

Polarizing ^3He nuclei with neodymium $\text{La}_{1-x}\text{Nd}_x\text{MgAl}_{11}\text{O}_{19}$ lasers

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Received December 12, 1986; accepted March 23, 1987

Optical pumping of helium, using the $2^3\text{S}-2^3\text{P}$ line at $1.083\ \mu\text{m}$, can be performed with a tunable neodymium laser [$\text{La}_{1-x}\text{Nd}_x\text{MgAl}_{11}\text{O}_{19}$ (LNA)]. The LNA crystal, longitudinally excited by an Ar^+ gas laser, delivers a usable power of about 300 mW. A ^3He cell at 0.3 Torr can thus nuclearly polarized up to 60%. Preliminary results are also obtained with a LNA laser pumped by discharge lamps.

Optical pumping is a convenient method used to polarize the 2^3S_1 metastable spin state of ^4He .¹ Applied to ^3He gas, it can result in large nuclear polarizations of the 1^1S_0 ground-state atoms.² The applications of spin-polarized helium atoms range over several fields of physics.^{3,4} They include the ^4He and now ^3He magnetometers, which can be used to measure the earth and the interplanetary magnetic field⁵; polarized beams of metastable helium atoms for the study of atomic collisions and to probe magnetic surfaces⁶; and polarized ^3He targets and beams in nuclear physics.⁷⁻⁹ Another application is the study of quantum properties of polarized ^3He fluids at low temperature, which are now being investigated.¹⁰

Optical pumping in helium requires a source of circularly polarized light at $1.083\ \mu\text{m}$, the wavelength of the $2^3\text{S}-2^3\text{P}$ transition of the helium atom. This has usually been achieved with helium discharge lamps, leading to nuclear polarizations of the order of 20%.¹¹ More recently, color-center lasers, using F_2^{+} centers in NaF (Refs. 12 and 13) and tuned to $1.083\ \mu\text{m}$, have produced much higher rates of ^3He optical pumping.¹⁴ However, the color-center-laser devices involve a cascade of three lasers (a Kr^+ laser, a dye laser, and a F_2^{+} laser¹³) and require colored crystals that must be operated at liquid-nitrogen temperature and replaced periodically. These difficulties led to a search for more convenient lasing elements.

We report here results of experiments performed to polarize ^3He gas with a laser making use of a crystal of $\text{La}_{1-x}\text{Nd}_x\text{MgAl}_{11}\text{O}_{19}$ (LNA), operating on the $^4\text{F}_{3/2}-^4\text{I}_{11/2}$ transition of the Nd^{3+} ions. Details of the properties and production of LNA crystals have been given in earlier publications.^{15,16} Recently it was shown that LNA lasers when end pumped by a cw Ar^+ or a cw Kr^+ gas laser^{17,18} and can be tuned around several peaks of the Nd^{3+} fluorescence,¹⁸ including the $1.083\text{-}\mu\text{m}$ wavelength. In the laser that we now describe, the active element is a cylinder cut from a single crystal of LNA, 1 cm long and 5 mm in diameter; the rod axis coincides with the hexagonal, or *c*, axis of the crystal. The ends are polished perpendicular to the cylinder axis and antireflection coated. It is situated at the center of a 80-cm-long cavity defined by two plane multiple dielectric mirrors (see Fig. 1). This crystal absorbs 70% of the incident light.

Mirror M_1 is fully reflecting for the laser radiation at $1.08\ \mu\text{m}$ and (partially) transparent for the pumping radiation. Output mirror M_2 is 90% reflecting for the laser radiation. A 10-cm focal-length converging lens L_1 focuses the pumping beam onto the LNA crystal with a beam waist of the order of $20\ \mu\text{m}$. L_2 is a 2.5-cm focal-length lens. In such a cavity, the laser beam waist at the crystal is approximately of the same size as the pump beam waist. These conditions were found to optimize the laser efficiency. The strongest fluorescence of LNA is at a wavelength of $1.054\ \mu\text{m}$, with a weaker fluorescence band peaking at $1.084\ \mu\text{m}$. This allowed us to tune the laser to $1.083\ \mu\text{m}$.¹⁸ In the case shown in Fig. 1 the tuning is accomplished by a single-plate Lyot filter *F* (a 7-mm quartz plate) and the fine tuning by an air-gap étalon *E*. Étalon *E* is made up of two prisms inserted at the Brewster angle in the laser beam; the coated faces are 50% reflecting and 2 or 3 mm apart; one half of étalon *E* is mounted on a piezoceramic, which permits servo locking of the air gap on an external signal.¹⁹ From pumping with 6 W of the 541-nm argon light on the crystal, an output power of 600 mW is obtained at $1.054\ \text{nm}$ and over 300 mW at $1.083\ \text{nm}$. When the beam waist at the crystals is exactly at the center of the M_1M_2 cavity (the required precision is $\pm 2\ \text{mm}$), the mode structure is composed of two longitudinal modes separated by some 200 MHz (in such a design, the spacing between successive cavity modes corresponds to the spatial-hole-burning interval). The cavity length of 80 cm was chosen so that the spread of the modes is within the room-temperature Doppler width of the ^3He absorbing atoms.

The fluorescence of a ^3He cell can be excited by such an LNA laser. The laser frequency is swept by varying the high voltage of piezo-mounted étalon *E*. Some of the nine fine and hyperfine components of the $2^3\text{S}_1-2^3\text{P}_{0,1,2}$ transition are resolved, such as the C_8 and C_9 ones (respectively, $2^3\text{S}_1, F = 3/2 \rightarrow 2^3\text{P}_0$ and $2^3\text{S}_1, F = 1/2 \rightarrow 2^3\text{P}_0$).²⁰ The width of these peaks is approximately 2 GHz; it results from the Doppler absorption width of the atoms and not from the laser. Such fluorescence signals can be used to servo lock the laser on the atomic frequency by applying a low-frequency small modulation to the piezo high voltage. Once locked on a given atomic component, the laser frequency remains stable for hours without requiring readjustment.

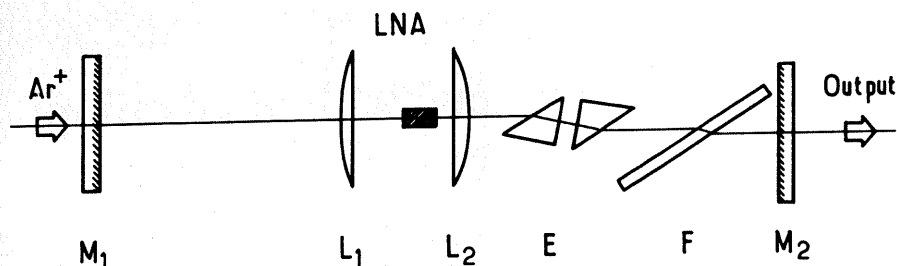


Fig. 1. Sketch of the LNA laser cavity (not to scale). M_1 is a dichroic plane mirror transmitting the pump light from an Ar^+ laser. M_1 is totally reflecting to the LNA laser radiation; M_2 transmits 10%. L_1 and L_2 are lenses (antireflection coated) with focal lengths of 10 and 2.5 cm, respectively. F is a single-plate birefringent Lyot filter, and E is an air-gap piezo-tuned étalon. The LNA crystal is 1 cm long.

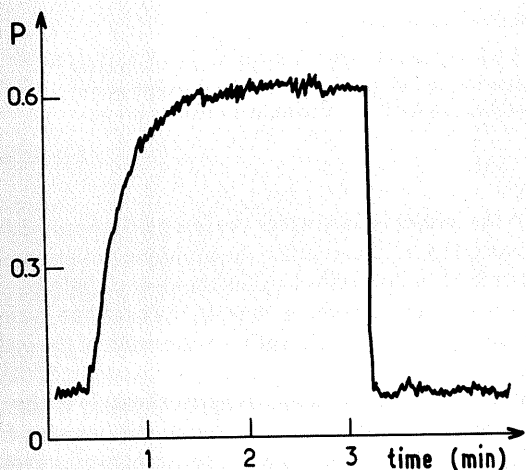


Fig. 2. Buildup of the nuclear polarization P of 3He gas when the laser is directed onto the cell; after reaching its limiting value, it was destroyed by a strong magnetic-field gradient.

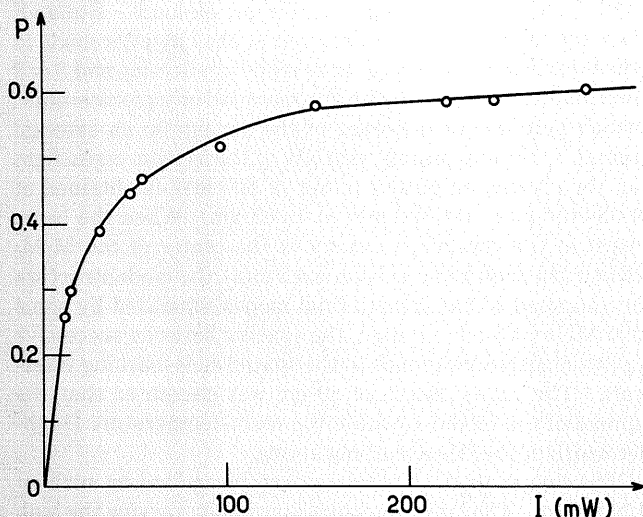


Fig. 3. Nuclear polarization P of 3He gas at 0.3 Torr, as a function of the intensity I of the LNA laser light incident upon the helium cell.

Using the output of this LNA laser, we have polarized 3He in a cylindrical glass cell of about 100-cm^3 capacity at a pressure of 0.3 Torr. A mirror is placed beneath the cell to reflect back the nonabsorbed pumping light. The laser beam is expanded to cover the surface of the 3He cell. The laser output is linearly polarized by the action of the several surfaces at the Brewster angle inside the cavity. The linear

polarization is transformed into circular polarization by a quartz quarter-wave plate external to the cavity. Great care is taken to keep the desired circular polarization above 95%.

A homogeneous magnetic field of a few gauss is applied to the cell parallel to the laser beam in order to provide an axis for the optical-pumping process. The orientation of the 3He nuclear spins is monitored by observing the circular polarization of the 668-nm helium line emitted by the discharge that is used to excite the helium gas.²¹ Figure 2 shows the buildup of the nuclear polarization when the laser is directed onto the cell; the limiting value is obtained after a few minutes; the polarization can be destroyed if necessary by a strong magnetic-field gradient. Figure 3 gives the nuclear orientation obtained as a function of the laser intensity incident upon the cell when the laser is tuned on the C_3 component. A similar curve is found for the laser on the C_9 component, with the difference that the resulting polarization is slightly lower at high laser intensity but higher at low intensity, as predicted by the model derived in Ref. 20 for 3He optical pumping. The maximum polarization obtained is 60% for 300-mW output from this LNA laser. The curve of Fig. 3 compares well with the similar one previously obtained with a color-center laser.¹⁴ At high laser power, the results reported in Ref. 14 are 10% better than the present ones; this can be explained by the slightly different mode structure of the laser in the two cases.

Some effort was made in order to operate a LNA laser pumped by arc lamps at the helium wavelength. The advantages for most applications would be the low cost and the potentially high output of this YAG-type laser. The main problem is the crystal growth of long LNA rods of sufficient optical quality; such difficulties are now partially solved at the Laboratoire d'Electronique et de Technologie de l'Informatique (LETI) in Grenoble.²² Recent results have been obtained with a 5-cm-long, 5-mm-diameter LNA crystal cut along its a axis. Pumped by two Kr^+ lamps in a YAG 904 Microcontrolle cavity, it can deliver a few watts of power on the main fluorescence peak, and it can be tuned to $1.083\ \mu\text{m}$ with a Lyot filter and a thin étalon. These results are promising but still preliminary.

Let us finally mention that LNA crystals can also be pumped by diode lasers, providing a weak-intensity but low-voltage source for some pumped helium applications, as reported elsewhere.²³

ACKNOWLEDGMENTS

The authors thank the group at LETI (see Ref. 22) for providing them with the LNA crystals grown in their labora-

tory. They also express their appreciation to F. Laloe at the Ecole Normale Supérieure for his continued interest and many stimulating conversations. They acknowledge the interest of NATO in this work.

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REFERENCES AND NOTES

1. L. D. Schearer, *Advances in Quantum Electronics*, J. R. Singer, ed. (Columbia U. Press, New York, 1961), p. 239.
2. F. D. Colegrove, L. D. Schearer and G. K. Walters, *Phys. Rev.* **132**, 2561 (1963).
3. D. S. Betts and M. Leduc, *Ann. Phys.* **11**, 267 (1986).
4. L. D. Schearer, *Ann. Phys.* **10**, 845 (1985).
5. L. D. Schearer, *Rev. Sci. Instrum.* **32**, 1190 (1961).
6. M. Onellion, M. W. Hart, F. B. Dunning, and G. K. Walters, *Phys. Rev. Lett.* **52**, 380 (1984).
7. G. C. Philips, R. R. Perry, P. M. Windham, G. K. Walters, L. D. Schearer, and F. D. Colegrove, *Phys. Rev. Lett.* **9**, 502 (1962).
8. S. D. Baker, E. B. Carter, D. O. Findley, L. L. Hatfield, G. C. Philips, N. D. Stockwell, and G. K. Walters, *Phys. Rev. Lett.* **20**, 738 (1968).
9. Workshop on polarized ^3He beams and targets, Princeton, N.J., 1984; AIP Conf. Proc. **131** (1985).
10. C. Lhuillier and F. Laloe, *J. Phys. (Paris)* **41**, C7, 51 (1980).
11. R. S. Timsit and J. M. Daniels, *Can. J. Phys.* **49**, 545 (1971).
12. L. F. Mollenauer, *Opt. Lett.* **5**, 188 (1980).
13. G. Trenec, P. J. Nacher, and M. Leduc, *Opt. Commun.* **43**, 37 (1982).
14. P. J. Nacher, M. Leduc, G. Trenec, and F. Laloe, *J. Phys. Lett.* **43**, L-525 (1982).
15. Kh. Bagdasarov, L. M. Dorozhkin, A. M. Kevorkov, Yu. I. Krasilov, A. V. Potemkin, A. V. Shestakov, and I. I. Kuratev, *Sov. J. Quantum Electron.* **13**, 639, (1983); Kh. Bagdasarov, L. M. Dorozhkin, L. A. Ermakova, A. M. Kevorkov, Yu. I. Krasilov, A. V. Potemkin, L. N. Ralskaya, P. A. Tseitlin, and A. V. Shestakov, *Sov. J. Quantum Electron.* **13**, 1082 (1983).
16. F. Laville and A. M. Lejus, *J. Cryst. Growth* **63**, 426 (1983).
17. D. Vivien, A. M. Lejus, J. Thery, R. Collongues, J. J. Aubert, R. Montcorge, and F. Auzel, *C. R. Acad. Sci. Paris* **298**, 195 (1984).
18. L. D. Schearer, M. Leduc, D. Vivien, A. M. Lejus, and J. Thery, *IEEE J. Quantum Electron.* **QE-22**, 713 (1986).
19. F. Biraben, *Opt. Commun.* **29**, 353 (1979); F. Biraben and P. Labastie, *Opt. Commun.* **41**, 49 (1982).
20. P. J. Nacher and M. Leduc, *J. Phys. (Paris)* **46**, 2057 (1985).
21. M. Pinard and J. van der Linde, *Can. J. Phys.* **52**, 1615 (1974).
22. J. J. Aubert, Laboratoire d'Electronique et de Technologie de l'Informatique, F38044 Grenoble Cedex, France (personal communication).
23. J. Hamel, A. Cassimi, H. Abu-Safia, M. Leduc, and L. D. Schearer, *Opt. Commun.* (to be published).