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β-decay angular correlations with neutral atom traps

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Abstract

We review the use of laser cooling and trapping techniques for nuclear beta-decay angular correlations. Coincidences between the beta (β) and recoiling nucleus allow the determination of the neutrino (ν) momentum more directly than previously possible. Highly spin-polarized samples are also possible, with polarization known from atomic observables, and the nuclear recoils both in singles and in coincidence with the β add interesting observables. Ongoing experiments are trapping elements that provide pure Fermi, pure Gamow–Teller, and mixed Gamow–Teller transitions to distinguish sources of new physics. To compete with the next generation of neutron β-decay experiments, cases are being carefully chosen to minimize or at least know recoil-order corrections.

Keywords: beta decay, laser cooling and trapping, standard model tests

(Some figures may appear in colour only in the online journal) Q1

1. Introduction

This paper will review nuclear β-decay experiments using laser cooling and trapping of neutral atoms. The atom traps make possible new experiments to study an old problem, nuclear β-decay.

This paper will emphasize techniques made possible by the atom traps, updating a previous review [1] with less info on atom trapping but more technical info on spin polarization techniques and β-decay experiments. The recoil momentum resolution can be determined to a few percent of its value, and a high degree of spin polarization can be achieved. Interesting complementary experiments in nuclear β-decay using ion traps are covered elsewhere in this volume. Ongoing beta–neutrino (β–ν) correlation experiments include measuring the daughter recoil momentum with a Penning trap [2], β^--recoil coincidences with a Paul trap [3], and other neutrino-induced kinematic shifts in a Paul trap [4].

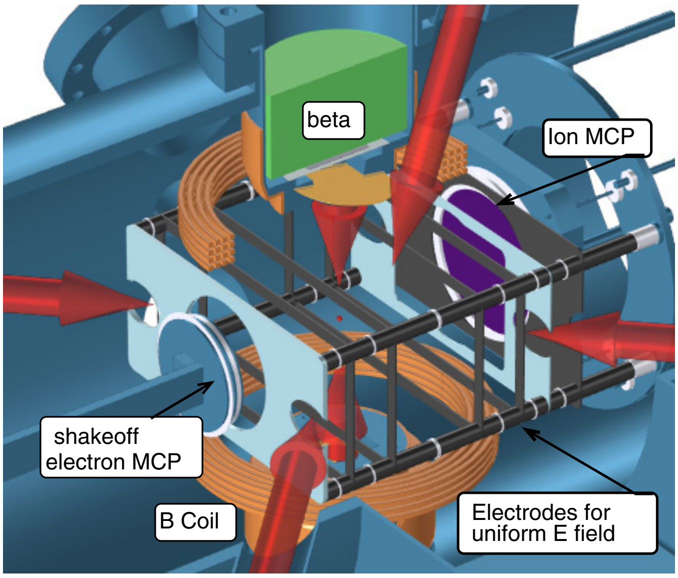

Figure 1. The present TRIUMF MOT apparatus. Magnetic field coils with current in opposite directions produce a B field with gradient $\sim$10 Gauss cm^{-1} that changes sign at the origin. All MOT ingoing beams have the same helicity, which means opposing beams either increase or decrease angular momentum, changing absorption rates with Zeeman shift to produce the linear restoring force. The MOT vertical beam shown reflects off a thin mirror in front of the β detector to provide better solid angle for β detection. The optical pumping beam shares the vertical path with the MOT beam. The uniform electric field collects ions from β decay to the 80 mm diameter ion MCP: dc stark shifts for alkali atoms are tiny and do not affect the trapping. The top laser beam, β detector, and mirror have twins at the bottom not shown. The 3 mm trap cloud is at the center.

1.1. The electroweak interaction and atom traps

There are several basic features of electroweak unification that trap experiments can test. The photon has 'heavy light' boson partners W^+, W^-, and Z^0 which mediate the weak interaction. These are all spin-1 'vector' bosons, which immediately implies that the Lorentz transformation properties of the effective low-energy 4-fermion contact operators are vector and axial vector. Measurements using atom traps have constrained other interactions by improved measurements of the historically valuable β–ν correlation.

For reasons that are not completely understood, the weak interaction is phenomenologically completely 'chiral': it only couples to left-handed neutrinos, and parity is maximally violated. The first experiments using the β-decay of laser-cooled polarized atoms have been completed, and there is promise for them to compete with and complement precision measurements of neutron β-decay and perhaps even μ decay to look for experimental manifestations of wrong-handed νs.

1.2. Features of magneto-optical trap

The workhorse trap in this field, a magneto-optical trap (MOT), can be treated as a classical damped harmonic oscillator [5]. The damping is provided by laser light from six directions (see figure 1), tuned a few natural linewidths lower than the frequency of an atomic resonance.

Atoms moving in any direction see light opposing their motion Doppler shifted closer to resonance, and preferentially absorb that light and slow down. This works naturally in three dimensions to cool the atoms. The temperatures reached by this 'Doppler-limited' technique are already small enough to produce negligible momentum changes in β-decay products, so the 'sub-Doppler' cooling methods that have been achieved experimentally and understood theoretically [6] will not be discussed further.

Producing a restoring force that depends linearly on position is more subtle. Continuous plane waves incident on a point particle cannot make a stable potential in three dimensions [7]. Opposed coils produce a magnetic field that changes sign at the trap origin, changing by Zeeman shifts of the atoms the absorption of opposing signs of circularly polarized light [5, 8].

The result is a damped harmonic oscillator, with a cloud size of order 1 mm defined by the temperature of the trapped atoms. The magnetic quadrupole field is generally weak enough—$\sim$10 Gauss cm^{-1} gradients—to produce minimal perturbation of the β and the recoiling nuclei, though it must be turned off to achieve spin polarization in a well-defined direction in space.

Because of the different light polarizations in the counter-propagating beams, a normal MOT will have atomic and nuclear spin polarization close to zero, though modified geometries have been used to deliberately spin-polarize atoms [9]. Because of the accuracy and frequency resolution of the near-resonant laser light, MOTs are inherently highly isotope and isomer selective. The mean lifetime of atoms in the MOT is $\sim$10 s at a vacuum of 10^{-9} Torr, limited by the average collision cross-section with background gas, as the momentum transfer in most collisions is more than adequate to eject the trapped atom.

1.3. More elements can be trapped now

Tens of thousands of photons must be absorbed to slow atoms from room temperature, so it is simplest for trapping neutral atoms to have strong transitions where spontaneous decay immediately returns the atom back to the state from which it was excited by the laser. The need for such a 'cycling transition' has been overcome in recent years for stable isotopes of many elements, albeit at low efficiency for trapping.

Alkali atoms have a single electron outside a closed noble gas core, which makes them ideal cases. Radioactive isotopes of all alkali elements but lithium have been trapped.

Alkaline earths can also be trapped using shorter wavelengths, if additional lasers are used to remove atoms from a metastable state. All alkaline earth elements except beryllium have had stable isotopes trapped.

By various methods, a P-shell electron from the closed core of a noble gas atom can be excited to an S state from which cycling transitions are possible with lasers. All stable noble gas elements have been trapped. Laser cooling transitions in a number of unusual species were proposed by Shimizu [10], some, such as oxygen, involving metastable states as in the noble gasses.

Other elements can be trapped with some efficiency if sufficient effort is given to the lasers, including silver, chromium, ytterbium, and mercury [1]. The natural spin selectivity of electric dipole transitions in atoms allows rare earth atoms like erbium [11], holmium [12], thulium [13], and dysprosium [14] to be trapped with a single frequency laser despite very complex level schemes, because most of the states have very different angular momentum from the ground state.

1.3.1. Loading the shallow MOT for alkalis. The MOT depth is on order 1 Kelvin. We give three examples of techniques used to load a MOT with radioactive atoms.

The short-lived ($t_{1/2}$ = 22.5 s) isotope ^{21}Na trapped at Berkeley was produced as a collimated atomic beam from a hot magnesium oxide production target. The atoms were slowed longitudinally by an unopposed laser beam as they traversed inside a tapered solenoid utilizing the Zeeman effect to keep the atoms in resonance (a 'Zeeman slower') before they entered the trap [15]. Untrapped atoms from the collimated beam sail through the apparatus, and backgrounds from untrapped atoms were found low enough to use this initial capture MOT for the decay measurements.

A vapor cell confines the atoms for many passes through the beams and many chances to be trapped, after re-thermalization upon contact with the walls replenishes the low-velocity tail of the Maxwell–Boltzmann velocity distribution [16]. Non-stick coatings for alkali atoms involve silicone polymers [17, 18]. Collection efficiencies for radioactive species from a mass-separated ion beam have been as high as 5×10^{-3}–0.01, reported by the Los Alamos group [19] and by the Stony Brook group [20]. To avoid the large radioactive background from untrapped atoms in a vapor cell geometry, both in the untrapped vapor and on the walls, the atoms must be transferred to a second MOT. The transfer efficiency is 75% in TRIUMF's geometry is achieved by lowering the trap laser intensity and pushing on the atoms with an unopposed beam tuned several linewidths higher than resonance to accelerate the atoms [21].

The metastable atomic states used to trap noble gas atoms do not survive collisions with walls, so neither a thermal beam nor a vapor cell are used. Whatever method used to excite the atoms, such as a Penning discharge, takes place near the lasers. An advantage is that noble gas atoms once deexcited can be recycled through a turbomolecular pumped vacuum system. These methods have been used to measure charge radii of helium isotopes using a MOT [22] and are being harnessed by a Seattle–Argonne–CAEN collaboration for a β–ν decay experiment in ^{6}He (see below).

Possible improvements in efficiency. The MOT relies on the emission process being front–back symmetric with respect to absorption, so it is limited by the spontaneous atomic decay rate, and it does not help to increase laser power beyond saturation. Stimulated emission of photons from excited states will transfer no momentum to the atom in the MOT geometry, so raising the laser power does not necessarily increase efficiency. Other light geometries have harnessed stimulated forces to slow atoms and improve MOT loading [23]. Possible ways to increase the capture velocity that have been used on stable species include frequency combs farther to the red [24], white light slowing [25], and light-assisted desorption [26]. Improvements in Zeeman slower design are being considered at Hebrew Institute of Jerusalem for cooling radioactive neon isotopes in metastable atomic states [27].

1.3.2. Dipole force traps. For a laser beam tuned very far off atomic resonance, almost no photons are absorbed. Nevertheless, the electric field of laser light perturbs the energy of atomic levels, with sign depending on whether the light is detuned higher or lower than the atomic resonance, as for a classical oscillator. For detuning lower than resonance, one laser beam focused to a diffraction-limited spot produces a three-dimensional minimum in potential energy, and hence a conservative trap potential [28]. This far off-resonance dipole force trap (FORT) can provide an environment to trap atoms with minimum perturbation [28]. Two of the dimensions are naturally very tightly confined ($\sim$0.1 mm) and the third can also be. By optical pumping in a FORT, the Los Alamos group has achieved high spin polarizations in ^{82}Rb (see below) [29].

Before going into more technical features of the β-decay experiments, we give more details on theoretical motivations.

2. Motivations and observables

For completeness, we summarize compactly the Lee and Yang Lorentz-invariant interaction [30] (treated more completely elsewhere in this issue [31]):

$$H_{\text{int}} = \sum_X (\bar{\psi}_p O_X \psi_n)(C_X \bar{\psi}_e O_X \psi_\nu + C'_X \bar{\psi}_e O_X \gamma_5 \psi_\nu) \tag{1}$$

where O_X denotes operators with the five different possible Lorentz transformation properties X—vector (V), axial vector (A), tensor (T), scalar (S), and pseudoscalar (P)—and implicitly includes all necessary contracted relativistic 4-indices.

The combinations of C_X and C'_X produce projection operators $1 \pm \gamma_5$ which couple to either left or right-handed neutrinos. In the standard model, the interaction between quarks and leptons is '$V - A$', so if we had written the interaction between quarks and leptons, then $C_V = C'_V$ and $C_A = -C'_A$, the combination given by exchange of the spin-1 W boson. Then only left-handed neutrinos are emitted. All values for C_X in principle can be altered or made nonzero when nucleons are constructed from quarks through QCD.

2.1. Decay observables

The general expression for the nuclear β-decay rate W in terms of the angular correlations and distributions of the leptons, including the possible spin-polarization of the nucleus, is given (using lepton momenta $\vec{p}$ and energy E and nuclear spin polarization and unit direction $\vec{I}$ and $\hat{i}$) by [32]:

$$W\,\mathrm{d}E_e\,\mathrm{d}\Omega_e\,\mathrm{d}\Omega_\nu = \frac{F(\pm Z, E_e)}{(2\pi)^5} p_e E_e (E_0 - E_e)^2\,\mathrm{d}E_e\,\mathrm{d}\Omega_e\,\mathrm{d}\Omega_\nu \frac{1}{2}\xi$$

$$\left[1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e} + F_{e\nu}\left(\frac{1}{3}\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_\nu} - \frac{\vec{p}_e\cdot\hat{i}}{E_e E_\nu}\right)T + \frac{\langle\vec{I}\rangle}{I}\cdot\left(A_\beta\frac{\vec{p}_e}{E_e} + B_\nu\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e\times\vec{p}_\nu}{E_e E_\nu}\right)\right],$$

$$T = \left(\frac{I(I+1) - 3\langle(\vec{I}\cdot\hat{i})^2\rangle}{I(2I-1)}\right) \tag{2}$$

where F is the Fermi function, and T is the degree of second-rank tensor alignment. The angular decay coefficients are expressed in terms of the C_X constants in the theory introduction to this volume [31]. Details of the Dirac algebra of these derivations are considered textbook and can be found in [33].

We will discuss below trap measurements of the β–ν correlation coefficient a, the β asymmetry with respect to spin A_β, the ν asymmetry with respect to spin B_ν, the second-rank tensor alignment term $F_{e\nu}$, and the time-reversal violating correlation coefficient D. The asymmetry of recoiling nuclei with respect to the nuclear spin is proportional to A_β+B_ν (see section 4.3). We ignore here observables that measure the spin-polarization of the leptons, as these have not been pursued yet with atom traps.

There is an additional time-reversal violating correlation not involving the nuclear spin, but instead $p_\gamma \cdot (p_\nu \times p_\beta)$ where the real γ-ray is emitted in the decay process, termed in the literature as 'inner bremsstrahlung'. This correlation has very interesting possibilities for measurement in trappable nuclei [34] and will be discussed below.

The decay rate and angular distributions are given by the absolute square of the matrix elements of H_{int}. That produces cross-terms between new interactions and the SM interactions that are therefore linear in the small new coupling coefficients. Such 'Fierz interference terms', collected together as b in equations (2), produce left-handed neutrinos as the SM does. Searches confined to them already assume the complete chirality and good time reversal symmetry of the SM. This is a natural thing to do in many theories, and some limits from particle physics in the literature simply assume this chirality without qualification.

The Fierz terms change the momentum dependence of the β spectra and β asymmetry, quantities difficult to measure because of the lineshape tails to lower energy. Fierz terms also change the recoil spin asymmetry, measured by time-of-flight (TOF) and position info that in general is more reliable than measurement of β momentum. Measurement of Fierz terms minimizes dependence on quantities difficult to know: the absolute polarization knowledge, and the Fermi/Gamow–Teller strength ratio in the presence of isospin mixing.

Terms are also produced that are squares of the new interactions. We will give simple arguments below why the β–ν correlation is sensitive to these. These terms are more general in the sense that they are insensitive to the chirality and time-reversal symmetry properties of the new interactions.

2.2. Simple helicity arguments for correlation values

Here we list a few cases that are simple to understand in terms of the lepton helicities, and some implications of the simple arguments.

2.2.1. Simple β–ν correlation. A simple helicity argument shows that $a = 1$ for pure Fermi decays in the standard model. The leptons are produced with opposite helicity in the standard model interactions. For $I^\pi = 0^+ \to 0^+$ decays, where the leptons must carry off no angular momentum, they cannot be emitted back-to-back. Thus these experiments are insensitive to the absolute chirality of the couplings, and only depend on the relative helicity of the two leptons.

This informal proof depends only on the nuclear spins and the helicities of the leptons (and the absence of orbital angular momentum). The result is independent of isospin mixing into other 0^+ configurations.

2.2.2. Simple spin correlations. The first demonstrated β asymmetry case, ^{60}Co, shares with trappable ^{80}Rb and ^{82}Rb the property that initial and final nuclear spins I_i and I_f are related by $I_i \to I_f = I_i - 1$. Suppose the initial nucleus is fully spin-polarized along the z-axis. A ν emitted along the positive z-axis is then forbidden—it would carry off $-1/2$ spin projection, and the deficit cannot be made up. It immediately follows that $B_\nu = -1$, and similarly $A_{\beta+} = +1$, for these decays that lower the nuclear spin.

An interesting case, made possible by trap measurements of the recoils, is illustrated in figure 2. A fully-polarized nucleus decays to its isobaric analogue nucleus with same spin. If the ν is emitted directly upwards, the β^+ cannot be emitted directly downwards. This corresponds to the vanishing of a linear combination of A_β, B_ν, $F_{e\nu}$, and a. Since this is purely a helicity argument, this correlation vanishes at this extreme angle independent of the Fermi/Gamow–Teller ratio in the decay, and independent of isospin mixing of parent or daughter with other nuclear configurations of same I. This correlation can be measured best in β-recoil coincidences, though gathering statistics is challenging.

2.3. Different nuclear transitions are sensitive to different physics

Different nuclear transitions available to atom traps are sensitive to different C_X constants. The Fermi decay of $^{38\mathrm{m}}$K β–ν correlation pursued at TRIUMF is sensitive to combinations of C_S and C_S'. The Gamow–Teller decay of ^{6}He β–ν correlation pursued by the Seattle collaboration [35] is sensitive to combinations of C_T and C_T'. The ^{80}Rb and ^{82}Rb experiments at TRIUMF

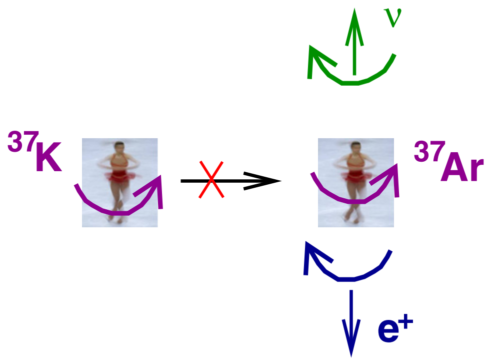

Figure 2. The leptons cannot be emitted this way in isobaric analogue decay. The decaying nucleus already has maximum spin projection, and the isobaric analogue twin decay product has the same total spin possible, so the leptons cannot add more (if they do not carry off orbital angular momentum). Recoil-β coincidences allow such measurements by determining the ν direction.

and Los Alamos are sensitive to different combinations of C_T and C_T' and to wrong-handed vector currents. The ^{21}Na mixed Fermi/Gamow–Teller β–ν correlation measured at Berkeley is sensitive to combinations of all constants, as are the spin-polarized experiments in ^{37}K pursued at TRIUMF. Further examples of all these transitions are found in neon isotopes, and development is ongoing at Hebrew University of Jerusalem to trap neon in metastable atomic states for this purpose [45]. The recoil spin asymmetry is insensitive to wrong-handed vector currents, while retaining sensitivity to scalar and tensor interactions, providing a tool to separate the new physics.

2.3.1. Recoil-order corrections. Experiments are now reaching the level of recoil-order corrections, a few tenths of a percent. In order to truly compete with the next generation of neutron decay angular correlation experiments, nuclear transitions must be chosen to minimize recoil-order corrections.

The pure Fermi case, $^{38\mathrm{m}}$K, is one of the well-characterized isobaric analogue superallowed ft cases. Radiative corrections produce real photons which, if undetected, perturb the momenta and produce a correction of ≈0.002 (corrected for in the Monte Carlo used in [36]). Recoil-order corrections enter at 3×10^{-4} [37] and are independent of nuclear structure. Second-order forbidden terms where the leptons carry off orbital angular momentum are suppressed to less than 10^{-6}.

In mixed Gamow–Teller/Fermi transitions, like that of the neutron, or ^{21}Na and ^{37}K below, the first-order in recoil induced tensor in the axial vector current—which is otherwise a nuclear-structure-dependent calculation—vanishes from isospin symmetry [37]. The first- and second-order recoil corrections in the vector current are given by the conserved vector current (CVC) hypothesis in terms of the electromagnetic moments [37]. In ^{37}K the weak magnetism is especially small because of the small magnetic moments of parent and progeny.

In the case of ^{6}He, while it is not such an isobaric analogue decay, the higher-order corrections in β-decay theory are either known or small. The recoil-order weak magnetism can be related to experimentally known M1 γ-ray decay by the CVC hypothesis. Although the first-class induced current d depends on nuclear structure, d is very small in this case because of accidentally favorable structure of the $A = 6$ nuclei [38].

2.4. New physics that contributes to β-decay

Typically direct exchange of leptoquarks (a particle explicitly changing a lepton into a quark) is considered as non-standard model physics contributing to β-decay. E.g., a spin-0 leptoquark can generate both 4-fermion Lorentz scalar and Lorentz tensor effective interactions. There are many constraints from other experiments, including proton decay limits, that tightly constrain such possibilities [39].

An explicit model has been worked out that does not need leptoquarks. One possible source of non-standard model scalar and tensor interactions is a higher-order interaction involving supersymmetric particles. Reference [40] has shown that if the entire SUSY space of parameters is considered, that left–right mixing between supersymmetric partners of the first-generation fermions can generate terms as large as 0.001 in the Fierz interference scalar–vector and tensor–axial vector terms. This left–right sfermion mixing is difficult to constrain in particle physics searches. This calculation has provided a benchmark for most of the correlation measurements discussed here. Null results at the Large Hadron Collider have moved up the mass scale of some but not all of the particles needed.

A powerful new constraint has been developed from the cross-section for $\mathrm{p} + \mathrm{p} \rightarrow e + \nu + X$ measured at the LHC. This reaction is related to β decay by an isospin rotation. This analysis constrains the sums of squares of C_X that contribute incoherently, and therefore cannot accidentally cancel [41]. These constraints are considerably tighter than present achieved experiments in β–ν correlations, though as in any effective field theory a scale is assumed which leaves some model dependence. There are also order-of-magnitude constraints from the interesting observation that wrong-helicity scalar and tensor interactions produce Lagrangian terms that give a mass to the standard model ν [42], which provide motivation to measure scalar and tensor interactions to determine how much they could contribute.

2.5. V_{ud} and isospin mixing in isobaric analogue decays

One motivation for measuring angular correlations in mixed Fermi/Gamow–Teller decays is to provide additional measurements of the Fermi strength and hence V_{ud}. This requires improvements in correlation measurements. The sensitivity has been worked out in detail in [43]. The systematically different dependence on isospin mixing could help test those calculations.

A MOT-based β asymmetry experiment is planned in ^{35}Ar by researchers at U. Leuven and U. Liege, as a case with most sensitivity for this purpose [44, 46].

Some of the observables considered here in ^{37}K and ^{21}Na decay are indeed relying on other measurements of V_{ud} and on theory calculations of isospin mixing [47]. We are trying to highlight observables that avoid this dependence.

2.5.1. Right-handed currents. Much of the parameter space in left–right symmetric models has been excluded in direct W searches that the LHC has extended to 2.5 TeV [48, 49] and in precision measurements of polarized μ decay [50]. However, in more complicated non-manifest left–right models, beta decay measurements with polarized nuclei are still useful [51, 52].

3. MOT-based β–ν correlations

In this section, we first sketch experimental methods for recoil-β coincidences with a MOT, and in the process identify complications arising from atomic physics. Then we summarize progress in experiments and show results.

3.1. Experimental methods

The low-energy (∼100 eV) nuclear recoils from β decay freely escape the MOT—they have transmuted to another element so the laser light no longer matters, and the B field is very small. Using an apparatus similar to figure 1, the recoils can be accelerated in a known electric field to a microchannel plate (MCP). Their time and position of arrival at the MCP, along with their known initial position in the trap cloud (which has size ∼1 mm), allows their momentum to be measured to within a few percent of its value. Together with measurement of the β momentum by more established detection techniques, this allows the reconstruction of the ν momentum in a much more direct fashion than possible previously.

Ions are produced ≈15% of the time in β^+ decay, and their kinetic energy is small enough that all angles can be collected efficiently by modest electric fields. One detection technique, microchannel plates, has between 50% and 70% detection quantum efficiency and excellent timing for the TOF measurements.

The electric field geometry is largely determined by the need to separate atomic charge states from each other, which provides enough info to determine the charge state and thus deduce the momentum. Another important constraint is to avoid backgrounds from atoms dwelling on electrodes by making them much larger diameter than the MCP.

There are geometry restrictions from the 1–2 cm diameter beams needed for the MOT, even if there is a second MOT simply catching atoms transferred from the first MOT. MOTs have been made with four beams [9, 53], but this does not help the geometry much. A dipole force trap, which can be formed by a single small-diameter beam, can solve much of this problem, if ways can be found to load it efficiently without producing backgrounds from untrapped slowly-moving atoms. Atoms have been transferred by carrying them in dipole force traps with focus mechanically moved, yet to gain efficiency have still used a MOT-like destination [54].

The uniformity of response to ions across the MCP is important for an angular distribution measurement. This can be done by calibration with ion beams [55]. It can also be done by selecting events kinematically that uniformly illuminate the MCP independent of the value of a [56].

Direct detection of the β energy is as difficult as with any other β-decay experiment, because of the detected energy loss from backscattered βs and from bremsstrahlung. However, there are kinematic regimes—recoil momenta less than Q/c, where Q is the maximum β kinetic energy—for which the β energy is uniquely defined from the other kinematic observables [57]. This allows the β energy to be deduced from the recoil momentum and the β direction, a very important technique at energies much less than the maximum for a given decay. It also allows unique construction of $\cos(\theta_{\beta\nu})$ for such recoils.

The low-energy atomic 'shakeoff' electrons emitted in the process can also be detected, using the same electric field. They can be used as a TOF trigger to measure the recoil momentum independently of the β [59]. The recoil momentum spectrum is sensitive to the β–ν correlation [58]. Since a large fraction of the electrons can be detected, this is an inherently high-statistics method compared to β-recoil coincidences. The shakeoff electrons can also simply be used as an indication of true decay events originating from the trap.

The atom cloud position and size can be measured by photoionizing a small fraction of the atoms with a pulsed laser. The photoions are then accelerated and collected with the same apparatus that detects the β-decay recoils, making a three-dimensional image of the cloud. This is critical to test for different cloud position as a function of polarization state when the sign of the optical pumping is flipped, and is also critical for the absolute atom location for β–ν correlations [36, 60]. By measuring the acceleration of the ion placed in the field, it also provides a textbook measurement of the average electric field.

Sometimes the neutral atom recoils can be detected in an MCP as well. E.g., the noble gas neutral atoms that are often the progeny of β^+ decay of alkali atoms form in metastable excited states roughly half the time, and these can produce secondary electron emission from MCPs at any energy. If they can be detected, the provide valuable information on the distance from atom trap to MCP that is independent of the electric field knowledge.

3.1.1. Trap-produced perturbations. Since the atoms trapped are not ideal point particles, it is important to note some of the complications produced by atomic physics and trap effects. More details of these effects can be found in [1], and they are only summarized briefly here.

Formation of ultracold molecules. Formation of molecular dimers is well-studied in MOTs for stable species [61]. The angle of the recoil can be perturbed by the existence of the other atom, as modeled by the Berkeley group [59], or in some cases the magnetic moment of the molecule allows it to be weakly trapped in the MOT's magnetostatic field. The main mechanism scales with the excitation rate of the atoms in the MOT. The distortion measured in a in ^{21}Na decay was as large as 7% with 5×10^5 atoms trapped, and was suppressed by Berkeley using a 'dark spot' MOT with atomic excitation rate minimized at trap center. It should be possible to control the excitation rate in any second MOT setup once the atoms have been transferred, after which laser detuning and intensity can be freely manipulated.

Atomic charge state dependence on recoil momentum. Work at Berkeley and TRIUMF has confronted an additional systematic error common to most other recoil momentum measurements, the possibility that the final atomic charge state depends on recoil momentum [63]. If the charge state of the atom depends on recoil or β momentum, the deduced angular correlations are perturbed. This can be fit simultaneously because it has a known and different dependence on the momentum spectrum than changes in a do, and this was done both in the Oak Ridge ^{6}He work [62] and in the TRIUMF $^{38\mathrm{m}}$K work. No correction was made in $^{38\mathrm{m}}$K with less than 0.002 change in a deduced [36]. This effect was constrained by calculation to be a negligible correction in the ^{21}Na work [63]. In the Seattle ^{6}He experiment accurate modern calculations are being done in this two-electron atom [64]. An upgrade of the TRIUMF work considers it essential in $^{38\mathrm{m}}$K to use a large enough electric field to fully separate the various charge states by TOF to allow for a simultaneous fit of this effect at the accuracy required.

Shakeoff electron measurements. A first measurement of the low-energy (below 30 eV) spectrum of atomic electrons from the decay of ^{37}K has been done at TRIUMF. The MOT quadrupole B field focusses electrons to the finite-sized electron MCP depending on their momentum, forming an integral spectrometer. The quadrupole field is then swept sinusoidally in time using an 'ac MOT' (see subsection 4.2.3) The results indicate somewhat higher electron energies than expected from extrapolations [66] of exact hydrogenic calculations in the literature [65]. These should be contained within the electron MCP to avoid biasing the kinematic observables, so these measurements will be pursued with a position-dependent electron detector.

The timing spectrum between β and electron shows no evidence for the known Ar$^-$ metastable state with known mean lifetime $\tau = 260$ ns [67]. The resulting upper limit on false A_β from Ar$^-$ metastable production is less than 0.08%.

3.2. Results and status of β–ν correlation experiments

3.2.1. β–ν correlation of $^{38\mathrm{m}}$K. TRIUMF's Neutral Atom Trap (TRINAT) group published result for the combination of coefficients $a/(1 + bm_\beta/\langle E_\beta\rangle) = 0.9981 \pm 0.0030$ (statistical)

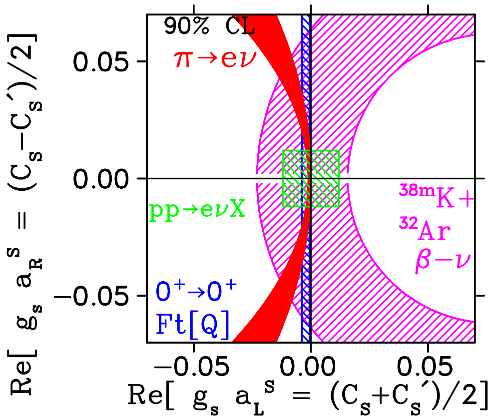

Figure 3. Constraints at 90% CL on scalar interactions. Blue rectangle is from 0^+ to 0^+ ft values dependence on Q and their constraint of the Fierz term [70]. The weighted average of TRINAT ^{38m}K β–ν correlation [36] and Seattle-ISOLDE (non-trap β-delayed p emission) ^{32}Ar [69] is the magenta ring. The EFT constraint from LHC pp→ e ν X [41] is the green box. The EFT treatment of the $(\pi \rightarrow e\nu)/(\pi \rightarrow \mu\nu)$ branching ratio is the narrow red boomerang [71]. (To plot the results of [41] and [71] we assume the centroid value of the scalar form factor $g_S = 1.02 \pm 0.11$ from [72]).

± 0.0037 (systematic) [36]. This is a slightly more accurate result than the Seattle/Notre Dame/ISOLDE work in β-delayed proton decay of ^{32}Ar [68, 69], which set the previous best general limits on scalars coupling to the first generation of particles.

Limits on scalar couplings. The limits on scalar interactions from two direct β-decay sources and two indirect experiments are shown in figure 3. The horizontal axis is the strength of scalar interactions that couple to normal-chirality νs, while the vertical axis is the strength of scalar interactions that couple to wrong-chirality νs. There are tight constraints on the scalar–vector Fierz interference term from the superallowed ft values as a function of energy release [70], because the Fierz term depends on the β energy (equations (2)). The β–ν correlation sets more general constraints on scalars that couple to either left or right-handed neutrinos [68]. The β–ν correlation results from ^{32}Ar have the same centroid as ^{38m}K with somewhat larger total error [69], and when that final error is decided the allowed area will decrease somewhat. Powerful but model-dependent constraints from $\pi \rightarrow e\nu$ decay are considered in [71]. A scalar interaction coupling to right-handed neutrinos produces a mass for the standard model neutrino, and order-of-magnitude estimates for this effect were done in [42].

3.2.2. Upgrade plans ^{38m}K. An upgrade using TRINAT is planned [73] with a goal of 0.001 error in a. Most systematic errors were determined from *in situ* calibrations using parts of the data set insensitive to a, and so were determined by counting statistics. Most of the errors in ion detection efficiency as a function of angle and position and in knowledge of the electric field would be made smaller if all ions are collected onto the ion detector. So an electric field to collect all ions is planned (in a philosophy similar to the Nab neutron decay experiment that plans to collect all protons). Such an electric field will also completely separate charge states +1 and +2 in TOF, allowing better determination of recoil-momentum-dependent electron shakeoff (see section 3.1.1). If the field is kept reasonably uniform by careful calculation of the potentials and geometry, its uniformity can be characterized well by combining TOF of zero-velocity photoions, the fastest TOF ions, and the slowest ones that started at maximum velocity in the wrong direction.

These specifications require a much larger ion detector (80 versus 25 mm) with good time and position resolution. To keep ions produced by atoms on surfaces from reaching the MCP, a much larger diameter for the field electrodes and larger vacuum chamber is needed. A larger β detector is needed to increase the efficiency of collection.

Overdetermined kinematics for most of the events ($p_{recoil} \leqslant Q/c$) also allow for determination of the β energy from other kinematic observables [57]. This should allow the separation of a from the Fierz term bm_β/E_β, removing the difficulty of understanding the β detector lineshape at small fractions of the highest β energy (in this case 5 MeV).

The recoil momentum spectrum will also be measured by coincidences between the recoils and the shakeoff electrons. This could lead to statistical 0.002 accuracy in b [73]. It remains to be seen whether systematic errors will be tolerable.

3.2.3. β–ν correlation of ^{21}Na. The laser-trapping group of Lawrence Berkeley Lab measured for the ^{21}Na $a = 0.551 \pm 0.0013 \pm 0.006$ [55], a measurement supported with more detail on a trapped-atom density-dependent effect in later work [59]. They developed the shakeoff electron-recoil coincidence high-statistics technique to use to test systematic errors [59].

3.2.4. ^{6}He. A collaboration has formed to measure the ^{6}He β–ν correlation. The collaboration has separately trapped ^{6}He in a MOT for a charge radius measurement [22], and built instrumentation for the ^{6}He$^+$ β–ν correlation carried out at the LPCTrap in CAEN [3]. At the University of Washington's tandem, ^{6}He is produced by ^{7}Li(d,^{3}He) reaction and an apparatus has been developed that can deliver $\sim 10^9$/s to the atomic experiments [74].

A uniform electric field apparatus similar to TRIUMF and Berkeley has been built [75]. The nuclear recoils have relatively high maximum kinetic energy, and the anticipated field will not collect all the recoils. A ^{6}He MOT is working with enough intensity for β–ν experiments, and first coincidences between βs and recoil ions in the detection trap chamber have been seen [35].

3.3. Beta–neutrino correlation summary

Figure 4 summarizes the contribution of β–ν correlation measurements to our knowledge of the Lorentz structure of the weak interaction, including the trap work in ^{21}Na and ^{38m}K. On the horizontal axis is plotted a variable showing the degree of Fermi versus Gamow–Teller strengths. The solid line shows the prediction of V and A interactions. Note that the relative sign between V and A is not determined, as the β–ν correlation is not sensitive to parity violation. The dashed line shows the prediction of a pure S,T theory. The history of this plot is quite interesting, as in the late 1950s and early 1960s there were conflicting experimental results in the ^{6}He $\beta\nu$ measurement. The eventual accepted measurement of a in ^{6}He [58, 96], together with the other measurements of figure 4, produces tight constraints in agreement with the interaction being purely V and A.

An analysis showing constraints on the Fierz term from β–ν correlation measurements is included in [59]. The maximum E_β in these measurements is considerably higher than the electron mass, which limits the sensitivity to considerably less than other methods thus far [70, 99].

3.4. Exotic particle searches from missing mass spectra

Before considering spin-polarized experiments, we consider searches for massive neutrinos and other exotic particles using kinematic reconstruction from the other decay momenta.

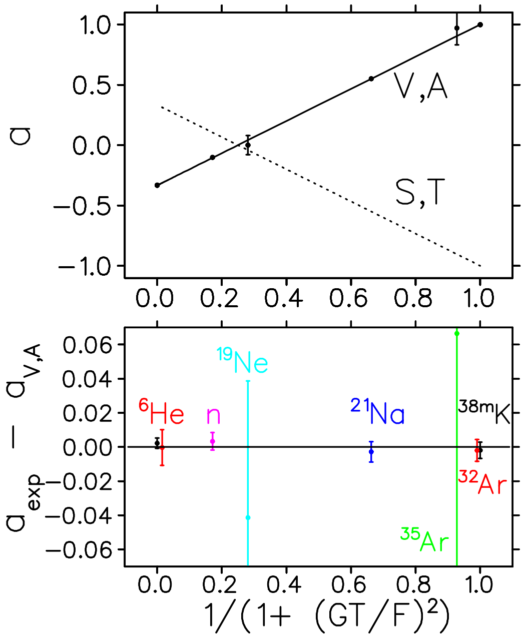

Figure 4. Present status of constraints on non-V,A interactions from measurements of the β–ν angular correlation coefficient a, updated from [95] (and as first plotted in [98]). The trap experiments in ^{21}Na [59] and $^{38\mathrm{m}}$K [36] are shown, along with ^{6}He [96] (the larger error bar falsely offset for display purposes from pure Gamow–Teller is from [3]), n [97], ^{19}Ne [98], ^{35}Ar [98], and ^{32}Ar [69] (offset falsely below pure Fermi), measurements by other techniques. 'GT' and 'F' are the Gamow–Teller and Fermi matrix elements, so the x-axis variable is unity for pure Fermi decay and zero for Gamow–Teller decay. The two trap-based β–ν correlation results show the utility of constraints with large Fermi components.

TRIUMF, using the neutral recoils from $^{38\mathrm{m}}$K decay, searched for admixtures of 0.7–3.5 MeV νs with the electron ν [77], searching for peaks in the equivalent of a missing mass spectrum for the ν. Astrophysical constraints on such νs can be evaded in low post-inflation reheating temperatures that produce fewer sterile νs [76]. The admixture upper limits are as small as 4×10^{-3}, and are the most stringent for νs (as opposed to $\bar{\nu}$s) in this mass range [78], although there are stronger indirect limits from other experiments. The three-body reconstruction is limited by the β detector energy response tail [77]. Though this technique is an improvement oversearching for kinks in β spectra, the sensitivity is limited by statistical fluctuations in the background and improves only with the square root of the counting time.

A more imaginative experimental proposal has been designed to measure the electron ν mass by β-recoil coincidences in the very small decay energy of tritium. It would, e.g., utilize electric field ionization of an optical lattice of Rydberg atoms excited by the passage of the low-energy β^- [79]. Such techniques could in principle search for keV sterile νs.

Two-body electron capture decay could provide a method free of the β detector response. A massive ν would produce a recoiling nucleus with lower momentum. There are complications from the high multiplicity of Auger electron and x-ray emission, as both can carry off substantial momentum and degrade the resolution, and detection Some details and possible isotopes are discussed in [1] section 2.3.

A trial two-body decay experiment at TRIUMF measured recoils with 2 eV kinetic energy from the γ decay of the 556 keV isomer in $^{86\mathrm{m}}$Rb. Here the recoiling atom is neutral, and

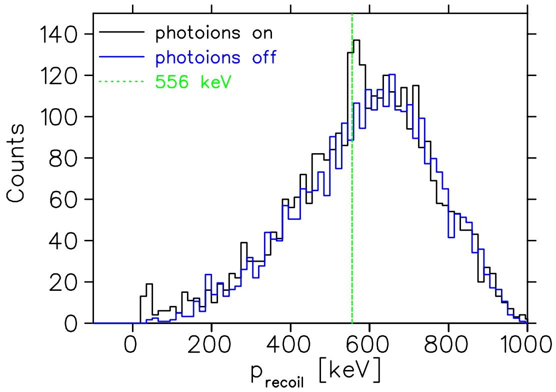

Figure 5. Recoils produced from the two-body 556 keV γ-ray decay of $^{86\mathrm{m}}$Rb make the small peak shown. The smooth background from accidental coincidences is measured with photoionization laser off. See text and [82].

was photoionized by Doppler-free two-photon ionization [81], a technique independent of the recoil momentum. The photoelectron was also detected and used as a TOF trigger. The experiment used high-momentum resolution spectrometer techniques developed for atomic physics experiments in the last decade, in particular TOF drift spaces and electrostatic lenses to make momentum resolution less dependent on cloud size [80]. Spectrometer calibration was done using the 2% internal conversion branch of $^{86\mathrm{m}}$Rb ejecting K and L electrons, which produced 920 keV momentum recoils with higher atomic charge states completely separated by TOF. The recoils from the massless γ-ray emission with full momentum 556 keV were identified, but the backgrounds from accidental coincidences were too large to place meaningful limits on massive particles producing lower-momentum recoils (figure 5). A substantial upgrade in photoionizing laser power could in principle produce 10^{-4} sensitivity [82] for massive spin 0 or spin 1 particles [83].

4. β-decay experiments with polarized nuclei

A variety of atomic methods exist to polarize laser-cooled neutral atoms and to accurately measure the polarization. For many experimental tests of maximal parity violation, the polarization must be known with error less than 0.1%. A key feature of the atom traps is that there are a variety of atomic methods to determine the degree of polarization independent of the nuclear decay.

There are a number of possible correlations to measure if the nuclei are polarized (see equations (2)). The momentum dependence of some observables can minimize the need for absolute polarization knowledge.

4.1. Experimental methods with polarized atoms in traps

The MOT has scrambled polarization and must be turned off. The laser light is straightforward with acousto-optical modulator switches. The magnetic quadrupole field can be extinguished to the level necessary in the presence of eddy currents by a variety of techniques, including the ac MOT [94] described in subsection 4.2.3.

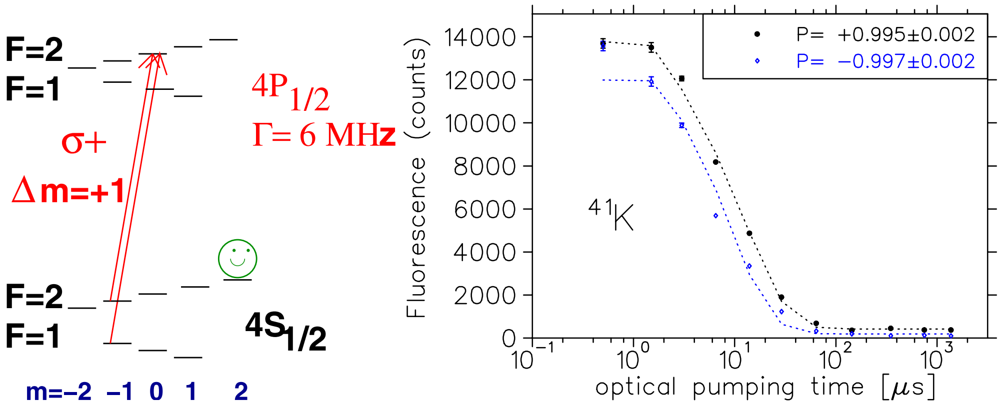

Figure 6. Left: optical pumping (see section 4.1.1). Right: the near-vanishing of the fluorescence from the optical pumping of ^{41}K atoms, which both produces and non-destructively measures the polarization of the atoms and nuclei.

4.1.1. Practical optical pumping. The atoms are typically polarized by optical pumping (see figure 6) [84]. Circularly polarized laser light shines on the atoms along the spin-polarization axis. The atoms are excited to Zeeman states with higher (or lower for σ^-) angular momentum projection, then decay spontaneously to states with possible spin projection changes $\delta \mathrm{m} = \pm 1$ or 0. The state population undergoes a biased random walk, which eventually puts all the atoms into the ground state with highest (or lowest) angular momentum. If the excited atomic state has the same total angular momentum as the ground state (e.g. in alkalis, a $\mathrm{S}_{1/2} \rightarrow \mathrm{P}_{1/2}$ transition), then after they are fully polarized, the atoms stop absorbing light, which minimizes heating of the atoms. The changing fraction of excited atoms provides a diagnostic for the degree of polarization. A sensitive probe is the rate of nonresonant photoionization by a pulsed laser with frequency that can ionize the excited state but not the ground state.

In principle optical pumping needs no magnetic field, because the quantization axis can be defined by the circularly polarized light. In practice, a small holding field helps. Decays can be measured with the MOT off and the cold atoms polarized and expanding freely, or a dipole force trap can be used to confine the atoms during optical pumping.

Alkali atoms need light at two frequencies to optically pump both ground states. This can produce a variety of coherent quantum mechanical phenomena as the photons perturb the atoms. Such effects can dramatically alter the simple picture presented so far. One example is termed coherent population trapping, considered a textbook atomic physics topic [85]. If the two frequencies are tuned to the hyperfine ground-state splitting, one of the two new eigenstates of the system does not absorb light at all, and the atoms are held in a state that is not fully polarized. It is straightforward to avoid this simply by detuning the frequency splitting.

The optical pumping considered so far requires mirrors for the light along the β detection axis, a major complication. A textbook scheme harnessed for electric dipole moment (EDM) experiments called transverse optical pumping [86] could simplify the geometry. Circularly polarized light at 90° to the B field is modulated at the Larmor precession frequency, and polarization builds up. Achieving 99.9% polarization would be challenging.

The B field coils complicate the geometry. Placing them in vacuum drops the inductance and makes them easier to turn off quickly, but βs scatter off them. There are laser-cooled atom traps with little or no magnetic field [87, 88] that in principle could be used.

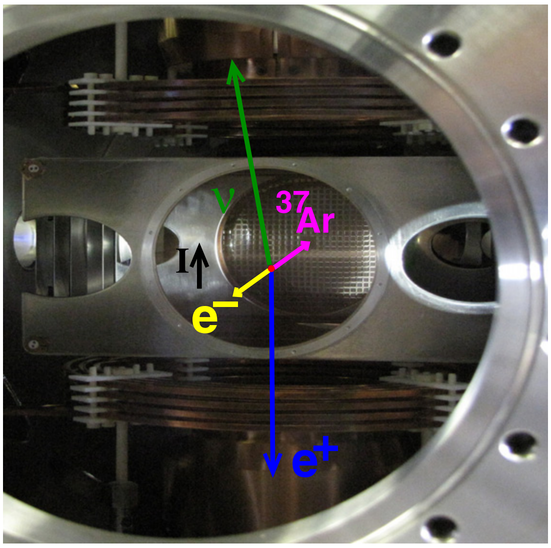

Figure 7. The apparatus of figure 1, illustrating the measurement of nuclear recoil, β^+, and shakeoff electron. **Q2**

Stress-induced birefringence of vacuum viewports can be a limitation to the circular polarized light quality and hence the polarization, and has been minimized by a variety of techniques including indium seals [89] and combinations of soft-metal wire seals and high temperature expoxies [90]. It is of course comparatively simple to use fluoroelastomer seals to relieve stress, but air permeation is a known limitation for ultra-high vacuum; PCTFE (polychlorotrifluoroethylene) may solve the permeation problem [91].

4.2. Experiment examples

4.2.1. Example: ^{82}*Rb.* After demonstrating polarization of ^{82}Rb ($t_{1/2}$ = 76 s) in a magnetostatic TOP trap [101], the Los Alamos trapping group has since loaded a dipole force trap with 10^4 atoms of ^{82}Rb [102]. They have achieved 99.2% ± 0.2% spin polarization for ^{87}Rb in a FORT, probing the polarization by a combination of microwave excitation, laser pushing, and atomic retrap techniques. Relatively high densities of atoms in the FORT produce interesting collective effects to improve the spin polarization—e.g. cross-sections for processes to eject unpolarized atoms from the trap have been shown to rise with density of mixed-spin atoms. The plan is to use this for ^{82}Rb β-decay correlation measurements [29].

4.2.2. Example: ^{37}*K.* TRIUMF does experiments with polarized ^{37}K by turning off the MOT and optically pumping the expanding cloud, cycling on few millisecond timescales.

Using this technique, nuclear vector polarizations of 97% ± 1% have been measured by the vanishing of excitation by $S_{1/2}$ to $P_{1/2}$ optical pumping as the ^{37}K atoms are polarized. Factors contributing to the imperfect polarization are discussed in the next subsection. An advantage of this technique is that the polarization of the same atoms that decay is continuously measured in a way that does not perturb the polarization. The neutrino asymmetry B_ν of ^{37}K has been measured to be $-0.755 \pm 0.020 \pm 0.013$, consistent with the standard model value with 3% error [60]. This is the first measurement of a neutrino asymmetry besides that of the neutron.

4.2.3. Upgrade: ^{37}K. The TRIUMF experiment is in the process of being completely upgraded by a collaboration including Texas A&M, U. Manitoba, and U. Tel Aviv [92, 93]. Statistics for a 0.02 measurement of the β and recoil asymmetry have been taken.

An ac MOT [94] allows the magnetic field to be switched off faster, by sinusoidally varying it (and flipping the MOT beam circular polarizations in sync) and switching if off when eddy currents are near zero. The B field has been switched off to 1% of its value in 100 μs. The width of Raman resonances in coherent population trapping has been used to determine the field inhomogenieties achieved to be less than about 10 milliGauss. How this translates into spin polarization depends on the competition between Larmor precession around the direction of the total B field and the optical pumping rate, but at optical pumping power presently delivered this limitation is at 0.2% level.

Counterpropagating optical pumping beams and stiffer SiC-backed mirrors have produced higher polarization and less movement of the atoms between spin states, reducing false asymmetries. The resulting polarization has been measured to be 99.6% $\pm$ 0.3% for ^{41}K (see figure 6) by methods that are being extended to be sensitive to the smaller number of ^{37}K atoms, with a goal of measuring the polarization of the atoms that undergo decay with similar accuracy.

Shakeoff electron coincidences are being used to tag events coming from the trap cloud, and greatly reduce background from untrapped atoms decaying from the walls of the chamber.

The microchannel plate must be elevated to 9 kV to reach the design goal for the E field, so extracting the fast signals with good impedance matching takes substantial care.

4.3. Spin asymmetry of recoils: search for tensor interactions

When parity violation was discovered, a large number of β-decay observables were suggested in the literature. Treiman noticed that the recoiling daughter nuclei from the β-decay of polarized nuclei have average spin asymmetry $A_{\mathrm{recoil}} \approx 5/8\ (A_\beta + B_\nu)$. This vanishes in the allowed approximation for pure Gamow–Teller decays in the standard model, making it a sensitive probe of new interactions [106]. It is a very attractive experimental observable, because knowledge of the nuclear polarization at the 1%–10% level is sufficient to be competitive.

Right-handed vector currents do not contribute, because they also cancel in the sum $(A_\beta + B_\nu)$. This leaves A_{recoil} uniquely sensitive to tensor interactions.

Using the detection of shakeoff electrons to determine the recoil TOF and momentum, TRIUMF has measured the recoil asymmetry with respect to the nuclear spin in ^{80}Rb, with result $A_{\mathrm{recoil}} = 0.015 \pm 0.029$ (stat) $\pm$ 0.019 (syst). The systematic error is limited by knowledge of first-order recoil corrections in this non-analogue Gamow–Teller transition, which can be constrained by the dependence of A_{recoil} on recoil momentum. This result puts limits on a product of left-handed and right-handed tensor interactions that are complementary to the best ^{6}He β–ν correlation experiment [107]. Much smaller statistical error is straightforward, but further progress requires either better nuclear structure-dependent calculations in difficult deformed nuclei, or extraction of recoil-order corrections by simultaneous measurement of other observables.

4.3.1. Recoil spin asymmetry in isobaric analogue decay. In the isobaric analogue decays, we have seen how the recoil-order corrections are much better understood. The prediction for the recoil spin asymmetry is nonzero, making the experiments more challenging. The existence of a Fierz interference term with different momentum dependence than in the ν spin asymmetry B_ν shows up here. The absolute polarization (if not determined by atomic techniques) can be floated and a non-standard model Lorentz tensor interaction can be searched for simultaneously. Possible trap candidates include ^{21}Na, ^{19}Ne, and ^{39}Ca, and this experiment is being pursued with ^{37}K at TRIUMF.

4.4. $F_{e,\nu}$

$F_{e,\nu}$ depends on the second-rank tensor alignment T, i.e. on the average value of I_z^2. Fully spin-polarized atoms have $T = -1$, while unpolarized atoms with equal population of all spin projections have $T = 0$. So the ratio of $F_{e,\nu}/a$ can be determined very accurately by changing alignment from 0 to -1, with all other systematics canceling. If accidental tensor-order alignment in the MOT beams can be avoided, the MOT-on data can be used naturally for the $T = 0$ measurement. This observable isolates the Gamow–Teller contribution in an isobaric analogue decay, and is sensitive to the absolute square of the Lorentz tensor terms.

4.5. Time-reversal violation

Because of the possibilities of achieving high efficiency of recoil detection and characterizing the atom cloud pointlike source position and polarization, it is natural in polarized β–ν coincidence measurements to consider the coefficient D of the time-reversal violating correlation from equations (2), $\hat{I} \cdot (\hat{p_\beta} \times \hat{p_\nu})$. This observable was immediately proposed after the discovery of parity violation [32]. Experiments have measured D using distributed sources in ^{19}Ne [103] and the neutron [104], with the latter measuring $D = -0.94 \pm 1.89 \pm 0.97 \times 10^{-4}$. Experiments in traps have been considered at TRIUMF, Berkeley, and KVI. An effective field theory treatment suggests that measurements of lower limits on EDMs coupled with other experiments constrain D to be less than 1×10^{-4} [105].

The geometry can be made more efficient for βs, because the polarization light is not along the β detection axis. Some gas detector windows are transparent enough to infrared light that trap and polarization light could go through them. Uniform electric fields can be generated with a symmetric arrangement of rods rather than open electrodes. Beta detection geometries of tens of percent are needed to try to contemplate the statistical accuracy at present numbers of atoms trapped in any facility.

4.5.1. Spin-independent time reversal. A new observable has been suggested that is not constrained by null EDM experiments, because it does not depend on any spin [34]. The case was worked out for ^{35}Ar, and several percent of the decays produce 100 keV γs. Detection of such γs has recently been demonstrated in neutron decay. There will be formidable backgrounds with higher-energy positrons in some trappable cases. The bremsstrahlung photons are highly correlated with the β direction, which will unfortunately suppress this triple scalar product. However, the new physics contributing to such a correlation is largely unconstrained, so a measurement at almost any accuracy would be interesting [34].

5. Conclusion

Neutral atom traps provide unique environments for precision experiments using radioactive isotopes. The first trap-based measurements in β-decay have been completed, and the results are improving constraints on interactions beyond the standard model. The ability to measure the momentum of the daughter nuclear recoils has produced two of the best β–ν correlation experiments. Adding the ability to reverse the spin of highly polarized atoms leads to unique observables with the potential to improve parity and time-reversal violation experiments.

Acknowledgments

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