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POLARIZATION OF CHANNELED PARTICLES*

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A method of polarizing channeled deuterons by their passage through a monocrystalline nickel foil magnetized to saturation and subsequently through a region of weak magnetic field is described. A beam with tensor polarization $P_{zz} = -0.32 \pm 0.010$ is obtained.

As energetic ions travel through a monocrystalline solid in certain crystallographic directions, the regular arrangement of the lattice atoms can guide them through the spaces between planes (planar channeling) or along channels formed by parallel rows of atoms (axial channeling). The impact parameters of successive collisions then become correlated so their distribution is not random, as it is for ions penetrating through amorphous solids. The experimental and theoretical studies of some of the resulting atomic and nuclear processes (e.g., ion ranges, energy losses, radiation damage, and nuclear reactions) have been reviewed recently.[1]

For the case of energetic light ions ($Z = 1$ or 2) impinging on metal monocrystals with energies ranging from 0.1 to 4.0 MeV, earlier work at this laboratory showed the influence of channeling effects on the yields of secondary particles,[2] on the energy loss,[3] and on charge-transfer processes.[4] It was observed that the energy losses and the secondary-particle yields[3] were smaller in directions in which the lattice was more transparent. It was also observed that ions traversing and escaping through regions of lower electron density (e.g., in the center of an axial channel) have a lower probability of capturing or losing electrons than do those traveling at random in the crystal.[4]

These findings led to the present search for polarization of well-channeled deuterons. The main requisite in preparing polarized deuterons is to populate some of the six components of the hyperfine states of the deuterium atom preferentially (three for each of the two magnetic quantum numbers). The technique investigated here is to direct the incident deuterons accurately in one of the channeling directions of a monocrystalline nickel foil magnetized to saturation; in an appropriate energy range the deuterons would capture polarized electrons (e.g., from the $3d$ states in Ni). These electrons have only one of the two possible spin orientations, since the spin directions point preferentially along the magnetic field lines, and three of the six hyperfine states will not be populated. The resulting polarized deuterium atoms emerging from the magnetized monocrystalline foil then travel through a weak uniform magnetic field for a sufficiently long time that part of the electron polarization is transferred to the deuteron by hyperfine interaction. Here "sufficiently long" means that the transit time is much longer than the period of Larmor precession of the nuclear magnetic moment. Since the populations of the three remaining hyperfine states are different in weak magnetic fields, a polarization of the deuteron can be expected. After passing through the weak magnetic field region the tensor polarization of the well-channeled deuterium atoms (now polarized in electron spin and nuclear spin) can be determined by measuring the angular distribution of the α particles emitted in the reaction $T(d,n)He^4$.

An essential feature of the polarization method described here is that only well-channeled deuterium atoms emerging from a monocrystalline foil are detected. This restriction has three important consequences. (1) For atoms that emerge from the foil well channeled, the axis of polarization will remain relatively unperturbed with respect to the direction of the emergent beam and the direction of magnetization. (2) The emergent beam is strongly concentrated in the direction of the channel axis (i.e., the deuteron flux per unit solid angle is greatly increased). (3) For monocrystalline ferromagnetic foils with thickness $\lesssim 1\ \mu$, a single magnetic domain is very likely to extend through the thickness of the film so that very weak external magnetic fields are sufficient to magnetize the foil to saturation. For nickel monocrystals the ease of magnetization decreases in the order [111] > [110] > [100].

In our experiments, in which the direction of magnetization was parallel to one of the [111] axes in the plane of the nickel foil, saturation magnetization is reached at fields of approximately 30 G.[5] A mass-analyzed, highly collimated D^+ ion beam with a half angle of 0.01° was incident on a Ni(100) foil (magnetized to saturation) within 0.1° of a [110] direction (i.e., well within the critical acceptance angle of ~1.6°-1.8°). Two different monocrystalline Ni(110) foils were used, their thicknesses being approximately 1.24 and 2.21 μ. Over an area four times that struck by the beam each foil thickness varied less than 3%. The structural quality of the foils was checked by Laue diagrams taken in back reflection and in transmission. The mosaic spread across the target area used was approximately 0.20° for both crystals. Two polycrystalline nickel foils with thicknesses of approximately 1.14 and 1.87 μ were also used to test a method of particle polarization proposed by Zavoiskii.[6]

Both monocrystalline and polycrystalline Ni foils were at first magnetized to saturation during the same run with high external magnetic fields of approximately 12 kG (higher than necessary). Subsequently the targets were mounted in a holder inside the vacuum chamber on a goniometer which permitted precision lateral motions along three orthogonal axes and rotation about two orthogonal axes. Inside the target holder the foils were kept in a magnetic field (approximately 160 G) parallel to the original magnetization direction (e.g., in the case of the monocrystalline foils parallel to one of the [111] directions in the plane of the foil). This was thought to prevent a possible demagnetization of the foils, in case of a mechanical or thermal shock. The target holder was magnetically shielded to reduce the fringing field extending away from the region of the foil.

As shown in Fig. 1, the atoms emerging from the foil were first passed through an aperture of half-angle ~0.15° at a scattering angle of 0°±0.1° with respect to the incident beam direction. They then spent $(1-2)\times10^{-7}$ sec in traversing a homogeneous magnetic field of ~10 G which can be directed along either the $\pm z$ or the $\pm y$ axis (i.e., either parallel or perpendicular to the direction of magnetization of the foil) by energizing one or the other of a pair of electromagnets. The charged atoms were deflected out of the beam by applying appropriate potentials to the insulated pole pieces, while the neutral atoms passed through the second collimator system (half-angle of acceptance ≈0.15°) and struck either a movable surface-barrier solid-state detector (to determine the energy spectrum in the emergent beam) or the T-Ti target (to determine the polarization).

Whenever the incident beam was parallel within 0.3° to the [110] axis in the monocrystalline Ni foil, the energy spectrum of the emergent beam (for both the total beam or the neutral fraction) consisted of two well-separated peaks[3]; the mean energy $\bar{E}_n$ of the lower one corresponded to the normal energy loss observed for polycrystalline targets of the same material and the same thickness, while the mean energy $\bar{E}_{ch}$ of the high-energy peak reflects the reduced loss rate for channeled particles. The mean energy loss $(d\bar{E}/dx)_{ch}$ for deuterons traversing the [110] axial channel in Ni had approximately half the loss $(d\bar{E}/dx)_n$ for nonchanneled particles undergoing random col-

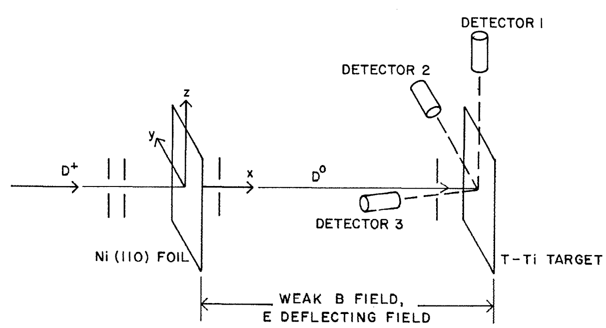

FIG. 1. Schematic diagram of experimental arrangement.

lisions (for the $\bar{E}_n$ range 80-150 keV). If the incident beam direction was within 0.1° parallel to the [110] axial channel, approximately 93% of the emergent particles that passed through the collimating system had mean energies $\bar{E}_{ch}$, while the remaining 7% had mean energies $\bar{E}_n$.

To avoid detection of this small residue of randomly scattered atoms, the incident-ion energy was so chosen that $\bar{E}_{ch}$ was in the range 100-130 keV and E_n was only a few keV. The latter is well below the threshold for the reaction $T(d,n)He^4$, which has a peak cross section of 5 b at the $J=\frac{3}{2}^+$ resonance in He^5 at $E_d=107$ keV; so the nonchanneled particles with mean energy $\bar{E}_n$ do not influence the angular distribution of the alpha particles emitted in the reaction $T(d,n)He^4$.

The analyzing power of the reaction can be calculated[7,8] on the assumption that the reaction occurs exclusively through the reaction channel with $l=0$ and $J=\frac{3}{2}^+$. Because the orbital angular momentum of the s-wave deuteron is zero the reaction cross section is axially symmetric about the polarization axis. Then for a determination of the angular distribution of the α or n particle emitted in the reaction, the relevant angle is then the center-of-mass angle φ between the outgoing particle (α or n) and the polarization axis. Under the assumption of a pure s-wave resonance, the cross section is then given by

$$\sigma(\varphi)=\sigma_0[1-\tfrac{1}{4}(3\cos^2\varphi-1)P_{zz}], \tag{1}$$

where σ_0 is the isotropic unpolarized cross section and P_{zz} is one element of a second-rank tensor (representing the expectation values of the Cartesian spin operator) if the $\pm z$ axis of polarization; P_{zz} is sufficient to determine the tensor polarization since the deuteron is a spin-1 particle. Since the spin system is symmetric about the polarization axis, the polarization state can be described by the fractional populations N_+, N_0, and N_- of deuterons with spin projections 1, 0, and -1. The tensor polarization P_{zz} is related to the fractional population N_0 by

$$P_{zz}=1-3N_0. \tag{2}$$

For the present case of axial symmetry, the remaining five elements of the symmetric tensor (trace zero) are $P_{xx}=P_{yy}=-\frac{1}{2}(1-3N_0)$ and $P_{xy}=P_{yz}=P_{zx}=0$, with $P_{xx}+P_{yy}+P_{zz}=0$. From Eq. (2) it follows that P_{zz} can vary between -2 and $+1$, and from Eq. (1) it follows that the largest effect can be measured at center-of-mass angles $\varphi=0°$ and $\varphi=90°$. For emerging deuterons in the energy range used in our experiments (100 keV $\le \bar{E}_{ch} \le$ 150 keV) the analyzing power is found to be independent of deuteron energy.

For the case in which the polarization was in the $\pm z$ direction (Fig. 1), solid-state counters 1, 2, and 3 detected the α particles emitted in such c.m. directions that $\varphi_1=7°$, $\varphi_2=90°$, and $\varphi_3=90°$. For an additional test, the polarization axis was reoriented by applying the weak magnetic field in the $\pm y$ direction. For this case, the c.m. angles were $\varphi_1=90°$, $\varphi_2=82°$, and $\varphi_3=7°$. From Eq. (1) one sees that P_{zz} or P_{yy} can be determined from the ratio

$$R_{\mu\nu}=\frac{\sigma_p(\varphi_\nu)}{\sigma_p(\varphi_\mu)}\left[\frac{\sigma_u(\varphi_\nu)}{\sigma_u(\varphi_\mu)}\right]^{-1}=\frac{\mathfrak{N}_p(\varphi_\nu)}{\mathfrak{N}_p(\varphi_\mu)}\frac{\mathfrak{N}_u(\varphi_\mu)}{\mathfrak{N}_u(\varphi_\nu)}, \tag{3}$$

where σ_p and σ_u are the differential cross sections for polarized and unpolarized deuterons and $\mathfrak{N}_p$ and $\mathfrak{N}_u$ are the corresponding counting rates. The ratio $\mathfrak{N}_u(\varphi_\mu)/\mathfrak{N}_u(\varphi_\nu)$ was determined by bombarding the T-Ti target with a collimated, unpolarized primary-deuteron beam with mean energies ranging from 100 to 150 keV. At a given energy and for a given set of angles φ_ν and φ_μ the sequence of measurements was two unpolarized runs, three polarized, and again two unpolarized. For polarization in the $\pm z$ direction $R_{\mu\nu}$ was found to be $+1.260\pm0.010$ when using detectors 1 and 2, and $+1.258\pm0.010$ for detectors 2 and 3; for the $\pm y$ direction, $R_{\mu\nu}=+0.787\pm0.011$ and $+0.852\pm0.010$ for detectors 1 and 3, and 2 and 3, respectively. From Eq. (2), our value of P_{zz} (or P_{yy}) was -0.32 ± 0.01 in each case. The value $-\frac{1}{3}$ would correspond to a fractional occupation $N_0\approx4/9$; for P_{zz} (or P_{yy})$=0$, i.e., for $N_0=N_+=N_-$, the value of N_0 would be ~3/9.

For comparison, the tensor polarization P_{zz} was found to be -0.245 and -0.26 ± 0.02 by two groups[9,10] using the atomic-beam method with separation in a strong quadrupole field, and -0.23 and -0.2 by groups[11,12] using the $2S_{1/2}$ metastable state of deuterium.

To test Zavoiskii's proposal[6] for polarizing deuterons, we passed deuterons through polycrystalline foils magnetized to saturation and observed $P_{zz}=-0.002\pm0.010$ for the 1.14-μ-thick foil and $P_{zz}=+0.003\pm0.010$ for the 1.87-μ-thick foil. These results indicate no significant tensor polarization (i.e., $P_{zz}\approx0$) and support some of the criticism[13] of the proposal.

It appears that the method of polarizing channeled particles will permit the development of a relatively inexpensive source of polarized ions.[14] Since we obtained 500 nA/cm² of channeled deuterium atoms with nuclear spin polarization (without a significant lattice damage for approximately 25 h of operating time), it appears feasible to obtain approximately 10-20 nA/cm^2 of polarized negative ions (by passing the beam through a second thin monocrystalline film). These intensities can probably be increased significantly by cooling the films, by somewhat relaxing the present requirements of strong collimation of the emergent beam (without a significant decrease in beam polarization, and by using films whose thicknesses are optimal for the deuteron velocity ranges used.

The method of polarizing channeled deuterons should work well also for other particles (e.g., protons, tritons, He^3, etc.) and for monocrystalline targets of other ferromagnetic and paramagnetic materials (e.g., Gd, Tb, Dy, Ho). Furthermore, highly textured, thin rolled foils of such magnetizable material may provide polarizing targets at even lower costs.

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STABILIZATION OF A HOT ELECTRON PLASMA BY HOMOGENEOUS TEMPERATURE EFFECTS

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The suppression of drift instabilities in a magnetoplasma having high electron temperature is obtained by avoiding transverse temperature gradients.

Recent methods of suppression of drift instabilities make use of a constraint external to the plasma provided by ac fields coupled to the plasma by various techniques.[1,2] The suppression, obtained for a particular value of frequency or phase of the stabilizing field, has not yet led to a clear understanding of the phenomena involved in the process of stabilization. The suppression of the low-frequency drift instabilities is obtained, with the stabilization method reported in this Let-