Spin-polarized ^{3}He nuclear targets and metastable ^{4}He atoms by optical pumping with a tunable, Nd:YAP laser

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Several Nd:YAP lasers were constructed which could be broadly tuned in the 1083-nm region which includes the helium 2^3S-2^3P transition, using a Lyot filter and thin, uncoated etalons within the laser cavity. 1 W of power could be extracted at 1083 nm through a 1% transmitting output coupler. This laser beam was used to optically pump metastable ^{4}He and ^{3}He 2^3S helium atoms in a weak discharge cell, spin polarizing the metastable ensemble. In a ^{3}He cell the polarization is transferred to the nuclear spin system. A ^{3}He target cell at 0.3 Torr was polarized to 52% in a few minutes. We describe the application of this system to the design of polarized targets for experiments in nuclear physics.

INTRODUCTION

The cw laser and tuning characteristics of Nd^{3+}:YAP were recently reported.[1] That work as well as this report is motivated by the operating wavelength range of the YAP laser, which includes emission around 1083 nm. This wavelength corresponds to the 2^3S-2^3P resonance transition in helium. As such, laser optical pumping in He^4 and He^3 may be performed, producing spin-polarized ensembles of helium atoms.[2-4] Such spin-polarized ensembles of helium have a variety of important applications as probes of terrestial and interplanetary magnetic field,[5,6] surface magnetic states,[7] polarized He^3 targets for use in nuclear physics,[8] and studies of the quantum properties of a low-temperature, polarized He^3 fluid.[9] Other potential applications include the study of squeezed states in helium, transverse cooling of metastable beams by lasers, and precision spectroscopy to test quantum electrodynamics.

In this article we report the use of the tunable Nd:YAP laser to polarize both helium-four metastable atoms and helium-three nuclei. This laser is particularly useful for applications in which relatively dense, polarized ensembles are required and for experiments in which the device must be operated for long periods without operator intervention. The Nd:YAP laser described here is a modified commercial Nd:YAG laser. It offers stable, modest cw power output which is easily tuned to the helium resonance transition. It is a particularly attractive pumping source for the production of polarized He^3 targets for nuclear scattering experiments.

In the sections following we describe the required modifications of a commercial Nd:YAG laser, its application to the optical pumping process in helium, and the design and construction of a target cell for nuclear scattering experiments.

YAP LASER CHARACTERISTICS

Two different commercial Nd:YAG lasers were modified for this application: Microcontrole, model YAG 90L and Laser Applications, Inc., series 9500. Both devices use CW Kr^+ arc lamps to pump the YAG rod and are capable of 60–70 W output, cw at 1064 nm. The principal modification is the direct replacement of the YAG rod with a Nd:YAP rod of the same dimensions, nominally 4 mm × 80 mn. Under similar conditions the YAP laser provides approximately the same power output as the unmodified YAG laser. However, maximum gain occurs at 1078.5 nm and the laser emission is linearly polarized since the crystal has an orthorhombic structure. The crystal was obtained from Heraeus.[10] It is cut with its "*a*" axis along the rod length. The crystal ends are AR coated and slightly wedged.

The cavity is defined by two plane mirrors separated by about 60 cm. One of the mirrors is totally reflecting; the other has a transmission of about 1% at 1083 nm. The cavity is shown in Fig. 1. Oscillation on the main peak is suppressed by the insertion of a Lyot filter. The Lyot filter was either a single quartz plate of 6 mm thickness or a three-plate filter with the thickest plate of 6 mm. The lyot filter was tuned to force oscillation of the YAP on the scondary peak near 1084 nm, according to the method described in Ref. 1. Fine tuning on the latter band is accomplished with the addition of one or more thin, uncoated solid etalons. The best performance was obtained when the thinnest etalon was on the order of 0.15 mm. A second etalon of 0.5 mm thickness provided a slightly narrower bandwidth. Nearly equivalent performance is obtained with a single 0.25-mm-thick fused quartz etalon. With this cavity, up to 1 W of output power at the helium transition (1083 nm) can be obtained. The bandwidth of the laser emission is on the order of 5 GHz, approximately 2.5 times greater than the Doppler width of the helium absorption line.

The alignment of the laser first requires a careful adjustment of the orientation of the YAP crystal with respect to

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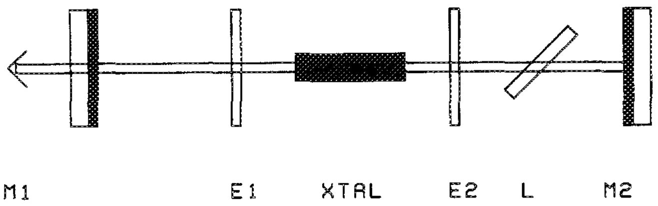

FIG. 1. Schematic representations of laser cavity. $M1$ is the 1% transmitting output coupler and $M2$ is total reflector at 1083 nm. $E1$ and $E2$ are solid, uncoated etalons of 0.15 and 0.25 mm thickness. L is the Lyot filter inserted at the Brewster's angle.

the orientation of the Lyot filter which is itself carefully oriented at Brewster's angle. When properly oriented, the Lyot filter insertion loss is less than 1%. Laser emission may be taken from the 1% transmitting output coupler or the faces of the Lyot filter.

The procedure for tuning the laser to 1083 nm, the wavelength of the helium 2^3-S-2^3P transition, is normally the following: at low pump power the Lyot filter and etalon(s) are inserted in the cavity and the output wavelength tuned to 1084.5 nm, the peak of the secondary band. The wavelength is then decreased by tilting the etalon(s) and simultaneously slightly rotating the Lyot filter. The procedure is repeated while increasing the pump power until the desired wavelength is reached, always avoiding having more than about 100 W of power circulating within the cavity (above this limit instabilities occur due to local heating of the frequency selective elements). The linewidth of the laser is on the order of 3–4 GHz when the laser is close to threshold and increases as the pump intensity is increased. The emission is multimode although the transverse mode structure can be minimized with the addition of limiting apertures within the cavity. The output power at the helium transition as a function of the power to the Kr$^+$ lamp is shown in Fig. 2. The tuning curve of the YAP laser under the conditions described above is shown in Fig. 3. The shape of the tuning curve suggests that with some additional effort it might be possible to continuously tune the laser through both fluorescence peaks at 1084.5 and 1079.5 nm.

HELIUM OPTICAL PUMPING RESULTS

The laser output beam can be used to excite fluorescence from a helium cell. By tilting etalon $E1$ the laser frequency can be swept through the fine and hyperfine structure of the 2^3S_1-$2^3P_{0,1,2}$ transition. In practice the tilt of this etalon is adjusted by a small stepper motor which is attached to the etalon holder. Under computer control we are then able to search for and then stabilize on one of the components of the helium transition. The long-term frequency and amplitude stability of this laser is rather good. For the application described here (and considering the emission linewidth), it is thus unnecessary to lock the frequency to an external source.

In^4 He the fluorescence spectrum consists of three fine structure components, D_0, D_1, and D_2, corresponding to the transitions from the 2^3S_1 state to the $2^3P_{O,1,2}$ states, respectively. The D_1 and D_2 lines lie within the Doppler width and are thus unresolved. The D_0 line is 0.1 nm below the $D_{1,2}$ combination and can be separately excited by the laser. In ^{3}He the presence of a nuclear spin, $I = \frac{1}{2}$, doubles the number of levels. The C_8 and C_9 components, originating on the 2^3S_1 $F = \frac{3}{2}$ and $F = \frac{1}{2}$ levels and terminating on the 2^3P_0 level are not resolved, but can be separated from the group of other components C_1-C_7, as described in Ref. 4.

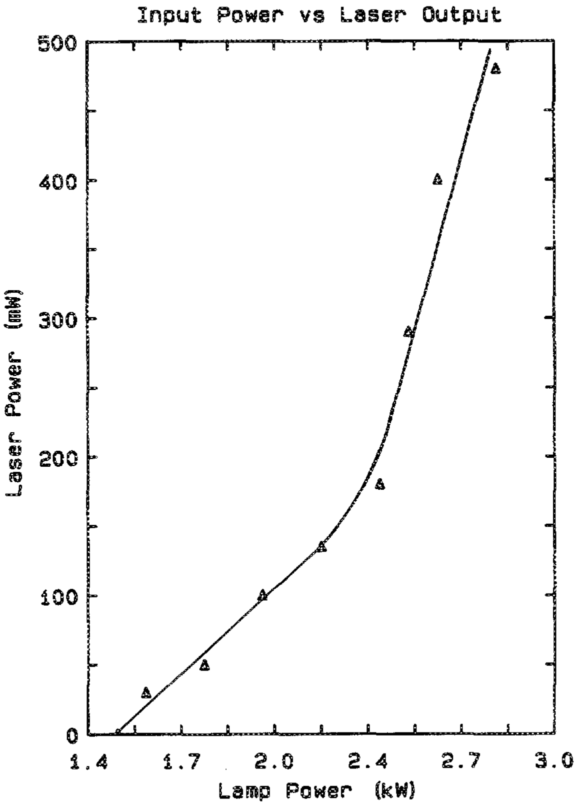

FIG. 2. Laser power output at the helium resonance transition as a function of the power to the Kr arc lamp in the Lasermetrics system. The knee at 2.4 kW is associated with the radial distribution of the population inversion in the YAP rod.

Using the power delivered by this tunable YAP laser, we have polarized by optical pumping a ^{4}He cell and a ^{3}He cell filled with 0.3-0.8 Torr of gas which is excited by a weak electric discharge. The function of the weak electrical discharge is to produce a small number of helium metastable atoms (10^{10} cm^{-3}) which interact with the laser photons. The laser beam is circularly polarized by placing a quartz quarter-wave plate in the beam path. The laser beam is expanded with a lens to fill the cell aperture and reflected back by a mirror after crossing the cell. The helium discharge cell is placed in an homogeneous magnetic field of several G parallel to the laser beam..

The helium spin polarization is monitored optically. In the case of ^{4}He, the optical pumping results in an electron-spin polarization of the 2^3S_1 metastable atoms. The metastable polarization is detected by observing the resonantly scattered pumping light. When pumping the ^{4}He metastable atoms with D_0 light from the YAP laser, dramatic changes in the fluorescence from the cell are observed. As shown in Fig. 4, at approximately 30 mW of incident D_0 light the resonantly scattered emission is reduced by 50%. At incident power levels above 100 mW the fluorescence, hence polarization,

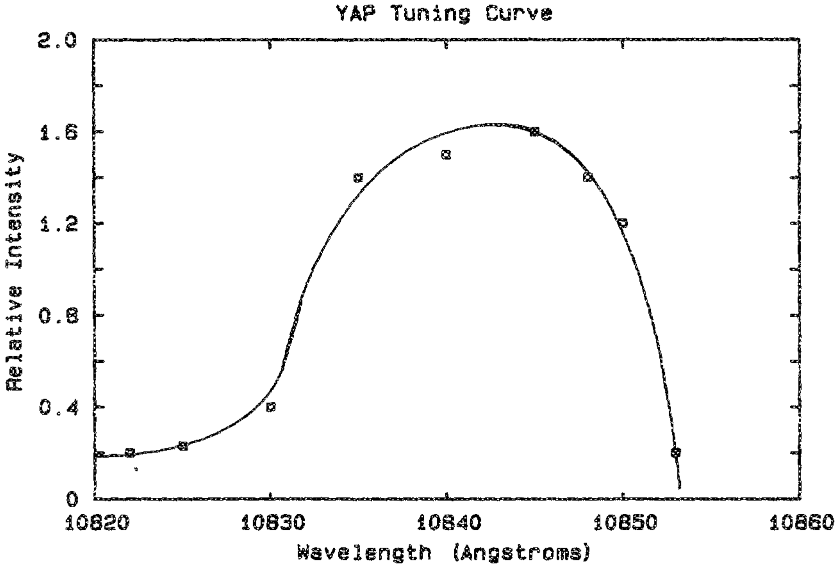

FIG. 3. Tuning curve obtained with the YAP laser. The Lyot filter suppresses the strong transition at 1079 nm and forces oscillation on the 1084-nm band. A single solid etalon is used to tilt tune through the range shown.

begins to saturate. Details of the pumping process to polarize the metastable atoms in a flowing helium afterglow using the YAP laser described here are given in Ref. 11.

Of perhaps more interest is the use of this YAP laser to orient the spins of the ^{3}He nucleus. With this laser we have routinely obtained ^{3}He nuclear polarizations in excess of 50% at densities of 10^{16} cm^{-3}, and importantly, production rates of 10^{16} polarized ^{3}He nuclei per second. We are then able to produce useful polarized targets for applications in nuclear physics.

The orientation of the nuclear spins following the optical pumping is also monitored optically using the polarization of the 688-nm helium line emitted by the discharge. This method of observation is described in detail in Ref. 12. The optical method used here has been calibrated also by direct nuclear magnetic resonance (NMR) observations. Figure 5 shows the buildup of the nuclear polarization as a function of time when the laser light is directed onto the cell. The time constant for reaching the limit is a few minutes. In the case of Fig. 5, the laser was tuned to the C_8-C_9 components; the laser power incident on the cell was about 200 mW. One could

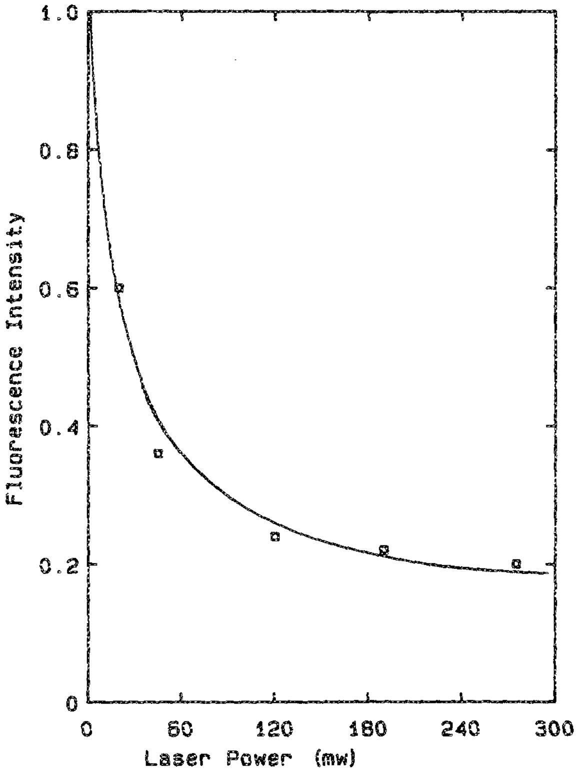

FIG. 4. Fluorescence intensity from an optically pumped discharge excited He-4 cell as a function of the YAP laser power output. The laser emission is circularly polarized at the $D0$ helium transition.

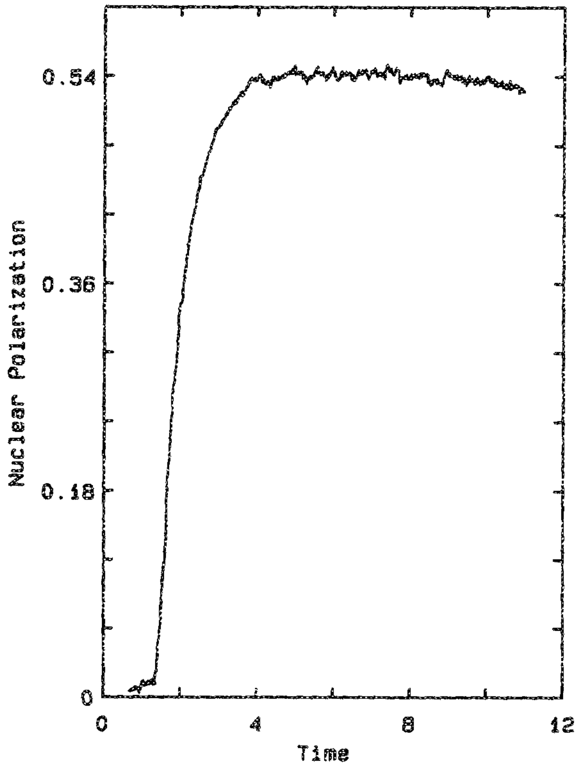

FIG. 5. Polarization of the nuclear spins in ^{3}He target cell when optically pumped by circularly polarized laser light on the C_8-C_9 helium transition as a function of time. The cell volume is 65 cm^3 at a pressure of 0.3 Torr.

also tune the laser approximately to the C_5 transition (2^3S_1, $F=\frac{3}{2}$ to 2^3P_1). Slightly greater power is available there but a lower polarization was obtained, partly because the broad laser emission line also excites other nearby components which are less efficient for optical pumping.

Substantial improvements are expected from reducing the laser bandwidth. Coated air gap and solid etalons and a Michelson interferometer have been successfully used to limit the bandwidth. Unfortunately, this has simultaneously resulted in a reduced tuning range. The difficulty is that the YAP laser, while operating at the helium resonance wavelengths, is operating very close to threshold and permits very little additional losses. However, the search for appropriate selective elements is in progress.

POLARIZED ^{3}He TARGETS

A number of fundamental measurements can be undertaken with a sufficiently dense ($\approx 5\times 10^{18}$ cm^{-3}), high polarization ($\approx$50%) target of ^{3}He. To the extent that the nucleons in ^{3}He are in a spatially symmetric S-state, its spin is due to the spin of the neutron with the two protons coupling to spin zero. Thus, if a polarized electron beam is scattered from a target of polarized ^{3}He, in this approximation the measured inclusive asymmetry essentially results from scattering from the neutron. In the quasielastic region,[13] for example, the asymmetry is directly proportional to the electric form factor of the neutron $G_E^n(Q^2)$, a fundamental quantity about which very little is known experimentally. In the deep-inelastic region it should similarly be possible to undertake measurements of the spin-dependent structure functions of the neutron.[14] A sum rule due to Bjorken[15] governs the difference of the proton and neutron structure functions and acts as a constraint on any model of the nucleon. There exists no experimental information on the deep-inelastic spin-dependent structure function of the neutron. A luminosity of 10^{33} cm^{-2} s^{-1} with 50% target polarization would make the measurement of the neutron electric formfactor feasible at existing facilities with 25-msr solid angle spectrometers. At future facilities, e.g., CEBAF, with more intense beams and large acceptance spectrometers, the accuracy would improve and the accessible kinematic range would widen for such an experiment.

With the original invention of the optical pumping method of polarizing ^{3}He by Colegrove, Schearer, and Walters,[3] there followed the development of targets of polarized ^{3}He for nuclear physics,[8] and many experiments[16] that utilized them. These targets used discharge lamps to optically pump ^{3}He and had densities of order 10^{17} cm^{-3} with polarizations of order 15%. This was the situation until the work of the Paris group in 1983.[17] They demonstrated that it was possible to use a laser to optically pump ^{3}He and thus obtained polarizations of 70%. In addition, they demonstrated the use of a cell at cryogenic temperatures in diffusive contact with the room-temperature cell, where the ^{3}He was polarized, to obtain densities of order 10^{18} cm^{-3} with 50% polarization. The figure of merit for asymmetry measurements in scattering experiments on polarized targets is $P^2\rho$, where P is the target polarization and ρ is the target density. Thus, if targets could be constructed using the laser-pumped double-cell system, improvements in the figure of merit of over two orders of magnitude could be expected. This realization prompted the Caltech group in 1985 to undertake an effort to investigate the feasibility of this idea.

A major concern in construction of a polarized target is the question of beam depolarization. This has been studied at Caltech using 3-MeV proton beams incident on a room-temperature single cell of ^{3}He, which was optically pumped by a discharge lamp. Beam currents of up to 1 μA were incident on densities of up to 4.5 Torr. The depolarization effects were found to be consistent with a model where depolarization occurs primarily through three-body collisional formation of $^3He_2^+$ followed by ambipolar diffusion to the wall.[18] Thus, for minimum ionizing electron beams, luminosities of 3×10^{32} cm^{-2} s^{-1} are quite attainable with polarization rates of order 10^{17} polarized ^{3}He per second. An effort is presently under way to construct a laser-pumped double-cell system, where the cold cell is made of copper and is kept at 77 K. This should result in a target of density 3×10^{18} cm^{-2} and polarization 40% able to sustain up to 40 μA of 1-GeV electrons.

An alternative method of scattering polarized electrons from a target of polarized ^{3}He is to use an internal target of density 2×10^{15} cm^{-2} of polarized ^{3}He in an electron storage ring with a stored current of 100 mA. This would provide a luminosity of 10^{33} cm^{-2} s^{-1} and, because of the low target densities, eliminate the beam depolarization problem. However, to date no storage ring has had longitudinally polarized beam capability, although the proposed pulse-stretcher-ring upgrade at Bates Laboratory at M.I.T. would have such a beam with an energy of 1 GeV. In addition, the HERA accelerator at Hamburg has plans for a 30-GeV longitudinally polarized beam in its electron stroage ring in the early 1990s, and this would be an excellent facility to perform the deep-inelastic measurements.

For the immediate future, prospects look good for targets of density 10^{19} cm^{-2} and polarization 40%. These should enable a measurement of the electric charge distribution of the neutron at low Q^2. In the longer term, internal targets of polarized ^{3}He in electron storage rings with longitudinally polarized electron capability, as well as intense linac beams with large acceptance spectrometers, should make possible better measurements of $G_E^n(Q^2)$, as well as the first measurements on the deep-inelastic structure function of the neutron.

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