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HIGHLY SPIN-POLARIZED PROTON SAMPLES– LARGE, ACCESSIBLE, AND SIMPLY PRODUCED

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Low temperatures in the neighborhood of 5 mdeg K have been produced by the nonmagnetic method of He^3-He^4 dilution.[1] Magnetic fields of about 100 kOe are available over large volumes with superconducting magnets. If proton spins could be brought to equilibrium under these conditions, the proton polarization P, defined in the usual way as $\tanh(g\mu_{NM}H/2kT)$, would equal 96%. Even at a temperature of 0.020°K, which does not strain the technology to its present limit, a polarization of 47% is obtainable. Thus, protons sufficiently polarized for use as polarized targets in nuclear physics experiments are, in principle, achievable by simple equilibrium methods. There are, however, problems encountered at the very low temperatures. These include spin-lattice relaxation times which could become impractically long, and formation of ordered states, both of which could prevent achievement of high polarizations. In additions, even if the full polarization could be obtained, the utilization of the target within the dilution refrigerator and superconducting magnetic field of 100 kOe could be extremely inconvenient and restrictive in an actual nuclear physics experiment, and the heating effects due to the high-energy beam at a reasonable intensity would likely nullify the useful proton polarization.

In this Letter, we propose a polarized proton system which should avoid the above stated difficulties. The sample envisaged is solid HD with small amounts of H_2 impurity present. Studies by Bloom[2] and, more recently, by Hardy and Gaines[3] and by Rubins, Feldman, and Honig[4] have shed considerable light on the HD proton spin-lattice relaxation rates as a function of temperature, magnetic field strength, and ortho-H_2 impurity concentration. These investigations indicate that the spin-lattice relaxation aspect of the problem is favorable. The situation regarding a nonordered state at low temperatures is also favorable because of the very low ortho-H_2 concentration needed in the proposed method. In addition, experimental evidence presently available[5] indicates that HD obeys the Curie susceptibility down to 0.2°K, the lowest temperature measured. Finally, a relaxation mechanism "switch" is proposed which enables the HD to relax rapidly enough at the lowest temperatures and thereby become polarized, but which subsequently can be "turned off", so that the high spin polarization remains metastable for very long times (days), even at 4°K and low external magnetic field strengths.

At temperatures in the liquid He^4 region and below, the relaxation is almost entirely dominated by the ortho-H_2 impurity relaxation, which causes relaxation of the main body of protons on the HD through cross-relaxation between ortho-H_2 and protons on the HD. Between 1 and 4°K, for HD with a concentration of about 1% normal-H_2 impurity, the overall proton relaxation time is temperature independent and less than a tenth of a second. From the theory,[6] one can expect the mechanism to remain effective down to 0.005°K, although this should be experimentally ascertained. This same sample, left standing for about two months at liquid-helium temperatures, undergoes ortho → para conversion of the H_2 impurities, leading to a new dominant relaxation mechanism[4] which is strongly temperature dependent, and extrapolates to a relaxation time of the order of a day at 4°K and an order of magnitude longer than that at 1°K. The ortho → para conversion process is independent of temperature,[7] and should occur in the 5-mdeg region also. Thus, one can envisage polarizing an HD sam-

ple at 0.005°K and 100 kOe, leaving the sample under these conditions for two months while the relaxation mechanism "switch", namely the ortho-H_2, "turns off" as ortho-H_2 converts to para-H_2, and then transferring the solid HD to ordinary liquid-helium-cooled Dewars in weak magnetic fields, where the high degree of polarization would be frozen in, because of the very long relaxation time.

In the limit of complete conversion of ortho-H_2 to para-H_2, the results of Ref. 4 indicate that the 4°K relaxation time in an external magnetic field of 2.5 kOe would be about 5 d. This time rises quadratically with external magnetic field and steeply as the temperature is lowered. Under optimum conditions, polarized blocks of HD could be conveniently stored for many days and made available for experiments when needed. The preparation process suggested above, requiring about two months at high magnetic field and very low temperatures, is quite feasible, using the persistent-current mode of operation of the superconducting magnet. The concentrations, however, were chosen only for simplicity of presentation, and use of optimum initial normal-H_2 concentration would lead to a somewhat shorter duration of the process. In addition, it may be possible to increase the ortho → para conversion rate without seriously affecting the relaxation rates of the protons. One such possibility is through compression[8] of the solid HD, which alters the phonon spectrum. It may also be possible to find a suitable catalyst.

The technique of polarizing at a favorably low temperature and high magnetic field and utilizing the frozen-in polarization at high temperatures may be extendable even to the liquid phase of HD. The proton relaxation time in liquid HD exceeds 30 sec, and at 100-kOe magnetic fields it should be possible to raise the temperature of solid HD and traverse the molecular-diffusion relaxation region[2,4] fast enough to avoid depolarization. It may be conceivable to operate small HD bubble chambers with polarized protons.

Although the polarized-proton HD targets are useful regardless of the state of polarization of the deuteron, it would be highly desirable if the deuteron were also polarized. The process described here for the H_2 impurity in HD also holds for the D_2 impurity, with the switching mechanism resulting from para → ortho conversion of the D_2. However, the magnetic moment of the deuteron is approximately a factor of 3 smaller than that of the proton, making the low-temperature requirements for high polarization more stringent than for the protons. The quadrupole moment of the deuteron in the bulk HD is not likely to result in too short a spin-lattice relaxation time[6] of the deuteron at liquid-helium temperatures for the method to work. However, measurements at liquid-helium temperatures of deuteron relaxation in HD with D_2 impurities is needed before the question of deuteron polarization can be answered. It should be noted that D_2 in its equilibrium $J=0$ ortho state is magnetic and may also be directly polarized with subsequent "switching off" of the dominant relaxation mechanism by para → ortho conversion, provided an ordered state does not form with pure ortho-D_2, and provided the relaxation time of ortho-D_2 is sufficiently long at liquid-helium temperatures.

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