\beta decay correlation studies using very cold, highly polarized sources

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The modern technologies of neutral atom traps and the production of ultra-cold neutrons (UCN) have opened up new vistas in the field of precision \beta decay studies which search for physics outside the Standard Model. The TRINAT collaboration uses a magneto-optical trap and optical pumping techniques to produce a highly polarized source of short-lived $^{37}$K from which the positron and recoiling nucleus escape with negligible distortions to their momenta. The UCNA collaboration is utilizing the favourable aspects of UCN (may be transported far from production backgrounds and are easily polarized) to measure correlations. These two experiments are discussed in the context of measuring the $V_{ud}$ element of the CKM mass-mixing matrix and as a test of weak right-handed currents.

Keywords: Angular distribution and correlation measurements; weak interaction and lepton aspects.

La tecnología moderna de trampas de átomos neutrales y la producción de neutrones ultra-fríos (UCN, por sus siglas en inglés) abrieron vistas nuevas en el campo de estudios precisas del decaimiento \beta que buscan física fuera del modelo estándar. La colaboración TRINAT usa una trampa magneto-óptica y técnicas de bombeo óptico para producir una fuente polarizada de $^{37}$K de vida corta de donde el positrón y el núcleo que escape vía retroceso con distorsión despreciable en su momento lineal. La colaboración UCNA usa los aspectos favorables de UCN (puede ser transportado lejos del lugar de producciones del fondo y son polarizados fácilmente) para medir correlaciones. Se discute estos dos experimentos en el contexto de medir el $V_{ud}$ de la matriz de mezcla CKM y como prueba de las corrientes débiles derecha.

Descriptores: Distribución angular y medidas de correlaciones; interacción débil y aspectos leptónicos.

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1. Introduction

Experiments in nuclear $\beta$-decay over the past half-century have played a critical role in developing the Standard Model (SM) of particle physics. Beginning with the classic experiment of C.S. Wu et al. [1] (which, together with the $\mu^+$ experiment of R.L. Garwin et al. [2], proved that parity is violated in $\beta$ decay), it continues to this day as precision low-energy experiments test SM predictions and meaningfully constrain new physics.

1.1. Status of $V_{ud}$ and CKM unitarity

The comparative half-life of a $\beta$ decay, or its $ft$ value, is used to extract a value for the Cabibbo-Kobayashi-Maskawa (CKM) mass-mixing matrix element $V_{ud}$ [3]. $f$ is the statistical rate function (which depends on the $Q$-value of the decay) and $t = t_{3/2}/BR$ is the partial half-life of the transition of interest. Their product $ft$ does not depend on the kinematics of the decay so it’s value should only depend on the physics of the weak interaction:

$$ft = \frac{K}{G_V^2|M_F|^2 + G_A^2|M_{GT}|^2}$$  \hspace{1cm} (1)

where $K/(\hbar c)^6 = 2\pi^3h ln 2/(m_e c^2)^5$ is a constant, $G_{V,A}$ are the vector and axial-vector coupling constants and $M_{F,GT}$ are the corresponding Fermi ($\Delta I = 0$) and Gamow-Teller ($\Delta I = 1$) matrix elements. If the conserved-vector current (CVC) hypothesis is correct, $G_V = G_F V_{ud}$ where $G_F$ is the purely leptonic Fermi coupling constant derived from muon decay and $V_{ud}$ is the CKM element relating the weak eigenstates of the first generation of quarks to the mass eigenstates. The reason superallowed decays are so favoured for extracting $V_{ud}$ quickly becomes evident: with $0^+ \to 0^+$ decays, the Gamow-Teller component is forbidden and $|M_F|^2$ is determined by isospin selection rules to be $\sqrt{2}$. Thus

$$ft = \frac{K}{2G_F^2|V_{ud}|^2}$$

for all superallowed decays. If CVC is not strictly true, we may expect to see variations in the values of $ft$ for different superallowed decays; if CVC does hold, we can average over a number of $ft$ values and turn them into a measurement of $V_{ud}$. In practice, however, isospin is not a perfect symmetry and there are radiative processes which have small effects on the decay. Thus there are theoretical corrections which much be applied: $\Delta \delta_R = 0$ is a transition-independent radiative correction; $\delta_R'$ is a nucleus-dependent radiative correction that does not depend on nuclear structure; $\delta_{NS}$ contains the nuclear-structure dependent radiative correction; and $\delta_C$ is an isospin symmetry-breaking correction. Including all of these corrections leads us to the corrected $Ft$ value [3]:

$$Ft = ft(1 + \delta_R')(1 + (\delta_{NS} - \delta_C))$$

$$= \frac{K}{G_F^2|V_{ud}|^2|M_F|^2(1 + \Delta_{R})}$$ \hspace{1cm} (2)

Currently, the thirteen most precisely measured cases are used and found to be constant to 0.03%, in excellent agreement with CVC. If one assumes validity of CVC, the $Ft$ values can be averaged together and one finds
\( \langle \mathcal{F}t \rangle = 3071.9(8) \) s [3]. Eq. (2) can then be re-arranged:

\[
|V_{ud}|^2 = \frac{2015.6 \pm 1.1 \text{ s}}{\langle \mathcal{F}t \rangle}
\]

(3)

from which one finds \( V_{ud} = 0.97425(22) \). Combining this with the 2008 PDG [4] values for \( V_{us} = 0.2255(19) \) and \( V_{ub} = 0.00393(35) \), perfect agreement with unitarity of the first row of the CKM matrix is found:

\[
|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1.0000(10).
\]

(4)

1.2. Angular correlations in \( \beta \) decay

In addition to the \( ft \) value, the angular correlations from \( \beta \) decay can also be used to search/place limits on a variety of physics outside the SM: exotic interactions [5], parity violation [6], time-reversal symmetry violation [7], second-class currents [8], sterile neutrinos [9] and supersymmetric models [10]. Here we focus on the spin-polarized angular distribution, given by [11]:

\[
\frac{d^3W(\vec{p}_\beta, \vec{p}_\nu, \vec{I})}{dE\beta d\Omega\beta d\Omega_\nu} = \frac{G_F^2}{(2\pi)^3} |V_{ud}|^2 p_\beta^3 E_\beta (E_\alpha - E_\beta)^2
\]

\[
\times \xi \left\{ 1 + a_{\beta\nu} \frac{\vec{p}_\beta \cdot \vec{p}_\nu}{E_\beta E_\nu} + b_{\nu} \frac{m_e}{E_\beta}
\]

\[
+ \frac{2 I}{I} \cdot \left[ A_{\beta} \frac{\vec{p}_\beta}{E_\beta} + B_{\nu} \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_\beta \times \vec{p}_\nu}{E_\beta E_\nu} \right]
\]

\[
+ c \left[ \frac{2 \vec{p}_\beta \cdot \vec{p}_\nu - (\vec{p}_\beta \cdot \vec{i})(\vec{p}_\nu \cdot \vec{i})}{E_\beta E_\nu} \right]
\]

\[
\times \left[ \frac{I(I+1)-3(\langle \vec{I} \cdot \vec{i} \rangle^2)}{I(2I-1)} \right] \}
\]

(5)

Here \( (E_\beta, \vec{p}_\beta) \) and \( (E_\nu, \vec{p}_\nu) \) are the four-vectors of the emitted leptons, \( E_\nu \) is the energy released, \( \vec{I} \) is the initial nuclear spin, and the correlation parameters \( a_{\beta\nu}, b_{\nu}, A_{\beta}, B_{\nu}, D \) and \( c \) are sensitive to the form of the weak interaction. For example, the classic experiment on polarized \( ^{60}\text{Co} \) [1] observed a large asymmetry of the emitted \( \beta \) relative to the polarization axis \( \vec{i} \), which proved that parity is not conserved in weak processes; if parity was conserved, the \( \beta \) asymmetry parameter \( A_\beta \) would equal zero and no asymmetry of the type \( \vec{I} \cdot \vec{p}_\nu \) would have been seen.

Built into the SM is the so-called \( (V - A) \) form of the weak interaction, meaning it is a combination of both vector and axial-vector currents. This leads to left-handed fermions which transform like \( SU(2)_L \) doublets and right-handed fermions which transform as singlets. The violation of parity is easily understood since \( V \) changes sign while \( A \) does not; so the \( (V - A) \) current cannot be an eigenstate of parity. It appears that this parity violation is maximal because no right-handed \( (V + A) \) interaction has been observed.

Left-right symmetric extensions to the SM propose that Nature is in fact inherently parity-conserving, but that the symmetry is suppressed at low energy scales such as nuclear \( \beta \) decay. The simplest extensions are based on the \( SU(2)_L \times SU(2)_R \) gauge group which is manifestly left-right symmetric. These models necessarily introduce new boson propagators which, much like the quarks, will have mass eigenstates that differ from the weak eigenstates. If we let \( W_1 \) represent the mass eigenstate of the predominantly left-handed boson, and \( W_2 \) the predominantly right, then the weak eigenstates can be parameterized as a linear combination of mass eigenstates according to:

\[
W_L = W_1 \cos \zeta + W_2 \sin \zeta
\]

(6)

and

\[
W_R = W_2 \cos \zeta - W_1 \sin \zeta
\]

(7)

where \( \zeta \) is a mixing angle. The lack of observation of the right-handed sector could be a consequence of a very small mixing angle and/or a very large \( W_2 \) mass.

In minimal left-right symmetric models, it is assumed that the coupling constants of the sectors are the same \( (g_R = g_L) \), the CKM matrices are the same \( (V^R_{ud} = V^L_{ud}) \) and there is no \( CP \)-violation between the sectors. In more general models [12], these assumptions are relaxed and the number of right-handed current parameters to be searched for increases. It is important to derive limits from various experiments which have differing sensitivities to different right-handed current parameters (e.g. collider searches, muon decay and \( \beta \) decay) because they are complementary.

2. UCNA: measuring \( A_\beta \) using ultra-cold neutrons

The \( \beta \) decay of the free neutron is theoretically much simpler because it is free of any iso-spin mixing and nuclear structure effects. As such, it represents a good case for extracting \( V_{ud} \) as a complement to the value derived from superallowed decays. Analogous with Eq. (2) for superallowed decays, the neutron’s \( ft \) value is:

\[
f^{Rt}_N = \frac{K}{G_F^2 |V_{ud}|^2 \left( |M_F|^2 + \frac{G_F^4}{G^2} |M_{GT}|^2 \right) (1 + \Delta^2)}
\]

(8)

where \( f^R = f(1 + \delta^R) = 1.71482(15) \) is the statistical rate function already corrected for structure-independent radiative corrections. Being a mixed Fermi–Gamow-Teller decay, the neutron’s \( ft \) value is complicated by the fact that though \( |M_{GT}| \) can easily be calculated to be \( \sqrt{3} \), \( G_A \) is not precisely known because the axial current is only partially conserved; currently it must be measured. In terms of the neutron lifetime, \( \tau \), and the ratio of axial to vector coupling constants, \( \lambda = G_A/G_V \), \( V_{ud} \) is found to be:

\[
|V_{ud}|^2 = \frac{4905.9 \pm 1.9 \text{ s}}{\tau(1 + 3\lambda^2)}.
\]

(9)

The PDG 2008 [4] recommendations are \( \tau = 885.7(8) \) s and \( \lambda = 1.2695(29) \), determined primarily from measurements.
of $A_\beta$. These values lead to $V_{ud} = 0.9743(19)$ if taken at face value, in perfect agreement with the superallowed decays albeit with almost $10 \times$ the uncertainty; however, Fig. 1 shows the result of recent experiments on the neutron lifetime and $\beta$ asymmetry. From this, it is seen that the present state is one of disarray, both in the lifetime and in $\lambda$.

The goal of UCNA is to measure the $\beta$ asymmetry to $\leq 0.2\%$ and precisely determine the value of $\lambda$. In the SM, the $\beta$ asymmetry for neutron decay is [13]:

$$A_\beta = A_\circ(1 + a_o + a_\mp / E_e + a_+ E_e)(1 + \delta), \quad (10)$$

where the parameters $a_o, \pm$ (recoil order corrections) and $\delta$ (a radiative correction) can be calculated well enough that theoretical uncertainties in $A_\beta$ remain below 0.1%, and

$$A_\circ = -2 |\lambda|^2 / (1 + 3|\lambda|^2). \quad (11)$$

The PDG value for $\lambda$ corresponds to $A_\circ = -0.1173(11)$. UCNA’s goal is to reduce the uncertainty to $\pm 0.0002$ or better which, as can be seen in Fig. 1, would reduce the uncertainty in $\lambda$ to $\pm 0.0006$. Once the lifetime discrepancy is resolved and the $\beta$ asymmetry measurement is complete, the value of $V_{ud}$ from neutron decay should have an uncertainty comparable to superallowed decays but with entirely different sources of systematic errors.

The favourable aspects of ultra-cold neutron (UCNs) are for the first time being utilized to reduce traditional problems in polarized neutron decay experiments, namely the generally large backgrounds and the difficulty in highly polarizing the neutrons. UCNs are loosely defined as neutrons whose energy is below the Fermi potential of certain materials [14], e.g. $335$ neV for $^{58}$Ni which corresponds to velocities of $\lesssim 8 \text{ m/s}$. Neutrons with an energy below a material’s $E_{\text{Fermi}}$ will totally externally reflect and be unable to penetrate the material; thus they are easily bottled and/or transported with high efficiency. In addition, UCN can be easily polarized by means of a few Tesla solenoid: neutrons with the wrong spin will encounter a potential barrier of height $\mu \cdot B = 60 \text{ neV/T}$, while neutrons with the opposite spin will freely pass through the potential well of the magnetic field.

The 800 MeV proton beam at the Los Alamos Neutron Science Center (LANSCE) are directed onto a tungsten target to produce spallation neutrons. Above the target is a solid deuterium source maintained at 5 K which converts some of the neutrons to UCN. The UCN are transported through 5 m of concrete shielding and passed through a 6 T pre-polarizing solenoidal magnet. Following this is our primary 7 T polarizing magnet, which has the ability to flip the spin of the UCN using a birdcage rf cavity. The UCN are finally directed into a 300-cm long $\times$ 12-cm diameter copper tube which contains the UCN within our decay spectrometer (see Fig. 2). The spectrometer’s homogeneous 1 T field is aligned with the decay trap axis so that the daughter electrons are contained and spiral along the field lines towards one of two identical detectors: a low-pressure MWPC $\Delta E$ detector backed by a 3.5 mm thick plastic scintillator $E$ detector, thick enough to stop any $\beta$ decay electrons. Not shown are additional thick scintillators behind the $E$ scintillators to veto high-energy events, and the proportional gas tubes/plastic scintillators surrounding the spectrometer to veto cosmic-ray muons.

Figure 3 shows the polarized $\beta$ spectrum summed over detectors as well as comparison to a simulation of the experiment using the PENELope [15] Monte Carlo (MC) code. The cleanliness and very large signal-to-noise ratio ($> 20:1$) of this spectrum can be attributed to having the spallation source of UCN very far away and very well shielded from the spectrometer. Systematic uncertainties associated with detector efficiencies and loading efficiencies of the two spin states are minimized using the super ratio of rates

$$S(E_e) = \frac{r(E_e)_{1\uparrow} r(E_e)_{2\uparrow}}{r(E_e)_{1\downarrow} r(E_e)_{2\downarrow}}$$

\begin{center}
\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Present status of $V_{ud}$ from neutron decay $A_\beta$ and $\tau$ measurement. For comparison, the horizontal bands show the value of $V_{ud}$ from superallowed decays [3] and the value expected if unitarity is assumed and one uses the PDG values for $V_{us}$ and $V_{ub}$.}
\end{figure}
\end{center}

\begin{center}
\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Schematic diagram of the UCNA experiment (not to scale). The UCN are injected via a side bore into a homogeneous 1 T holding field. The $\beta$’s are observed by one of two identical $\Delta E - E$ detectors.}
\end{figure}
\end{center}
where \( r(E_c) \) is the rate measured in detector 1(2) when the neutron spin state was up(down). The experimental asymmetry is then given by

\[
A(E_c) = \frac{1 - \sqrt{S(E_c)}}{1 + \sqrt{S(E_c)}}.
\]

As described in a recent publication [16], we find \( A_o = -0.1138(46)(21) \) where the first uncertainty is statistical and the second systematic. For comparison to other experiments shown in Fig. 1, this corresponds to \( \lambda = -1.260(13) \) which is consistent with the present status at this 1% precision. Presently, our systematic uncertainty is dominated by our knowledge of the UCN polarization and the electron detector response function however both of these have been improved during our 2008 run which we are currently analyzing. In addition, our rates were increased such that we have enough statistics to reach below the 1% level of precision in \( A_e \) corresponding to 0.25% in \( \lambda \).

3. TRINA T: polarized correlations using trapped \( ^{37}K \)

The \( \beta^+ \) decay of \( ^{37}K \) [17], being a predominantly \( I^\pi = 3/2^+ \rightarrow 3/2^+ \) mixed Fermi/Gamow-Teller decay to the ground state of \( ^{37}Ar \), is sensitive to physics beyond the SM through the spin-polarized angular distribution given in Eq. (5). All of the correlation parameters depend on the form of the weak interaction and are functions of \( \lambda \equiv g_A M_{GT}/g_V M_F \), where \( g_A (g_V) \) are the axial-vector (vector) semi-leptonic form factors and \( M_{GT} (M_F) \) are the Gamow-Teller (Fermi) matrix elements of the decay. Putting together the known half-life \( (t_{1/2} = 1.2533(10) \text{ s}) \), ground state branching ratio \( (97.89(11)\%) \) and \( Q_{EC} \)-value \( (6.14746(23) \text{ MeV}) \), we find the \( ft \)-value of the decay of \( ^{37}K \) is known to \( \pm 0.15\% \). Analogous with the neutron, the \( ft \) value relative to the \( ft \) value of superallowed decays is given by \( ft/ft = \frac{1}{2}(1 + \lambda^2) \) from which one finds the magnitude \( |\lambda| = 0.5754(16) \). We determined the sign to be positive by measuring \( B_\nu \) [18]. This leads to definite predictions for the correlation parameters within the SM (see Table I). Any observed deviation from these predictions would be an indication of new physics.

In addition to the parameters defined in Eq. (5), a \( \beta^-\text{recoil} \) coincidence in specific to our geometry allows us to measure a combination of these correlation parameters which is very sensitive to new physics, particularly RHCs. We have termed this observable \( R_{slow} \) because only events where the daughter nucleus recoils slowly are observed; this preferentially picks the Gamow-Teller component of the decay so that the sensitivity to \( \lambda \) vanishes in the limit that only slow recoils are kinematically accepted. In the further limit that the \( \beta^- \) is fully relativistic and emitted back-to-back with the \( \nu \) along the polarization axis, \( i \), of a perfectly aligned nucleus, the ratio

\[
R_{slow} \equiv \frac{dW(\hat{i} \cdot \hat{p}_\beta = -1)}{dW(\hat{i} \cdot \hat{p}_\beta = +1)}
\]

is given by the expression in Table I, from which it is easy to show that the numerator vanishes for a \( (V - A) \) interaction.

Our goal is to reach a precision of \( \lesssim 0.1\% \) in measuring these correlations – particularly \( A_\beta, B_\nu, \) and \( R_{slow} \) – which would be competitive with current experimental limits. The proposed experiment will once again use the TRINA T facility and copious production of \( ^{37}K \) from ISAC. There are two methods we have devised for observing the decay products:

1. in the same manner as described in Refs. [18, 19]; and
2. using the newly developed shake-off electron detection technique pioneered by Berkeley [20] and tested at TRINA T in a previous experiment [21].

We first describe how we polarize the atoms and then briefly discuss the merits of both methods in the context of measuring the spin-polarized correlations \( B_\nu, A_\beta \) and \( R_{slow} \).

3.1. Polarization

The MOT does not provide a polarized source of atoms, so we either must

(a) load the atoms into a trap which does, or

(b) release the atoms, quickly polarize them for a brief period when we make our asymmetry measurements, and then turn the trap back on to recollect them before they expand too far and are lost.

Efficient loading of a Circularly-polarized Far Off-Resonance dipole force Trap (CFORT) – which only traps one magnetic sublevel and so provides a fully polarized source of atoms –
Table I. Standard model predictions of the correlation parameter values for the decay of $^{37}\text{K}$. The uncertainties quoted result from the precision to which $\lambda$ is known.

<table>
<thead>
<tr>
<th>Correlation</th>
<th>SM prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta - \nu$</td>
<td>$a_{\beta\nu} = \frac{1-\lambda^2/3}{1+\lambda^2} = 0$</td>
</tr>
<tr>
<td>correlation:</td>
<td></td>
</tr>
<tr>
<td>Fierz interference</td>
<td></td>
</tr>
<tr>
<td>$b = 0$ (sensitive to scalars/tensors)</td>
<td></td>
</tr>
<tr>
<td>$\beta$ asymmetry:</td>
<td>$A_{\beta} = \frac{-2\lambda}{1+\lambda^2} \left( \frac{\sqrt{3} - \lambda}{\sqrt{3} + \lambda} \right)$</td>
</tr>
<tr>
<td>$\nu$ asymmetry:</td>
<td>$B_{\nu} = \frac{-2\lambda}{1+\lambda^2} \left( \frac{\sqrt{3} + \lambda}{\sqrt{3} - \lambda} \right)$</td>
</tr>
<tr>
<td>Alignment parameter:</td>
<td>$c = \frac{4\lambda^2/5}{1+\lambda^2}$</td>
</tr>
<tr>
<td>Time-violating $D$ coefficient:</td>
<td>$R_{\text{slow}} \sim \frac{1-a_{\beta\nu}-2c_{\text{align}}/3-(A_{\beta}-B_{\nu})}{1-a_{\beta\nu}-2c_{\text{align}}/3+(-A_{\beta}-B_{\nu})} = 0$</td>
</tr>
</tbody>
</table>

proved impossible due to the hyperfine structure of $^{37}\text{K}$; we have so far been unable to load more than 1% of the atoms from a MOT. We therefore have chosen to release the laser-cooled atoms and quickly polarize them using optical pumping techniques. Unlike many other polarized experiments, we are able to measure the polarization of the cloud in situ by fitting the observed excited state populations as a function of time to a rate-equation model of the optical pumping process. We achieved $96.5(8)\%$ average nuclear polarization after 200 $\mu$s of optical pumping, and could count polarized $\beta$ decays for another 1200 $\mu$s before we would turn the MOT back on to recollect the expanding cloud of atoms. Subsequent tests with a better holding field configuration indicates we can do even better: $\gtrsim 98.5\%$. Every 700 ms we switch the polarization state of the optical pumping light and hence flip the nuclear spin of the $^{37}\text{K}$.

3.2. The $\nu$ Asymmetry

![Diagram](image)

The detection trap used in our first experiment on polarized $^{37}\text{K}$ is shown in Figs. 4(a) and (b), and is very similar to our search for scalar currents in $^{38}\text{K}^{+}$ [5]. We have a micro-channel plate (MCP) to detect recoils in a back-to-back geometry with a $\beta$-telescope consisting of a double-sided Si-strip detector (DSSSD) and a BC408 plastic scintillator; both of the recoil and $\beta$ detectors are position sensitive. Electrostatic hoops generate a $-810$ kV/cm uniform electric field which increases collection efficiency of the recoiling $^{37}\text{Ar}$ ions and separates their different charge states.

The neutrino asymmetry is measured by looking at the recoil position spectrum in coincidence with a $\beta$ in the DSSSD–...
scintillator telescope when the atoms are polarized positively versus negatively. In the case that the $\beta$ is emitted perpendicular to the polarization axis, Fig. 4(c) shows schematically how the neutrino asymmetry is reflected by the recoil asymmetry along the polarization axis: since, to a good approximation, the decay occurs from rest, any momentum the $\nu$ carries off along the polarization axis must be equal and opposite to the momentum the recoil has along that same direction; the recoil position asymmetry will therefore have a magnitude which scales with $P B_{\nu}$, where $P = \langle \vec{P} \rangle / I$ is the average nuclear polarization.

Table II lists the sources of uncertainty in our first $B_{\nu}$ measurement as well as how well we expect to improve on the error budget [19]. The largest systematic, the position and velocity of the cloud, is likely to remain our largest systematic; not only will technical improvements help reduce it (such as better retro-reflecting the laser beams, for example), but greater overall statistics will allow us to better define the cloud parameters which will also reduce uncertainties associated with them.

### 3.3. The $\beta$ Asymmetry

The $\beta$ asymmetry can be measured in our system using the plastic $\Delta E$ and CaF$_2$ E “phoswich” detectors. By placing these detectors along the polarization axis, as shown in Fig. 4(b), a simple asymmetry of detected $\beta$s in these detectors will give a measurement of $A_{\beta}$. We attempted such a measurement during the previous $B_{\nu}$ experiment, but found that too many atoms were lost from the trap and ended up implanting onto the mirrors in front of the detectors; these atoms depolarized before decaying generating a large background which we could model and understand, but not well enough for a precision measurement of $A_{\beta}$.

The development of the shake-off electron technique provides new promise for a precision $A_{\beta}$ measurement: with essentially no loss of statistics (since every $\beta^+$ decay results in at least one shake-off electron), the coincidence of a $\beta$ in the phoswich detector with a shake-off electron will ensure we only count events where the atom decayed from the trap. This technique would remove the background problems, but at the cost of requiring a different detector set-up: whereas the $B_{\nu}$ measurement described earlier uses a $\beta$-telescope opposite the recoil detector, the shake-off electron technique replaces this telescope with an MCP electron detector; the same electric field used to accelerate the positively charged ions accelerates the negatively charged shake-off electrons in the opposite direction onto the $e^-$ detector.

The techniques for shake-off electron detection have been developed as part of E956 and have proven 35% efficiency for detecting the $e^-$. We have since demonstrated 50% efficiency using stable species and are extremely optimistic about the high rates expected from this measurement. We are planning to replace the scintillator–CaF$_2$ phoswiches with solid-state detectors, likely a thin DSSSD backed by a thick Si(Li)

### Table II. Systematic uncertainties of our $B_{\nu}$ measurement and expected improvements.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\sigma_{\text{syst}} / B_{\nu}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>cloud position/velocity</td>
<td>$\pm 1.2$</td>
</tr>
<tr>
<td>cloud size/temperature</td>
<td>$\pm 0.3$</td>
</tr>
<tr>
<td>cloud polarization</td>
<td>$\pm 0.4$</td>
</tr>
<tr>
<td>binning</td>
<td>$\pm 0.3$</td>
</tr>
<tr>
<td>MCP position calibration</td>
<td>$\pm 1.0$</td>
</tr>
<tr>
<td>MCP position efficiency</td>
<td>$\pm 0.5$</td>
</tr>
<tr>
<td>$\hat{x}_{\text{MCP}}$–OP alignment</td>
<td>$\pm 0.3$</td>
</tr>
<tr>
<td>electric field</td>
<td>$\pm 0.2$</td>
</tr>
<tr>
<td>$E_{\beta}$ threshold</td>
<td>$\pm 0.1$</td>
</tr>
<tr>
<td>Total</td>
<td>$\pm 1.8$</td>
</tr>
</tbody>
</table>

3.4. The $R_{\text{slow}}$ correlation

The kinematics and geometry of the $R_{\text{slow}}$ measurement is depicted in Fig. 4(d). It is based on the position of recoil events in the MCP given a $\beta$ coincidence in one of the $\beta$ detectors along the polarization axis. We draw the $\nu$ as back-to-back to the $\beta$ because, if it was parallel, the recoil would have too much energy and the electric field would not be strong enough to sweep the ion onto the MCP; this is how we preferentially choose slow recoils. Now consider the spins of the particles (depicted by the fat arrows), recalling that the decay is

\[
\frac{3^+}{2} \rightarrow \frac{3^+}{2} \quad: 
\]

in the bottom cartoon where the $\beta$ is emitted in the same direction as the initial nuclear spin, the spins of the leptons recoiling $^{37}$Ar can sum up to the initial spin, so this is allowed in the SM. It is forbidden in the top cartoon since in this case the $\beta$ goes opposite the initial spin and helicity cannot be conserved. If there is a RHC, however, the situation is reversed and it is the top panel which is allowed. Finite detector sizes and the fact that the neutrino is not constrained to lie along the polarization axis relax the idealized situation, however simulations confirm that the position dependence of recoils for these events remains heavily suppressed in the SM and that $R_{\text{slow}}$ retains a high sensitivity to RHCs.

This observable does not require the $\beta$-telescope nor the $e^-$ detector; it only requires $\beta$ detectors along the polarization axis. Furthermore, the dependence on the $\beta$ energy is not strong, so the phoswich detectors would suffice although larger Si detectors with better energy resolution would help increase the low rates of these events. Our plan would be to measure $R_{\text{slow}}$ in parallel with both the $B_{\nu}$ and $A_{\beta}$ experiments; combined, the low statistics of these events will be

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mitigated, although this will likely remain the most statistics-limited measurement we plan to observe.

4. Conclusions

Modern technologies providing very cold, polarized sources of decaying nuclei and the very precise correlation experiments that can be performed on them are allowing nuclear physics to continue to probe the structure of the weak interaction. As examples, two experiments have been described, one using ultra-cold neutrons and the other laser-cooled atoms with optical pumping techniques. Both promise to continue to provide exciting results in the near future.

12. P. Herczeg, Prog. in Part. and Nucl. Phys. 46 (2001) 413.
21. TRIUMF E956, J.A. Behr spokesperson.