Spin Resonance of Free Electrons Polarized by Exchange Collisions*†

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An experiment is described in which thermal electrons, $t_e \approx 400°K$, become polarized in detectable numbers by undergoing exchange collisions with oriented sodium atoms during which the atom orientation is transferred to the electrons. The collisions establish interrelated equilibrium values for the atom and electron polarizations which depend upon the balance between the polarizing agency acting upon the atoms (optical pumping) and the disorienting relaxation effects acting both on atoms and electrons. When now the electrons are furthermore artificially disoriented by gyromagnetic spin resonance, an additional reduction of the atom polarization ensues which is detected by an optical monitoring technique, thereby allowing a determination of the free-electron spin g factor, g_s. Since it was experimentally convenient, at this stage only the ratio $g_J(\mathrm{Na})/g_s = 1.000026 \pm 0.00003$ was determined, showing no significant difference between g_s and g_J(Na), the g factor of the $^2S_{\frac{1}{2}}$ sodium ground state. From the experimental strength and width of the electron disorientation signal a lower limit was obtained for the sodium exchange cross section with thermal electrons: $Q > 2.3 \times 10^{-14}$ cm^2. This may be compared with a theoretical exchange cross section, $Q = 2.3 \times 10^{-14}$ cm^2, which is derived under the assumption that the $3s^2\,S_0$ state of the Na^- ion has essentially zero binding energy, thereby causing strong singlet scattering while the triplet scattering is negligible in comparison. Spin-orbit coupling during collisions of the electrons with the atoms of the inert argon buffer employed to slow down wall diffusion is discussed as the chief cause for the shortness of the observed free-electron spin relaxation time, $T_e \approx 6 \times 10^{-5}$ sec.

INTRODUCTION

CONSIDERABLE interest exists in experimental determinations of the free-electron spin magnetic moment μ_s in terms of the Bohr magneton μ_0 with accuracies high enough to provide further tests for the theoretical values,

$$\mu_s/\mu_0 = 1 + (\alpha/2\pi) + \text{higher terms},$$

obtained from quantum electrodynamics.[1–3] There are experimental values available[4,5] with an accuracy of about 10^{-6} for $g_J(H)/g_p$, the ratio of the g factors of the hydrogen ground state to that of the proton, which after a small relativistic bound state correction yield accurate g_s/g_p values that can be combined with other experimental data for[6] μ_p/μ_0 to obtain the desired ratio μ_s/μ_0. However, a *direct* experimental determination of the free-electron spin g factor in terms of g_p or $g_J(H)$ with an accuracy of 10^{-6} or better would be highly desirable. Various experimental schemes[7] have been proposed to accomplish this; however, no accuracies higher than 5×10^{-3} appear to have been reported so far. The present experiment was carried out on thermal electrons and an accuracy of 3×10^{-5} was achieved in preliminary measurements which also indicated that an increase in accuracy by one or two orders of magnitude should be possible.

* Supported by the U. S. Office of Ordnance Research.
† Early results of this work were reported at the 123rd meeting of the American Association for the Advancement of Science, December 26, 1956.
[1] J. Schwinger, Phys. Rev. **73**, 416 (1948).
[2] R. Karplus and N. Kroll, Phys. Rev. **77**, 536 (1950).
[3] C. M. Sommerfield, Phys. Rev. **107**, 328 (1957).
[4] Koenig, Prodell, and Kusch, Phys. Rev. **88**, 191 (1952).
[5] R. Beringer and M. A. Heald, Phys. Rev. **95**, 1474 (1954).
[6] J. H. Gardner and E. M. Purcell, Phys. Rev. **76**, 1262 (1949).
[7] Reviewed by H. A. Tolhoek, Revs. Modern Phys. **28**, 277 (1956).

PRINCIPLE OF EXPERIMENT AND APPARATUS

The electrons were polarized by allowing them to undergo exchange collisions with oriented sodium atoms in which the total spin component with respect to the axis of orientation, a magnetic field H_0, is conserved and the orientation of the atoms is transferred to the initially unpolarized electrons by exchange of the spin directions. Electrons and atoms, the latter polarized by optical pumping, were allowed to diffuse in an inert buffer, argon or helium at pressures of a few centimeters Hg. Since the electron-sodium collisions tend to equalize the polarization ratios of sodium atoms and electrons, the mere presence of free electrons reduced the sodium equilibrium polarization because the disorienting relaxation effects acting upon the electrons are passed on to the sodium atoms. In the same fashion, resonance disorientation of the electrons by a magnetic rf field of the proper frequency fulfilling the gyromagnetic resonance condition,

$$\nu_s = g_s \mu_0 H_0/h,$$

caused a further decrease in the sodium orientation. This orientation decrease was detected by an optical-absorption monitoring technique, thereby allowing a determination of the free-electron spin g factor g_s. A typical experiment (see Fig. 1) employed a spherical

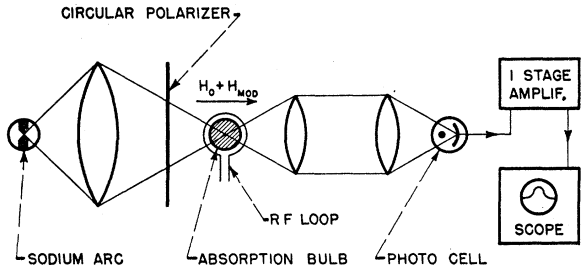

FIG. 1. Free-electron spin resonance apparatus.

200-cm³ absorption bulb heated to around 140°C which contained 70 mm of 2.5×10^{18} atoms per cm³ argon and sodium vapor of a density of about 8×10^{9} per cm³, corresponding roughly to a pressure of 10^{-7} mm. The sodium density N was estimated from the ratio of the transmitted to the indident light fluxes I_1/I_0 with the help of the formula[7a] for "line absorption"

$$1-(I_1/I_0)\approx 1.4(\pi \ln 2)^{\frac{1}{2}} r_0 c N d/\Delta\nu_A,$$

which holds for small absorption and the source width equal to the absorber width $\Delta\nu_A$, r_0 being the classical electron radius and d the thickness of the absorbing layer. The value 3×10^{9} sec^{-1} was taken for the pressure-broadened absorption line width $\Delta\nu_A$. For the purpose of ionization and generation of free electrons, the absorption bulb was placed between two capacitor plates (not shown in Fig. 1) to which 25-Mc/sec rf pulses of around 10^{-3} sec duration at a repetition rate of about 10 per second were applied synchronously with the sweep of the oscilloscope used for the observation of the disorientation signals and the sawtooth modulating field H_{mod}. Under these conditions, after each discharge pulse the electron temperature drops within 50 microseconds to the gas temperature. The electron density,[8,9] n, decays due to volume recombination approximately according to $1/n=(1/n_0)+\alpha t$, since wall diffusion of the electrons and ions can be neglected as long as the observation interval is short compared with the average ambipolar wall diffusion time $T_D=(1/D_a)(R/\pi)^2$ which, with D_a(argon)$=91$ cm²/sec at 1 mm pressure, is about 1 sec. Rough measurements of the rf conductivity σ of the decaying plasma at 25 Mc/sec indicated a decay of n from 3.2×10^{8} cm^{-3} to 1.6×10^{8} cm^{-3} during the 0.1 sec long usable portion of the observation interval, the connection[10] between n and σ being given by $n=(m/e^2)\omega_c\sigma$. The value 2×10^{10} sec^{-1} was assumed for the electron collision frequency ω_c in the argon buffer.

The optical system[11] now functioned in the following way: Light from the sodium arc was made circular polarized by a commercial polarizing plate and served to orient the sodium atoms in the bulb by optical pumping.[12] The transmitted light then was focussed upon a vacuum photocell connected to an oscilloscope through an amplifier. The amplified photocurrent was a measure of the sodium orientation P since the oriented atoms absorb less than unoriented ones. The axial magnetic field $H_0\approx21.4$ gauss was provided by a Helmholtz coil 30 inches in diameter. The modulation field was furnished by a separate ring coil. The rf loop was energized from a 62.08-Mc oscillator for the electron spin disorientation field and simultaneously from a second tunable oscillator in order to induce consecutively the four $\Delta m_F=\pm1$ transitions between the magnetic sublevels of the $F=2$ sodium hfs level at about 15.10, 15.36, 15.63, and 15.92 Mc which served to calibrate the magnetic field H_0.

INTERDEPENDENCE OF POLARIZATIONS

We now consider the factors relating the electron and sodium polarizations p and P. Of the N atoms, disregarding their nuclear spins, and the n electrons contained in one cubic centimeter, N_+ and n_+ have their spins up, N_- and n_- have them down. We define $P=(N_+-N_-)/N$; $p=(n_+-n_-)/n$. The cross section for exchange of the spin direction when oppositely oriented electrons and atoms meet will be denoted by Q. For simplicity the atoms are considered at rest, while at absolute temperature t_e the electrons are assumed to move with fixed speed $v=(3kt_e/m)^{\frac{1}{2}}$, their velocity distribution being neglected. Then the time variation of n_+ due to electron-sodium collisions alone is given by $\dot{n}_+=vQ[N_+n_--N_-n_+]$ which leads to $\dot{p}=f(P-p)$ for the electron polarization and $\dot{P}=F(p-P)$ for the atom polarization. Here the frequency of collision of an electron with sodium atoms, $f=vQN$, and that for a sodium atom to be hit by electrons, $F=vQn$, have been introduced. On the other hand, the atoms are continuously polarized by optical pumping and depolarized by relaxation effects of characteristic time T_a. In the absence of free electrons the time variation of P due to these processes is described[11] by

$$\dot{P}=cI_0(\bar{P}-P)-(1/T_a)P,$$

which can be rewritten

$$\dot{P}=(1/\tau)(P_I-P),\quad \tau=T_a/(cI_0T_a+1),$$

where $P_I=cI_0T_a\bar{P}/(cI_0T_a+1)$ is the equilibrium polarization corresponding to a finite light intensity I_0 and $\bar{P}$ is the saturation polarization obtainable with the optical pumping. The relaxation effects of characteristic time T_e acting on the electrons in the absence of sodium atoms would cause their polarization to decay according to $\dot{p}=-(1/T_e)p$. By combining all these contributions to $\dot{P}$ and $\dot{p}$ when the corresponding processes are simultaneously present, we get

$$\dot{p}=f(P-p)-(1/T_e)p,$$
$$\dot{P}=F(p-P)+(1/\tau)(P_I-P).$$

By setting $\dot{p}$ and $\dot{P}$ equal to zero, we now obtain the equilibrium polarizations $\mathbf{p}$ and $\mathbf{P}$,

$$\mathbf{p}=fT_e(fT_e+F\tau+1)^{-1}P_I,$$
$$\mathbf{P}=(fT_e+1)(fT_e+F\tau+1)^{-1}P_I.$$

The effect of resonance disorientation of the electrons

[7a] A. C. G. Mitchell and M. W. Zemansky, *Resonance Radiation and Excited Atoms* (Cambridge University Press, 1934), Chap. III.
[8] M. A. Biondi and S. C. Brown, Phys. Rev. **75**, 1700 (1949).
[9] A. von Engel, *Ionized Gases* (Clarendon Press, Oxford, 1955).
[10] Cf. e.g., H. Belcher and T. M. Sugden, Proc. Roy. Soc. (London) **A201**, 480 (1950).
[11] Cf. H. G. Dehmelt, Phys. Rev. **105**, 1487 (1957); **105**, 1924 (1957).
[12] Cf., e.g., A. Kastler, J. Opt. Soc. Am. **47**, 460 (1957).

by a magnetic rf field[13] is equivalent to shortening the electron relaxation time. It can be described by substituting for $1/T_e$ the modified quantity $1/T_e'=(1/T_e)+(1/T_{rf})$, where T_{rf} is the rf disorientation time which we define for exact resonance and which is connected with the rf field amplitude H_1 and the characteristic time T_2^* by $\omega_1^2T_2^*T_{rf}=1$. Here $\omega_1=\pi g_s\mu_0H_1/h$ would be the precession circular frequency in the field $H_1/2$. The time $T_2^*=1/\pi\Delta\nu$ is a measure of the total experimental electron line width $\Delta\nu$ and, assuming small atom polarization, is given by

$$1/T_2^*\approx(1/T_e)+f+(1/T_2'),$$

while T_2' represents the contribution by the magnetic field inhomogeneity. As a consequence of the foregoing, the atom polarization is a function of the rf field H_1 acting upon the electrons, $\mathbf{P}=\mathbf{P}(H_1)$. For a given light intensity I_0 and therefore given τ, a measure of the optical signal resulting when the magnetic field H_0+H_{mod} is swept through the resonance value is provided by

$$S(H_1)=[\mathbf{P}(0)-\mathbf{P}(H_1)]/P_I,$$

the maximum possible signal being

$$S(\infty)=fT_eF\tau(F\tau+1)^{-1}(fT_e+F\tau+1)^{-1}.$$

Radio-frequency saturation will become appreciable for $H_1>H_1^*$, the latter quantity being defined by $S(H_1^*)=\frac{1}{2}S(\infty)$. For the corresponding critical disorientation time T_{rf}^*, one obtains

$$1/T_{rf}^*=f(F\tau+1)^{-1}+(1/T_e).$$

In order to use the experimentally observed signal $S_{exp}\approx0.1$ to put a lower limit on Q, we note that

$$0.1=S_{exp}<S(\infty)<fT_eF\tau=nNT_e\tau v^2Q^2.$$

With the experimental values $v=1.1\times10^7$ cm sec^{-1}, $N=8\times10^9$ cm^{-3}, $n=1.6\times10^8$ cm^{-3}, $\tau=2\times10^{-2}$ sec, and $T_e=6\times10^{-5}$ sec, we have

$$Q>2.3\times10^{-14}\text{ cm}^2.$$

Here T_e was obtained from the experimental line width data by assuming

$$\Delta\nu(\text{electron})-4\Delta\nu(\text{Na})\approx1/\pi T_e\approx5.6\times10^3\text{ sec}^{-1}.$$

EXCHANGE CROSS SECTION

The large observed exchange cross section Q can be understood as follows: There is evidence that the $3s^2\,{}^1S_0$ state of the Na^- ion exists,[14,15] its binding energy W being close to zero. In this case the cross section for singlet s scattering, Q_- (only s-wave scattering need be considered at the low energies of interest here) can be expressed approximately for small energies E of the impinging electron by[16,17]

$$Q_-=4\pi(\hbar^2/2m)(E+|W|)^{-1}.$$

This approaches the maximum possible cross section $4\pi\lambda\!\!\!^{-2}$ for $|W|\ll E$. The cross section for triplet scattering, Q_+, should be much smaller than Q_- since no bound triplet level exists and the above resonance effect does not occur. Therefore, as an approximation we neglect Q_+. Under this assumption one finds for the exchange cross section, $Q=\frac{1}{4}Q_-$. For thermal electrons (400°K) and $|W|\ll E$, the exchange cross section‡ then assumes nearly its upper limit $\bar{Q}$,

$$\bar{Q}=(\pi\hbar^2/3mkt_e)=2.3\times10^{-14}\text{ cm}^2,$$

which in accordance with the earlier simplifying assumption of a fixed electron velocity has not been averaged over the electron energy distribution. In order to see that the exchange cross section Q is one-fourth as large as the singlet scattering cross section Q_-, we consider the asymptotic behavior of a mixed state Ψ which consists of equal parts of properly symmetrized singlet and triplet states,

$$\Psi=\tfrac{1}{2}[f(1)g(2)+f(2)g(1)][v_+(1)v_-(2)-v_+(2)v_-(1)]+\tfrac{1}{2}[f(1)g(2)-f(2)g(1)][v_+(1)v_-(2)+v_+(2)v_-(1)].$$

For the case of interest here, that the electron 1 in the free state f is initially at a large distance from the scattering atom in whose ground state g the electron 2 moves, $f(2)g(1)$ is nearly zero and can be neglected. The state then reduces to $\Psi=f(1)g(2)\,v_+(1)v_-(2)$, which corresponds to a definite situation where the electron 1 is free and has its spin up while the bound one 2 has its spin down; v_+ and v_- denote the spin functions with $m_s=+1$ and $m_s=-1$, respectively. If we now, as usual, represent $f(1)$ as a plane wave, Ψ will be associated with an electron stream of current density j of which $j/2$ will correspond to the singlet and $j/2$ to the triplet wave. Since only the singlet part is assumed to be scattered by the atom, the total scattered (singlet) current is given by $i_-=\frac{1}{2}jQ_-$. This current now consists of electrons 50% of which have exchanged their spins with the scattering atom. For the total current of spin-exchanged electrons, $i=\frac{1}{2}i_-$, we obtain therefore

$$i=\tfrac{1}{4}jQ_-,\quad\text{or}\quad Q=\tfrac{1}{4}Q_-.$$

ELECTRON SPIN RELAXATION

The main electron spin relaxation mechanism appears to be spin-orbit coupling during electron-argon collisions, which can be fairly accurately analyzed. First

[13] Cf., e.g., Bloembergen, Purcell, and Pound, Phys. Rev. **73**, 679 (1948).
[14] G. Glocker, Phys. Rev. **46**, 111 (1934).
[15] D. R. Hartree and W. Hartree, Proc. Cambridge Phil. Soc. **34**, 550 (1938).
[16] E. Wigner, Z. Physik **83**, 253 (1933).
[17] N. F. Mott and H. S. W. Massey, *Theory of Atomic Collisions* (Clarendon Press, Oxford, 1947), Chap. 2.

‡ For the exchange cross section Q to approach its maximum value, $\bar{Q}=\pi\lambda\!\!\!^{-2}$, It would be sufficient that a level of one multiplicity, singlet or triplet, bound or virtual, lie much closer to zero than the free electron energy E, while the closest level of the other multiplicity is much further away than E.

we try to find the angle α through which a spin precesses during such a collision. Noting that simultaneously appreciable precession angles and scattering cross sections will occur only in p scattering and that the penetrating parts of the orbitals of a free, low-energy p electron around an argon atom and of a loosely bound p electron in a potassium atom should be very similar, we can calculate α from the doublet splitting $\delta\nu$ [cm^{-1}] and the classical period of revolution, $T=\hbar^3(4\pi^2me^4)^{-1}n^3$, for potassium p orbitals of high principal quantum number n. We obtain

$$\alpha=2\pi c\sin\vartheta T\delta\nu=2.8\times10^{-5}\sin\vartheta n^3\delta\nu,$$

where ϑ is the angle which the spin direction makes with the resultant of spin and orbital angular momentum. Numerically, with $n^3\delta\nu=10^3$ cm^{-1} which for $n>12$ is practically constant, we find

$$\alpha=0.028\sin\vartheta.$$

The relaxation time T_e which is associated with the random walk steps α which the tip of the unit spin vector executes on the unit sphere and with the frequency of collisions with argon atoms, f_p, is given by[17a]

$$1/T_e=\tfrac{1}{2}f_p\langle\alpha^2\rangle_{Av}=\tfrac{1}{2}vq_pN_A\langle\alpha^2\rangle_{Av}.$$

With $\langle\sin^2\vartheta\rangle_{Av}\approx\frac{2}{3}$ and the experimental value $T_e=6\times10^{-5}$ sec and taking $N_A=2.5\times10^{18}$ cm^{-3}, $v=1.1\times10^7$ cm/sec, we find from this for q_p, the partial cross section for p scattering,

$$q_p=2.5\times10^{-18}\text{ cm}^2.$$

This value can be compared with a theoretical value extrapolated from Holtsmark's calculations.[18] Since in the limit of large de Broglie wavelength or small electron energy E the exact shape of the short-range scattering potential is immaterial, a square well may be substituted, for which it can be shown[17] that $q_p\propto E^2$ for $E\to0$. In this way one finds $q_p=1.03\times10^{-24}t_e^2$ cm^2, where t_e is the absolute electron temperature. Again for simplicity we have not taken an average over the energy distribution of the electrons, assuming instead a fixed energy $E=\frac{3}{2}kt_e$. With $t_e=400°$K we get numerically

$$q_p=1.65\times10^{-19}\text{ cm}^2.$$

The strong temperature dependence of q_p and therefore T_e is in agreement with the experimentally observed quenching of the electron signal by weak electric rf fields which heat up the electrons. It is likely that even the electric rf field associated with the H_1 field caused appreciable heating of the electrons since the electron signal got weaker and weaker with increasing frequency and at 120 Mc/sec no signal could be observed in the present apparatus. The assumption of some increase in t_e by this H_1 heating and proper averaging would make the theoretical and experimental q_p values more nearly equal also.

[17a] D. Pines and C. P. Slichter, Phys. Rev. **100**, 1014 (1955).
[18] T. Holtsmark, Z. Physik **55**, 437 (1929).

ELECTRON-SODIUM g-FACTOR RATIO

As the chief goal of the present experiment a preliminary determination of the free electron spin g factor in terms of the g factor of the $S_{\frac{1}{2}}$ Na ground state was carried out by comparing the free-electron precession frequency ν_s with the sum of the four $\Delta m_F=\pm1$ transition frequencies associated with the $F=2$ hfs level of the sodium atoms in the same sample and the same magnetic field. The sodium transitions were observed also by the optical method discussed earlier. During a run the free electron resonance was continuously displayed on the oscilloscope screen while the four Na resonances ν_1 to ν_4 were consecutively superimposed on the free-electron resonance. Typical resonances are shown in Fig. 2. The sodium frequency sum has the value

$$\sum\nu=(g_J\mu_0+2\mu_I)H_0/h,$$

where g_J denotes the electronic g factor of the sodium ground state and μ_I is the magnetic moment of the sodium nucleus. By using the field-independent ratio, $(\nu_s-\sum\nu)/\nu_s$, we can now form with $I=\frac{3}{2}$

$$g_J/g_s=1-3(g_I/g_s)-(\nu_s-\sum\nu)/\nu_s.$$

Employing the atomic-beam value[19] $g_J/g_I=-2487.8$,

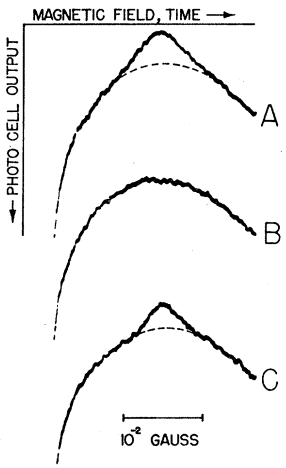

FIG. 2. Oscilloscope traces of electron and sodium resonances. The blank trace B was obtained by operating the equipment with the frequencies of the rf fields for electron and sodium resonances adjusted to off-resonance values. This trace served only to establish the dashed baselines which are shown in trace A, depicting the electron signal at about 62.1 Mc/sec and in trace C which displays one of the four sodium signals, namely that at about 15.9 Mc/sec. The signal peak intensities have been adjusted to about the same value and one easily notices the larger width of the electron resonance on a magnetic field scale. On a frequency scale the electron and sodium signal line widths turn out to be about 14.4 kc/sec and 2.2 kc/sec, respectively. The high light-intensity spikes at the beginning of the traces are the result of the ionizing discharge pulse at the beginning of each sweep cycle. The slow curvature of the remaining part of the baseline was either connected with afterglow effects in the decaying plasma or imperfections in the electronic equipment which were not further analyzed.

[19] P. Kusch and H. Taub, Phys. Rev. **75**, 1477 (1948).

in place of g_s/g_I, we finally have

$$g_J/g_s=1+1.2059\times10^{-3}-(\nu_s-\sum\nu)/\nu_s.$$

With our preliminary experimental value for

$$(\nu_s-\sum\nu)/\nu_s=(118\pm3)\times10^{-5},$$

we now obtain,

$$g_J/g_s=1.000026\pm0.00003,$$

showing no difference in our limit of accuracy between the g factors of the free electron and the sodium ground state. Further experiments with the aim of improving the experimental accuracy and extending the method to much lower buffer gas pressures and eventually to near vacuum are in progress.

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Charge Exchange Cross Sections for Helium Ions in Gases*

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The charge exchange cross sections have been determined for a helium ion beam in several stopping gases. The cross sections for electron loss by a fast helium atom (σ_{01}) and for electron capture by an ion (σ_{10}) are reported for energies between 4 and 200 kev. The target gases studied were hydrogen, helium, nitrogen, oxygen, neon, and argon. σ_{01} increases monotonically throughout the energy range for all gases studied, obtaining values of 10^{-6} cm^2 at 200 kev. In all stopping gases except helium, σ_{10} passes through a maximum of approximately 3×10^{-16} cm^2 near 50 kev, whereas for helium this cross section decreases throughout the energy range as expected for the resonant exchange reaction. Evidence is presented that the metastable excited state of the helium atom is of importance in the charge exchange process.

INTRODUCTION

PREVIOUS investigations of charge exchange collisions for fast particles in gases which have been reported by this laboratory include determinations of the equilibrium charge distribution of a particle beam after traversing a thick gas target[1] and measurements of the absolute cross sections for electron capture and loss by fast hydrogen atoms and ions.[2] The target gases were hydrogen, helium, nitrogen, oxygen, neon, and argon, and the energy range was from 4 to 200 kev. The present paper reports measurements of the electron loss cross sections for fast helium atoms passing through the above gases and in the same energy range.

The literature of charge exchange, prior to 1952, has been summarized by Massey and Burhop[3] and was also reviewed by Allison and Warshaw[4] in 1953. As is evident from these reviews, large discrepancies frequently exist between the results of the various investigators. Since publication of these reviews, there have appeared several reports of measurements of the charge exchange cross sections for energetic helium atoms and ions. Stedeford and Hasted,[5] repeating the work of Keene,[6] obtained somewhat different results and emphasized the difficulty of this type of measurement. Working at the University of Chicago, Snitzer[7] has reported measurements of the ratio of the cross sections for electron capture and electron loss in gases and Krasner[8] determined the cross section for electron loss by fast helium atoms in the energy range from 100 to 450 kev. More recently, Allison *et al.*[9] have reported measurements of σ_{10}, σ_{12}, σ_{21}, and σ_{20} where the usual notation σ_{if} is used, with i denoting the initial charge state and f the final charge state. Fedorenko[10] has reported values for the cross sections σ_{12} in several gases for energies less than 40 kev. This energy region has also been investigated by de Heer[11] who studied

* Work done under the auspices of the U. S. Atomic Energy Commission.
† Now at National Carbon Research Laboratories, Cleveland, Ohio.
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[9] Allison, Cuevas, and Murphy, Phys. Rev. **102**, 1041 (1956).
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[11] F. J. de Heer, Ph.D. thesis, University of Leiden, Amsterdam, 1956 (unpublished).