Laser Trapping of Short-Lived Radioactive Isotopes

Z-T. Lu, C. J. Bowers, S. J. Freedman, B. K. Fujikawa, J. L. Mortara, and S-Q. Shang
Department of Physics and Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

K. P. Coulter* and L. Young
Argonne National Laboratory, Argonne, Illinois 60439
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We describe an experiment which demonstrates the feasibility of trapping significant quantities of short-lived radioactive atoms with laser light. A thermal beam of 22.5 sec half-life ^{21}Na atoms was produced on-line at the LBL 88" Cyclotron. After decelerating the beam using a Zeeman-tuned slowing technique we stored about 4×10^3 ^{21}Na atoms in a magneto-optical trap. The number of trapped atoms is large enough to be used in experimental studies of the beta decay of ^{21}Na. The basic method can be adapted for other rare isotopes.

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The recently developed methods [1–3] for manipulating atoms with laser light have promising applications in several areas of science and technology. So far these techniques have only been used for stable isotopes, but adapting them to radioactive species would be extremely useful in several experiments with implications for nuclear and particle physics. For example, measurements in a series of isotopes of the mixing between opposite-parity atomic levels is recognized as a method for reducing the present systematic uncertainty in the Weinberg angle at low momentum transfer [4]. Implementing this program will require precision measurements with limited supplies of rare radioactive atoms. Trapped radioactive atoms are ideal for certain experimental tests of fundamental symmetries and searches for time-reversal-invariance breaking electric dipole moments. In beta-decay studies, systematic errors associated with source scattering could be completely eliminated and the recoiling daughter nucleus would be directly observable. Precisely characterized nuclear orientations should be achievable with traps. Trapped radioactive sources would enable beta-decay correlation measurements with unprecedented precision, leading to new tests of the fundamental weak interaction and searches for physics beyond the standard model [5]. Many of the methods already developed with stable atoms can obviously be applied to radioactive isotopes but there are significant new difficulties. The total number of atoms available for trapping is many orders of magnitude smaller than so far considered. For very short-lived atoms the experiment must be done on-line at the accelerator. Removing an adequate fraction of the limited number of reaction products from the target and then quickly transporting them to a high vacuum region where they can be captured and loaded into a trap is a significant challenge. To get adequate numbers of trapped atoms, losses must be minimized during each step of the process. Experiments to study the decay process itself are especially sensitive since atoms which are lost are potential sources of background. Despite the difficulties developing the appropriate tools for loading rare and exotic atoms into traps would provide new opportunities with great scientific potential.

This Letter reports the successful loading of a magneto-optical trap (MOT) [1] with ^{21}Na atoms produced on-line at the Lawrence Berkeley Laboratory 88" Cyclotron. Sodium-21 decays by positron emission to its mirror, ^{21}Ne, with a 22.5 sec half-life [6]. We selected ^{21}Na for the first experiments because some of the necessary techniques can be developed with experiments using stable isotope ^{23}Na [1,2] which has similar hyperfine levels. More importantly, the mirror beta decay of ^{21}Na is an interesting "laboratory" for studying the fundamental weak interaction. For example, an accurate measurement of the beta asymmetry can be utilized in a precision test of the $V-A$ structure of the weak interaction. The very short ^{21}Na lifetime makes this experiment particularly challenging, but a demonstration that ^{21}Na can be successfully trapped provides an optimistic assessment of the prospects for longer-lived isotopes.

About 800 mW of laser light is provided to the experiment with a Coherent model 899 ring dye laser pumped with a Coherent model Innova-300 argon-ion laser. The dye laser is stabilized to the D_2 line of ^{23}Na with a Doppler-free saturated-absorption reference signal. However, an acousto-optic modulator shifts the reference light frequency by about 1.6 GHz [7], compensating for the isotope shift between ^{23}Na and ^{21}Na. Tuning for the isotope shift is a delicate operation because the fluorescence from the small number of available ^{21}Na atoms is observable only if all components of the experiment are adjusted correctly and functioning properly. The MOT for ^{21}Na is designed to operate on the $F=2$ to $F'=3$ D_2 resonance transition. An electro-optic modulator provides a 15% intensity repumping sideband in order to optically pump ^{21}Na atoms out of the $F=1$ ground-state hyperfine sublevel. Two polarization preserving optical fibers carry laser light to the experimental area, near the end of the accelerator beam line, about 50 m away from the area where the lasers are operated. At the experiment, 120 mW is available for trapping and slowing of

the atomic beam, and 90 mW for transverse cooling.

Figure 1 shows the experimental arrangement. A ^{21}Na beam effuses from an oven under continuous proton bombardment. The atomic beam is collimated with transverse laser light [8], decelerated with a counterpropagating laser beam [2], and finally loaded into a magneto-optical trap. The ^{21}Na atomic beam production scheme is inspired by the one described in Ref. [9] but differs significantly in the implementation. A stainless steel oven is loaded with 0.5 g of natural magnesium in the form of file shavings. The oven is imbedded in a copper block which is heated from the back by an external power source. A 50 μm thick tungsten foil is pressure sealed to one side of the oven. Sodium-21 is produced with the ^{24}Mg$(p,\alpha)^{21}$Na reaction using a 200 nA, 25 MeV proton beam from the LBL 88″ Cyclotron. The proton beam stops in the oven and the energy averaged (p,α) cross section is about 100 mb. Atoms leave through a 1 mm diam 1 mm long cylindrical orifice. In equilibrium, the sodium vapor pressure is substantially higher than that of magnesium, about 4 torr compared to 6×10^{-2} torr at the typical operating temperature of 500 °C. Measurements of the time delay of the radioactive atoms following the start of irradiation indicate that the average dwell time for ^{21}Na in the oven is about 40 sec. While sodium escapes much more rapidly than magnesium, the number of ^{21}Na atoms produced is small and we estimate there is 10^9 times more magnesium than sodium in the atomic beam.

The ^{21}Na beam flux is quantitatively verified by stopping the beam on an aluminum flag and counting the number of positron annihilation photon coincidences with a pair of 3″×3″ NaI(Tl) detectors. Figure 2(a) shows a typical annihilation photon spectrum in one of the NaI(Tl) detectors. Figure 2(b) shows a typical decay spectrum of the coincidence rate after the atomic beam is blocked by an aluminum plate. The measured lifetime, 21.53 ± 0.56 (statistical error only), is roughly consistent with that of ^{21}Na, demonstrating that this is the principal positron emitting activity present. We estimate that $(5\text{–}10)\times10^6$ ^{21}Na atoms per sec are emitted from the oven under the typical operating conditions (proton beam current of 200 nA and oven temperature of 500 °C), assuming that all the ^{21}Na atoms stick, after hitting the aluminum flag.

Extremely low background pressures are essential for avoiding collisional losses in atom traps but the vacuum conditions near a heated oven under proton bombardment are usually poor. One benefit of trapping from an atomic beam is that the pressure in the trap region can easily be improved with differential pumping. A turbo-molecular pump maintains a pressure of 10^{-6} torr in the oven chamber. Two stages of differential pumping provided by two Varian 500 liter/sec ion pumps reduce the pressure to 4×10^{-10} torr in the region of the MOT.

The divergence of the ^{21}Na atomic beam is significant. To enhance the on-axis flux at the trap an orthogonal pair

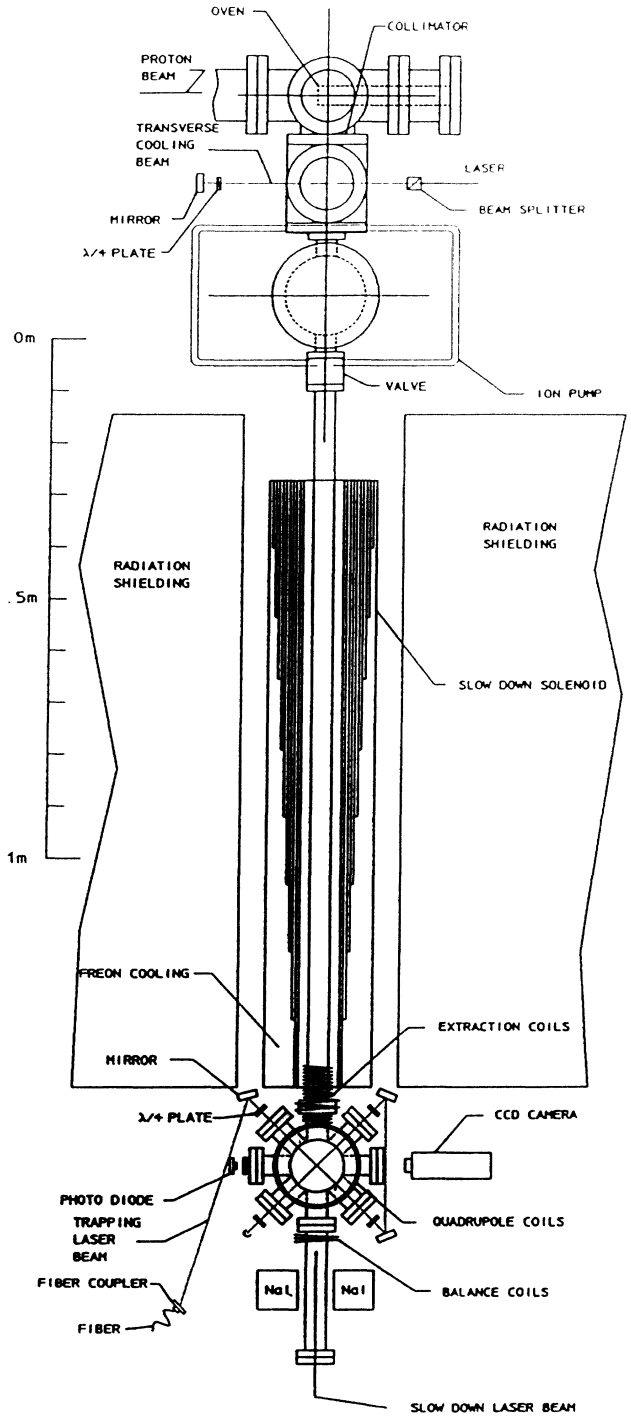

FIG. 1. Plan view of the apparatus for trapping ^{21}Na atoms at the end of the cyclotron beam line.

of counterpropagating laser beams cool the transverse energy spread of the atomic beam near the oven orifice [10]. Following this region, a 1.2 m long solenoid wound with a linearly decreasing number of coils provides a field which varies from 110 to 15 mT along the path of the beam. A counterpropagating σ^+ polarized laser beam, detuned to

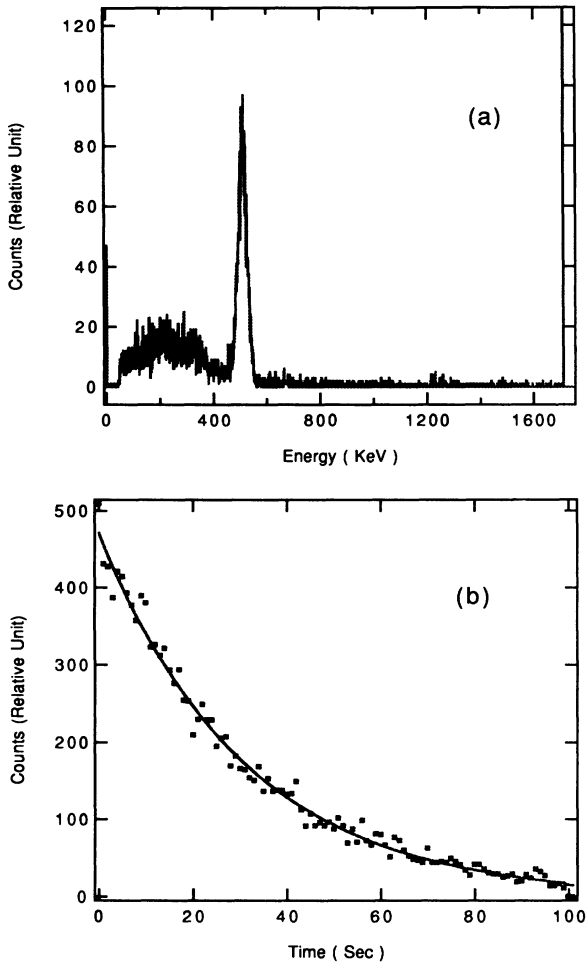

FIG. 2. (a) Spectrum of the energy deposited in one of the NaI(Tl) for coincident triggers. (b) Dead-time corrected coincidence count rate vs time shows the characteristic curve decay of ^{21}Na. The fitted half-life was 21.53 ± 0.56 sec (statistical error only) for this run.

the red by about 20 MHz from the zero-field $F=2$ to $F'=3$ transition, and focused onto the oven orifice, slows the atomic beam. The Zeeman shift in the decreasing magnetic field compensates for the variation of the Doppler shift as the atoms are slowed. To maximize the trap loading efficiency a set of critical "extraction coils" are located at the end of the solenoid [3]. The strategy for loading the trap is described in more detail in Ref. [10]. Briefly we stop the beam at the center of the magneto-optical trap with a rapid deceleration at the end of the path. Reducing the time spent when the longitudinal velocity is small minimizes the beam divergence caused by the transverse velocity components. The extraction coils are comprised of three separate solenoids; the currents are adjusted to ensure that the laser light induced slowing force is large in the last instant. This method yielded a 20% loading efficiency [10] for those atoms in the atomic beam that crossed the MOT region in an off-line experiment with a similar apparatus and

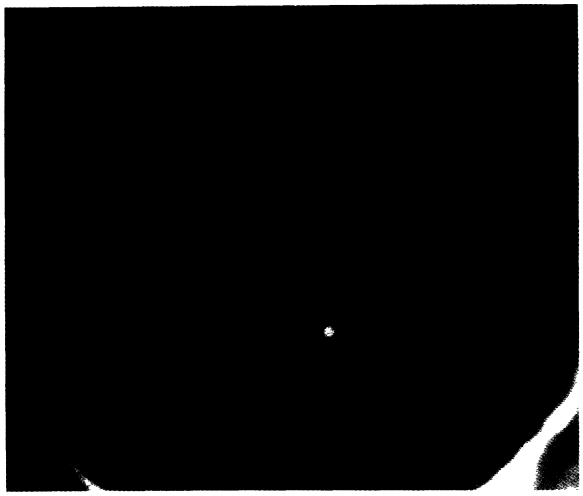

FIG. 3. One frame recorded by the CCD camera showing the optical fluorescence from the trap. The bright spot is due to trapped ^{21}Na atoms. The bright areas at the lower corners are due to scattered light.

stable sodium. The efficiency for the on-line apparatus, obtained from measurements with stable sodium, was lower, only about 4% to 5%. Measurements of the efficiency for the radioactive beam gave a somewhat lower value but the uncertainty is large. In any case, a lower capture efficiency is expected for ^{21}Na because the oven is run 300 °C hotter and a smaller fraction of atoms are slowed by the system. However, the principal limitation on capture efficiency at the cyclotron was the available laser light. This available laser intensity will be increased in future experiments by moving the lasers and eliminating the optical fibers.

The magnetic field coils for the MOT are 12 cm in diameter, separated by 6 cm. The field gradient is about 2 mT/cm. Three pairs of counterpropagating trapping beams are formed by a set of mirrors. The circularly polarized opposing pairs are obtained with $\frac{1}{4}$ wave plates and retroreflection mirrors. In operation there are seven laser beams passing through the trap region. Since the slowing beam has no counterpropagating partner, the laser beam intensities must be carefully adjusted to ensure stability.

The apparatus is aligned with a beam of ^{23}Na by simply loading the oven with natural sodium. Once ^{23}Na is efficiently trapped the light frequency is readjusted for the isotope shift and hyperfine spacing appropriate for ^{21}Na. The oven is reloaded with magnesium and exposed to the 25 MeV proton beam. The radioactive beam is adjusted by heating the oven while the ^{21}Na annihilation radiation is monitored as described above. The presence of trapped radioactive atoms is verified by observing the optical fluorescence emitted from the trap with a charged coupled device (CCD) camera shown in Fig. 1.

Figure 3 is a frame from the CCD camera showing the fluorescence of trapped ^{21}Na. Although the system was

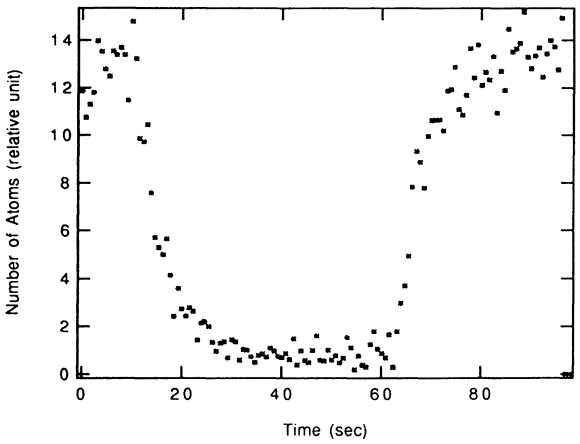

FIG. 4. Time spectrum of the optical fluorescence from trapped ^{21}Na atoms as the transverse cooling beams are turned off and on. The mean loading time is 5.5 sec and mean decay time is 5.3 sec.

not optimized we were able to load the trap with about 4×10^3 atoms, providing a clear fluorescence signal. Figure 4 shows the variation in the trap fluorescence as the transverse cooling laser beams are turned on and off. The fluorescence is approximately 16 times brighter when the transverse cooling beams are on. The mean lifetime of the trap is 5.3 ± 0.3 sec (6.3 sec after accounting for the ^{21}Na radioactive decay). The mean filling time is 5.4 ±0.5 sec. These times do not affect the loading efficiency as it is defined here. However, increasing the loading and decay time by improving the vacuum and reducing collisional losses from the magnesium in the atomic beam would significantly increase the number of atoms in the trap.

In summary, we have demonstrated that short-lived radioactive atoms can be efficiently loaded into a magneto-optical trap. The significant number of radioactive atoms trapped shows that the method of trapping from an atomic beam is very appropriate for on-line experiments at accelerators and our technique should prove useful in fundamental experiments in nuclear and particle physics. In principle ^{21}Na is not the first radioactive species that has been successfully loaded into a neutral atom trap. Rubidium-87 was trapped several years ago [11], but the half-life is extremely long, 5×10^{10} yr, making it a significant fraction of natural rubidium. This experiment demonstrates that it is possible to load traps efficiently enough to study very short-lived atoms. Our method is rather general and we are proceeding to investigate the range of applicability in experiments studying other radioactive species, particularly alkali isotopes.

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*Present address: University of Michigan, Ann Arbor, MI 48109.

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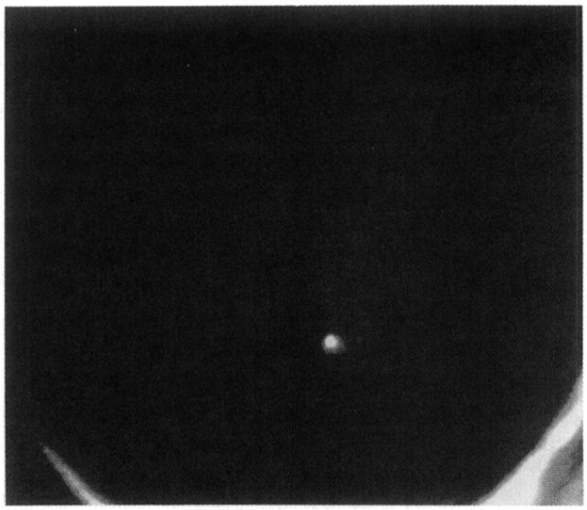

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