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Measurement of the neutrino asymmetry in the β decay of laser-cooled, polarized ^{37}K

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Abstract

A measurement of the neutrino asymmetry is presented which represents the first search for new physics using polarized radioactive atoms initially cooled and confined in a magneto-optical trap. Optical pumping and photoionization techniques are used to generate and measure, in situ, a highly spin-polarized (96.5(0.8)%) sample of the short-lived β^+-emitter ^{37}K. The angular distribution of neutrinos from this polarized decay, inferred from the daughter recoil asymmetry, is used to search for a hypothetical $V + A$ current in the weak interaction. We find the ν asymmetry parameter to be $B_\nu = -0.755 \pm 0.020(\text{stat}) \pm 0.013(\text{syst})$, in agreement with the standard model's purely V–A interaction.

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1. Introduction

Many extensions to the standard model (SM) propose that parity symmetry, which is maximally violated by the weak interaction, is restored at some higher energy scale [1–3]. In the simplest manifest left–right symmetric models [4], the SM electroweak gauge group $\mathrm{SU}(2)_L \otimes \mathrm{U}(1)$ is extended to include a right-handed sector and is given identical couplings, CKM matrices and neutrino sectors. Only three new parameters are introduced: the mass of the new W_R boson that couples to right-handed neutrinos, a *CP*-violating phase, ω, and an angle, ζ, describing the level of mixing between the weak ($W_{L,R}$) and mass eigenstates ($W_{1,2}$, with masses $M_{1,2}$):

$$\begin{aligned} W_L &= W_1 \cos\zeta - W_2 \sin\zeta, \\ W_R &= (W_1 \sin\zeta + W_2 \cos\zeta) e^{i\omega}. \end{aligned} \tag{1}$$

Nuclear β decay is sensitive to the W_R either directly or through mixing with the W_L, with dependencies that scale like M_1^2/M_2^2 and $\tan\zeta$, respectively. In more general models, the two sectors have different couplings, CKM matrices and neutrinos (though the $\nu^{(R)}$ must be light enough to be produced), which increases the parameter space [5]. This makes limits from β decay, μ decay and collider searches complementary because their dependencies differ [6].

A number of active research programs [7–10] continue searching for such right-handed currents. The advent of neutral atom trapping techniques [11] in the mid-1980s introduced a powerful new technique for precision β decay studies because they provide a backing-free, cold, localized source of isotopically-selected atoms. Recently, two experiments using a magneto-optical trap (MOT) have produced measurements of the $\beta - \nu$ correlation parameter [12,13]. As a first step toward searching for right-handed currents, the β asymmetry of ^{82}Rb has been observed using a magnetic time-orbiting potential trap [14].

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2. Principle of the measurement

In this Letter we present a novel technique combining optical pumping (OP) with a MOT to produce a highly spin-polarized sample of laser-cooled atoms. These near-ideal conditions are utilized to make a precision measurement of the neutrino asymmetry parameter, B_ν, in the β decay of a polarized nucleus. This parameter is an observable in the angular distribution of the decay [15]:

$$\begin{aligned}\frac{d^5\Gamma_{\text{angular}}}{dE_e\,d\Omega_e\,d\Omega_\nu} \propto \Bigg\{ & 1 + a_{\beta\nu}\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} + b\frac{m_e}{E_e} \\ & + P\hat{\imath}\cdot\left[A_\beta\frac{\vec{p}_e}{E_e} + B_\nu\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e\times\vec{p}_\nu}{E_eE_\nu}\right] \\ & + c\left[\frac{\vec{p}_e\cdot\vec{p}_\nu}{3E_eE_\nu} - \frac{(\vec{p}_e\cdot\hat{\imath})(\vec{p}_\nu\cdot\hat{\imath})}{E_eE_\nu}\right] \\ & \times\left[\frac{I(I+1)-3\langle(\vec{I}\cdot\hat{\imath})^2\rangle}{I(2I-1)}\right]\Bigg\}, \end{aligned} \qquad (2)$$

where $(E_l, \vec{p}_l)$ are the four-momenta of the leptons, and $P = |\vec{I}|/I$ is the nuclear polarization of the parent nucleus along a direction $\hat{\imath}$. The values for the correlation parameters $a_{\beta\nu}, b, c, A_\beta, B_\nu$ and D depend explicitly on fundamental symmetries of the weak interaction [15]. They are also potentially sensitive to new physics; in particular, a non-zero value for D would violate time-reversal symmetry, while the β and ν asymmetry parameters, A_β and B_ν, can be used to search for right-handed currents. B_ν defines the dependence of the polarized angular distribution on the correlation between $\vec{p}_\nu$ and the initial nuclear polarization. In the present experiment this dependence is measured by detecting the nuclear recoils in coincidence with βs observed perpendicular to $\hat{\imath}$. Given this particular geometry and since the decay is of a free atom laser-cooled so as to be initially at rest, the relevant component of $\vec{p}_\nu$ is of equal magnitude and opposite sign to that of the recoil $\vec{p}_{\text{recoil}}$. Finite detector acceptances and averaging over E_β complicate the analysis, but the observed $\hat{x}$ recoil asymmetry (defined below) remains closely related to $\cos\theta_{\hat{\imath},\nu}$, and so is primarily sensitive to B_ν.

The ν asymmetry has previously been measured only in ^{19}Ne [16] (to 14%) and the neutron [17] (to 0.4%). The focus of this work is the mixed Fermi/Gamow–Teller β^+ decay of the mirror nucleus ^{37}K [18] which has a 97.89(11)% $I^\pi = \frac{3}{2}^+ \rightarrow \frac{3}{2}^+$ branch to the ground state with $Q_{EC} = 6.1475(2)$ MeV. For this transition and within the SM, $A_\beta^{\text{SM}} = -\frac{2}{5}\lambda(\sqrt{15}-\lambda)/(1+\lambda^2)$ and $B_\nu^{\text{SM}} = -\frac{2}{5}\lambda(\sqrt{15}+\lambda)/(1+\lambda^2)$ where λ is the ratio of Gamow–Teller to Fermi matrix elements, $\lambda \equiv g_A M_{\text{GT}}/g_V M_F$. The magnitude $|\lambda| = 0.5754(16)$ was inferred from the measured ft value [19]. The only other transition of appreciable strength is a pure GT branch to the $\frac{5}{2}^+$ 2.8 MeV level in ^{37}Ar at 2.07(11)%, with all others <0.25% [20].

We define the experimental ^{37}Ar-recoil position asymmetry along $\hat{x}$ to be

$$\mathcal{A}_{\text{Ar}}(x) \equiv \frac{N_{\text{Ar}}^+(x) - N_{\text{Ar}}^-(x)}{N_{\text{Ar}}^+(x) + N_{\text{Ar}}^-(x)}, \qquad (3)$$

where $N_{\text{Ar}}^{\pm}$ is the observed number of recoils for polarization along $\hat{\imath} = \pm\hat{x}$. This asymmetry, which scales like PB_ν, is compared to a Monte Carlo (MC) simulation which calculates the expected asymmetry after integrating over β energies and the detector acceptances. The other non-zero correlations, $a_{\beta\nu}$ and c, do not give rise to an asymmetry but do contribute to the denominator of Eq. (3) and are therefore included in the simulations. Recoil-order corrections (given by CVC) [21] and estimates of radiative [22] corrections to the observables are $\lesssim 0.25\%$, which is negligible compared to the present experimental uncertainty and so are not included in the present analysis.

3. The experiment

The radioactive beam facility at TRIUMF, ISAC, provided 6×10^7 ^{37}K$^+$ ions/s to the TRIUMF Neutral Atom Trap facility [23]. Many of the same techniques used by our group to measure the $\beta - \nu$ correlation parameter in $^{38\text{m}}$K continue to be utilized in the present experiment (see [12] and references therein). The mass-separated 30 keV ion beam was implanted into a heated Zr foil which neutralized and released [24] the short-lived ($t_{1/2} = 0.972$ s) ^{37}K atoms into a vapour-cell 'collection' MOT. We use a 30 ms pulse of laser light every 700 ms to gently push these cooled, isotopically selected atoms with 75% efficiency directly into a 2nd 'detection' MOT [25] where we house our particle detectors (see Fig. 1). We wait 50 ms for the atoms to collect before initiating the polarization and counting sequence.

3.1. Particle detection

βs emitted perpendicular to the polarization axis are observed by a double-sided Si-strip detector (DSSSD) plus BC408 plastic scintillator β-telescope as shown in Fig. 1(a). The DSSSD provides a ΔE signal with 0.1×0.1 mm^2 position information, while the 6.5 cm thick scintillator stops the β and measures the full energy. The recoils are detected in a microchannel plate (MCP) detector consisting of three 600 µm thick plates in the Z-stack configuration, biased at ≈1 kV/plate. The resistive-anode readout was calibrated with an α source and mask to within ±0.1 mm at the edges of the active area (defined by a 2.4 cm diameter passive collimator) where non-linearities are largest; the position resolution of the device was found to be ±0.25 mm. Charged recoils are accelerated and separated into different charge states by time-of-flight with respect to the β trigger using a uniform electric field of $\vec{E} = -810(10)\hat{z}$ V/cm. Both of these detectors have already been very well characterized from the analysis of our unpolarized $^{38\text{m}}$K data [12].

In extending the techniques used in our scalar search [12] to this spin-polarized case, two BC408 + CaF$_2$(Eu) "phoswich" detectors were added to the system as shown in Fig. 1(b) to observe βs emitted along the polarization axis. Both the plastic (1″ in diameter and 2 mm thick) and CaF$_2$(Eu) (1.2″ in diameter and 20 mm thick) are read out by the same photomultiplier tube, with the signals separated by short and long gates (32 ns and 5 µs, respectively). The βs have been shown to be clearly