Magneto-optic Trapping of β-Decaying $^{38}K^m$, ^{37}K from an on-line Isotope Separator

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A magneto-optic trap (MOT) can provide a well-polarized, backing-free, localized source of radioactive atoms for β-decay experiments. We have trapped approximately 6000 atoms of $^{38}K^m$ ($t_{1/2} = 0.925$ s) and 2000 atoms of ^{37}K (1.226 s) produced at the TRIUMF on-line separator TISOL in a vapor-cell MOT. We have measured optical isotope shifts and deduced the nuclear charge radii, which show an unusual lack of change at the neutron number $N = 20$ shell closure. Plans include a search for scalar contributions to the β^+-ν correlation in the $0^+ \rightarrow 0^+$ decay of $^{38}K^m$. [S0031-9007(97)03637-5]

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The novel use of magneto-optically trapped radioactive atoms promises improvements in performing symmetry tests of the standard model. Optically trapped atoms are confined in a small volume in space (a few mm^3), have negligible source thickness, and can be optically pumped to achieve close to 100% atomic and nuclear polarization. These conditions are favorable for carrying out experiments to study weak interaction symmetries in β decay [1–3], and to measure isotopic dependence of parity nonconservation (PNC) in heavy atoms [2,4–6]. Here we measure nuclear properties of ground and isomeric states of the trapped atoms.

Among alkali atoms, which have simple electronic structure convenient for laser trapping, potassium isotopes offer rich opportunities for β-decay experiments. ^{37}K and $^{38}K^m$ each decay predominantly by a single superallowed transition. The β-ν correlation in a $I^\pi = 0^+ \rightarrow 0^+$ Fermi decay is sensitive to the exchange of hypothetical scalar bosons. Limits on the scalar interaction are poor, both from β decay and from high-energy experiments, and a 1% measurement of the β-ν correlation coefficient a would be competitive [7]. Among alkali atoms, isomeric $^{38}K^m$ has the only such pure Fermi decay. The mixed Fermi-Gamow-Teller ($I^\pi = 3/2^+ \rightarrow 3/2^+$) decay of ^{37}K is suitable for β-asymmetry experiments and positron longitudinal polarization measurements [8], which are sensitive to the presence of right-handed currents in the weak interaction.

The half-lives of $^{38}K^m$ (0.925 s) and ^{37}K (1.226 s) are an order of magnitude shorter than isotopes trapped in related work elsewhere [1,4,9]. This creates an experimental challenge in the production and trapping of these isotopes; however, the shorter lifetimes make it easier to achieve trap lifetimes long enough that nearly all trapped atoms undergo radioactive decay while in the trap (collisions with residual gas at 10^{-9} Torr produce a trap lifetime of 10 s).

Here we report the successful coupling of a magneto-optic trap (MOT) to the copious production of an on-line isotope separator (TISOL). With this arrangement we have trapped approximately 6000 atoms of $^{38}K^m$ or 2000 atoms of ^{37}K, sufficient to begin β-decay experiments. We have measured the isotope shifts of ^{37}K, $^{38}K^m$ in the trapping transition: the deduced nuclear charge radii show an unusual lack of change at the major neutron number $N = 20$ shell closure. We also will describe plans for β-decay experiments.

At TISOL, a 1 μA 500 MeV proton beam from the TRIUMF main cyclotron bombards a 10 g/cm^2 CaO powder target heated to 1200 °C. Alkalis diffusing out of the target are surface ionized and extracted as a 12 keV ion beam. The beam is mass separated in a magnetic dipole and electrostatically transported to a clean room housing the lasers and experiment; differential pumping brings the final beam line vacuum down to 5×10^{-10} Torr. We can sustain yields of 3×10^7/s $^{38}K^m$ and 1×10^7/s ^{37}K.

We have coupled our MOT to the TISOL ion beam via a neutralizer similar to that used at ISOLDE [10] (Fig. 1). Metals exist with work functions both higher and lower than the ionization potential of alkalis, so alkali atoms in equilibrium with a surface can be either predominantly ions or neutral atoms. The 12 keV K^+ beam is stopped in a hot (1300 °C) rhenium tube; the atoms diffuse to the surface, are emitted as thermal ions, and are guided by electric fields to an 800 °C hafnium region where they are neutralized and collimated into the vapor cell. The MOT captures atoms from the low-energy tail of the Boltzmann distribution; multiple collisions with the walls (Pyrex with

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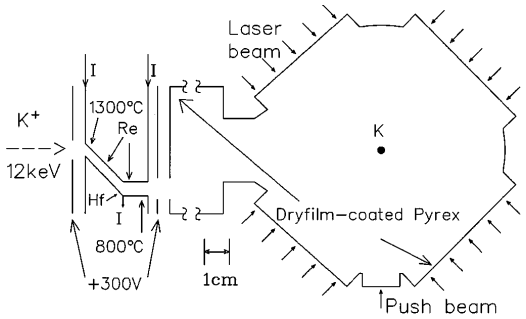

FIG. 1. Schematic of neutralizer and magneto-optic trap cell. Break denotes 10 cm long Dryfilm-coated Pyrex tube.

nonstick Dryfilm coatings [11]) replenish that low-energy tail by rethermalizing the atoms, in principle allowing a large percentage to be trapped [12].

Our vapor-cell MOT is a standard six-beam trap [13] with 4.5 cm diameter beams, 200 mW of power per beam, detunings from 3 to 7 linewidths Γ, and magnetic field gradient $dB/dz = 13$ G/cm. The beams are from a commercial Ar^+ ion laser-pumped Ti:sapphire ring laser, locked to the $D2$ ($4S_{1/2} \rightarrow 4P_{3/2}$) transition of K (766.5 nm) by Zeeman-dithered saturation spectroscopy of natural K [14]. Since we cannot resolve the narrow excited-state hyperfine structure in ^{39}K or ^{41}K using saturation spectroscopy, to minimize our error for the isotope shift measurements we lock to the unresolved transitions from the ^{41}K $F = 1$ ground state, which span ± 2 MHz. The ground-state hyperfine splitting of ^{37}K was known [15] to be very similar to ^{41}K, so trapping ^{41}K provides useful tests. Because of the narrow $4P_{3/2}$ hyperfine splitting ($\approx 2\Gamma$), atoms are quickly lost from the $F = 2 \rightarrow 3$ cycling transition, via absorption to $F = 2$ and $F = 1$ excited states and subsequent decay to the $F = 1$ ground state, in a few cycles. So trapping of ^{41}K and ^{37}K requires two frequencies with nearly equal intensity [16]. The two frequencies, as well as the necessary shifts from the stable K references, are generated using acousto-optic modulators. The $I = 0$ ^{38}K^m has no hyperfine structure, so its trapping requires only one laser frequency.

Using a charge coupled device (CCD) camera shielded by a 1 nm FWHM interference filter, we can detect as few as 500 trapped atoms in the presence of scattered trap light from the cell. The number of trapped atoms is deduced from the fluorescence of the trap laser light. The resulting efficiency is 6×10^{-4} trapped stable ^{41}K atoms per incoming ion incident at the neutralizer. Trapping efficiency for ^{37}K and ^{38}K^m was a factor of 3 smaller, due to decay losses as the isotopes diffuse out of the stopping foil; at the high foil temperatures necessary for quick diffusion, neutralizer outgassing limits the trap lifetime to 0.5 s. (The neutralizer has delay times of ≈ 10 s at lower temperatures that produce a 5 s trap lifetime.) Measures to achieve longer trap lifetimes without sacrificing yields are discussed below. Trapping efficiencies for ^{41}K have remained the same before and after radioactives were introduced, indicating no observable damage from radioactivity to the Dryfilm coating.

We have measured the isotope shift of ^{37}K and ^{38}K^m in the $D2$ transition used for trapping. The trapped atoms were displaced from their equilibrium position with a weak ($<1\%$ of trap intensity) probe beam (Fig. 2). The displacement as a function of probe frequency can be fit well with a superposition of Lorentzians, one for each transition (Fig. 3). This technique preserves the number of atoms; however, the high-intensity trapping lasers perturb the atomic levels. This dynamic Stark shift Δ ("light" shift) was determined by measuring the resonant frequency as a function of trap laser intensity (at fixed detuning) and extrapolating to zero intensity. The small nonlinearity of Δ with laser intensity I was fit using the 2-level formula $\Delta = (\delta^2 + \Gamma^2 I/2I_0)^{1/2} - \delta$, where δ is the trap detuning and I_0 is the saturation intensity [17]. The probe beam intensity was kept low enough to not induce an additional light shift, and the trap displacement (≈ 1 mm) was small enough to induce negligible Zeeman shift. We tested the method with stable ^{41}K, and we find we are dominated by systematic errors, conservatively estimated to be 2 MHz for the uncertainty in laser lock, and 2 MHz (1 MHz) for the extrapolation to zero power for ^{37}K (^{38}K^m). The light shift for ^{38}K^m was 2 times smaller for the larger laser detuning (7Γ vs 3Γ) used, hence the smaller error. For the isotope shifts with respect to ^{39}K, we find -265 ± 4 MHz for ^{37}K and -132 ± 3 MHz for ^{38}K^m. Reducing the errors further would require techniques sensitive to a few 1000 atoms with the trap laser light off, as well as a laser lock using a Doppler-free method without crossover

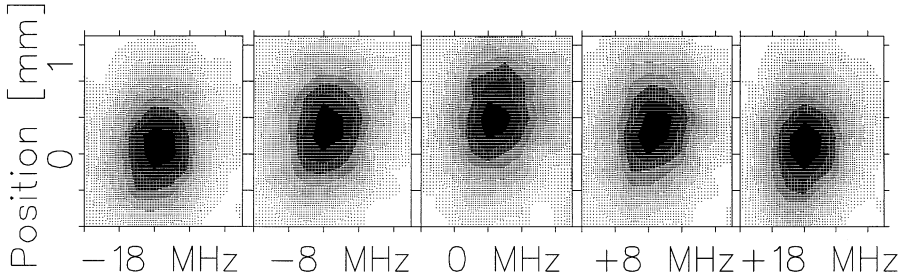

FIG. 2. CCD image of approximately 6000 trapped ^{38}K^m atoms, and the cloud displacement for given push beam detunings.

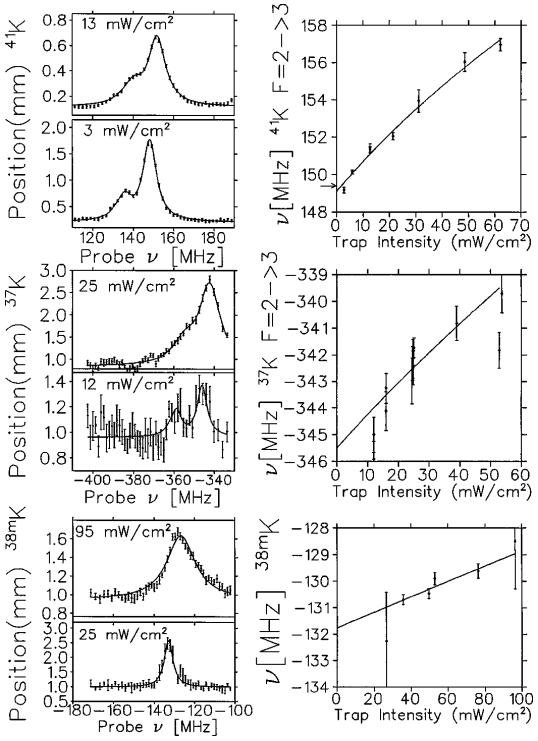

FIG. 3. Isotope-shift data for ^{37}K, ^{38}K^m, and representative data for stable ^{41}K. Left: Position of ^{41}K,^{37}K, ^{38}K^m atoms versus probe frequency (labeled by trap laser intensity) with Lorentzian fits. Right: Extrapolation of centroid frequency to zero trap intensity at fixed detuning. Arrow shows known ^{41}K $F = 2 \rightarrow 3$ $\nu = 149.4$ MHz [19]. Consistent data for ^{41,37}K for probe light from $F = 1$ ground state not shown.

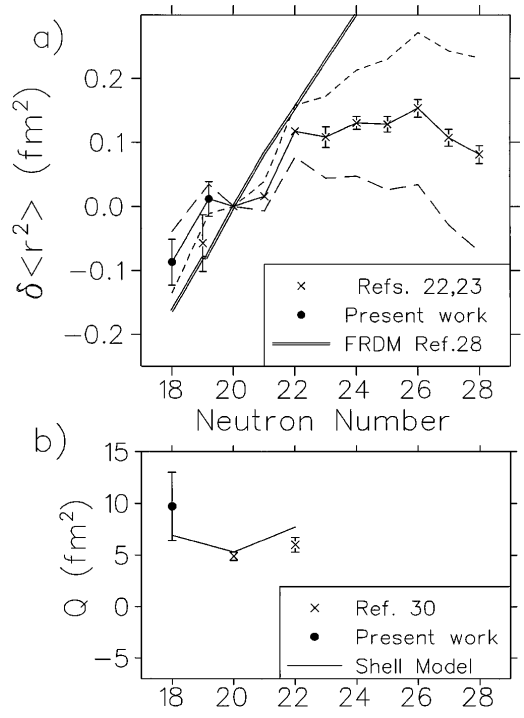

FIG. 4. (a) Difference in mean squared charge radii $\langle r^2 \rangle$ of K isotopes with respect to ^{39}K. ^{38}K^m plotted offset from ^{38}K ground state for clarity. Thin solid line connects data after correction for specific mass shift; dotted and dashed lines indicate the systematic change in $\delta\langle r^2 \rangle$ center values for $\pm 1\sigma$ changes in specific mass shift [23]. Double-thick solid line is finite-range droplet model [28]. (b) Electric quadrupole moments of ^{37,39,41}K compared to shell-model calculation.

resonances [18] (such as resonant fluorescence at 90° to an atomic beam [19]).

The dependence of trap fluorescence on trap laser frequency has been used elsewhere to measure isotope shifts [9,20], but the narrow hyperfine splittings and unknown quadrupole moment of ^{37}K—i.e., the lack of a well-separated cycling transition in ^{37,39,41}K—make this simple technique inapplicable, as many transitions contribute.

To deduce nuclear charge radii from isotope shifts [21], one must determine separately the "normal" mass shift (the trivial reduced mass change with nuclear mass), the "specific" mass shift from the nuclear mass's effect on the electron cloud (determined in [22,23] by comparison to muonic x-ray data for ^{39,41}K), and from these deduce the "field" shift due to the change in nuclear charge radius. To convert field shifts to charge radii, we can use the same constant of proportionality as calculated in [23] for the $D1$ line, because in ^{39,40,41}K the field shifts are known to be the same in $D1$ and $D2$ to within 0.3 MHz [19].

Our deduced charge radii for ^{37}K and ^{38}K^m are shown in Fig. 4, along with the ^{38}K ground state and other isotopes measured at ISOLDE [22]. The lines indicate how the center values of $\delta\langle r^2 \rangle$ would systematically change for $\pm 1\sigma$ changes in the specific mass shift [23].

The ^{38}K^m has, within errors, the same charge radius as the $I^\pi = 3^+$ ground state. This is consistent with the lowest-order shell-model wave functions ($1d_{3/2}$ neutron and proton holes, either coupled to maximum spin $I^\pi = 3^+$ and isospin $T = 0$ or $I^\pi = 0$ and $T = 1$) which have similar spatial dependence. A more detailed calculation based upon spherical Hartree-Fock calculations obtained with the SGII Skyrme interaction [24] and constrained by the $2s1d$ shell-model orbital occupancies [25] predicts the ground state has a larger $\langle r^2 \rangle$ by only 0.014 fm^2. The difference is small because the $2s$ and $1d$ occupancies for the two states are similar.

In many instances in medium-mass nuclei, charge radii become smaller at a major neutron shell closure (for example, K and Ca at the $N = 28$ shell closure, and Rb and Sr at $N = 50$) [26,27]. In contrast, the change in experimental K charge radii across $N = 20$ is roughly consistent with the finite range droplet model [26,28] prediction of a smoothly changing increase (Fig. 4). These results are qualitatively similar to more detailed results in Ar and Ca isotopes recently obtained at ISOLDE [29], which show that the $N = 20$ shell closure is the only major shell closure that does not exhibit a dramatic change in behavior of charge radius vs neutron number. A more quantitative interpretation in the K isotopes is limited by

the uncertainty in the specific mass shift, as well as the present experimental errors.

From the frequency splitting between the $F = 2 \rightarrow 3$ and $F = 2 \rightarrow 2$ transitions, we can deduce the quadrupole moment of ^{37}K. From the known magnetic moment [15], we can extrapolate the known hyperfine A coefficient for the $4P_{3/2}$ state in ^{39,41}K (the hyperfine anomaly is known to be small) [15,19]. The result for the hyperfine $B_{4P3/2}$ coefficient is 5.4 ± 1.8 MHz. The resulting nuclear electric quadrupole moment is compared with literature results for ^{39,41}K in Fig. 4, using the same 20% Sternheimer corrections for atomic shielding [30]. The result is consistent with shell-model calculations within the $2s1d$ [25] and $2s1d$-$2p1f$ [31] configuration spaces (Fig. 4).

To avoid the trap lifetime limitation from the hot neutralizer, and because of the large backgrounds from the buildup of the ^{38}K ground state (produced at about $10\times$ the rate of the isomer), it is essential to move the atoms with an isotopically selective laser push to a clean, high-vacuum measurement trap. We have demonstrated 45% transfer efficiency for ^{41}K to a second MOT 50 cm away, adapting the "leaky" MOT technique used at JILA [32] by adding a spatially narrow push beam to our vapor-cell MOT (Fig. 1).

For β-decay studies, the MOT provides a sample of atoms in a localized volume with virtually zero source thickness, allowing detection of the nuclear recoil momentum. In the $0^+ \rightarrow 0^+$ Fermi decay of ^{38}K^m the leptons carry away zero angular momentum (in the allowed approximation). Unlike the standard model interaction, mediated by the W vector boson exchange, a scalar interaction demands equal helicities for the emitted lepton and antilepton. Thus for vector bosons back-to-back emission of the leptons is forbidden, while back-to-back emission is maximal for scalar boson exchange. We therefore plan to measure back-to-back coincidences between β^+ and ^{38}Ar recoils: the recoils will have lower energy if the leptons are emitted back-to-back. Measurement of the β-ν correlation of ^{37}K, which has almost identical Q value and therefore kinematics, will allow tests of systematic errors. We estimate we need 10^4 trapped atoms of ^{38}K^m in our planned geometry to impose a 1% (statistical) limit on scalar interactions in a week of counting.

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