1 Summary

In this progress report we will update the physics case for the $^{38\mathrm{m}}$K β-ν correlation, which remains compelling even in the presence of null results for new physics from the LHC. We will briefly discuss two competitor experiments in β-ν correlations from ion traps.

We will briefly describe the present status of our ^{37}K experiment, which is in the middle of taking a full data set on the beta asymmetry and hopefully recoil asymmetry and beta-nu correlation now.

We will qualitatively revisit the two intended experimental techniques for the $^{38\mathrm{m}}$K β-ν correlation experiment and describe what we need to implement them. In particular we will describe an ongoing upgrade to our shakeoff electron detector, and highlight our need to test its ability to reject background not in the trap.

It is especially important to do this for the case of interest, as the mass 38 beam includes the 7 minute half-life ^{38g}K with a 2.17 MeV γ-ray. We have seen in the past that this can migrate to the walls of the detection chamber, and need to test a simple reduction for this (we have installed an edge-welded bellows to impede migration).

Another important reason to use ^{38m}K is that we have reached much smaller cloud sizes (0.7 mm FWHM vs. 1.8 FWHM in ^{37}K), which enables better tests of timing and position resolution in this geometry. (The difficulties of cooling ^{41,37}K isotopes with narrow hyperfine splitting are well-known– the width quoted here is after implementing a clever cooling scheme [11] in the literature and is a nice improvement over our previous experiments.) We have since Gorelov 2005 Ref. [10] achieved 0.3 mm FWHM in ^{85}Rb by a combination of technical improvements that should translate well to $^{38\mathrm{m}}$K, but need to be tried on the nuclear spin I=0 isotope.

We included simulations and a projected table of systematic errors in the original proposal. Here we will limit ourselves to technical status and remaining progress needed to meet the design goals, and a brief discussion of the plans.

We note also that there is some synergy with the ^{37}K program. We can spin-polarize the I=0 $^{38\mathrm{m}}$K atom without changing its decay, and test the symmetry of the ^{37}K detection apparatus.

2 Physics case

2.1 Motivation: β decay after first LHC null results

The physics case remains compelling, but needs to be stated in some detail.

A new phenomenological analysis of the cross-section for p + p $\rightarrow$ e + ν constrains with LHC data both scalar and tensor couplings for mass scales higher than direct searches [3]. This is in some sense a precision measurement done at high energy. It is sensitive to the sum of the squares of the various amplitudes possible. It is not competitive with nuclear beta decay in couplings to normal-chirality neutrinos, so if we can become competitive measuring the Fierz interference term (see below) that would reach a better accuracy than this analysis.

However, the constraints on scalar and tensor couplings to wrong-chirality neutrinos are very powerful. We show these in Fig. 1. The constraints are not out of conceivable reach, though we would have to do better than proposed. Effective field theories (EFTs) must set a mass scale, here set quite high. Constraints actually become a little stronger with modestly less high mass scale

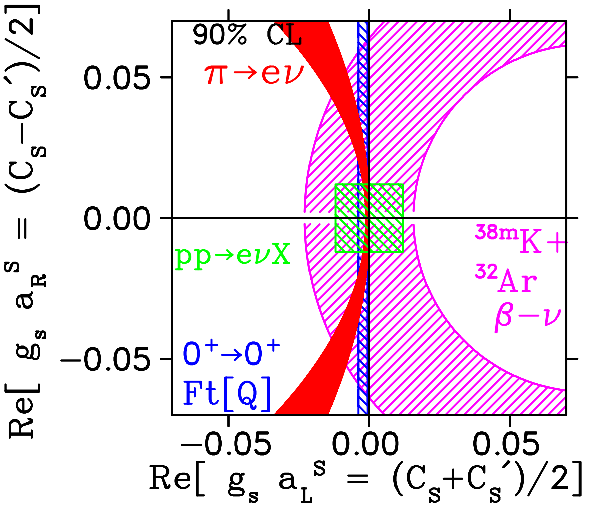

Figure 1: Constraints at 90% CL on scalar interactions. Blue rectangle is from 0^+ to 0^+ ft values dependence on Q and their constraint of the Fierz term [5]. The weighted average of TRINAT $^{38\mathrm{m}}$K β-ν correlation [10] and Seattle-ISOLDE (non-trap β-delayed p emission) ^{32}Ar [6] is the magenta ring. The EFT constraint from LHC pp→ e ν X [3] is the green box. The EFT treatment of the $(\pi \rightarrow e\nu)/(\pi \rightarrow \mu\nu)$ branching ratio is the narrow red boomerang [7]. (To plot the results of Refs. [3] and [7] we assume the centroid value of the scalar form factor $g_S = 1.02 \pm 0.11$ from [8]).

(V. Cirigliano, private communication) but one can fine-tune models to escape them. A scalar degenerate in mass to the W with small enough couplings, for example, escapes this analysis. Similar arguments apply to the EFT-based constraints from $\pi \rightarrow e\nu$ branch shown in Fig. 1.

A 2005 supersymmetry analysis [2] found regions of SUSY parameter space that could be constrained or measured by 0.001 accuracy measurements in β decay. Simplifying assumptions are typically made that don't consider some of these couplings, so β decay could be a suprisingly interesting probe. Theorists tell us that some of this space will be eliminated by null LHC results [4], though many of those depend in interesting ways on the mass of two partners at once, and a full reanalysis would be needed. We would not expect such an analysis to be undertaken without some serious advances in β decay experimental accuracy, which should be forthcoming in the next generation of experiments.

We are intrigued by a recent theory PRL [8] that believes it has calculated the scalar form factor for the nucleon needed to make such an exclusion plot, now believed consistent with unity. That paper also suggests a large enhancement of two orders of magnitude of the pseudoscalar form factor, normally ignored in beta decay because of its momentum dependence. We are not sure if we have higher-order sensitivity to this effect and should probably not have mentioned it, but it does indicate expanding theoretical interest in this field.

2.2 Progress in other experiments

There have been excellent advances in ^{6}He and ^{8}Li β-ν correlation work from ion traps [9], but we restrict ourselves here to scalar interactions.

The best limits on scalar interations coupling to normal-helicity neutrinos come from the Fierz term constraints from the lack of energy dependence of the superallowed Ft values (see Fig. 1). Our goal is not only to improve our constraints on more general scalar interactions, but to compete directly with our own measurement of the Fierz term. The accuracy of superallowed Ft values have improved, while the detailed dependence on different cases is typically being interpreted to test isospin mixing corrections within and across major shells. Such a comparison assumes no scalar interaction, which could be seen as a bias that limits its previous utility to constrain that scalar interaction, in ways that are difficult to define precisely. (We have only found [5] from 2005 explicitly working out scalar constraints; we are curious whether the large isospin mixing theory change near 2008 is thought to change the scalar constraints.)

Two experiments elsewhere are now pursuing β-ν correlations to limit scalar interactions, the WITCH experiment at ISOLDE and the LPC trap of Caen at GANIL. WITCH has made a first proof of principle with large statistical error. The Caen group has taken a data set with statistical error 0.002 with systematics under analysis[1]. The nucleus in both cases in ^{35}Ar, a mixed Fermi/Gamow-Teller decay with a known small GT component. The physics motivation there is usually said to be another measurement of Vud with different corrections, not a test of scalar interactions.

If such errors are achieved systematically, they will begin to require accurate isospin mixing corrections to the Fermi/Gamow-Teller ratio, along with recoil-order corrections. Even in an isobaric analog nucleus, there are some limitations to this process, particularly for spin greater than 1/2 (e.g. a 2nd-order in recoil axial vector contribution with some nuclear structure dependence). In pure Fermi decays such as ^{38m}K, there are no such corrections until 0.0001 level, and isospin mixing does not change the angular correlation. So we believe it will remain important to pursue a pure Fermi case.

3 TRINAT experimental progress

Experimental progress: The ^{37}K experiment S1188, spokesperson D. Melconian, took data in December 2012 with several percent statistical error for β and recoil asymmetry experiments and a β-ν correlation.

Yields 2014 The experiment is continuing now; yields of ^{37}K were 1x10^{-8} from 70 μA of protons on high-power TiC, two to three times the yields achieved in 2005. The yield increased more than an order of magnitude from 50 to 70 μA, and the high-power target is not thought to be at full temperature yet. We have trapped about 4,000 ^{37}K atoms, more than before. We would expect similar production and trapping of ^{38m}K, as the half-lives are similar, and in the past the yields have been similar from TiC.

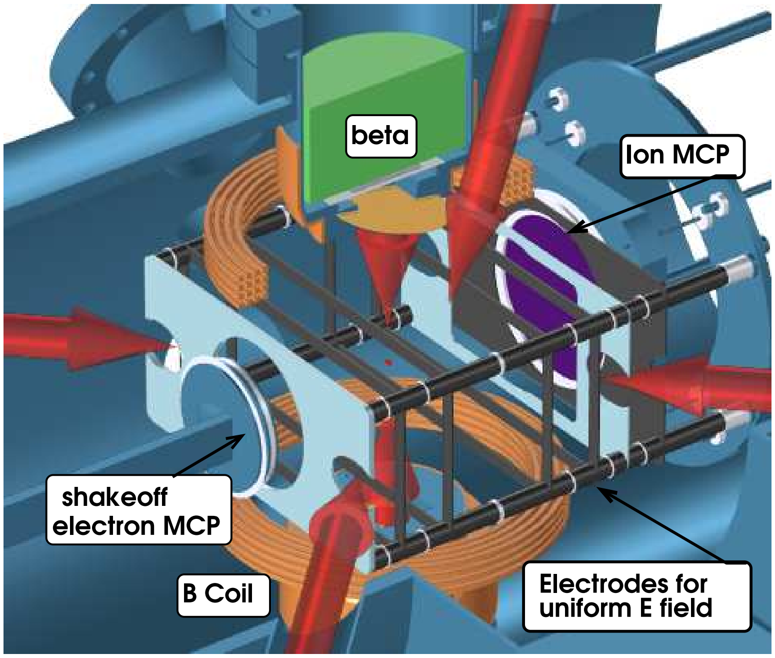

Figure 2: The present TRINAT detection MOT apparatus. Magnetic field coils with current in opposite directions produce a B field with gradient ∼ 10 Gauss/cm that changes sign at the origin. All MOT ingoing beams have the same helicity, which means opposing beams either increase or decrease angular momentum, 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.

3.1 ^{37}K technical progress sketch

We sketch the present ^{37}K apparatus (Fig. 2), and then discuss contemplated modifications for ^{38m}K.

An AC MOT [12] 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 asymme-

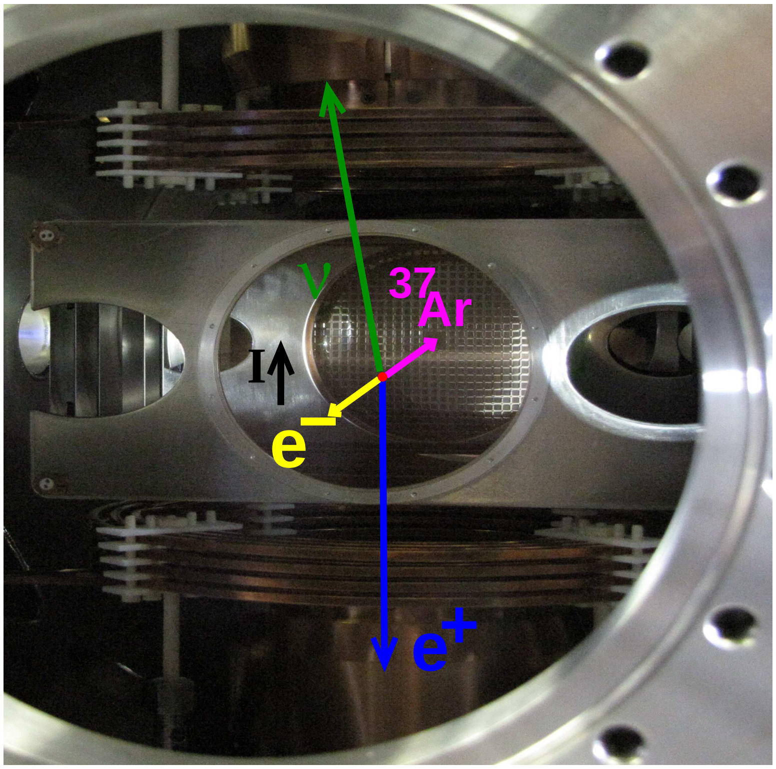

Figure 3: The apparatus of Fig. 2, illustrating the measurement of nuclear recoil, β^+, and shakeoff electron.

tries. The resulting polarization has been measured to be 99.6±0.3% for ^{41}K 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.

3.2 Relevance to ^{38m}K

3.2.1 Qualitative needs

First a qualitative description of what we need. This might stand alone adequately without referring to the full proposal.

S1070 has 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 Ref. [10]). 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 mm vs. 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 ($\mathrm{p}_{\mathrm{recoil}} \leq \mathrm{Q/c}$) also allow for determination of the β energy from other kinematic observables [13]. 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).

That is the primary method, the β-recoil coincidence method. A second, higher-statistics method would measure the recoil momentum spectrum by coincidences between the recoils and the shakeoff electrons. This could lead to statistical 0.002 accuracy in b [14]. For the same number of decays, this method has much better statistical accuracy than any forseeable trap-based geometry for β-recoil coincidences, because of the limitation of β solid angle in the geometries with space taken by MOT beams. (Dipole force traps have been contemplated, but there are technical difficulties and potentially large backgrounds from poor loading.)

However, the percentage change in observables as $a_{\beta-\nu}$ changes is considerably smaller for the recoil momentum spectrum, so systematic errors become a higher fraction of the contribution. It is difficult to anticipate all systematic errors, so we want to explore them in the present apparatus. We are analyzing the ^{37}K data for $a_{\beta-\nu}$ (the thesis project of a local student) but some systematics require the actual isotope. E.g. we achieved smaller trap clouds in the ideal $^{38\mathrm{m}}$K atom because of technical limitations in cooling the ^{37}K atom with its narrow hyperfine splitting and overlapping atomic states.

3.2.2 Modifications contemplated

We list some technical modifications contemplated for S1070. We believe the modifications need some testing with ^{38m}K before a final design is constructed.

Electric Field

The electric field uniformity is somewhat compromised in this ^{37}K design by the relatively large gap between the central electrodes, needed to allow the optical pumping light and vertical MOT beams to enter. Replacing the β detectors with viewports would allow the field to be much more uniform. Then the electron MCP would be replaced with a large β detector for a geometry similar to Gorelov 2005 [10].

However, one main reason to build the vacuum chamber this large was to allow for electrostatic rings of large enough diameter that background from decaying atoms on the rings can't reach the periphery of the 80 mm diameter MCP. This is calculable– what is not calculable is how much our new position-dependent electron detector can suppress such backgrounds without this requirement. It is a major decision to change this field assembly– it requires either removing the coils from the vacuum to make room for the field, or an entire new vacuum chamber. It will help enormously to try out these effects first with $^{38\mathrm{m}}$K.

The microchannel plate must be elevated to 9 kV to reach the design goal of 1 kV/cm for the E field, so extracting the fast signals with good impedance matching takes substantial care in the design. This has proven to be a large technical challenge that has not yet been met. The electrostatic field is adequate, and the difficulty is elevating the commercial MCP and delay-line anode design. This is work in progress, but we may need to put a mesh in between the electric field region and ion MCP to allow the ion MCP to sit at its commercially designed potential.

3.2.3 dimers

We want to find a signature for molecular dimers at higher cloud density and control their formation if we find them. This was a known effect in Berkeley's ^{21}Na experiments, producing several percent effects. Naive scaling by isotope lifetimes will suppress such effects in ^{38m}K, but the rates of dimer formation are unknown if not measured. We had proposed earlier using the AC MOT to eject dimers, but we now believe that stability criterion for the magnetostatic field and adiabatically following of the spin at our low frequency that this is unlikely to provide much suppression. Instead, photoassisted dimers formation rate will scale with laser intensity, a simpler extrapolation to low formation than varying the density. We have full control of light frequency and intensity in our second MOT now, and can suppress the dimers this way, similar to what Berkeley achieved with a 'dark spot' MOT [15]. We want to design this into the final apparatus and want to characterize this now that the yields have risen.

4 Request and summary

Our shift request is 6 shifts for the present ^{37}K geometry within the next year or so (i.e. in the next ^{37}K beamtime). The experiment remains a compelling test of the standard model for low-energy beta decay, with smaller higher-order corrections than even in neutron beta decay. It will help us enormously to begin development on several new features on $^{38\mathrm{m}}$K with its 38gK background (smaller cloud size, molecular dimer formation, backgrounds with electron-recoil coincidences with position-sensitive detector) now rather than try to design the full apparatus without this data.

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