tions of energy-integrated cross sections. As obviously expected, from Fig. 1, the angular distributions are well fitted except for the reaction (^{20}Ne, ^{16}O) at forward angles.

Since this discrepancy in the ^{20}Ne-induced reaction exists only in the forward angles and rapidly disappears at backward angles, it may be reasonably conjectured that the origin of this anomalous part of the cross section corresponds to the direct breakup of the projectile. The fact that the ^{20}Ne nucleus is one of the most α-like nuclei seems to enhance the argument. It should also be noted that in the present theoretical treatment the breakup process was excluded because of the use of a form factor corresponding to the α particle confined to the surface region, as previously explored in Refs. 2–4. By relaxing this restriction, the theory can be extended to include the contributions of such a breakup process, and a study of this is now under way.

It was mentioned above that these reactions are initiated from different cluster modes in the projectiles with $L_\alpha = 0$, 2, and 4, respectively, for ^{20}Ne, ^{13}C, and ^{14}N. Detailed examination of the analysis showed that the transition strength strongly depends on these L_α values—especially their magnetic substates—as is reflected by a subtle difference in the shapes of the spectra of these reactions: For instance, had we chosen $L_\alpha = 2$ for ^{14}N, we would have obtained poorer fits to the data for the spectra of the reaction (^{14}N, ^{10}B).

In conclusion, despite the large energy losses involved, the continuum spectra presented here can be successfully interpreted as resulting from direct-transfer reactions. Note that the elastic scattering of the present collisions have their grazing angles at about 5° to 8°; thus all the observed spectra were taken much beyond the grazing angles. If a macroscopic model, such as that of Wilczynski,[6] had been used, an entirely different feature would have been predicted for the present reactions; the present approach, in terms of the direct-reaction theory, explains the experimental spectral shapes and angular distributions and provides a quantitative understanding. The discrepancy seen in the reaction (^{20}Ne, ^{16}O) analysis is not considered to be a drawback of the method. In fact, the possibility of extending the analysis to include the breakup process is an advantage which demonstrates the flexibility built into the method.

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[1] See review articles by W. U. Schröder and J. R. Huizenga, Ann. Rev. Nucl. Sci. 27, 465 (1977); N. Lefort and Ch. Ngo, Ann. Phys. (Paris) 3, 5 (1978).
[2] T. Udagawa, B. T. Kim, and T. Tamura, in Proceedings of the Institute of Physical and Chemical Research Symposium, Hakone, Japan, September 1979, edited by H. Kamitsubo and M. Ishihara (unpublished), p. 3.
[3] T. Udagawa, T. Tamura, and B. T. Kim, to be published.
[4] T. Udagawa and T. Tamura, Phys. Rev. Lett. 41, 1770 (1978), and references therein.
[5] M. Ichimura, A. Arima, E. C. Halbert, and T. Terasawa, Nucl. Phys. A204, 225 (1973); T. Tamura and T. Udagawa, Phys. Lett. 71B, 273 (1977).
[6] J. Wilczyński, Phys. Lett. 47B, 484 (1973).

Proposal for an Intense Polarized Li-Ion Source

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We propose to use optical pumping with a high-power dye laser to produce the polarized Li atoms necessary for a polarized Li ion source. It should be possible to produce very intense beams of highly polarized Li ions.

There are a variety of polarized-ion sources being used for nuclear-reaction experiments at the present time.[1] One of these is a polarized ^{6}Li$^-$ ion source that was developed at Heidelberg.[2] In that source thermal ^{6}Li atoms emerge from an oven through a Laval nozzle and after being polar-

ized by state selection in a hexapole magnet are subjected to rf transitions to increase the nuclear polarization. The ^{6}Li atoms are then ionized on a heated oxidized tungsten surface to form polarized $^6Li^+$ ions, which are extracted, focused, and passed through a K vapor target where some of the polarized $^6Li^+$ ions convert into polarized $^6Li^-$ ions. Both the ionizer and the K charge-exchange cell operate in a high magnetic field (i.e., $B > B_{crit}$). The Heidelberg polarized $^6Li^-$ ion source produces about 150 nA of current on target with a vector polarization $P_z > 0.52$.[2] Research on both polarized $^7Li^-$ and $^{23}Na^-$ ion sources is currently in progress.[2] The purpose of this paper is to demonstrate that by the use of optical pumping one can produce a very high flux of ^{6}Li atoms with almost completely polarized nuclei. This will enable one to produce a polarized $^6Li^-$ ion source that is both simpler and greatly superior to the Heidelberg source. Using optical pumping should also enable one to produce a high flux of polarized ^{7}Li atoms, ^{23}Na atoms, and other alkali atoms.

First we estimate the nuclear polarization expected using optical pumping. Figure 1(a) shows a schematic diagram of our proposed apparatus for producing optically pumped polarized Li atoms. Thermal Li atoms emerge from an oven through a Laval nozzle. The Li atoms travel from the nozzle to the hot oxidized-tungsten surface ionizer. In transit to the surface ionizer the beam of Li atoms is optically pumped with left curcularly polarized light from a cw dye laser at $\lambda = 6710$ Å, corresponding to the $2^2S_{1/2} \rightarrow (2^2P_{1/2}$ and $2^2P_{3/2})$ transitions in Li. A state-of-the-art commercial cw dye laser using Rhodamine 101 as a dye and pumped with a high-power Ar or Kr ion laser can produce 0.2–1.9 W of power at $\lambda = 6710$ Å with a bandwidth of $(1-4)\times 10^{10}$ Hz. The nuclear spin of ^{6}Li is 1, and the ground state of ^{6}Li is $2^2S_{1/2}$. Thus the hyperfine doublet in the ground state has $F = \frac{3}{2}$ or $F = \frac{1}{2}$, with six sublevels: $F = \frac{1}{2}$, $m_F = -\frac{1}{2}$; $F = \frac{1}{2}$, $m_F = \frac{1}{2}$; $F = \frac{3}{2}$, $m_F = -\frac{3}{2}$; $F = \frac{3}{2}$, $m_F = -\frac{1}{2}$; $F = \frac{3}{2}$, $m_F = \frac{1}{2}$; and $F = \frac{3}{2}$, $m_F = \frac{3}{2}$. We call these sublevels 1–6, respectively. The $2^2P_{1/2}$ and $2^2P_{3/2}$ levels in ^{6}Li are separated by 10^{10} Hz. The hyperfine doublet in the ground state of ^{6}Li is separated by about 2.3×10^8 Hz. These energy levels of ^{6}Li are shown in Fig. 1(b). The thermal Li atoms as they go from the nozzle to the surface ionizer may have a component of velocity parallel to the laser beam. We estimate that this leads to a Doppler broadening of the ^{6}Li absorption of 10^9 Hz. Thus a dye laser with a bandwidth of (2–4)

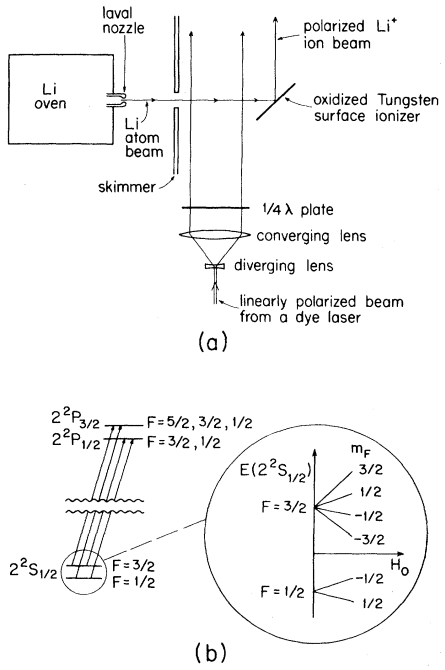

FIG. 1. (a) Schematic of an apparatus to produce a beam of optically pumped polarized Li atoms with a high flux at the surface ionizer. Although not shown, both the atom beam and the ionizer are in a magnetic field parallel to the laser beam in order to maintain the polarization of the Li atoms. The diameter of the laser beam is shown much larger than the hole in the skimmer for clarity. For most efficient pumping the laser beam should be located just behind the hole in the skimmer and with a diameter only slightly larger than the hole in the skimmer. The laser beam may be reflected back through the Li-atom beam one or more times to increase the duration of the optical pumping. (b) The relevant energy levels of ^{6}Li. The inset shows the energy of the sublevels of the $2^2S_{1/2}$ level of ^{6}Li in a weak magnetic field.

$\times 10^{10}$ Hz overlaps all the absorption due to the $2^2S_{1/2} \rightarrow (2^2P_{1/2}$ and $2^2P_{3/2})$ transition in ^{6}Li. We have calculated the occupation probability of each of the six ground-state sublevels as a function of the time during which ^{6}Li is optically pumped, as suming each of the sublevles is equally populated initially. Figure 2 shows the results of our calculations. Our calculations are similar to the calculations on the optical pumping of Na by Franzen and Emslie.[3] Franzen and Emslie treat the case where only the $3^2S_{1/2} \rightarrow 3^2P_{1/2}$ absorption line in Na is used for the optical pumping. For Li the $2^2P_{1/2}$ and $2^2P_{3/2}$ levels are separated by only 10^{10} Hz and one cannot obtain a high-power commercial dye laser with a bandwidth greater than the Doppler broadening of 10^9 Hz but less than 10^{10}

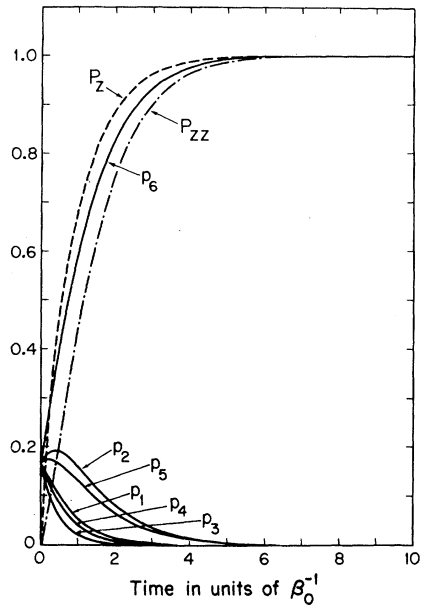

FIG. 2. The occupation probabilities p_i of the ground-state sublevels for a beam of optically pumped ^{6}Li atoms as a function of the time. The time is measured in units of β_0^{-1}. Also shown are the nuclear vector polarization P_z and the nuclear tensor polarization P_{zz} as a function of the pumping time. For our proposed source single-pass pumping times of $9\beta_0^{-1}$ are possible.

Hz. Thus one must use both the $2^2S_{1/2} \rightarrow 2^2P_{1/2}$ and $2^2S_{1/2} \rightarrow 2^2P_{3/2}$ lines for the optical pumping. For the case where both lines are used, substantial polarization of the Li atoms is produced provided there is no reorientation in the excited states. Because the Li atoms are in a vacuum and no collisions occur there is neither reorientation in the excited states nor relaxation in the ground state. Following Franzen and Emslie, the time scale is in units of β_0^{-1}, where β_0 is the average absorption probability per atom per unit time for unpolarized ^{6}Li atoms. The quantity β_0 is given by $\beta_0 = \int^\infty I_\nu \sigma_\nu d\nu$, where I_ν is the number of photons/(sec cm^2 Hz) in the laser beam and σ_ν is the absorption cross section for light of frequency ν by an unpolarized ^{6}Li atom.[4] Since the bandwidth of the dye laser is large compared to the absorption width of the ^{6}Li atoms, the expression for β_0 can be written as $\beta_0 = I_0 \int_0^\infty \sigma_\nu d\nu$, where I_0 is the value of I_ν at line center. It can be shown that $\int_0^\infty \sigma_\nu d\nu = \pi c r_0 f$ where c is the speed of light, r_0 is the classical radius of the electron, and f is the oscillator strength of the transition.[5] For the absorption by ^{6}Li of left circularly polarized light $f = 0.38$. Thus $\beta_0 = \pi c r_0 f I_0 = 1.00 \times 10^{-2} I_0$. If the dye laser used has a beam diameter of 0.56 cm and produces 400 mW of power at $\lambda = 6710$ Å with a bandwidth of 2×10^{10} Hz then $I_0 = 2.7 \times 10^8$ photons/(cm^2 sec Hz). Thus $\beta_0 = 2.7 \times 10^6$ sec^{-1}, or $\beta_0^{-1} = 3.7 \times 10^{-7}$ sec. The thermal ^{6}Li atoms have a most probable thermal velocity of about 1.7×10^5 cm/sec. The ^{6}Li atoms take about 3.3×10^{-6} sec to travel across the dye laser beam. Consequently the ^{6}Li atoms are optically pumped for a time[4] that is about $9\beta^{-1}$. Figure 2 shows that for a pumping time of $9\beta_0^{-1}$ virtually all the ^{6}Li atoms end up in sublevel 6 with $F = \frac{3}{2}$, $m_F = \frac{3}{2}$, and hence most of the nuclei have $m_I = 1$. The nuclear vector polarization $P_z = N_1 - N_{-1}$ and the second-order nuclear tensor polarization $P_{zz} = 1 - 3N_0$ both are near 1. In the expressions for P_z and P_{zz} the symbol N_{m_I} is the probability for the nuclear spin to have z component m_I. If the polarization of the laser beam is changed from left circularly polarized to right circularly polarized then almost all the ^{6}Li atoms can be pumped into the sublevel with $F = \frac{3}{2}$, $m_F = -\frac{3}{2}$, and with almost all the nuclei having $m_I = -1$.[6]

The situation for ^{7}Li is very similar. With currently available dye lasers the ^{7}Li atoms in a thermal beam can be optically pumped so that most of the nuclei have $m_I = \frac{3}{2}$.

We now estimate the ratio of the flux of Li atoms obtained using optical pumping to that obtained using a hexapole magnet for state selection. The acceptance solid angle of a hexapole magnetic for atoms in the correct spin state is $\Omega = 2.09 \mu H_m / kT$, where μ is the magnetic moment of the atom, H_m is the field strength at the pole tips, and kT is the thermal energy of the atoms. The acceptance solid angle for the Heidelberg source is $\Omega = 10^{-3}$ sr.[2] Of the atoms that emerge from the Li oven only $\frac{1}{2}$ of those in the solid angle Ω get through the magnet. The factor $\frac{1}{2}$ comes about since only $\frac{1}{2}$ the atoms are in the correct spin state to be focused toward the axis by the hexapole magnet. If the surface ionizer of our proposed apparatus has an area of 1 cm^2 (about the area of the ionizer in the Heidelberg source) and is located about 3 cm from the nozzle, then the solid angle for an atom to leave the nozzle and strike the surface ionizer is about $\Omega = 10^{-1}$ sr. Thus we expect that the number of polarized Li atoms per time per area at the location of the surface ionizer will be about 200 times larger using optical pumping than using a conventional hexapole magnet for state selection provided that the flux of Li atoms out of the Laval nozzle is the same in the two cases.[7]

In summary, the use of optical pumping to pro-

duce a beam of polarized Li atoms will result both in high nuclear polarization and in a very large flux of Li atoms. Thus optical pumping should enable one to produce a polarized Li ion source that is greatly superior to existing sources. We hope to construct a polarized Li source in the future. A high-flux beam of polarized Li atoms produced by optical pumping may have uses other than the production of polarized Li ions. For example, an optically pumped beam of polarized Li atoms may be useful for making a polarized Li target.[8] Optical pumping may also be useful for producing high-flux polarized beams of the other alkali atoms: Na, K, Rb, or Cs. Unfortunately at the present time there are no high-power tunable lasers that operate at the wavelength for the resonant absorption in H (1215 Å) so that an optically pumped source of polarized H atoms is not possible.

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[1]T. B. Clegg, in *Proceedings of the Fourth International Symposium on Polarization Phenomena in Nuclear Reactions*, edited by W. Grüebler and W. König (Birkhauser, Basel and Stuttgart, 1976), p. 111.

[2]E. Stephens, W. Dreves, H. Ebinhause, M. Kohne, F. Fiedler, P. Egelhol, G. Englehardt, D. Kassen, R. Shäfer, W. Weiss, and D. Fich, Nucl. Instrum. Methods 143, 409 (1977).

[3]W. Franzen and A. G. Emslie, Phys. Rev. 108, 1453 (1957).

[4]The lifetime of the 2^2P level in Li is 2.7×10^{-8} sec. Therefore even with nine photons absorbed in the time of transit across the laser beam the time the Li atom spends in the 2^2P level is small compared to the transit time. It can also be shown that both induced emission from the 2^2P level and imprisonment of the resonance radiation are unimportant for our source.

[5]W. Heitler, *The Quantum Theory of Radiation* (Oxford Univ. Press, New York, 1954), 3rd ed., p. 180.

[6]If the circular polarization of the light is changed from left to right circular polarization and then back again repeatedly, spending equal time with each circular polarization, the nuclei in the atom beam will have zero vector polarization on the average. Thus one can produce a $^6Li^-$ ion beam with a time-average $P_z = 0$ and $P_{zz} \simeq 1$.

[7]The optical pumping calculations presented assume that the absorption of the laser light is small. In order to estimate the maximum number of Li atoms per unit time that can be polarized it is necessary to consider the case where absorption is large. Allowing for absorption and using commercially available lasers we estimate that with existing dye lasers it is possible to polarize $5\times10^{15} - 1\times10^{17}$ atoms/sec. If one can obtain a dye laser with 400-mW power and a bandwidth of about 10^9 Hz (the Doppler width of the Li absorption) and centered at the wavelength for the $2^2S_{1/2} \rightarrow 2^2P_{1/2}$ absorption then we estimate that it is possible to polarize 2×10^{17} atoms/sec. If 10^{16} atoms/sec are ionized to form Li^+ the ion current is 1.6×10^{-3} A. With ion currents this large space-charge blowup of the beam may be a problem.

[8]Research on polarized ^6Li targets is in progress. See J. Ulbricht, F. Wittchow, U. Holm, K. D. Stahl, and H. Ebinhaus, in *Proceedings of the Fourth International Symposium on Polarization Phenomena in Nuclear Reactions*, edited by W. Grüebler and V. König (Birkhauser, Basel and Stuttgart, 1976), p. 875; also G. T. Garvey, private communication. Dr. Garvey and his associates are currently constructing a polarized Li target.