Scalar Interaction Limits from the β-ν Correlation of Trapped Radioactive Atoms

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We have set limits on contributions of scalar interactions to nuclear β decay. A magneto-optical trap provides a localized source of atoms suspended in space, so the low-energy recoiling nuclei can freely escape and be detected in coincidence with the β. This allows reconstruction of the neutrino momentum, and the measurement of the β-ν correlation, in a more direct fashion than previously possible. The β-ν correlation parameter of the $0^+ \rightarrow 0^+$ pure Fermi decay of $^{38}K^m$ is $\tilde{a} = 0.9981 \pm 0.0030\,^{+0.0032}_{-0.0037}$, consistent with the standard model prediction $\tilde{a} = 1$.

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The angular correlation of neutrinos and betas in nuclear beta decay is historically one of the main experimental probes of the vector and axial vector nature of the weak interaction [1]. A recent experiment using ^{32}Ar decay is the only β-ν correlation measurement in pure Fermi decay, which is sensitive to scalar interactions [2].

We use a magneto-optical trap (MOT) [3] to provide a backing-free source of atoms with well-defined position and negligible thermal energy. We then detect the low-energy nuclear recoil in coincidence with the emitted β^+, and directly deduce the ν direction and the β^+-ν correlation. We also determine critical response functions of our detectors *in situ* from the decays themselves. Atom trap β-ν experiments are also pursued elsewhere [4].

In the $0^+ \rightarrow 0^+$ Fermi decays the leptons carry away no net angular momentum. Back-to-back β-ν emission is forbidden in the standard model, because the W vector boson exchange produces leptons with opposite helicity and their spins add to one. The angular distribution is

$$W(\theta_{\beta\nu}) = 1 + b\frac{m_\beta}{E_\beta} + a\frac{\mathrm{v}_\beta}{\mathrm{c}}\cos(\theta_{\beta\nu}).$$

The β-ν coefficient a is $+1$ for W exchange, and a is -1 for a scalar boson producing same-helicity leptons. In terms of scalar coupling constants C_S and C_S', and assuming for simplicity $C_V = C_V' = 1$ [5]

$$a = [2 - (|C_S|^2 + |C_S'|^2)]/(2 + |C_S|^2 + |C_S'|^2),$$

$$b = -2\sqrt{1-(\alpha Z)^2}\,\mathrm{Re}(C_S + C_S')/(2 + |C_S|^2 + |C_S'|^2)$$

The limit on the Fierz interference term b from the dependence of $0^+ \rightarrow 0^+$ decay strengths on $\langle E_\beta \rangle$ is very stringent, $b = -0.0027 \pm 0.0029$ [6], but the coupling $C_S + C_S'$ describes scalars that couple only to the left-handed ν. Measurements of a constrain scalar interactions independent of chirality or time-reversal properties [2,7].

The isobaric analog decays of the pure Fermi transitions are well characterized. Lowest recoil-order corrections to the allowed approximation value of $a = 1$ ($< 3 \times 10^{-4}$ in our case, $^{38}K^m$) do not depend on nuclear structure, and higher order corrections are <0.0002 [8,9]. Radiative corrections (see below) [9] can also be calculated to the order required independent of nuclear structure. In addition, $^{38}K^m$ decay is known to proceed cleanly to the ground state, with experimental limits on excited-state branches of $<2 \times 10^{-5}$ [10]. Disagreement with $a = 1$ greater than these corrections would be from a standard model-violating scalar interaction.

A scalar term could be produced by the exchange of scalar bosons found in standard model extensions [7]. There is a phenomenological window open for sleptons, although couplings to the first generation are thought to be small [7]. A QCD-induced scalar interaction is a second-class current that is $<5 \times 10^{-5}$ in the standard model [11]. β-ν correlations are complementary to scalar constraints from pseudoscalar $\pi \rightarrow \nu e$ decay [12]. The possibility of constraining scalar interactions from loop corrections to ν masses is considered in Ref. [13]. The best previous β-ν experiment used β-delayed protons from ^{32}Ar decay to determine $\tilde{a} = a/(1 + bm_\beta/\langle E_\beta \rangle)$ to be $0.9989 \pm 0.0052 \pm 0.0036$ [2].

Our apparatus was also used to constrain massive ν_x-ν_e admixtures [14]. A beam of $^{38}K^m$ ($t_{1/2} = 0.924$ s, $Q_{\beta^+} = 5.022$ MeV) is produced at TRIUMF's ISAC facilities [15], stopped and released as neutral atoms with a 900 °C Zr foil [16], and captured with $\approx 10^{-3}$ efficiency in a vapor-cell MOT. The MOT traps only the $^{38}K^m$ and none of the ground state ^{38}K beam contaminant. To escape backgrounds from untrapped atoms of ^{38}K and ^{38}K^m, we transfer the trapped atoms with 75% efficiency by a chopped laser push beam to a 2nd MOT equipped with the nuclear detectors (Fig. 1). The duty cycle entails the following: push atoms from the first trap for 20 ms, wait 50 ms to transfer, change the 2nd MOT laser frequency and power to minimize cloud size, wait 1 ms to let cloud reach equilibrium, count for 150 ms, repeat [17]. No atoms are lost from the trap during the frequency switch. The MOT force uses laser light and a weak ($dB_z/dz = 20$ G/cm) magnetic quadrupole field, so the Ar recoils escape the trap without perturbation. We accelerate the positive Ar ions produced by electron shakeoff [18] with a uniform electrostatic field to separate them in time of flight (TOF) from the neutral Ar^0 atoms.

The β telescope is a position-sensitive $22 \times 22 \times 0.49$ mm double-sided Si-strip detector (DSSSD) backed by a $\varnothing 6.5$ cm $\times$ 5.5 cm long BC408 plastic scintillator, and is separated from the trap vacuum by a 125 μm thick Be foil located 2 mm from the DSSSD to minimize angle straggling. The telescope coincidence rejects 95% of the 2.17 MeV γ rays from untrapped ^{38}K ground state. The gain is actively stabilized at the low count rates of $<$200 Hz using a stabilized light pulser.

The Ar recoils, which have 0–430 eV of initial kinetic energy, are detected by a Z stack of three uncoated microchannel plates (MCP). A fixed aperture defines a 24.0 mm active diameter for the TOF[E_β] analysis (see below). The resistive anode position readout is calibrated with a mask and an α source to have 0.25 mm resolution within the 20 mm diameter used for the reconstructed angular distribution analysis. The E field accelerates the Ar^{+1} ions to 4.8–5.3 keV. We measured the MCP efficiency in this energy range to be constant to accuracy 0.0060 by comparing the rate of β-recoil coincidences for four values of $E_{\hat{z}}$. The β-ν correlation analysis is done with the ions, because the efficiency for neutral recoils is not as well understood. The angle dependence of the MCP efficiency was assumed constant over the small impact angles of $\pm 5°$, with error (Table I) spanning the small effect seen in the literature [19], consistent with our analysis of recoils that uniformly illuminate the MCP.

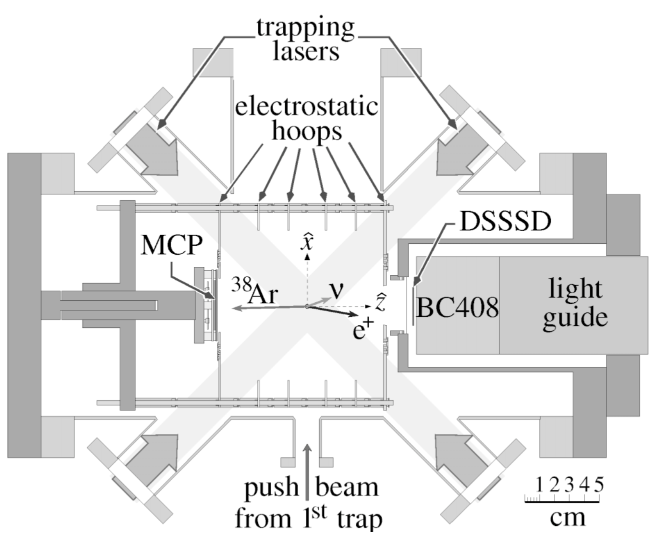

FIG. 1. Top view of the 2nd MOT apparatus with the recoil and β detectors.

We maintain a population of ≈ 2000 atoms of ^{38}K^m in the detection MOT. The trap lifetime, limited by residual gas, is 45 s, so 97% of the ^{38}K^m atoms decay while in the trap. Atoms on the walls produce a β^+ singles background of $<$2% and a negligible coincidence background consistent with accidental coincidences, measured by deliberately releasing the atoms to the walls. Ions from the walls are excluded from the MCP by the electric field. Ions from the trap strike no material before reaching the MCP. The E field electrodes are made from glassy carbon to minimize β^+ scattering effects.

The average trap-MCP distance is determined to be 61.08 ± 0.01 mm from a fit to the leading edge of the TOF peak of the fastest Ar^0 recoils (Fig. 2). These were shown to be Ar^0 by applying the E fields of 400 and 800 V/cm; the leading edge was undistorted by any detection of the $\tau_e = 260$ ns [20] Ar$^-$ metastable state.

We image the cloud by photoionizing a small fraction of the ^{38}K^m atoms with a pulsed laser and accelerating them to the MCP. The $\hat{x}$, $\hat{y}$, and $\hat{z}$ distributions (see Fig. 1) are fit well with Gaussians of 0.8, 1.1, and 0.65 mm FWHM. The $\hat{z}$ distribution (along the trap-MCP axis) limits the timing resolution for Ar^{+1} recoils to 5 ns. Two CCD cameras image the trap laser fluorescence, and the trap centroid was kept constant to ± 0.05 mm.

We performed two independent analyses of the data set. In the first analysis, we fit the TOF spectra of ion recoils for various β^+ energy cuts (Fig. 3) to a Monte Carlo (MC) simulation based on GEANT [21]. Qualitatively, for fixed E_β, the recoil TOF increases monotonically with $\cos(\theta_{\beta\nu})$. The TOF of the ions with most sensitivity to a increases with decreasing E_β. We fit simultaneously to Ar$^{+1,+2,+3}$ charge states.

In the second analysis we use the complete momentum information measured for the β and the recoil to deduce

TABLE I. List of $\tilde{a}$ uncorrelated systematic errors.

$\langle E \rangle$ field/trap width:	0.0017
E field nonuniformity	0.0014
$E_{\beta+}$ Detector Response:	
Line shape tail/total 0.101 ± 0.006	0.0006
511 keV Compton summing/total to 10%	0.0009
Calibration including nonlinearity	0.0017
MCP Eff[E_{Ar^+}] measured constant 4.8–5.3 keV	0.0007
MCP Eff[θ]/XY trap position	0.0008
e^- shakeoff dependence on p_{recoil} $s = 0^{-0}_{+.014}$	$^{+0}_{-0.0018}$

the momentum of the ν and the β-ν angle (Fig. 3). The kinematics are overdetermined for $p_{\rm recoil} < Q_{\beta+}/c$ [22], so this was done either using the measured E_β or determining it from the recoil momentum. The measured angular distribution is fit to the MC simulation as a function of a, and agrees with the TOF[E_β] analysis.

We present the details of the TOF[E_β] analysis and detailed evaluation of systematic errors. This analysis lets us constrain critical physical and instrumental effects, but requires excellent β telescope characterization. Table I shows systematic errors, determined by MC simulations varying each parameter by its possible error and determining its effect on a, with other parameters refit as appropriate. Some errors in the table are summaries of more than one correlated systematic error. These line items are uncorrelated, so we add them in quadrature to determine the total systematic error.

We can test the MC simulation of the β^+ energy line shape response with the β-recoil coincidences. From Fig. 2, the E_β spectra in coincidence with neutral recoils for TOF intervals from 1500–1800 ns are peaks determined by the detector resolution and the angular acceptance, and a tail determined by β^+ backscatter, bremsstrahlung, and $\sim$20% of the tail from scattering off inactive volumes. From this and from detailed kinematic reconstruction of the β-Ar^{+1} coincidences, we have determined that both the size of this tail and the 511 keV Compton summing agree with the MC simulation; they are listed in Table I.

The E_β calibration is determined by a MC fit to the energy spectrum in coincidence with recoils with 370 ns $\leq$ TOF $\leq$ 900 ns, which includes all the observed Ar$^{+1,+2,+3}$ recoils. We use the expression $x_{ADC} = x_0 + c_2\ T_\beta/(1 + qT_\beta)$, with nonlinear term $q = (0.33 \pm 1.49) \times 10^{-3}$ MeV^{-1}. The calibration parameters are not sensitive to the value of a. Use of an E_β calibration determined from the β singles spectrum over the fit range produces a value of a consistent within the error in Table I. The fit to the coincidence energy spectrum has $\chi^2/N = 21.8/23$, and the fit to the β singles energy spectrum has

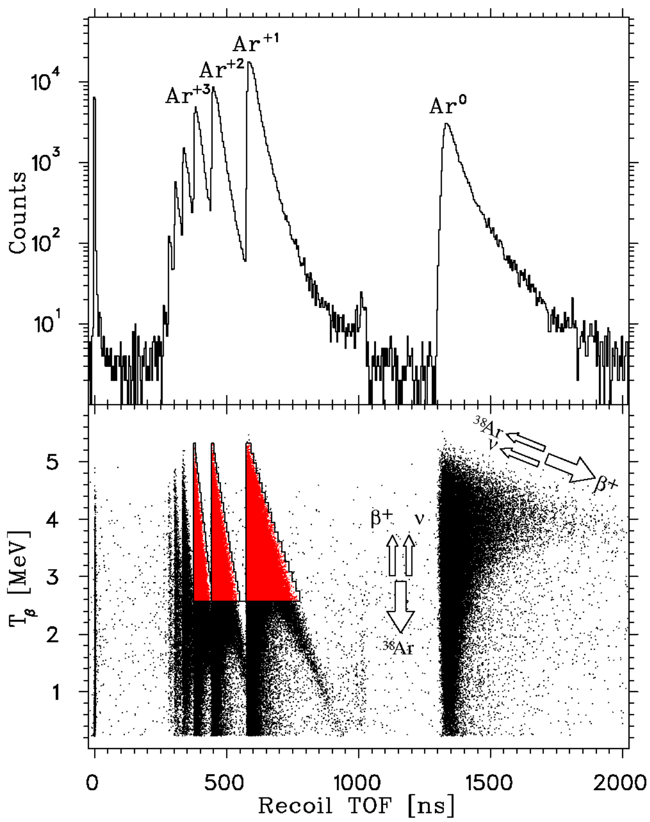

FIG. 2 (color online). Bottom: Scatter plot of recoil TOF vs T_β with one dot shown for each of 500 000 events. The suppressed back-to-back lepton emission produces longer recoil TOF. The E field separates the Ar charge states. The analysis cuts are shown. Top: TOF projections of the 2D scatter plot. The 0.1% background at TOF $\approx$ 1020 ns is from β's scattering off the MCP into the β telescope and can be rejected kinematically.

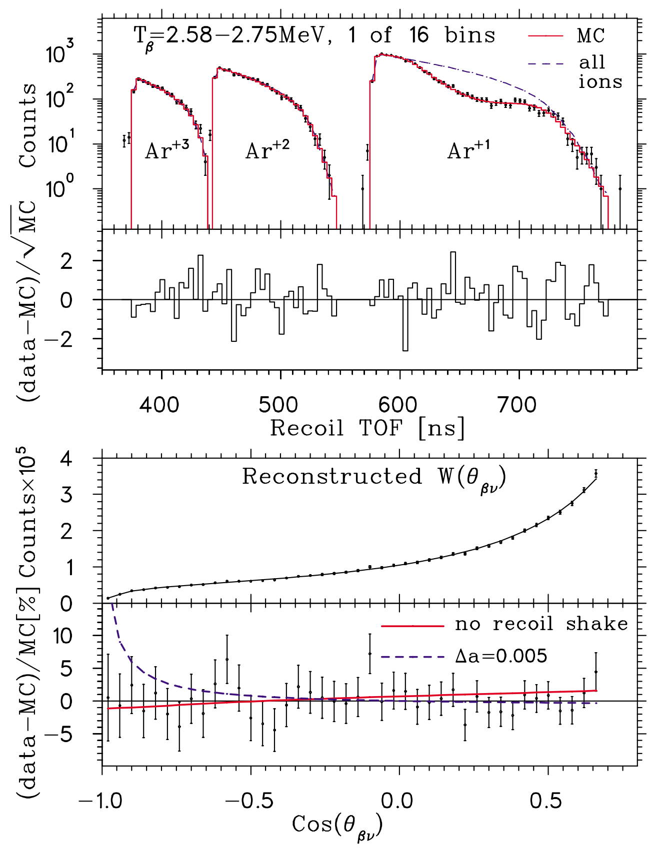

FIG. 3 (color online). Top: lowest of 16 T_β bins for the MC fit to the Ar$^{+1,+2,+3}$ data, and residuals. The confidence level for the entire fit is 52%. Data have been binned to show sensitivity to a. Fits are done with 4 ns bins. The dip in Ar^{+1} is from the finite MCP size: the dashed curve has an artificially larger MCP collecting all ions. Bottom: Fit to reconstructed angular distribution, showing residuals. Also shown are the effect of a change in a by 0.005, and the effect of recoil energy-dependent shakeoff.

$\chi^2/N = 10.8/11$. We use the Fermi function and corrections of [23].

We are working to extend the experiment to $T_\beta \leq 2.5$ MeV, to independently determine b. The fits become poorer, and systematic errors from β scattering, the low-energy line shape tail, and possible additional sources are not fully understood. The T_β cutoff eliminates almost all backscattered events, as well as all possible contamination from untrapped ^{38}K ground state decays.

We include order-α radiative corrections. These are dominated by undetected momentum carried away by real bremsstrahlung photons, which we include in the MC event generator [24]. They change a by 0.003 in the ^{32}Ar experiment [2,9]. Because the β^+ energy spectrum is also affected, and we use the β^+ spectrum itself for our E_β calibration, our net result is that the radiative corrections change a by considerably less in our experiment.

Three independent measures determine the E field. The leading edge TOF of the Ar ion spectra implies $E_{\hat{z}} = 807.7 \pm 0.16$ V/cm, independent of a and consistent for all charge states. The field nonuniformity is constrained by the TOF of the photoionized ^{38}K^m atoms, and by a population of "wrong-way" recoils produced from β's firing the MCP, which give central values 807.7 and 808.3 V/cm. The nonuniformity is <1.0 V/cm/cm and the resulting error in a is 0.0014.

We collect 89%, 99.6%, and 99.9% of the $\mathrm{Ar}^{+1,+2,+3}$ ions in coincidence for $T_\beta > 2.58$ MeV. This finite acceptance is a source of systematic error (see Fig. 3); since a fixed aperture defines the MCP size, the acceptance contributes part of the dependence of a on the E field and trap position, as quantified by the MC analysis (Table I).

Dependence of the probability of electron shakeoff on the recoil ion energy has been seen in ^{6}He β^- decay [18]. A recent simple estimate relates this effect to oscillator strengths and suggests that it is larger in β^+ decay [25]. The recoil energy spectrum to lowest order is distorted by $(1 + sE_{\mathrm{rec}})$. We constrain this effect experimentally by fitting s and a simultaneously in our TOF[E_β] fit for $\mathrm{Ar}^{+1,+2,+3}$. We only include s in the Ar^{+1} spectrum, because the model of Ref. [25] using semiempirical oscillator strengths [26] suggests that s for Ar^{+2} (or Ar^{+3}) would be 0.11 (or 0.05) the size of s for Ar^{+1}. We find $s = -0.013 \pm 0.020$, a result in a nonphysical region with one σ upper limit $s < 0.014$ and change in a: $\Delta_a = 0^{+0}_{-0.0018}$. The estimate of Ref. [25] is $s = 0.031$. A similar fit of the Ar^{+1} reconstructed angular distribution to a and s gives consistent results and error (Fig. 3). We can constrain s and a simultaneously because the greatest sensitivity to a is at the null in the angular distribution, and 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 with the recoil momentum spectrum.

Our fit values for a and b are strongly correlated in the E_β region used. Although we fit as a function of E_β, careful investigation of the correlations shows that the physical observable we report here is, for $|b| < 0.04$, effectively indistinguishable from that reported by Ref. [2], $\tilde{a} = a/(1 + bm_\beta/\langle E_\beta \rangle)$, but with $\langle E_\beta \rangle = 3.3$ MeV. We find $\tilde{a} = 0.9981 \pm 0.0030^{+0.0032}_{-0.0037}$, in agreement with the standard model. If we vary b from -0.0075 to $+0.0021$, the 90% confidence range of the Fierz interference term limits in Ref. [6], then a changes from 0.9971 to 0.9984, while $\tilde{a}$ changes by $<1 \times 10^{-4}$. Our measurement has comparable errors to Ref. [2] with an entirely different experimental method.

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