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## LARGE $He^3$ NUCLEAR POLARIZATION

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We have attained a nuclear polarization of 40% in $He^3$ gas at room temperature by optical pumping techniques. Substantial $He^3$ polarization at moderate pressures and in a favorable environment makes practical for the first time nuclear scattering experiments involving polarized $He^3$ targets and, possibly, polarized $He^3$ ion sources. The polarization realizable in a particular experimental arrangement depends on the $He^3$ sample pressure, on sample geometry, and on the character of the resonance radiation employed for optical pumping. These factors and the means for measuring the polarization are discussed in this paper.

The $He^3$ nuclear polarization is achieved as a result of collisions involving metastability exchange between ground-state $He^3$ atoms and optically pumped metastable $2\,^3S_1$ $He^3$ atoms created in the sample cell by a weak electrical discharge. A discussion of the physical principles involved in the polarization process has been given earlier.[1]

$He^3$ polarization was measured as a function of pressure in a 65-$cm^3$ spherical Pyrex cell. Spectroscopically pure $He^3$ was used. The polarization is produced by illuminating the cell with an intense beam of circularly polarized 1.08-micron resonance radiation from helium discharge lamps. The lamps were constructed from quartz blanks 3 cm in diameter and separated by 1 mm. They were filled to a pressure of 4 mm Hg. The lamps were excited by 100 watts of radiant power at 2450 Mc/sec provided by a Raytheon diathermy generator, Model CMD5. The microwave power was coupled into the lamp with a simple dipole antenna and reflector. The light was directed along the axis of symmetry of a solenoid and focused on the $He^3$ absorption cell at the center. The sense of circular polarization of the light and its direction relative to the external magnetic field determine the orientation of the nuclear spins. The weak electrodeless discharge was maintained in the absorption cell by a 50-Mc/sec oscillator.

The polarization was measured, as described in reference 1, by comparing the intensity of the $He^3$ slow-passage nuclear magnetic resonance (NMR) signal at 600 kc/sec with that from protons in benzene under the same experimental conditions. The highest polarization occurred at the weakest self-sustaining cell discharge intensity and decreased rapidly as the discharge intensity was increased. This effect seems reasonable since collisions with the discharge products are known to shorten the metastable lifetime[2] and may also constitute a ground-state relaxation mechanism.

Figure 1 indicates the dependence of the polarization on the pressure of $He^3$ gas in the absorption cell, always using the weakest self-sustaining cell discharge level. The absolute polarization values depend greatly on such factors as the experimental geometry, lamp intensity, and cell

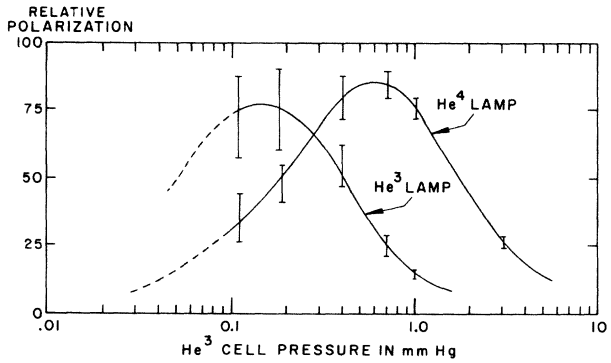


FIG. 1. Relative polarization measured by NMR as a function of the cell pressure for both $He^3$ and $He^4$ pumping radiation.

discharge level. For our experimental conditions, the curves in Fig. 1 can be normalized at 1-mm pressure where the $He^3$ polarization achieved with a single $He^4$ lamp was $25 \pm 5\%$; with two lamps pumping simultaneously, $40 \pm 5\%$ polarization was obtained.

The $He^3$ and $He^4$ lamps have slightly different spectral characteristics, which accounts for the difference between the two curves in Fig. 1. The 1.08-micron line in helium is split into a doublet separated by about 1 Å, and the $He^4$ doublet is shifted 1 Å toward the blue relative to the $He^3$ doublet.[3] As a result, for a $He^3$ lamp pumping a $He^3$ cell, both doublet components ($2\,^3S_1 - 2\,^3P_{1,2}$ and $2\,^3S_1 - 2\,^3P_0$) are pumped, while $He^4$ light induces only the $2\,^3S_1 - 2\,^3P_0$ transitions in $He^3$. A $He^4$ lamp actually provides more light within the $2\,^3S_1 - 2\,^3P_0$ absorption line of $He^3$ than does a $He^3$ lamp, because the component intensities of the 1.08-micron doublet are unequal.

At low cell pressures, $He^3$ lamps are more effective in producing polarization, because both components of pumping light are effective in the optical pumping process. As the cell pressure is increased, however, collisions involving optically excited atoms in the $P$ states lead to mixing of the $P$-state populations, and it has been shown that the $2\,^3S_1 - 2\,^3P_{1,2}$ radiation becomes ineffective in the pumping process.[2] Thus at higher pressures, where only $2\,^3S_1 - 2\,^3P_0$ transitions produce polarizations, $He^4$ lamps become more effective.

The fall-off in attainable polarization at low pressures is due to quenching of the metastable atoms as a result of wall collisions; this effect can be reduced by increasing the cell size. The polarization fall-off at high pressures is not completely understood but might result from a shorter metastable lifetime at higher pressures, or from a combination of $P$-state mixing and electron exchange between ground-state atoms and atoms in the $P$ states. Either mechanism would short circuit the optical pumping process.

Optical techniques can also be used to measure the $He^3$ polarization. To a very good approximation, the distribution of metastable atoms among the six available $2\,^3S_1$ Zeeman levels is determined completely by their interaction with the polarized ground state ($1\,^1S_0$). Thus the relative populations of the various metastable levels can be calculated in steady state, in terms of the ground-state nuclear polarization, from the rate equations coupling the metastable and ground-state Zeeman levels. Since the relative probabilities of stimulating electric-dipole transitions from each of the metastable Zeeman levels to the $2\,^3P_0$ levels are calculable, one can in turn relate the metastable level populations to the fraction of $He^4$ pumping light absorbed by the $He^3$ cell. Subject to the condition that only $2\,^3S_1 - 2\,^3P_0$ transitions are induced by the pumping radiation (experimentally realized by using a $He^4$ lamp), we derive the following relation between the ground-state nuclear polarization $P$ and the pumping light absorbed by the $He^3$ cell:

$$\Delta I/I_0 = P(6 - 2P)/(3 + P^2), \qquad (1)$$

where $I_0$ is the fraction of pumping light absorbed when the $He^3$ is unpolarized, $I$ that when it is polarized, and $\Delta I = I_0 - I$. The validity of the equation has been confirmed experimentally for polarizations below 25% by direct comparison with NMR determinations of the polarization.

With as weak a discharge in the $He^3$ cell as can be made self-sustaining, the time constant for the sample polarization to build up is 10 to 30 seconds. With the discharge extinguished, the polarization decays in about 600 seconds. This long relaxation time provides a convenient method for selecting materials suitable for construction of polarized $He^3$ target cells to be used in nuclear scattering experiments. A number of $He^3$ Pyrex cells were prepared containing samples of various metals. Brass, copper, aluminum, and a number of nonferromagnetic alloys caused no measurable decrease of the 600-second $He^3$ relaxation time. However, the relaxation time was decreased to a value so low as to prevent any measurable polarization when even small pieces of ferromagnetic material were introduced into the $He^3$ cell or brought into close proximity of the cell from the outside. This drastic reduction in $He^3$ spin-lattice relaxation time is thought to result from nonadiabatic diffusion (i.e., rapid with respect to the $He^3$ Larmor period) of the $He^3$ atoms through magnetic field gradients produced by the ferromagnetic material. Such a relaxation mechanism can be quite effective when dealing with nuclear magnetism in low-pressure gases and in weak magnetic fields – a situation unique to these experiments and accounting for the fact that this relaxation mechanism has not been observed previously in NMR experiments.

The techniques described here have recently been employed to demonstrate a polarized $He^3$ target suitable for use in nuclear scattering experiments.[4] For scattering experiments requiring a higher $He^3$ target density than this method provides, the long polarization relaxation time

(600 seconds) suggests the utilization of techniques involving substantial compression of the polarized $He^3$ gas.

The possibility of using the polarized neutral $He^3$ gas as a source of polarized $He^{3+}$ or $He^{3++}$ ion beams, for use in particle accelerators, has been considered and is thought to be feasible.[5] The ions would be extracted from the aforementioned weak discharge which is employed in polarizing the neutral atoms. As a result of the $He^{3+}$ hyperfine interaction, the theoretical upper limit for the ion beam nuclear polarization will be one half the polarization of the neutral $He^3$ gas from which the ions are derived.

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## EXPERIMENTAL DETERMINATION OF THE BRANCHING RATIO $\Gamma(\eta \to \pi^+\pi^-\gamma)/\Gamma(\eta \to \pi^+\pi^-\pi^0)$†

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The spin ($J$), parity ($P$), isotopic spin ($I$), and $G$-parity ($G$) of the $\eta$ meson have now been fairly well established,[1] mostly through studies of the Dalitz-Fabri plot for the most readily observable decay mode

$$\eta \to \pi^+ + \pi^- + \pi^0. \tag{1}$$

The generally accepted result is

$$J^P I^G = 0^- 0^+. \tag{2}$$

Direct observation,[2] in a heavy-liquid bubble chamber, of the mode

$$\eta \to \gamma + \gamma \tag{3}$$

eliminates the possibility $J = 1$, and thus strengthens the assignments of Eq. (2). The expected decay mode

$$\eta \to \pi^0 + \pi^0 + \pi^0 \tag{4}$$

is difficult to observe and has not yet been established.[2] However, the ratio

$$\Gamma(\eta \to \text{"all neutrals"})/\Gamma(\eta \to \pi^+\pi^-\pi^0) = 3.0 \pm 0.5 \tag{5}$$

has been found in several experiments.[1] The "neutrals" are expected to correspond to Reactions (3) and (4), if Eq. (2) is correct. One also then expects the $\eta$ to decay via the electromagnetic mode

$$\eta \to \pi^+ + \pi^- + \gamma. \tag{6}$$

Previous to the present experiment, Reaction (6) had not been observed. The branching ratio

$$R(\pi^+\pi^-\gamma/\pi^+\pi^-\pi^0) \equiv \Gamma(\eta \to \pi^+\pi^-\gamma)/\Gamma(\eta \to \pi^+\pi^-\pi^0)$$

was found to be consistent with zero[1,3,4] (with upper limit about 0.2). Thus, there have been reservations as to the correctness of Eq. (2).

We have determined the value of $R(\pi^+\pi^-\gamma/\pi^+\pi^-\pi^0)$, using $\eta$'s produced in the Alvarez 72-inch hydrogen bubble chamber via the reaction

$$\pi^+ + p \to \pi^+ + p + \eta, \tag{7}$$

where the $\eta$ subsequently decays via

$$\eta \to \pi^+ + \pi^- + X^0, \tag{8}$$

and where $X^0$ is an unknown neutral (or neutrals).

Our experimental result is that $X^0$ is always a