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Weak interaction symmetries with atom traps

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Abstract. Neutral atoms trapped with modern laser cooling techniques offer the promise of improving several broad classes of weak interaction experiments with radioactive isotopes. For nuclear β decay, demonstrated trap techniques include neutrino momentum measurements from beta-recoil coincidences, along with methods to produce highly polarized samples. These techniques enable experiments to search for non-Standard Model interactions, test whether parity symmetry is maximally violated, search for 2nd-class tensor and other tensor interactions, and search for new sources of time reversal violation. Ongoing efforts at TRIUMF, Berkeley, and Los Alamos will be highlighted. Trap experiments involving fundamental symmetries in atomic physics, such as time-reversal violating electric dipole moments and neutral current weak interactions, will be briefly mentioned.

PACS. 23.40.Bw Weak-interaction and lepton (including neutrino) aspects – 14.60.Pq Neutrino mass and mixing – 32.80.Pj Optical cooling of atoms; trapping

1 Introduction

The organizers requested a review of results in fundamental symmetries using radioactive beams since the last ENAM conference in 2001. Personal bias narrows the topic to weak interactions using radioactive species and neutral atom traps, mainly concentrating on β decay work, with a small section on precision experiments with high-Z radioactive atoms.

This selection of topic ignores the most interesting symmetries work presented at this conference, limits on 2nd-class currents in $A = 8$ by T. Sumikama *et al.* [1] measuring β emission correlations with spin alignment of mirror Gamow-Teller transitions. Ongoing β-ν correlation measurements with a Penning trap (the WITCH recoil spectrometer [2]), the $^6He^+$ transparent Paul trap [3], and a β-γ Doppler shift measurement in an ^{14}O Paul trap [4] are slighted here, as are Q-values determined with mass traps [5]. The status of V_{ud} measurements was presented [6], along with an overview of all fundamental symmetries [7]. Neutral atom traps for precision measurements of charge radii [8] were also presented.

The workhorse trap in this field is the magneto-optical trap (MOT). A MOT can be treated as a damped harmonic oscillator [9]. The damping is provided by the absorption of laser light a few linewidths lower than an atomic resonance, so that atoms absorb light opposing their motion Doppler-shifted closer to resonance. A force linearly dependent on position is produced by Zeeman shifts from a weak ($\sim$ 10 G/cm) magnetic quadrupole field, which reverses sign at the origin and so selects which handedness of circularly polarized light will be absorbed as a function of position. A normal MOT will have atomic and nuclear polarization close to zero. Because of the near-resonant laser light, MOTs are inherently isotope and isomer selective.

One can immediately see several broad classes of experiments that MOTs can assist. Nuclear recoils from β decay freely escape the MOT —they have transmuted to another element so the laser light no longer matters,

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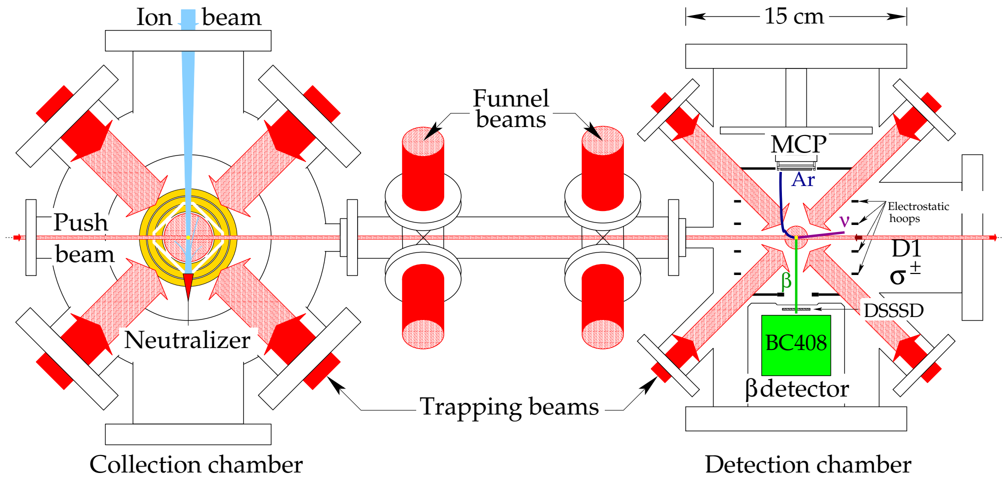

Fig. 1. Prototypical TRIUMF Neutral Atom Trap 2-MOT apparatus. A vapor cell MOT traps radioactives with 0.1% efficiency, and then the atoms are transferred with high efficiency [10] to a second trap with detectors. A uniform electric field collects ion recoils to a microchannel plate, where their position and TOF with respect to the β^+ is measured.

and the B field is very small. Using an apparatus similar to fig. 1, measurement of the recoil momentum together with the β momentum allows the reconstruction of the ν momentum in a much more direct fashion than possible previously. (Measurement of the β energy is difficult, but there are kinematic regimes —recoil momenta less than Q/c— for which the neutrino momentum is uniquely defined from the other kinematic observables [11].) So the angular distribution of ν's with respect to the β direction, the β-ν angular correlation, can be measured.

A variety of methods exist to polarize laser-cooled neutral atoms and to accurately measure their polarization, and these will be described below. Knowledge of the polarization of the decaying species is a limiting systematic error in many neutron β decay and μ decay experiments. For most experimental tests of maximal parity violation, the polarization must be known with error less than 0.1%.

The cold, confined atom cloud also provides a bright source for Doppler-free precision spectroscopy of high-Z radioactive atoms. On the order of 10^7 photons/s are emitted into 4π for a saturated electric dipole transition. High-Z atoms have larger electron wavefunction overlap with the nucleus, enhancing contact interactions like the weak interaction. *E.g.*, atomic parity violation effects, which measure the strength of the neutral weak interaction, scale with Z^2N.

Tens of thousands of photons must be absorbed to slow atoms from room temperature, so neutral atoms must have reasonably strong cycling transitions to be trapped. Reference [12] reviews MOTs and lists elements that can be trapped in them, to which Ag, Cr, and Yb are recent additions. Radioactive isotopes of most alkali elements (Na, K, Rb, Cs, Fr) have been trapped, along with metastable nobel gas atomic states of He and Kr, and there are plans for alkaline earth elements Ba and Ra. For a more detailed review of the atomic physics and loading of MOTs for radioactive species, see [13], along with a more recent review [14].

2 Beta-neutrino correlations

The standard electroweak model unifies electromagnetic and weak interactions, which are mediated by exchange bosons of spin 1, the photon for electromagnetism, and the W^+, W^-, and Z^0 for the weak interaction. Historically, the β-ν correlation has provided the best evidence that the effective contact interaction was primarily vector and axial vector, which in modern theories is due to exchange of the spin-1 bosons.

Berkeley has published the first β-ν correlation using an atom trap [15]. Their abstract quotes the result $a = 0.5243 \pm 0.0091$ for ^{21}Na, which has a standard model prediction 0.558. They present evidence for a dependence of a on the density of atoms trapped, and if an extrapolation to zero density is done, the value for a is brought into agreement with the standard model. They suggest a possible mechanism, distortions of the recoil momentum produced when the decay originates from a molecular dimer trapped in the weak MOT magnetic field. A Gamow-Teller branch to an excited state is also being remeasured, although to explain the full deviation the branch would have to be 7% rather than the compiled value of 5.0 ± 0.13%.

TRIUMF has now submitted a paper with its β-ν correlation result for $^{38\mathrm{m}}$K, a pure Fermi decay sensitive to scalar interactions [16]. The result is in agreement with the Standard Model with somewhat greater accuracy than the Seattle/Notre Dame/ISOLDE work in β-delayed proton decay of ^{32}Ar [17], which set the previous best general limits on scalars coupling to the first generation of particles. The TRIUMF work was done with two thousand atoms trapped at a time, at densities less than 0.5% of those in the Berkeley work, avoiding the possibility of trap density distortions. TRIUMF has also published limits on admixtures of MeV-mass neutrinos with the electron neutrino [18]; nonzero admixtures are still allowed by astrophysics and must be constrained experimentally, and the results are listed in PDG2004.

2.1 Atomic charge state dependence on recoil momentum

Berkeley has confronted an additional systematic error common to most recoil momentum measurements, the possibility that the final atomic charge state depends on recoil momentum. This is important to many experiments in this field, so we show some detail here.

This effect was first postulated, modelled, and measured in ^{6}He β^- decay work at Oak Ridge [19]. Atomic electrons in the daughter can be treated as suddenly moving with the recoil velocity, and a plane wave expansion of the resulting sudden approximation matrix element produces an effect proportional to the square of the recoil velocity. A recent elegant estimate by Berkeley relates this effect to oscillator strengths and suggests that it could be larger in β^+ decay [20] because of the difference in atomic binding energies. The recoil energy spectrum to lowest order is distorted by $(1 + sE_{\text{rec}})$.

At TRIUMF we can constrain this effect experimentally in two ways. We can fit s and a simultaneously in our TOF[E_β] fit for $\text{Ar}^{+1,+2,+3}$. We fix $s = 0$ for charge states higher than one, because the model of ref. [20] using semiempirical oscillator strengths [21] suggests that s for the higher charge states is much smaller than for Ar^{+1} (specifically, $s[+2]/s[+1] = 0.11$ and $s[+3]/s[+1] = 0.05$). We find $s = 0.008 \pm 0.022$, which when included changes a by -0.0002 ± 0.0020. We can constrain s and a simultaneously in this method because we fit as a function of E_β. A fit to the total TOF spectrum summed over all E_β would be more strongly correlated to the recoil momentum spectrum.

We can also simultaneously fit a and s to the fully reconstructed angular distribution, using recoil angle and TOF information. for the Ar^{+1} data, as shown in fig. 2. Here we can constrain s and a simultaneously because the greatest sensitivity to a is at the null in the angular distribution. The result is $s = 0.036 \pm 0.027$, producing a change in a of -0.0022 ± 0.0017. This is in agreement with our other experimental analysis.

Our values of the recoil shakeoff parameter s are in rough agreement with the simple Berkeley estimate [15]. The effect on a is much smaller in our case than they had estimated in ^{21}Na, because our experimental methods use the full energy and angle information and because in our experimental case a is closer to unity.

3 Polarized β-decay experiments

The standard model electroweak bosons also couple only to left-handed neutrinos, and hence the current is called $V - A$ or vector minus axial vector. The leptons and quarks come in weak isospin doublets, which provides cancellations necessary for the theory to be renormalizable; *i.e.*, there are no "2nd-class current" weak-interactions which violate isospin.

Polarized experiments in which the polarization can be known atomically can search for the presence of a right-handed ν. Much of the two-parameter space in the simplest "manifest" left-right symmetric models has been excluded by proton-antiproton collider experiments and by superallowed ft values [22,23]. Indirect limits from the K_L-K_S mass difference also strongly constrain left-right models, although these limits have some model dependence; *e.g.*, reasonable simplifying assumptions must be made about the complicated Higgs sector in left-right models [24,25]. However, in more complicated non-manifest left-right models direct polarized beta decay measurements are still competitive [25].

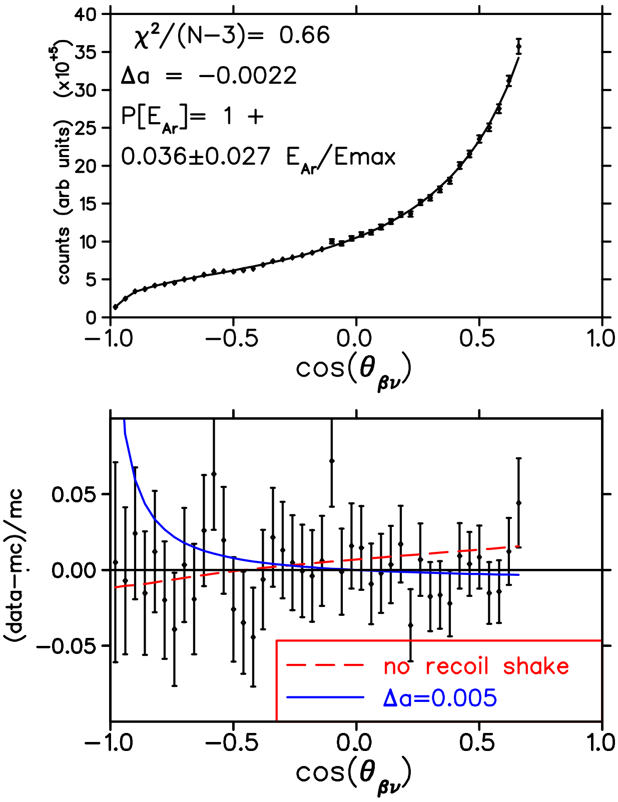

Fig. 2. Constraints from TRIUMF data on the dependence of recoil electron shakeoff on the recoil momentum.

The absence of 2nd-class currents can be tested in both polarized and unpolarized observables in isospin-mirror mixed Fermi/GT decays, like ^{21}Na and ^{37}K. The Berkeley publication of a also measured weak magnetism in agreement with the standard model [15], *i.e.* consistent with no 2nd-class currents, although the value achieved is not yet competitive.

Los Alamos has demonstrated polarization of $t_{1/2}$ = 76 s ^{82}Rb in a TOP trap, which continuously rotates the polarization of the atoms and nuclei, allowing one detector to measure the entire angular distribution [26]. They plan to add a recoil detector, and pursue experiments to test maximal parity violation in the charged current sector and search for tensor interactions [27].

TRIUMF has begun experiments with polarized ^{37}K by turning off the MOT and optically pumping the expanding cloud. Nuclear vector polarizations of $97 \pm 1\%$ have been measured by the vanishing of fluorescence in $S_{1/2}$ to $P_{1/2}$ optical pumping as the atoms are polarized.

The neutrino asymmetry B_ν of ^{37}K has been measured to be 0.989 ± 0.035 of the standard model value [28], the first measurement of a neutrino asymmetry besides that of the neutron.

Berkeley has measured precision hyperfine splittings in ^{21}Na using optical hyperfine pumping and microwave transitions [29]; these techniques are applicable to polarized β-decay experiments.

Combining polarization with recoil observables allows a number of unique experiments. The spin asymmetry of slow-going recoils (*i.e.*, back-to-back β-ν emission) vanishes in mixed Fermi/Gamow-Teller decays independent of the size of the Fermi component, and is being measured at TRIUMF. Treiman proposed long ago [30] to measure the spin asymmetry of the nuclear daughters in singles, an observable which is proportional to $A_\beta + B_\nu$ (a reasonable but in reality nontrivial result) and which vanishes for pure Gamow-Teller transitions. Thus the polarization does not have to be as well known. Right-handed currents also cancel, but the observable is sensitive to possible tensor interactions. Possible cases include ^{80}Rb, ^{82}Rb, and ^{47}K, and experiments are actively being pursued at TRIUMF.

3.1 Circularly polarized dipole force trap

A trap unique to neutral atoms promises arbitrarily high polarization. The circularly polarized far-off resonant dipole force trap (CFORT) for Rb has now been efficiently loaded and demonstrated at JILA in Boulder [31]. A dipole force trap from a diffraction-limited focussed beam ordinarily traps atoms if it is tuned to the red of resonance, and expels them if tuned to the blue. So if linearly polarized light is tuned just to the blue of the $S_{1/2} \to P_{1/2}$ ($D1$) resonance, it repels all the atoms. However, if the atoms are fully polarized, the coupling of circularly polarized light to this transition vanishes. The same coupling coefficients apply as for real absorption, and the atoms already have maximum angular momentum and cannot absorb more. The light is still red-detuned with respect to the $D2$ transition, so the fully polarized substate, and only that substate, is trapped. The quantization axis is defined by the laser light direction. This trap is not limited by imperfect circular polarization, which merely makes the trap shallower. TRIUMF is developing this trap for ^{37}K.

4 Weak interaction atomic physics

The traps also offer bright sources for Doppler-free spectroscopy, particularly in high-Z atoms where time reversal violating effects are enhanced [32], and where precision measurements could measure the strength of weak neutral nucleon-nucleon and electron-nucleon interactions. Physics with francium atoms has been vigorously pursued at Stony Brook. Several facilities plan work with radioactive atom traps, including plans and efforts at KVI Groningen, Legnaro, and TRIUMF. Explicit atomic parity violation experiments using laser-cooled radioactive atomic beams have been considered in [33].

The enhancement of nuclear Schiff moments by octupole deformation, and their manifestation in time-reversal violating electric dipole moments (EDMs) of high-Z atoms, was covered at this conference by Engel [34]. There are several experiments underway to take advantage of this effect. Work on a radium atomic beam and Zeeman slower is progressing at Argonne, with a plan to load a MOT and then a dipole force trap based on a CO_2 laser [35]. Radium has a convenient forbidden transition at 714 nm with $\sim 10\%$ of an allowed $E1$ strength. KVI is building a MOT for barium atoms in preparation for a radium trap and EDM experiment [36]. Recent atomic theoretical work has been done [37] to try to confirm some of the interesting radium atomic properties [38].

Work in a radon EDM experiment led by a University of Michigan group has demonstrated 50% transfer of a ^{120}Xe isotope-separated beam at ISAC/TRIUMF to a mockup of an EDM cell [39], and the Michigan group is proceeding with spin-exchange optical pumping tests to take place at Stony Brook.

Measurement of the electron EDM is the goal of a fountain experiment by the group of Gould at LBL, who have measured the scalar dipole polarizability of cesium [40] and are preparing a cesium EDM experiment, with eventual plans for a francium EDM experiment. This group developed the ^{229}Th source for used for ^{221}Fr trapping at JILA [41].

The nuclear anapole ("not a pole") moment is a parity-violating electromagnetic moment induced by the weak interaction between nucleons. Two measurements presently exist, in Cs and Tl isotopes, and the results are neither consistent with each other nor with other parity-violating nuclear experiments [42]. An experiment to measure anapole moments in francium atoms [43] is being actively pursued by a Maryland/Stony Brook collaboration, continuing the long-standing program at Stony Brook in francium atomic lifetimes [44] and precision hyperfine splittings enabling extraction of the hyperfine anomaly and knowledge of the distribution of nuclear magnetism [45].

INFN Legnaro has demonstrated Fr yields [46] and have coupled their Fr ion beam to a MOT. They have pioneered a number of innovative loading techniques [47] in stable Rb and are in the process of applying these to Fr.

5 Conclusion

Neutral atom traps provide a suitable environment for precision experiments using radioactive isotopes. The first trap-based measurements in β decay have now been published. Results from francium atomic spectroscopy have long been in evidence, and several labs have plans for electric dipole moment measurements in radium, radon, and francium.

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