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SPIN POLARIZATION OF ELECTRONS EJECTED IN COLLISIONAL IONIZATION OF FAST, POLARIZED METASTABLE DEUTERIUM ATOMS*

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If one of the incident particles in an atomic collision is polarized and the polarization of one of the product particles is measured, useful information about the collision process may be obtained. Notable examples of this kind of study in atomic physics are the work of Lichten and Schultz,[1] who measured the polarization of hydrogen atoms in the $2^2S_{1/2}$ state produced by electron bombardment of polarized ground-state hydrogen atoms; of Bederson and co-workers,[2] who measured the change in polarization of ground-state potassium atoms produced by collisions with electrons; and of Pritchard, Burnham, and Kleppner,[3] who studied spin exchange in differential scattering of polarized alkali atoms on other atoms and molecules.

The spin polarization of electrons can be measured by the Mott scattering.method which is based on a spin-orbit coupling effect leading to an azimuthal intensity asymmetry in the wide-angle scattering from a thin gold foil at energies on the order of 100 keV. This method was widely used in work on beta decay[4] and is now a very useful tool in atomic and electron physics. It has been employed in work on photoionization of polarized alkali atoms[5] and on spin-orbit interactions in low-energy electron scattering from heavy atoms and molecules.[6]

In the experiment reported here, Mott scattering was used to determine the polarization of the electrons ejected in collisions between fast, polarized metastable deuterium atoms[7] and the atoms or molecules of a diamagnetic target gas. Although it is not possible to produce a pure beam of metastable deuterium atoms, D(2S), free of ground-state atoms, D(1S), the measurement can be done because the collisional ionization cross section is much higher for D(2S) than for D(1S).[8] The electron polarization gives information about the dominant ionization process. If the deuterium atoms have an electronic polarization of unity, electrons produced in a direct knockout from the deuterium will also be completely polarized. Electrons knocked out of the target gas will have zero polarization. Another possibility is that the D(2S) atom picks up one electron from the target gas to form a negative ion which subsequently autoionizes. This process would lead to a partial polarization of the electrons. The latter process appears to be the most likely one since a direct knockout from the D(2S) atoms would lead to fast positive ions, whereas it was found that the number of slow ions produced is about equal to the number of electrons ejected.[8] The assumption of ionization via autoionizing negative-ion states is also supported by the observation that a stable singlet state of D^- can be formed in this type of collision.[9]

The experimental setup is shown schematically in Fig. 1. The metastable deuterium atoms were obtained by a charge-exchange process in which deuterons pick up electrons from ce-

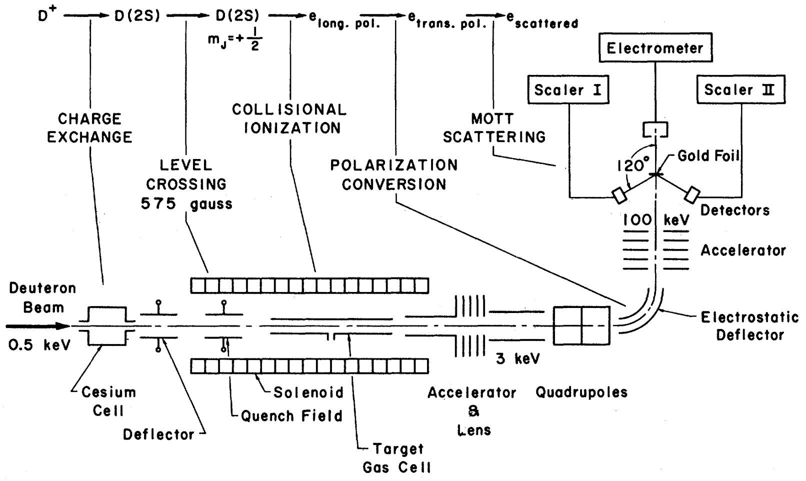

FIG. 1. Schematic diagram of the apparatus (not to scale). The plane of the Mott scattering is perpendicular to the plane of the diagram rather than as shown here.

sium preferentially forming the $n = 2$ state of deuterium.[10] At deuteron energies from 500 to 1000 eV, about 25% of the neutral particles emerging from D^+-Cs collisions are in the $D(2S)$ state; the rest are in states that decay immediately to the $D(1S)$ state.[11] The remaining charged particles were removed from the beam by an electric field weak enough to avoid excessive Stark quenching of the metastable atoms. The $D(2S)$ atoms then entered an axial magnetic field of 575 G where, because of the crossing of the $D(2^2S_{\frac{1}{2}}, M_J = -\frac{1}{2})$ and $D(2^2P_{\frac{1}{2}}, M_J = +\frac{1}{2})$ levels, a small transverse electric field strongly mixed these states and caused those atoms originally in the $(2^2S_{\frac{1}{2}}, M_J = -\frac{1}{2})$ state to decay to the ground state. The neutral beam, now consisting of ground-state atoms and metastable atoms in the $M_J = +\frac{1}{2}$ state, entered a gas cell where the atoms ejected electrons. Any electron polarization had to be parallel to the magnetic field. The electrons followed helical trajectories along the magnetic field until they reached the end of the solenoid where they were accelerated to an energy of 3 keV. Since Mott scattering is sensitive only to the polarization component perpendicular to the plane of scattering, the longitudinal polarization of the 3-keV electron beam was converted into a transverse polarization by means of a 90° electrostatic deflection in the horizontal plane. Since the deflector has astigmatic focusing properties, an electrostatic quadrupole doublet was added to the system in order to achieve optimal beam focusing in the horizontal and vertical planes. After acceleration to 100 keV the electrons were scattered from a thin gold foil. Two surface-barrier detectors were used to count the electrons scattered through an angle of 120° in a vertical plane. Measurement of the counting rates of the two channels simultaneously makes the ratio, C_1/C_2, independent of the incident beam current. In order to eliminate the apparatus asymmetry, another measurement of C_1/C_2 is required during which the beam polarization is either reversed or made zero. An unpolarized electron beam was produced by quenching all metastable deuterium atoms by means of a high electric field in the deflector located between the cesium cell and the solenoid. From the scattering asymmetry the electron polarization, P, was obtained by reference to calculated and tabulated asymmetry functions for single scattering from gold.[12] In order to account for the effect of multiple scattering in the foil, the theoretical asymmetry value was reduced by a factor of 0.87 ± 0.05, determined in previous measurements with foils of different thicknesses. Wall-scattered background electrons were practically eliminated by the design of the scattering chamber and by use of pulse-height discrimination.

The measured electron polarization at several deuteron energies is shown by the solid curves in Fig. 2. The polarization reaches a maximum of 33% for a deuteron energy of about 750 eV with H_2 as the target gas.

In order to determine the polarization P_m of the electrons which originated from collisions of metastable deuterium atoms, we made use of the measured values I_p and I_0, where I_p is

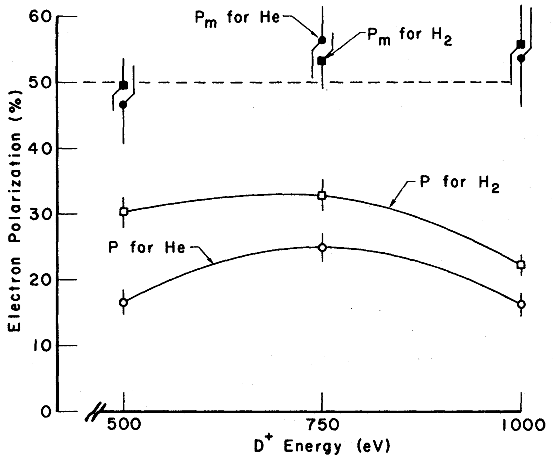

FIG. 2. The polarization P of all the ejected electrons and the polarization P_m of the electrons ejected in collisions of metastable atoms at several deuteron energies for helium and hydrogen as target gas.

the current of polarized electrons and I_0 the current of unpolarized electrons obtained by quenching all metastables in the deflector. If we use the symbol x for the fraction of metastable deuterium atoms in the atomic beam, and σ_m and σ_g for the cross sections for ionization in metastable-atom and ground-state-atom collisions, respectively, we can write the following expression for the polarization P of the electron beam: $P=[P_m x\sigma_m+P_g(1-x)\sigma_g]/[\sigma_g+x(\sigma_m-\sigma_g)]$, and $\sigma_m/\sigma_g=(R+x-1)/x$, where $R=I_p/I_0$ and P_g is the polarization of electrons ejected by ground-state atoms. The measurements showed that R is energy dependent. Solving for P_m we find $P_m=[PR-P_g(1-x)]/(R-1+x)$. Fortunately, P_m depends largely on R, which could be measured in this experiment, and only slightly on x. Over the range of deuteron energies used here, x is known from other work[11] to be about $\frac{1}{4}$ without state selection and, therefore, about $\frac{1}{8}$ for this experiment. Therefore, $x=\frac{1}{8}$ was used for the evaluation with an uncertainty of ±10%. A small polarization of ground-state atoms is introduced by the quenching of the metastable atoms in the state $(2^2S_{\frac{1}{2}}, M_J=-\frac{1}{2})$ by level crossing. Since $\frac{2}{3}$ and $\frac{1}{3}$ of these transitions go to the $M_J=-\frac{1}{2}$ and $+\frac{1}{2}$ ground state, respectively, a fraction $x\simeq\frac{1}{8}$ of the atomic beam has an atomic polarization of -33%, and the electrons ejected in collisions of these ground-state atoms could have any polarization between -33% and zero. Therefore, $P_g=(-33\%)x(1_{-1}^{+0})=-2\pm2\%$ was used in the computation of P_m.

The polarization P_m of the electrons originating from collisions of metastable deuterium atoms is given by the full circles and squares in Fig. 2. It is about 50% for both target gases over the energy range investigated. The electronic polarization of the metastable atoms was unity since the state selection by level crossing quenched all atoms in the $(2^2S_{\frac{1}{2}}, M_J=-\frac{1}{2})$ state, and the solenoid field was strong enough to decouple the electron spin from the nuclear spin completely. The fact that P_m is approximately 50% for several deuteron energies and for two different target gases is strong evidence for a dominant ionization process in which target electrons in both spin states are picked up with equal probability to form negative ions of deuterium which subsequently autoionize, ejecting one of the electrons indiscriminately.

The collisional ionization from polarized metastable atoms is also of interest as a source of polarized electrons.[8] The maximum polarization of 33% is not impressive compared with polarizations of 80 to 90% obtained by photoionization of alkali atoms[13] and by scattering of electrons from mercury atoms.[14] On the other hand, it may be possible to get larger average beam currents than are available from other methods.[15]

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[1] W. Lichten and S. Schultz, Phys. Rev. 116, 1132 (1959).

[2] K. Rubin, J. Perel, and B. Bederson, Phys. Rev. 117, 151 (1960); R. E. Collins, M. Goldstein, B. Bederson, and K. Rubin, Phys. Rev. Letters 19, 1366 (1967).

[3] D. E. Pritchard, D. C. Burnham, and D. Kleppner, Phys. Rev. Letters 19, 1363 (1967).

[4] H. Frauenfelder and R. M. Steffen, in Alpha-, Beta-, and Gamma-Ray Spectroscopy, edited by Kai Siegbahn (North-Holland Publishing Company, Amsterdam, The Netherlands), Vol. 2, p. 1431.

[5] R. L. Long, Jr., W. Raith, and V. W. Hughes, Phys. Rev. Letters 15, 1 (1965).

[6] W. Hilgner and J. Kessler, Phys. Rev. Letters 18,

983 (1967).

[7] Deuterium was used rather than the lighter isotope of hydrogen because its hyperfine splitting is smaller, making it easier to maintain a high electronic polarization with a modest magnetic field, and because it is easier to get a substantial beam of deuterons at a given low velocity.

[8] B. Donnally, in Fifth International Conference on the Physics of Electronic and Atomic Collisions, Leningrad, July, 1967 (to be published), Abstracts, p. 543.

[9] B. L. Donnally and W. Sawyer, Phys. Rev. Letters 15, 439 (1965), and in Proceedings of the Second International Symposium on Polarization Phenomena of Nucleons, Karlsruhe, September, 1965, edited by P. Huber et al. (Birkhauser Verlag, Stuttgart, Germany, 1966), p. 71.

[10] B. L. Donnally, T. Clapp, W. Sawyer, and M. Schultz, Phys. Rev. Letters 12, 502 (1964).

[11] B. Donnally and R. Becker, to be published.

[12] G. Holzwarth and H. J. Meister, "Tables of Asymmetry, Cross-Section and Related Functions for Mott Scattering of Electrons by Screened Gold and Mercury Nuclei" (unpublished); G. Holzwarth and H. J. Meister, Nucl. Phys. 59, 56 (1964).

[13] V. W. Hughes, M. S. Lubell, M. Posner, and W. Raith, in Proceedings of the Sixth International Conference on High Energy Accelerators, Cambridge, Massachusetts, September, 1967 (to be published); P. Coiffet, Compt. Rend. 264B, 160, 454 (1967).

[14] H. Deichsel and E. Reichert, Phys. Letters 13, 125 (1964), and Z. Physik 185, 169 (1965); K. Jost and J. Kessler, Phys. Rev. Letters 15, 575 (1965), and Z. Physik 195, 1 (1966), and Phys. Letters 21, 524 (1966).

[15] Our measurements show that the electron current was of the order of 10^{-3} of a 1-keV deuteron beam current which passed through the apparatus before cesium vapor or H_2 gas were admitted to the cells. Thus, if a 10^{-5}-A deuteron current were available, we could expect a current of polarized electrons of about 10^{-8} A. Actually, a current of 10^{-5} A of deuterons is a conservative value for this estimate since J. L. McKibben and co-workers [Bull. Am. Phys. Soc. 12, 463 (1967)] measure beams of several hundred microamperes of 500-eV protons in a geometry similar to that needed for a source of polarized electrons.

FREQUENCY SPECTRUM OF SPONTANEOUS AND STIMULATED LINE-NARROWING EFFECTS INDUCED BY LASER RADIATION*

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In an earlier Letter,[1] a laser-induced line-narrowing effect was utilized in a precise determination of isotope shifts in two Ne transitions. A recent paper[2] also reports observation of this effect and its application in studying some linewidth parameters in Ne. These experiments study fluorescence arising from the lower level of a Doppler-broadened laser transition to a third level. [See Fig. 1(a).] Viewed along the laser axis, the broad fluorescence line shape is dramatically influenced by the laser field. For a standing-wave field detuned from its atomic center frequency, the laser-induced change signals appear as resonant increases in intensity over two narrow intervals symmetrically located on opposite sides of the fluorescence center frequency. The fluorescence from the upper laser level [Fig. 1(c)], similarly viewed, would exhibit narrow resonant decreases in its over-all emission profile.

The over-all features of this effect may be described by noting that the standing-wave laser field selectively interacts with atoms whose velocities cause a Doppler shift of one of its traveling-wave components into resonance; this produces changes in the laser level populations—an increase in the lower level population and a decrease in the upper level population—over two narrow intervals symmetrically located about the center of the velocity distribution. A recent Letter[3] has analyzed the line-shape details for the cascade case [Fig. 1(a)] in terms of two-quantum transitions from level 2 to level 1, and predicts differing widths for the two laser-induced change signals. A similar line-shape asymmetry, described below, would appear in the change signals from the upper laser level [Fig. 1(c)]. Note that in the latter case, however, the 0 → 1 emission act is an inherently single-quantum event, re-

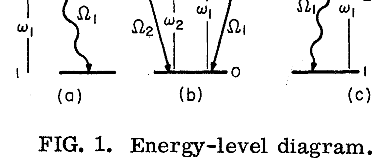

FIG. 1. Energy-level diagram.