From the Atomic to the Femtoscale

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Abstract: Atom traps of lithium can be used to provide a new window on few-body atomic and nuclear systems. The trapped atoms form an excellent sample, dense and motionless, for precision measurements. This talk describes experiments using ultracold lithium atoms to study ionization dynamics (a persistent few-body dynamical problem) and outline proposed precision measurements of isotope shifts to determine charge radii of short-lived lithium isotopes (a challenging few-body nuclear physics problem).

Introduction

The lithium atom, with three electrons and six through eleven nucleons, is a hotbed of activity for few-body theorists in both atomic and nuclear physics. Atomic theorists have the advantage that the forces in the problem, Coulomb interactions, are well known. This advantage simplifies development of many-body techniques for both structure and dynamics [1]. On the atomic physics side, there has been recent effort devoted both to precision calculations of atomic structure [2-5] and to understanding the dynamical correlation between the outgoing electrons in photo triple-ionization [6-9]. On the nuclear physics side, a long-standing program to calculate properties of few-body nuclei has now reached $A \leq 10$ [10,11]. In these calculations, the nucleon-nucleon potentials are adjusted to fit the large collection of *pp* and *np* scattering data. Impressively, the calculations have fit the binding energies of all $A \leq 10$ nuclei to an rms deviation of $\approx$400 keV, predicted the absence of stable A=5, 8 nuclei [12], and simultaneously predicted rms proton radii, rms neutron radii, quadrupole moments and magnetic moments.

Against this backdrop of theoretical activity, experiments are essential, both as a test of existing calculations and to motivate further development of many-body methods. In what follows, we describe two experiments using trapped lithium that address both dynamical and structural many-body problems. The first is to visualize four-body Coulomb breakup using a trapped lithium target combined with recoil ion and electron imaging techniques. The second proposed experiment deduces the charge radius of short-lived lithium isotopes by combining precision spectroscopy on the stationary (i.e. Doppler-free) sample of trapped atoms with accurate atomic calculations.

Ionization dynamics with trapped lithium

The study of multiple ionization of atoms is spurred by both practical and fundamental interest. On the applied side, multiple ionization plays an important role in plasmas, astrophysics, strong-field laser ionization and new laser schemes. On the fundamental side, the interest is to develop techniques to handle the many-body problem by building up from prototypical systems. Significant effort has been expended on the simplest three-body Coulomb problems, electron impact of ionization of hydrogen [13] and double ionization of helium [14]. Only recently has there been some effort to tackle the four-

body problem in the form of the photo triple-ionization of lithium [6-9], spurred by the initial experimental observation of this process [15].

A single photon liberating the three electrons in lithium is a rare process as the incoming photon interacts predominantly with a single electron and the ejection of the other two is a manifestation of the correlated motion of the three electrons. Theory originally developed for photo double-ionization of helium at high energy was adapted to predict the asymptotic limits (E_{photon}) of the lithium charge-state ratios, 3+/2+ and 2+/1+ [6]. Other methods were also developed to predict the charge state ratio at the asymptotic limit [7] and over the intermediate energy range [8]. Addressing the question of what is the mechanism for the triple ejection from lithium directly was the work of Malcherek, Rost and Briggs [9]. Near threshold, the Wannier configuration (symmetric breakup) is allowed, in contrast to the situation in photo double-ionization of helium where back-to-back emission of the two outgoing electrons is forbidden due to parity. The Wannier mode is thought to evolve to another breakup mechanism as the excess energy above threshold (203 eV) is increased [16]. A visualization and understanding of this change in mechanism as a function of excess energy would be a major step for many-body dynamics.

Before we discuss the case of triple ionization of lithium and the use of an atom trap, we review the situation for double ionization of helium. The mechanisms in photo double-ionization of helium have been mapped out over a wide range of energy and geometry, as summarized in the review article by Briggs and Schmidt [14]. Two basic methods have been used; the classical method electron-electron coincidence using two energy and angle-resolved spectrometers [17] and the recoil-ion–electron coincidence method [18]. In the classical method, the kinematics of the two outgoing electrons are specified completely by the position and pass energy of the electron spectrometer. However, the solid angle of a typical apparatus is of order 10^{-5} and the coincidence rate of about 2 events/min. In the recoil ion (COLTRIMS: cold target recoil ion momentum spectroscopy) method, one electron is captured in coincidence with the recoil ion. Here the solid angles approach 4 for the ion and electrons below 20 eV and the coincidence rate increases commensurately in a configuration that is similar in spirit to a small-scale high-energy physics experiment. Assuming that the photon momentum, target momentum and target energy are negligible, then the complete kinematics of the breakup can be reconstructed by measuring the momenta of the recoil ion and one electron. The electron and ion momenta are measured by recording the time and position of their arrival on separate detectors. The momentum resolution of better than 0.1 au (au = atomic unit = $m_e c$) is required to observe the recoil ion at 1 eV excess energy , where $p \approx 0.07$ au. With this resolution, one is able to conclude immediately from the hole in the center of the recoil ion image that the Wannier configuration is forbidden [18]. The price for an enhanced count rate is that small target momentum (< 0.1 au) is required to fully exploit the technique. This then precludes using an effusive beam of helium, which at 300 K has a momentum spread of 4.3 au. For the photo double-ionization experiments with helium, a supersonic jet at 30 K with a 0.3 mm skimmer at 8 mm was employed in conjunction with a small area photoionization source to achieve a momentum spread of less than 0.1

au, in both the transverse and longitudinal directions. The experiments used a target thickness of 10^{10} / cm^2.

Now we come to the use of trapped lithium atoms for probing ionization mechanisms. We employ the workhorse magneto optical trap (MOT) of lithium, with roughly 100 million atoms in a 1 mm ball to yield a target density of 10^{11} atoms/cm^3. The lithium atoms are cooled to a temperature of roughly 1mK, which corresponds to a momentum of ≈ 0.006 au. Thus, the target requirements for a photoionization experiment using the COLTRIMS method are fulfilled and one may contemplate visualization of the photo-triple-ionization of lithium.

As a precursor to photo triple-ionization, which requires not-easily-accessible ≈200 eV photons, we have used electrons to ionize the trapped lithium atoms. An initial effort focused on the double-to-single ionization ratio from 200 to 1500 eV impact energy [19]. In this study, the 2+/1+ ratios observed were somewhat lower than the only earlier observation [20], but in reasonable agreement with semi-empirical predictions [21, 22]. The apparatus is shown in Fig 1.

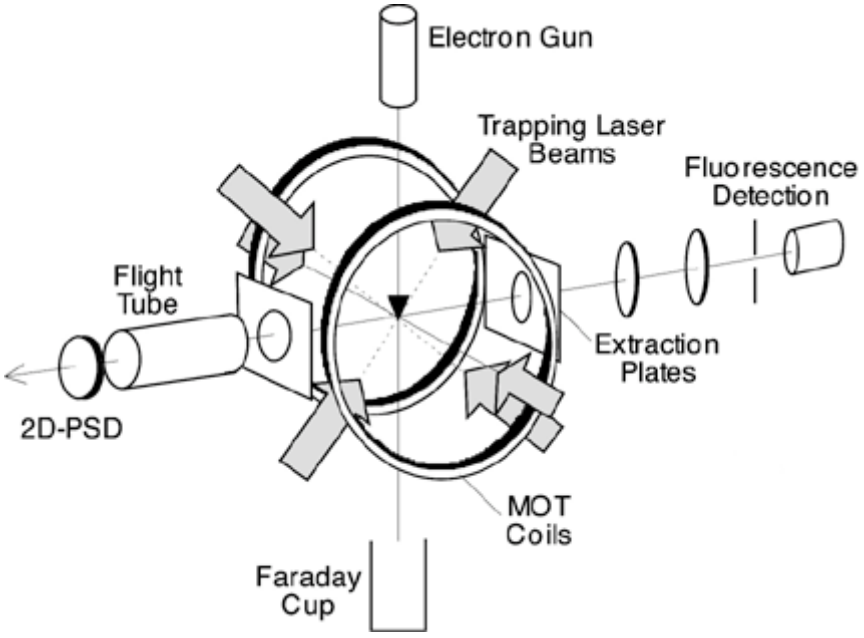

Fig 1. Apparatus for studies of electron-impact ionization of trapped lithium. The trap is loaded from a resistively-heated oven (320^o C) with a 1-mm orifice located about 10 cm from the trapping region (not shown). Also not shown is a slowing laser beam, red-shifted by 200 MHz and frequency-broadened to ≈300 MHz, which opposed the effusing Li atomic beam and enhanced the capture efficiency by ≈20x.

A striking observation of this experiment was the complete absence of the 3+ bare-naked lithium ion, which was predicted to be ≈10% of the 2+ yield at 1000 eV impact energy

[21-23]. With improvements to the apparatus, namely, the addition of the slowing beam and redesign of the time-of-flight to provide time and space focusing, we were able to observe Li^{3+} ion after electron impact ionization. Patience was definitely required as the count rate for Li^{3+} was 1 count/ 2min. The yield was 100X smaller than the semi-empirical predictions, with the 3+/2+ ratio being 1.08 (15) x 10^{-3} in comparison to the semi-empirical Born-Bethe prediction of 112 x 10^{-3}. The magnitude of this disagreement is remarkable, and *a priori* could be attributed to either a problem with the experiment or with the calculation. However, the shake prediction for 3+/2+ ratio [7], 0.47 x 10^{-3}, and an estimate of the asymptotic limit of the 3+/2+ ratio using photoabsorption data and sum rule analysis [24], 0.28 x 10^{-3}, identifies the problem as being the semi-empirical method. We take this as a cautionary note for modelers who wish to use semi-empirical methods to estimate direct multiple ionization channels in plasmas, astrophysics and strong-field laser ionization.

As to the original motivation, to understand the mechanism of triple ejection of electrons from lithium, this remains an area for future study. The specifications in terms of trapped atom number and momentum spread have been achieved. The main challenge is to design the fields and detectors to extract and image the low-energy ejected electrons and ions in coincidence. Currently the stray fields in the apparatus are too large to reliably image 1-eV electrons. The source of these fields may be the accumulation of electrons (necessary for ionization in our test apparatus) on insulating posts. Measurements with a photoionization sourcewould eliminate this source of stray fields and in combination with a redesigned TOF extraction region would be the next step.

Charge radii of exotic lithium nuclei

Remarkably, *ab initio* nuclear many-body theory has reached a point of being able to predict structural properties (energy levels, parities, proton radii, neutron radii, electric quadrupole moments, magnetic moments) of nuclei where A≤10 [10-12]. While many of the A≤ 10 nuclei are stable and have been studied with traditional nuclear physics methods, e.g. electron scattering [25], there are a number of short-lived nuclei in this region that require special methods. In this range, the lithium nuclei, stable ^{6}Li and ^{7}Li, ^{8}Li (τ = 840 ms), ^{9}Li (τ = 178) and ^{11}Li (τ = 8.7 ms), pose an interesting problem for both atomic and nuclear theorists. It was originally pointed out by Drake [26] that information about nuclear size could be deduced from atomic structure measurements if both experiment and theory could be performed to adequate accuracy. The basic idea is that if all other contributions to the isotope shift can be calculated with sufficient accuracy, then a comparison between theory and experiment can determine the nuclear charge radius. While this may seem an tall order, since the nuclear size contribution to the isotope shift (for neighboring A's in lithium) is a mere 2 MHz out of a total shift of ≈10 GHz, the method has been used with success in heliumlike systems [27]. Of course, the move to a lithiumlike system increases the difficulty of the atomic structure calculation that is undergoing current refinement with the addition of QED recoil corrections [5]. The theoretical uncertainty for the $2\,^2P_{1/2} - 2\,^2S$ isotope shift for ^{7}Li – ^{6}Li is 10534.13 ± 0.07 MHz, and the contribution from the nuclear rms charge radius $(r_{rms})^2$ is 1.94 MHz. Thus, theory contributes only 3.5% uncertainty to the determination of the square of the nuclear charge radius. If one can measure the isotope shift to an precision

of ≈100 kHz, i.e. splitting the natural linewidth 5.3 MHz to about 1 part in 50, then the uncertainty is at ≈ 5% level.

We now look at the predictions for r_{rms} of lithium isotopes using different nuclear potential models, AV18, IL2T, IL3L, IL4A as shown below in Table 1. It is clear that a measurement at the 5% level will distinguish between the AV18 and the other models, but that distinguishing IL2T, IL3L and IL4A will require substantial improvement in atomic theory as well as experiment.

Table 1: Predictions of r_{rms} using different nuclear models [10,11].

Model	$(r_p)_{rms}$ (fm)			
	6Li	7Li	8Li	9Li
AV18	2.50(1)	2.29(1)	2.31(1)	2.22(1)
IL2T	2.39(1)	2.25(1)	2.09(1)	2.09(1)
IL3L	2.44(1)	2.32(1)	2.11(1)	2.14(1)
IL4A	2.38(1)	2.26(1)	2.07(1)	2.06(1)

The development of a method, any method, to measure nuclear charge radii of short-lived isotopes is of considerable interest. Of particular interest is the exotic, halo nucleus ^{11}Li, whose matter radius is virtually identical to that of ^{208}Pb! Although the nuclear theorists have not yet turned their attention to this particular isotope of lithium, it is clearly within reach. An ongoing program at GSI, Darmstadt, Germany has been pursuing the determination of the charge radius of ^{11}Li by resonance ionization spectroscopy [28]. In this scheme, one measures the isotope shift of the two-photon transition 2s – 3s. One detects the atoms that have made the 2s-3s transition by resonantly ionizing those which fluoresce back to the 2p state. Because the isotope shift transition is two-photon and Doppler-free, one can operate with an atomic beam and a power buildup cavity to induce the 2s-3s transition

Our approach is to measure the 2s-2p transition with trapped atoms. Due to the small velocities of the cooled and trapped atoms, there is no Doppler broadening and the sample is perfect for precision spectroscopy. Since we are probing an allowed transition, the scattering rate of photons is comparable to the inverse lifetime of the excited 2p state, (τ = 27 ns) and a single atom can easily scatter 10 million photons/s. With a 1% collection/detection efficiency, a single atom can give a signal rate of 100,000 cts/s. The trapping process can be quite efficient with a typical capture efficiency of 10^{-4} of the atoms. Even with relatively low production rates of the exotic nuclei (say 10^6/s), we should be able to make a good measurement. The next issue is the timescale required for trapping. Each 670 nm photon scattered gives a velocity kick to a lithium atom of 8.5 cm/s. Thus, the time required to slow a 1000 m/s lithium atom to a stop assuming a scattering rate of 1/4τ is only 1.2 ms, well within the lifetimes of the unstable lithium isotopes.

We would start first with the ^{8}Li isotope, being the easiest to produce at ATLAS (Argonne Tandem Linac Accelerator System) as well as the longest-lived of the exotic nuclei. The ^{8}Li would be produced by a ^{7}Li beam impinging upon a cooled D_2 target at ≈20 MeV. The one nucleon transfer reaction has a fairly large cross section (≈100 mb). The outgoing divergent beam would be recompressed using a superconducting solenoid and mass analyzed using a dipole magnet. A test run in August of 2002 showed that an extremely clean beam of ^{8}Li could be delivered into a spot size of 5mm at a flux of 10^{6}/s when scaled to operating intensities in the linac.

The trapping apparatus envisioned at the end of the production beamline for ^{8}Li is shown below in Fig 2.

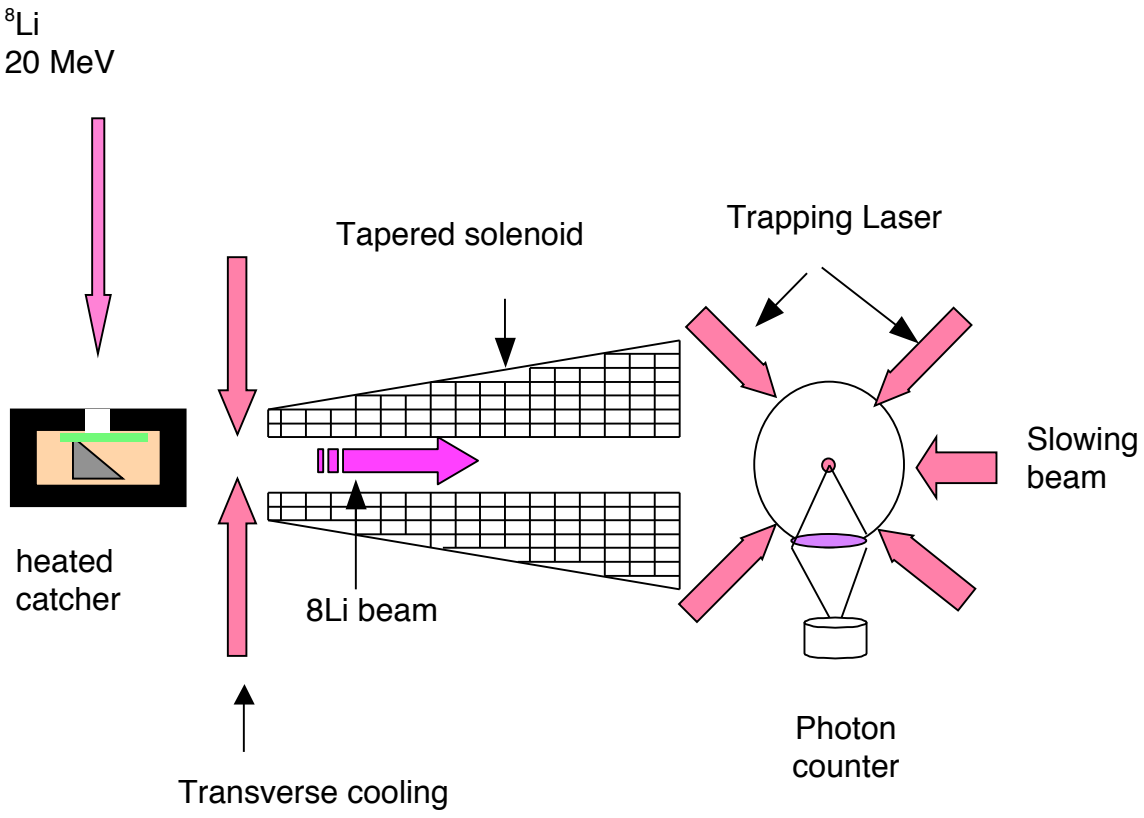

Fig 2. Apparatus for trapping and spectroscopy of ^{8}Li. The ^{8}Li beam is slowed by passage though a thin tantalum foil and then stops in a heated graphite catcher (≈2000^{o} C). The ^{8}Li atoms effuse from the catcher in the heated oven and then out a collimating nozzle to the rest of the slowing and trapping apparatus. Transverse cooling and longitudinal slowing is expected to give a capture efficiency around 10^{-4}. An incident beam of 10^{6} ^{8}Li/s would then produce a steady state of 100 trapped ^{8}Li for spectroscopic interrogation.

Finally, it is interesting to note that the measured ^{6}Li - ^{7}Li stable isotope shifts remain in partial disagreement with theory. The earlier measurements were made either in an atomic beam [29,30] or in a cell [31]. A worthwhile precursor experiment would be to measure the 2s-2p ^{6}Li – ^{7}Li isotope shifts in using trapped, ultracold atoms, where Doppler problems are negligible.

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