray" portion cannot exceed that of a simple aperture, and the field arising from the diffraction portion equals that of a simple aperture. Their combined intensity, then, depends on relative phase and cannot exceed 4 times the intensity scattered by an aperture.

The negative results of Forrester and Mittenthal are thus to be explained entirely on the basis of the breakdown of the Born approximation in their case.

[1] O. Halpern and E. Gerjuoy, Phys. Rev. **76**, 1117 (1949).
[2] A. T. Forrester and L. Mittenthal, Phys. Rev. **81**, 268 (1951).
[3] D. Bohm, *Quantum Theory* (Prentice-Hall, Inc., New York, 1951), p. 553.
[4] H. C. van de Hulst, *Optics of Spherical Particles* (J. F. Duwaer en Zonen, Amsterdam, 1946). This excellent work deserves wider circulation than it seems to have attained.

Ionization by the Collision of Pairs of Metastable Atoms

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MICROWAVE techniques are used to measure the variation in electron density following the interruption of a discharge.[1] It is found that the electron density actually increases for approximately a millisecond after the electric field is removed from a helium or neon discharge (see Fig. 1). Analysis of the data indicates that the delayed ionization results from the collisions of pairs of metastable atoms, as suggested by T. Holstein.

After the maintaining field is removed from the discharge, ionization by electron impact ceases; however, electrons continue to be produced by metastable-metastable collisions. The electrons, which quickly (<100 μsec) come into thermal equilibrium with the gas, diffuse to the walls ambipolarly.[2] The metastable atoms produced during the discharge are lost by diffusion to the walls, by de-exciting collisions with gas atoms, and by metastable-metastable ionizing collisions. Experimental data indicate that the ionization loss is small compared to the diffusion and collision loss; hence, the metastable concentration is given by

$$M\simeq M_0\exp(-t/T_m), \tag{1}$$

where M_0 is the metastable concentration immediately following the discharge and

$$1/T_m=(D_m/\Lambda^2)+\nu_d. \tag{2}$$

Here T_m is the metastable mean decay time, D_m is the metastable diffusion coefficient, ν_d is the frequency of de-exciting collisions with gas atoms, and Λ is the characteristic diffusion length of the container.[2] The electron density is given by

$$n=A\exp(-t/T_D)-B\exp(-2t/T_m), \tag{3}$$

where

$$T_D=\Lambda^2/D_a, \tag{4}$$

D_a being the ambipolar diffusion coefficient.[2]

Figure 1 shows typical data for helium. At late times, the pro-

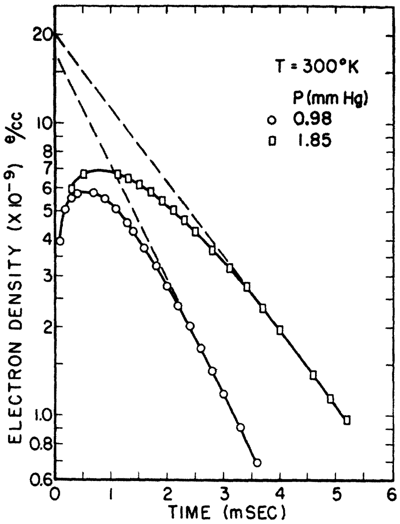

FIG. 1. Production of electrons in helium.

duction of electrons by metastables becomes negligible, and the electron density decays according to the first term of Eq. (3). We extrapolate this terminal slope toward zero time and take the difference between the actual curve and the extrapolated curve. This yields the second term of Eq. (3), which is shown plotted in Fig. 2.

If we consider the volume loss of metastables to arise from binary collisions between metastables and normal atoms, we may

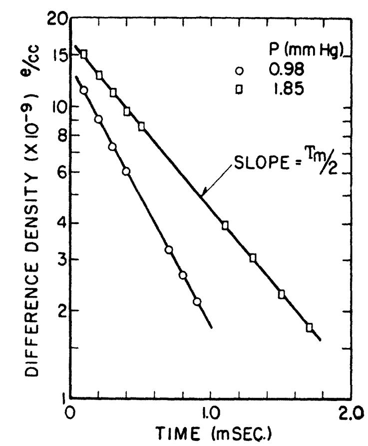

FIG. 2. Loss of metastables in helium.

replace the term ν_d of Eq. (2) by Cp, where C is a constant, and p is the gas pressure.[3] Multiplying Eq. (2) by p we have

$$p/T_m = (D_m p/\Lambda^2) + Cp^2. \tag{5}$$

In Fig. 3 are plotted values of p/T_m *vs* p^2. The intercept of the curve gives the value $D_m p/\Lambda^2$, and the slope of the curve yields C. The diffusion takes place in a container with diffusion length $\Lambda = 0.735$ cm.[2] From Fig. 3 we find $D_m p = 520 \pm 20$ (cm²/sec)·(mm Hg) and $C = 55 \pm 6$ (mm Hg·sec)$^{-1}$. Runs on several samples of helium give values differing from these results by less than ten percent. Optical absorption experiments by Ebbinghaus yield values of $D_m p = 535$ and $C = 107$.[4] The difference in the values of the volume loss coefficient, C, may be attributed to differences in gas purity. With specially purified helium[5] (estimated impurity $<1:10^8$), we obtain the value $C = 55$, given above; however, with Airco reagent helium (estimated impurity $\sim 1:10^4$), we obtained

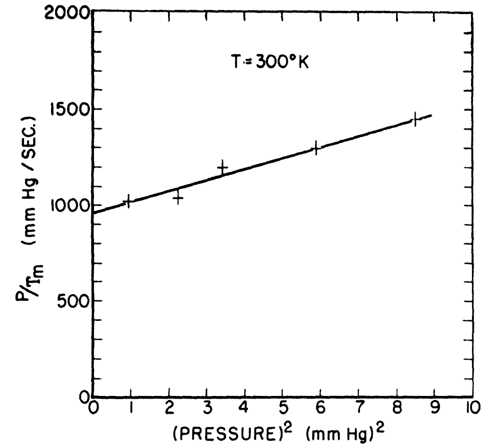

FIG. 3. Diffusion and volume loss of metastables in helium.

a value $C = 100$. A more complete investigation of the volume loss of metastables is in progress.

Data similar to that shown in Figs. 1–3 have been obtained for neon, giving values of $D_m p = 200 \pm 20$ and $C = 230 \pm 20$. These results may be compared with Phelps' and Molnar's[6] value of $D_m p = 150 \pm 30$, obtained by optical absorption. The rather good agreement between the diffusion coefficients obtained from the present measurements and from the optical absorption experiments indicates that the proposed metastable-metastable origin of the ionization is correct. Independent confirmation of the metastable origin of the ionization has been obtained by irradiating the discharge with light of the proper wavelength to raise a metastable atom to a radiating state. A decrease in the metastable concentration results, and we observe a corresponding decrease in the electron density rise of Fig. 1.

In a recent article Johnson *et al.*[7] reported on electron density measurements in helium. They explain their failure to observe an increase in density following the discharge by the fact that their higher electron densities and gas pressures destroy the metastables. Actually, the 10-μsec discharge period they use is too short to permit the metastables to reach more than a fraction of a percent of their equilibrium concentration. As we decrease our discharge time from its usual value of 300 μsec to 10 μsec, we find that the initial density rise diminishes and finally disappears.

The author wishes to thank Dr. T. Holstein for his assistance during the course of this work.

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[6] A. V. Phelps and J. P. Molnar, Bell Telephone Laboratories, private communication.
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The Spin of O^{18}

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OBSERVATION of the microwave absorption spectrum of $O^{16}O^{18}$ and $O^{18}O^{18}$ in the 5-mm region shows that the spin of O^{18} is zero.

In the region between 58,300 Mc and 59,900 Mc, all of the expected $O^{16}O^{18}$ and $O^{18}O^{18}$ lines have been observed and identified.