INTENSE POLARIZED ELECTRON BEAMS FROM OPTICALLY PUMPED HELIUM DISCHARGES*

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Spin conservation in ionizing reactions involving optically oriented 2^3S_1 metastable helium atoms in a helium discharge has been exploited to produce a continous beam of polarized electrons. A beam polarization of $(10 \pm 0.5)\%$ is measured, with beam current 0.2 μA. Electrons extracted from the pulsed discharge afterglow have polarization $(14 \pm 0.7)\%$. The apparatus is simple and versatile, and should be readily adaptable to atomic and nuclear scattering experiments.

Optical-pumping techniques can be used to induce a high degree of electron spin polarization in 2^3S_1 metastable helium atoms present in an active helium discharge or discharge afterglow.[1,2] Ionization-producing reactions involving atoms in this optically pumped state should yield polarized electrons if such reactions conserve spin angular momentum. Polarization analysis of electrons extracted from the reaction region thus can serve as a diagnostic tool both in the identification of important ionization-producing reactions, and also in testing their spin conservation. In the course of such studies we have established that cumulative ionization processes involving 2^3S_1 atoms play a major role in the dynamics of active helium discharges, and we have produced a beam of intense polarized electrons that is inexpensive, simple, and would appear to be readily adaptable for use in atomic and nuclear scattering experiments.

Our experiments are conducted using a 100-cm^3 spherical Pyrex bulb containing helium gas at pressures ranging from 0.05 to 1.0 Torr. A schematic diagram of the discharge cell is shown in Fig. 1. A weak electrical discharge serves to produce a steady-state 2^3S_1 population in the range 10^{10}-$10^{11}/cm^3$. This is the most highly populated excited state, although the 2^1S_0 metastable state population may be as high as one-third that of the 2^3S_1 state. Other excited states are populated to a much lesser extent. Circularly polarized 1.08-μ resonance radiation (2^3S_1-$2^3P_{0,1,2}$) incident along the direction of an externally imposed magnetic field (nominally 5 G) causes a redistribution of the 2^3S_1 atoms among the three available magnetic sublevels ($m = +1, 0, -1$), the atoms being "pumped" toward either higher or lower m values, depending on the sense of circular polarization of the pumping light. Details of the pumping process may be found elsewhere.[2] Electrons produced in the discharge are extracted through a 2-mm-diam × 2-mm-long aluminum exit canal in a direction parallel to the magnetic field and pumping radiation. The electrons can also be extracted from the afterglow of a pulsed discharge, thus providing information on ionizing reactions occurring only in the afterglow period.

Spin-polarization analysis of the extracted electrons is accomplished by Mott scattering from a gold foil.[3] The extracted electrons are focused by a five-element electron filter lens,[4] accelerated to 120 keV, and the beam polarization is converted from longitudinal to transverse by means of a 108° electrostatic analyzer. The electrons hit a gold-foil target, and the up-down asymmetry of electrons elastically scattered at 120° relative to the incident beam provides a measure of spin polarization. Instrumental asymmetries are easily canceled merely by comparing the observed asymmetries when the source is pumped by right and left circularly polarized radiation, respectively, since the direction of the resulting electron spin polarization is opposite in the two cases.

The polarization of the extracted electron beam depends upon the extent to which atoms in the optically pumped 2^3S_1 state contribute to ionization in the source. The experimental results given below establish definitely that cumulative pro-

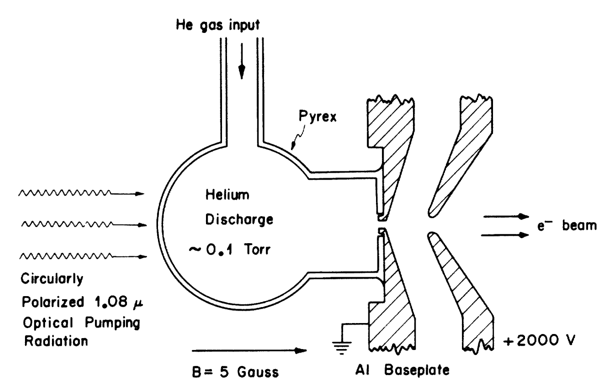

FIG. 1. Simplified drawing of the discharge cell, base plate, and extraction electrode (not to scale).

cesses involving 2^3S_1 atoms are major contributors to ionization in a helium discharge over the range of pressures studied. This is consistent with the conclusions of previous work[5-7]; in particular, the metastable-metastable reactions

$$\mathrm{He}(2^3S_1) + \mathrm{He}(2^3S_1) \to \mathrm{He}(1^1S_0) + \mathrm{He}^+ + e^-, \quad (1a)$$

$$\mathrm{He}(2^1S_0) + \mathrm{He}(2^3S_1) \to \mathrm{He}(1^1S_0) + \mathrm{He}^+ + e^-, \quad (1b)$$

$$\mathrm{He}(2^1S_0) + \mathrm{He}(2^1S_0) \to \mathrm{He}(1^1S_0) + \mathrm{He}^+ + e^- \quad (1c)$$

are known to be significant sources of ionization in helium discharges at pressures of a few Torr.[5,6] At thermal energies, the cross section are all about 10^{-14} cm^2 [6]; thus for typical 2^3S_1 and 2^1S_0 populations of 5×10^{10} and 1.5×10^{10}, respectively, the electron production rate from these reactions is nearly 10^{13} cm^{-3} sec^{-1}.

In the active discharge, electrons are lost primarily by ambipolar diffusion to the container walls at a rate no less than $n_e D_a/\Lambda_0^2$ cm^{-3}, where n_e is the electron density, D_a the ambipolar diffusion coefficient, and Λ_0 the lowest mode diffusion length. In these experiments, $\Lambda_0 = 0.77$ cm and $D_a \simeq 5\times 10^5$ cm^2/sec for a typical gas pressure of 0.1 Torr and average electron energy of a few eV; thus we estimate the electron loss rate as approximately $10^6 n_e$ cm^{-3}. In the steady state, electron production must occur at the same rate. Thus we can see that metastable-metastable reactions alone support a steady-state electron concentration of about 10^7 cm^{-3}.

The only other way in which 2^3S_1 metastable atoms can contribute electrons to the discharge is through electron impact ionization.[8] This process would appear to be negligible under our experimental conditions; the cross section is $\leq 6.5 \times 10^{-16}$ cm^2 for all electron energies above the ~5-eV threshold,[9] leading to electron production at a rate $2\times 10^3 n_e$ (≥ 5 eV). This obviously cannot support the $10^6 n_e$ loss rate calculated above. A similar analysis of ionization production by electron impact on ground state atoms, with cross section $\simeq 3\times 10^{-18}$ cm^2 for electrons of energy ≥ 25 eV,[10] leads again to the conclusion that this mechanism is probably negligible.

We conclude that for weak helium discharges at ~0.1 Torr pressure, the metastable-metastable Reactions (1a)-(1c) are responsible for most of the electron production. The electron polarization produced in such reactions can be estimated as follows. Labeling the 2^1S_0 population by N_1 and the populations of the $m=+1$, 0, and -1 magnetic sublevels of the 2^3S_1 state by N_+, N_0, and N_-, respectively, we can write the rate equations for production of electrons with $m=+\frac{1}{2}$ and $m=-\frac{1}{2}$ (designated by n_+ and n_-) as

$$dn_+/dt \sim \tfrac{1}{2}(N_1)^2 + 2N_1N_+ + N_1N_0 + 2N_+N_0 + N_+N_- + \tfrac{1}{2}N_0^2, \quad (2a)$$

$$dn_-/dt \sim \tfrac{1}{2}(N_1)^2 + 2N_1N_- + N_1N_0 + 2N_-N_0 + N_+N_- + \tfrac{1}{2}N_0^2. \quad (2b)$$

Subject to experimental verification, conservation of spin angular momentum has been assumed; hence the reaction cannot occur for triplet metastable collision partners with identical magnetic quantum numbers of either $m=+1$ or $m=-1$. It is further assumed that for the spin-allowed reactions, the rate is independent of the magnetic quantum numbers of the reactants. The steady-state polarization P is then

$$P = \frac{n_+ - n_-}{n_+ + n_-} = \frac{2(N_1+N_0)(N_+-N_-)}{(N_1+N_++N_0+N_-)^2 - N_+^2 - N_-^2}. \quad (3)$$

The populations N_+, N_0, and N_- can be estimated crudely in terms of the intensity of the pumping radiation and the relaxation time characterizing the return to thermal equilibrium of an initial nonequilibrium population distribution. The relative numbers of triplet and singlet metastables are determined by their respective absorptions of 1.08- and 2.06-μ resonance radiation. For our experimental conditions, with relaxation occurring predominantly as a result of metastable collisions with the container walls, we estimate $N_1:N_+:N_0:N_- = 5:10:3:2$ with an uncertainty in each figure of about 30%. Thus, we estimate $P \simeq 43\%$ for electrons produced by metastable-metastable reactions.

The spin polarization and beam current of electrons extracted from the active optically pumped discharge was measured as a function of both helium-sample pressure and discharge intensity. The results are presented in Figs. 2 and 3. The sizable polarizations measured indicate clearly that the optically oriented 2^3S_1 atoms contribute in a major way to ionization in an active helium discharge. The highest polarization, $(10\pm 0.5)\%$, is attained at about 0.08 Torr and with a metastable population of about 6×10^{10}/cm^3; under these conditions, the extracted beam current is 0.2 μA. The half-width of the energy spread, measured with the filter lens, is about 10 eV; this should be regarded as an upper limit since the resolving power of the filter lens is presently unknown.

The fact that the measured beam polarization

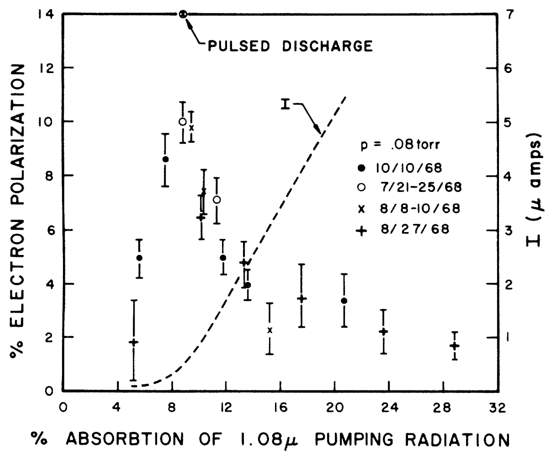

FIG. 2. The electron polarization P_e and the electron current I extracted from the active discharge are plotted as a function of discharge intensity. The discharge intensity is characterized by the relative absorption of the 1.08-μ pumping light, which in turn is directly related to the density of 2^3S_1 atoms.

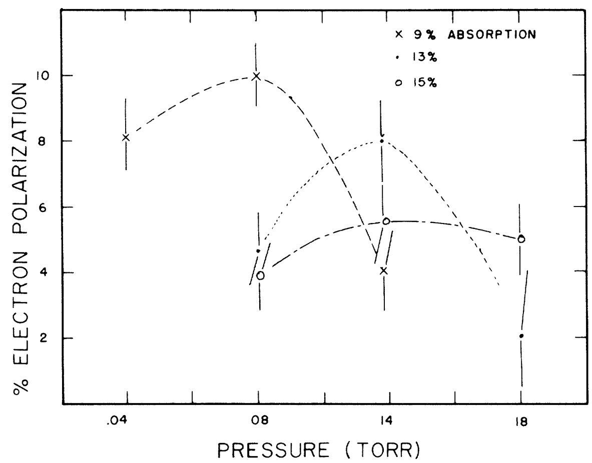

FIG. 3. The electron polarization P_e versus helium gas pressure. Each curve is characterized by the percent absorption of 1.08-μ resonance light which is directly related to the density of 2^3S_1 atoms.

is smaller than that calculated from Eq. (3) is not surprising since one must expect an unpolarized beam component from secondary electrons, which arise principally from Auger emission when ions and metastable atoms collide with the aluminum exit canal.[11] Further studies of the importance of this effect are now being made.

The dependence of beam polarization upon gas density and discharge intensity is not completely understood, but presumably is related to such factors as rapid diffusion of metastables to the container walls at low pressures, collisional mixing in the optically excited P states at high pressures, and radiation trapping at the higher discharge levels. Also, the secondary electron beam component is probably dependent on both density and discharge levels.

It should be noted that the average electron lifetime in the bulb before extraction is sufficiently short to preclude the possibility that spin exchange reactions with optically pumped 2^3S_1 atoms[12] contribute significantly to the beam polarization.

Measurements also were made on electrons extracted during the afterglow period in a pulsed discharge. Here there is no doubt that metastable-metastable reactions are responsible for all electron production.[6] For these measurements, the discharge was pulsed on for 50 μsec out of every 150 μsec, and electrons were extracted during the 100-μsec afterglow period by pulsing the center electrode of the filter lens. At the optimum gas pressure of 0.1 Torr, the measured beam polarization was $(14 \pm 0.7)\%$, with average beam current 0.01 μA. We conclude that spin angular momentum is indeed conserved in ionizing metastable-metastable collisions. Again, as is the case for electrons extracted from the active discharge, an unpolarized beam component (Auger electrons) may be masking an even larger electron polarization in the gas.

Studies of the secondary electron contribution to the beam are presently underway. Future work is planned using a flowing-afterglow technique with provision for introducing impurities[13,14]; this will allow investigation of the spin dependence of Penning reactions involving 2^3S_1 and 2^1S_0 helium metastable atoms.

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DISTORTIONLESS PROPAGATION OF LIGHT THROUGH AN OPTICAL MEDIUM*

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The equations describing the propagation of optical radiation through a medium of two-level atoms are presented in a way that emphasizes their relation to Poynting's theorem. Two classes of solutions which propagate without distortion are discussed. These solutions, together with the well-known hyperbolic secant solution, are analogous to the three possible types of motions of a simple pendulum.

Consider a medium consisting of N two-level atoms per unit volume imbedded in a homogeneous dielectric which is characterized by an index of refraction $\eta = (\epsilon_0 \mu_0)^{1/2}$. It will be assumed that the magnetic permeability μ_0 is approximately equal to unity while the dielectric constant ϵ_0 may differ from unity. Conservation of energy for light propagating through such a medium is expressed by Poynting's theorem[1]

$$\partial u(\vec{x}, t)/\partial t + \nabla \cdot \vec{S}(\vec{x}, t) = -\vec{E}(\vec{x}, t) \cdot \partial \vec{P}(\vec{x}, t)/\partial t, \tag{1}$$

where $u(\vec{x}, t)$ is the energy density of the electromagnetic field, $\vec{S}(\vec{x}, t)$ is its Poynting vector, and $\vec{E}(\vec{x}, t)$ is the electric-field strength.

For the case of a quasimonochromatic electromagnetic field linearly polarized in the $\hat{e}_1$ direction and propagating in the $\hat{e}_3$ direction, one may write

$$\vec{E}(\vec{x}, t) = \hat{e}_1 \mathcal{E}(z, t) \cos(\omega t - kz), \tag{2a}$$

$$u(\vec{x}, t) = (\epsilon_0/4\pi) \mathcal{E}^2(z, t) \cos^2(\omega t - kz), \tag{2b}$$

$$\vec{S}(\vec{x}, t) = (c/4\pi)(\epsilon_0/\mu_0)^{1/2} \hat{e}_3 \mathcal{E}^2(z, t) \cos^2(\omega t - kz). \tag{2c}$$

A more general expression for the field could be used; however, the solutions presented below can be written in the form of Eq. (2a).

The state of a two-level atom may be expressed as

$$\Psi(\vec{x}, t) = a(t)\psi_a(\vec{x}) + b(t)\psi_b(\vec{x}), \tag{3}$$

where ψ_a and ψ_b are the eigenfunctions of the unperturbed atomic Hamiltonian, which correspond to the eigenvalues $\frac{1}{2}\hbar\Omega$ and $-\frac{1}{2}\hbar\Omega$, respectively. Alternately, the state of the atom may be represented by the real variables X, Y, and Z, which are defined according to[2]

$$(X - iY)e^{-i(\omega t - kz)} \equiv 2ab^*, \tag{4a}$$

$$Z \equiv aa^* - bb^*. \tag{4b}$$

These variables satisfy the condition $X^2 + Y^2 + Z^2 = 1$ when $aa^* + bb^* = 1$.