Laser-Induced Change in Nuclear Reaction Rate: $^6Li(\alpha,\gamma)^{10}B$

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Laser-polarized lithium vapor with density 10^{14} cm^{-2} in a differentially pumped cell was developed and used as a target in the nuclear fusion reaction $^6Li(\alpha,\gamma)^{10}B$. A large change (25%) in reaction cross section relative to an unpolarized target was observed.

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Optically pumped atomic vapors have been proposed as polarized targets for enhancing nuclear reaction rates in thermonuclear fusion reactors,[1,2] for polarization-sensitive nuclear-reaction studies in high-energy storage rings,[3] and for study of parity nonconservation in the strong interaction.[4] Previous experiments have inferred nuclear polarization from atomic (optical) measurements.[5,6] In this Letter, we report the first use of an optically pumped target in a nuclear reaction, α fusion with ^{6}Li. A large change (25%) in reaction cross section relative to an unpolarized target was observed. Prospects for the use of this target to study parity nonconservation in the strong interaction are also considered.

The specific experiment is motivated by the possibility of our determining the parity-nonconserving admixture of the 2^+, $T=1$, 5.116-MeV and the 2^-, $T=0$, 5.112-MeV levels of ^{10}B by measuring the vector analyzing power of the fusion reaction, using polarized ^{6}Li. Calculations based on the Weinberg-Salam model of the weak interaction yield an asymmetry,

$$A=(N_\uparrow-N_\downarrow)/(N_\uparrow+N_\downarrow)\simeq -3\times 10^{-4}, \quad (1)$$

where $N_{\uparrow(\downarrow)}$ is the $^{10}B(2^+)$ γ-ray yield for ^{6}Li polarized parallel (antiparallel) to the α beam.[7] This reaction is particularly well suited for use of a polarized vapor target as the isospin-forbidden-reaction resonance total width (at 1176 keV, laboratory) is so narrow (3 eV) that the "thick target yield" is obtained when the beam energy loss in the target exceeds the beam energy spread.

Lithium *atoms* are polarized by the irradiation of the vapor with circularly polarized laser light at the central frequency of the $2s_{1/2}$-$2p_{1/2}$ (D_1) atomic resonance near 670.8 nm (see Fig. 1). Successive cycles of absorption for which $\Delta M_F=+1$, followed by spontaneous or collision-induced decay for which $\Delta M_F=\pm 1$ or 0, result in transfer of population to the $F=\frac{3}{2}$, $M_F=\frac{3}{2}$ state of the ground level, corresponding to high *nuclear* and electronic polarization.

Several Torrs of a molecular buffer gas are required to achieve high polarization of the optically thick ($Nl \gtrsim 10^{12}$ cm^{-2}) sample for several reasons[8]: (i) Collisions with buffer-gas molecules randomize the velocity distribution of the Li atoms, making it possible for all atoms to interact with the single-frequency laser light. (ii) Because of the randomization of velocity, the dwell time of the Li atoms in the laser beam is increased. (iii) Polarization of optically thick samples is usually limited by the reabsorption by polarized atoms of fluorescence light of the wrong polarization from other radiatively decaying atoms (resonance trapping). In many experiments with high-density polarized alkalis, the resonance trapping problem is mitigated with use of high-pressure nitrogen.[9] Quenching collisions, resulting in transfer of excitation energy from the alkali-metal atom to the nitrogen molecule, enable the alkali to deexcite nonradiatively, greatly reducing the depolarizing effect. For a lithium nuclear target, however, high-pressure nitrogen would be unacceptable because of chemical reactivity and high stopping power for the megaelectronvolt energy α-particle beam.

Molecular hydrogen was determined to be the best choice for a buffer gas. It is an efficient quencher, does not react quickly with Li vapor at $\simeq$600 °C, and has a low stopping power for the α beam (minimizing the reduction in nuclear reaction yield due to dilution of the Li target). The minimum required pressure is a complicated function of laser power, geometry, and collision rates. Under our experimental conditions 5 to 10 Torr was empirically determined to be optimal.

Prior to the nuclear-reaction measurements, the atomic properties of the target were characterized by a two-laser pump-probe experiment. A strong (up to 500 mW) circularly polarized beam was used to produce the polarization; a weak ($\simeq 1$ μW) circularly polarized "probe" beam was frequency scanned across the D_1 and D_2 resonances to measure the vapor's absorption. The total ^{6}Li

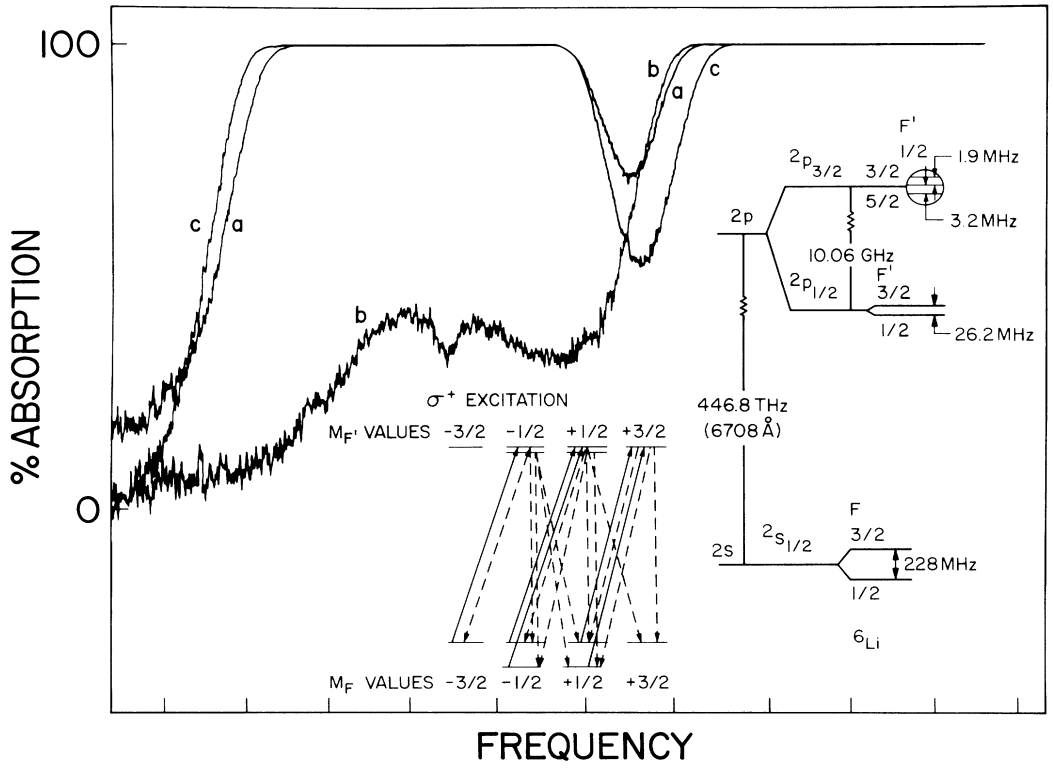

FIG. 1. Absorption of low-power probe laser through cell at 10-Torr H_2 pressure, 10^{14} ^{6}Li cm^{-2} with 400-mW counterpropagating circularly polarized pumping laser: *a*, pump beam blocked; *b*, probe beam circularly polarized same sense as pump beam; *c*, probe opposite polarization to pump. Inset: Fine and hyperfine structure and the optical pumping scheme for the 670.8-nm $D_{1,2}$ resonance transitions.

density is determined by fitting the absorption curve (with the strong beam absent) to a theoretical line shape.[10] The change in apparent density when the fixed frequency strong beam is present is due to the enhanced population of the $(F=\frac{3}{2}, M_F=\frac{3}{2})$ level. The laser-induced polarization P_z^e is defined as the percentage of ^{6}Li atoms in the $(\frac{3}{2},\frac{3}{2})$ level. The corresponding nuclear vector polarization is the fraction of nuclei in the $(I=1, M_I=1)$ level.

A sample of the data appears in Fig. 1 which shows optical pumping of a Li vapor of density 1×10^{14} cm^{-2} in 10 Torr of H_2. The reduced absorption on the D_1 line and increased absorption on the D_2 line with pump and probe beams having the same polarization is evidence of large atomic polarization. However, the data also show, at higher pump power, that the absorption on the D_2 resonance begins to decrease, implying that the total density of the absorbing Li atoms in the cell has also decreased. We ascribe this effect to the photoactivation of the reaction $Li+H_2 \rightarrow LiH+H$, via excitation of the Li atom to the $2p$ state.[11] A comparison of curves *a* and *b* shows a reduction in absorption on the D_1 due to optical pumping. Curve *c*, with the sense of relative circular polarization of the pump and probe reversed, shows the D_1 absorption enhanced, confirming strong polarization. Detailed analysis of these curves indicates that, although the polarization of the atoms is close to $P_z^e=0.9$, the pump has caused the Li atomic density to be reduced by almost 50%, presumably because of the formation of LiH molecules in which the Li *nucleus* is likely unpolarized. The use of He as the buffer gas eliminates the chemical reactivity problem, but resonance trapping effects limited the Li density which could be efficiently pumped to $\lesssim 5\times10^{12}$ cm^{-2}.

The polarization dependence of the ^{6}Li$(\alpha,\gamma)^{10}$B(5.166 MeV,2^+) reaction cross section may be written

$$\sigma=\sigma_0(1+\tfrac{1}{2}Pzz-\epsilon RPz), \qquad (2)$$

where P_z and P_{zz} are the vector and tensor polarizations of the ^{6}Li nuclei, respectively, $\epsilon=\langle 2^+|V_{PNC}|2^-\rangle/\Delta E(2^+,2^-)$ is the parity-nonconserving admixture of the 2^+ and 2^- states, and R is an "enhancement factor" because the primary reaction through the 2^+ state is isospin forbidden.[7] While the vector analyzing power $\epsilon R\simeq 5\times10^{-4}$, is the quantity of interest in the parity-nonconservation experiment, Eq. (2) shows a much larger dependence on the cross section via the tensor polarization. In this initial experiment, use was made of the tensor analyzing power to probe the ^{6}Li *nuclear* po-

larization, complementing the measurements of *electronic* polarization made optically.

The experiment was set up at the Rutgers University 2-MV Van de Graaff accelerator. Circularly polarized laser light from a ring-dye laser was sent through the lithium vapor target antiparallel to the particle beam. The α beam was accelerated to the resonance energy (1176-keV+40-keV energy loss in 5 Torr of hydrogen buffer gas) and then magnetically analyzed with a 17° bending magnet and a set of slits 2 m downstream. A feedback loop, based on the slip currents, regulated the terminal voltage and beam energy spread to $\simeq \pm 700$ eV about the set point determined by the magnet NMR setting. A quadrupole lens near the analyzing slits brought the ion beam to a tight focus of diameter <1 mm, at the entrance to the vapor cell 2 m farther downstream. Such tight collimation was essential to the reduction of "thick target yield" due to the α beam striking any surfaces coated with (unpolarized) ^{6}Li in the vicinity of the vapor cell. Between the quadrupole lens and the vapor cell the beam passed through a differential pumping system before passing through a 2-mm-diam aperture on the end of a 5-cm-long, tapered, differentially pumped canal. This canal was electrically heated to $\simeq 800$ °C to keep it clear of lithium. The α beam transmitted through the cell was typically 20–30 particle μA. The beam current was determined calorimetrically by the deflection of the beam to the sensor of a laser power meter. This beam deflection was necessary to protect the laser beam entrance window from particle beam damage.

The nuclear resonance was monitored via the γ cascade from the ^{10}B(2^+) level, see Fig. 2, with use of two 5×5-in.^{2} NaI(Tl) detectors encased in 2 in. of lead. Careful design of the vapor cell, surrounding insulation, and heat shield resulted in a source of detector distance of only 1.5 in., yet with negligible attenuation of γ rays of energy >0.5 MeV, and providing complete thermal isolation of the detectors from the cell. The 2-in. lead shield resulted in a room γ-ray background reduction by a factor of 10.

Operation of the cell at 610 °C ($Nl \simeq 10^{15}$ cm^{-2}) and with low buffer-gas pressure, 1 Torr He, yielded γ-ray spectra and excitation curves with good statistics. However, in order to achieve good polarization of the Li vapor, it was necessary to use a buffer gas of 5 Torr of H_2 and operate the cell at 540 °C. Even at this temperature, at which the density was 6×10^{13} cm^{-2}, the circularly polarized pump beam (200 mW) was almost totally absorbed. Under these conditions the resonance count rate was only a small fraction of the room background. For the entire γ spectrum the resonance count rate was 0.7 sec^{-1} on a background of 30 sec^{-1}; for the portion of the γ spectrum above the ^{208}Tl(2.61 MeV) room background line, the yield was 0.15 sec^{-1} on a background of 1.0 sec^{-1}. Of the background, approximately 20% was determined to be accelerator produced.

The nuclear resonance in the $2.85 < E_\gamma < 5.35$ MeV part of the spectrum, obtained with an optically pumped vapor, is shown in Fig. 3. The corresponding laser-induced alignment signal, defined as $[N(\text{on}) - N(\text{off})]/$

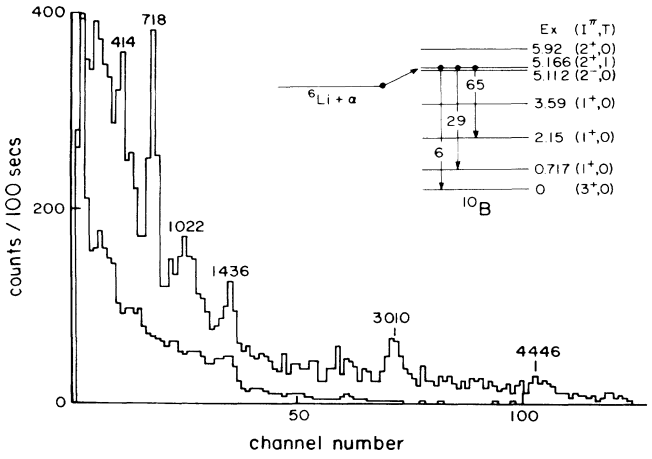

FIG. 2. γ-ray spectrum obtained in two 5×5-in.^{2} NaI(Tl) detectors from the lithium vapor target at 610 °C in 1 Torr He. Inset: ^{10}B nuclear energy levels illustrating fusion to and decay of the 5.166-MeV 2^+ state.

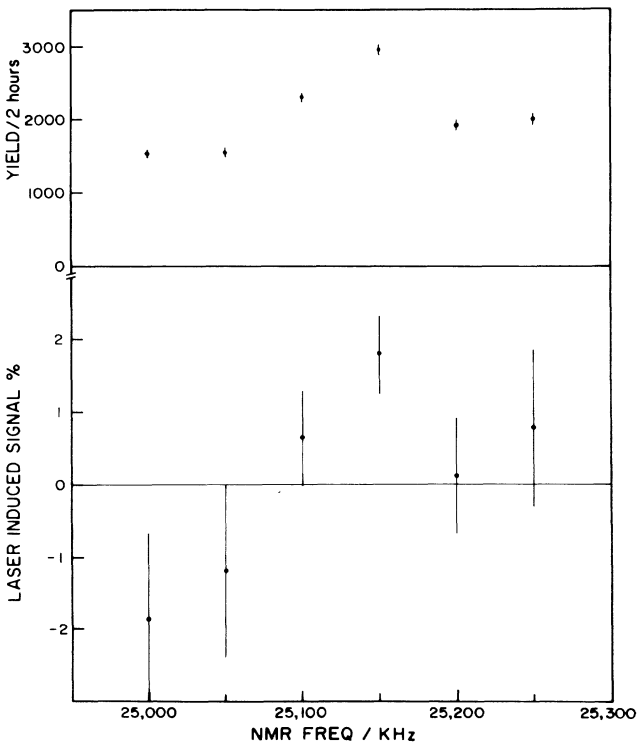

FIG. 3. (Top) Nuclear resonance for γ rays from 2.85 to 5.35 MeV obtained in the optically pumped ^{6}Li vapor target. (Bottom) Laser-induced alignment signal corresponding to the γ-ray yield resonance.

$[N(\text{on})+N(\text{off})]$, where $N(\text{on})$ and $N(\text{off})$ are the total counts recorded with the laser on and off, respectively, is also shown. From these data, and from similar data obtained with different cuts of the γ spectrum, the ^{6}Li nuclear alignment in the ^{6}Li vapor probed by the α beam was determined to be $P_{zz}=0.5\pm0.2$.

On the basis of a realistic "two-component" model, i.e., that the sample consists of a mixture of totally polarized and unpolarized components, we have $P_z=P_{zz}=0.5\pm0.2$. The observed P_{zz} is consistent with the previous optical measurements of electronic polarization of the Li atomic vapor, which gave $P_z^e=0.9\pm0.05$, together with the assumption that under these conditions, approximately 30% of the ^{6}Li is in the form of (unpolarized) LiH. Our nuclear measurements were not sensitive enough to determine if the presence of the high-current-density α beam itself produced depolarization. However, a significant increase in pump-beam absorption on admitting the α beam was observed. Since the absorption of a weak beam (without the pump) remained unchanged because of the α beam, the inference is that some depolarization due to the presence of the charged particle beam does occur.

These results demonstrate high nuclear polarization in an optically pumped target at densities sufficiently high for nuclear-reaction studies. The parity-nonconservation experiment in ^{10}B is now possible at a dedicated accelerator, over several months, with improvements in count rate. An immediate order-of-magnitude improvement is possible with higher-efficiency γ detection (and enhanced background suppression) and higher beam current. A major potential improvement, requiring technological development, would be a material enabling many wall collisions without depolarization,[12] i.e., allowing the wall to play the role of buffer gas. This would narrow the nuclear resonance and allow a significantly higher effective target density. Similar targets could be used for higher-cross-section studies in electron, proton, or heavy-ion storage rings.

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