# Beta Decay of Rubidium-82 in a Magnetic TOP-Trap

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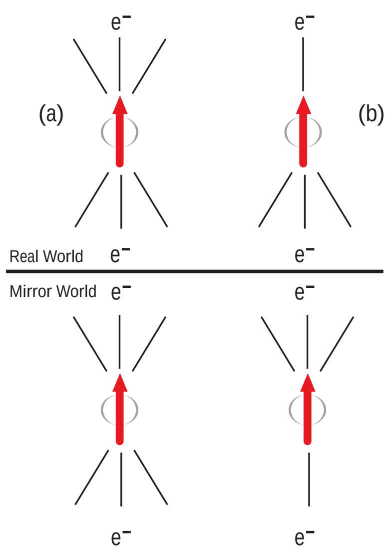


**Figure1: (a) If parity (or space-reflection symmetry) were preserved in nuclear beta decay, no asymmetry would be detected in the distribution of electrons relative to the spin-orientation of the parent nucleus. In this scenario, the real world and mirror world would be indistinguishable. (b) Due to parity violation, electrons observed in nature exhibit an asymmetry in their angular correlation with the nuclear spin direction. In the experiment of Wu *et al*.[2], this asymmetry was first observed in the beta decay of cobalt-60 that was cooled to a low temperature and spin-aligned in a magnetic field.**

## Introduction

Of the four fundamental forces in nature (electromagnetic, strong, weak, and gravity) the weak interaction is unique in that it violates parity, or space-reflection symmetry. More than four decades have passed since the first suggestion by Lee and Yang that parity could be violated in weak interactions[1] and the subsequent discovery in the beta decay of polarized cobalt-60 nuclei.[2] Today, maximal violation of parity symmetry is accommodated in the standard model describing a purely vector-axial vector (V-A) helicity structure for the weak interaction. This structure was developed largely upon the empirical observations of nuclear beta decay during the latter half of the past century.[3,4] Despite the phenomenological success of the standard model, the fundamental origin of parity violation is unknown and modern pursuits in nuclear beta decay continue to serve as a probe of the origin of symmetry and symmetry-breaking in the weak interaction.[4]

Parity violation is manifest in nuclear beta decay as an asymmetry in the angular distribution of beta particles emitted relative to the spin orientation of the parent nucleus (see Figure 1). In pure Gamov-Teller (GT) transitions, wherein the nucleus undergoes a change in angular momentum by one unit ($\Delta J = 1$), the electrons are emitted preferentially in a direction opposite to the spin of the parent nucleus. Furthermore, because both the electron and the antineutrino that emerge from the decay must each carry away one-half unit of angular momentum (intrinsic spin) it follows that the electron must carry off its spin angular momentum aligned anti-parallel to its direction of motion. In other words, the weak interaction is *left-handed* (see Figure 2). An electron-nuclear spin asymmetry can be defined,

$$\chi(E,\Theta) = \mathbf{A} P \beta(E) \cos\Theta \,,$$

where $E$ = the electron energy,
$\beta(E)$ = its velocity relative to light,
$\Theta$ = the angle between the electron momentum vector and the nuclear spin orientation,
$P$ = the polarization of the parent nucleus, and
$A$ = the observable of interest (the correlation coefficient) which is nonzero when parity symmetry is violated

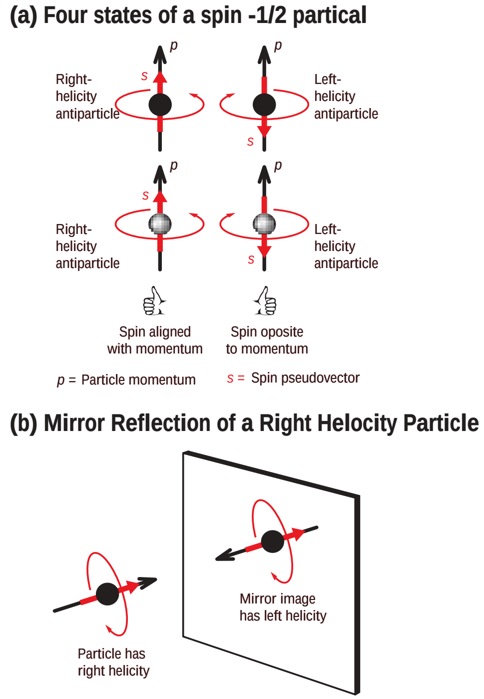


**Figure 2 The four states of a lepton. The helicity of a particle relates its intrinsic spin to its direction of motion. (a) Leptons such as the electron and neutrino emitted in nuclear beta decay are spin-1/2 particles and, because spin is quantized, they have four independent states. A particle is said to have right-handed helicity if its spin and momentum point in the same direction and left-handed helicity if these two vectors point in opposite directions. (b) The mirror image of a right-handed particle is a left-handed particle and *visa versa.* A pseudovector such as spin (angular momentum) does not change direction under spatial inversion whereas a regular vector such as momentum does. The weak interaction is said to be left-handed in that it appears to couple only to left-handed particles and right-handed anti-particles. Consequently, the weak interaction violates parity (or space-reflection) symmetry.**

## Experimental History

The value of the correlation coefficient is uniquely defined within the framework of the standard model and precision measurements are aimed to search for new physics that is thought to be manifest in the presence of interactions beyond the standard model. The pure GT transitions still offer the most direct route to study parity violation in nuclear beta decay because they proceed solely through the axial-vector coupling responsible for parity violation. To date, the most precise measure of the electron-nuclear spin correlation coefficient (A) comes from a modern experiment that used polarized cobalt-60 nuclei.[5] In that experiment the angular dependence of the asymmetry was verified, and a value of $A = -1.01 \pm 0.02$ was deduced for the correlation coefficient, in agreement with expectations for a pure GT, electron emitter with $\Delta J = 1$. Due to difficulties in reducing systematic error associated with absolute polarization and electron scattering effects in a solid sample, it appears unlikely that precision can be significantly improved using conventional technology. The advent of optical and magnetic traps for neutral atoms provides a new technology to harness a point-like, essentially massless source with a potentially high degree of polarization.

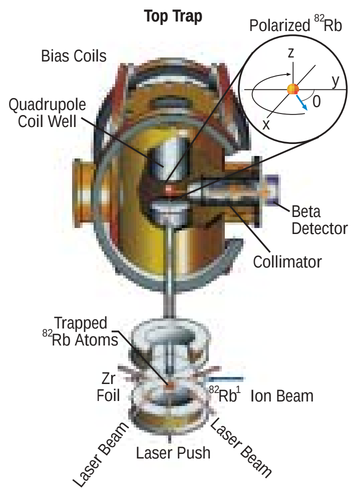


**Figure 3. Schematic diagram of the apparatus used to trap, transfer, and retrap rubidium-82 atoms. After implanting radioactive rubidium-82 ions into a zirconium catcher foil, neutral rubidium-82 atoms are released into MOT-I, where they are trapped and confined to a small cloud at the center of a glass cell. The atoms are then transferred to the experimental chamber of MOT-II through a hexapole guide tube using an optical push-beam. After retrapping in MOT-II, the TOP-trap is rapidly switched on where the direction of the magnetic bias field that aligns the nuclear spin rotates uniformly in a plane. This rotating beacon of spin-polarized rubidium-82 nuclei is used to measure the parity-violating correlation by detecting the positron energy in a plastic scintillator and recording a snap-shot of the nuclear-spin orientation from knowledge of the magnetic-field configuration.**

## Our New Approach

Our research aims specifically at exploiting magnetically trapped rubidium-82 in a new generation of fundamental-symmetry experiments. Rubidium-82, a pure and allowed GT beta decay nucleus, has the appropriate atomic structure and lifetime (75 seconds) to be exploited in a magneto-optical trap (MOT). We previously reported a world record by trapping several million radioactive rubidium-82 atoms in a MOT.[6,7] Since that time, we have successfully mounted a prototype experiment aimed to measure the positron-nuclear spin correlation coefficient from polarized rubidium-82 atoms confined to a time-orbiting-potential (TOP) trap.[8] Rubidium-82 follows from the electron capture of the longer lived parent, strontium-82, which is produced at the Isotope Production Facility at the Los Alamos Neutron Science Center (LANSCE). Strontium-82 is placed in the hot-ion source of a mass separator, which selectively ionizes, separates, and implants rubidium-82 ions into a zirconium foil located inside our primary trapping cell. Subsequent heating of the implantation foil releases neutral rubidium-82 atoms into this cell where they are cooled and trapped in a MOT (see Figure 3). The atoms are then transferred to a second, high-vacuum chamber using a short pulse of laser light. The atoms are retrapped in a second MOT and prepared for loading into the TOP trap. Once retrapped, the atoms are further cooled and optically pumped into the fully stretched atomic ground state, ensuring that the nuclear spin is aligned with the local magnetic field. The TOP trap confines the atom in a quadrupole field gradient to which a rotating bias field is added. The rotation frequency (830 Hz) is small relative to the Larmor precession frequency, consequently the nuclear spin vector adiabatically follows the bias magnetic field vector. The TOP trap thus serves to provide a rotating beacon of spin-polarized rubidium-82 nuclei to study the parity violating angular correlation of positrons ensuing from the beta decay process. Positrons are detected in a plastic scintillator after they pass through a thin stainless-steel window that separates the detector from the high-vacuum chamber.

## Experimental Results

Prototype experiments were performed to address a number of experimental details in measuring the positron-spin correlation coefficient. The fruits of these efforts have been submitted for publication[9] and are highlighted in Figure 4. In Figure 4a we show the angular distribution obtained after binning one of our data samples according to the reconstructed angle between the positron momentum vector and the spin-direction of the decaying nucleus. The data are well described by a cosΘ distribution with a preponderance of positrons emitted in the same direction as the nuclear spin, which is expected for rubidium-82 positron decay. The data distinctly demonstrate the successful confinement of a rotating, nuclear-polarized sample of rubidium-82 atoms in a TOP trap and marks the first observation of parity-violation in nuclear beta decay using atom-trapping technology. By integrating the data over the observed emission angle we obtained an unpolarized sample and the differential energy spectrum for positrons. This spectrum is shown in Figure 4b, where comparison to detailed Monte Carlo simulations indicates that the rubidium-82 spectrum is consistent with a pure and allowed GT decay and that our understanding of the positron detection optics in our experiment is well understood.

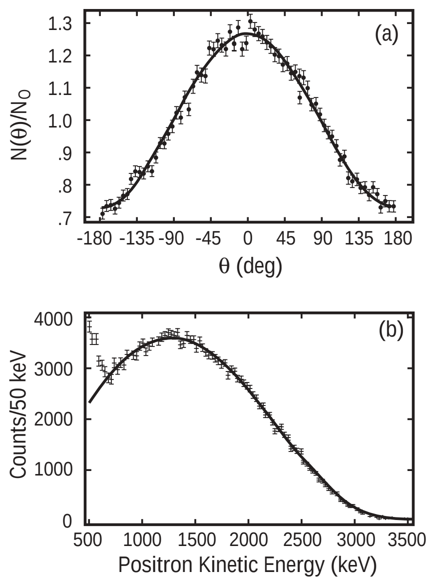


**Figure 4. Rubidium-82 beta-decay data accumulated over a period of six hours. (a) The angular distribution obtained after binning the events as a function of positron-nuclear spin angle and integrated over positron kinetic energy above a threshold of 800keV . The solid curve results from a cosine fit to the distribution, the nonzero amplitude resulting from parity-violation and indicating the successful confinement and polarization of rubidium-82 atoms in the TOP trap. (b) The differential positron kinetic energy spectrum obtained after integrating out the angular degree of freedom. The solid curve results from detailed Monte Carlo simulations that account for the full decay scheme for rubidium-82 decay and the details of the positron detection optics. The spectrum departs from a pure positron signal at low energy due to Compton scattering of 776 keV gamma rays fom the $2^+$ state of the krypton-82 daughter nucleus.**

## Future Directions

Detailed analysis of these proof-of-principle experiments indicated several improvements necessary before we can realize a precision measurement of the correlation coefficient of interest. In the absence of background, the amplitude of the angular correlation is directly proportional to the product AP. Hence it follows that, in order to extract the correlation coefficient (A), one requires independent knowledge of the absolute polarization (P). We have not, as yet, instrumented the appropriate hardware to measure the polarization but plans are now in place to perform such measurements using high-resolution charge-coupled device (CCD) camera images of the atom cloud. This, in conjunction with a mapping of the magnetic-field distribution over the trap region, then allows one to determine the global polarization of the atom cloud.

The amplitude of the angular correlation shown in Figure 4a is smaller than expected because the absolute polarization of the atom cloud is less than optimal and also from background associated with atoms that are ejected from the trap. A number of mechanisms are responsible for atoms to be lost from the trap. These wayward atoms make their way to the walls of the vacuum chamber where they subsequently decay from an unpolarized state, producing an uncorrelated background that falsely masquerades as a signal with less-than-maximal parity violation. We can circumvent this background through optimization of the trapping procedure and through the design of a positron telescope capable of discriminating positrons that are emitted from the trap region.

## Summary & Outlook

In summary, we have successfully demonstrated the feasibility to exploit a TOP trap to explore fundamental symmetries such as parity violation in a new generation of beta decay experiments. We have a golden opportunity at Los Alamos to play an active and lead role in the next generation of fundamental symmetry experiments that exploit trapped radioactive atoms. The combination of nuclear chemistry, atomic-, nuclear-, and particle-physics capabilities inherent in this collaboration makes the possibility of precision and world-class experiments unique, and it is unlikely that such an experiment will take place elsewhere in the foreseeable future. The success of future experiments hinges on our ability to optimize and measure the polarization of the atom cloud and the design and construction of an efficient positron telescope capable of reducing background to an acceptable level. The necessary upgrades and improvements to our experiment will now be the focus of our attention. We hope also that successful measurements with polarized rubidium-82 will pave the way to a whole new class of experiments, including the possibility to exploit trapped lithium-8 atoms … but that is another story!

## References/Further Reading


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