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Design of a unique open-geometry cylindrical Penning trap

M. Mehlman [a,b,*], P.D. Shidling [a], S. Behling [a,c], L.G. Clark [d], B. Fenker [a,b], D. Melconian [a,b]

[a] Cyclotron Institute, Texas A&M University, 3366 TAMU, College Station, TX 77843-3366, United States
[b] Department of Physics and Astronomy, Texas A&M University, 4242 TAMU, College Station, TX 77843-4242, United States
[c] Department of Chemistry, Texas A&M University, 3012 TAMU, College Station, TX 77842-3012, United States
[d] College of Engineering, Texas A&M University, 3126 TAMU, College Station, TX 77843-3126, United States

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ABSTRACT

The Texas A&M University Penning trap facility is an ion trap system currently under construction, and will be used for precision nuclear physics experiments with radioactive beams provided by the Cyclotron Institute. Its primary focus is to carry out experiments to search for possible scalar currents in $T=2$ superallowed β-delayed proton decays, which, if found, would be an indication of physics beyond the standard model. In addition, TAMUTRAP will provide a low-energy, spatially localized source of ions for various other applications. The experiment is centered around a unique, compensated cylindrical Penning trap that employs a specially optimized length/radius ratio in the electrode structure that is not used by any other facility. This allows the electrode structure to exhibit an unprecedented 90 mm inner radius, which is larger than in any existing trap, while at the same time remaining a tractable overall length. The trap geometry was designed from first principles to be suitable for a wide range of nuclear physics experiments. In particular, the electrode structure allows for a near quadrupole electric field at the trap center, a feature necessary for performing precision mass measurements.

1. Introduction

Low energy precision β-decay experiments have proven to be an excellent complement to high energy physics for placing new constraints on physics beyond the standard model (SM) [1–3]. Up to this point, it has been possible to explain the results from such experiments by a time reversal invariant $V-A$ interaction displaying a maximal violation of parity; however, more precise measurements of correlation parameters [4] and $\mathcal{F}t$ values [5–7]

$$\mathcal{F}t = \frac{\hbar(\hbar c)^6 2\pi^3 \ln 2}{(m_e c^2)^5 G_F^2 |V_{ud}|^2 |M_{fi}|^2 (1+\Delta_R^V)} \tag{1}$$

(where m_e is the mass of the electron, G_F is the Fermi coupling constant, $|V_{ud}|$ is an element of the CKM matrix, $|M_{fi}|$ is the Fermi matrix element, and Δ_R^V is the nucleus-independent radiative correction) in particular β-decays can serve to test for the presence and properties of any non-SM processes that may occur in such interactions.

* Corresponding author at: Cyclotron Institute, Texas A&M University, 3366 TAMU, College Station, TX 77843-3366, United States. Tel.: +1 979 845 1411; fax: +1 979 845 1899.
E-mail addresses: mehlmanmichael@gmail.com, mehlmanmichael@tamu.edu (M. Mehlman).

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1.1. Motivation

The initial experimental program at the upcoming Texas A&M University Penning Trap (TAMUTRAP) facility will seek to improve the limits on non-SM processes in the weak interaction, in particular scalar currents, by measuring the $\beta-\nu$ correlation parameter, $a_{\beta\nu}$, for $T=2$, $0^+ \rightarrow 0^+$ superallowed β-delayed proton emitters (the generic decay scheme is shown in Fig. 1, and the preliminary list of nuclei to be studied is outlined in Table 1).

The general β-decay rate with no net polarization or alignment is given by Ref. [8]

$$\frac{d^5\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto 1 + \frac{p_e}{E_e} a_{\beta\nu} \cos\theta_{\beta\nu} + b\frac{m_e}{E_e} \tag{2}$$

where Ω_e and Ω_ν are the solid angles of the beta particle and neutrino, E_e, p_e, and m_e are the energy, momentum, and mass of the beta particle, $\theta_{\beta\nu}$ is the angle between the beta particle and neutrino, and b is the Fierz interference coefficient. Thus, it is possible to determine the $\beta-\nu$ correlation parameter by means of an experimental measurement of the angular distribution between the β and ν. For the strict $V-A$ interaction currently predicted by the SM (in pure Fermi decays) the $\beta-\nu$ angular distribution should yield a value for $a_{\beta\nu}$ of exactly 1. Any admixture of a scalar current to the predicted interaction, a result of particles other than the expected $W^{\pm}$ being exchanged during the decay, would result in a measured value of $a_{\beta\nu} < 1$.

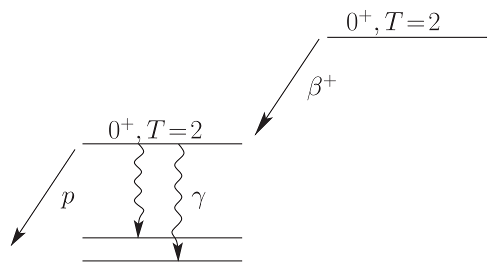

Fig. 1. Decay scheme for a generic $T=2$, $0^+ \rightarrow 0^+$ superallowed β-delayed proton decay.

Table 1
The $T=2$ nuclei that will compose the initial experimental program measuring $a_{\beta\nu}$. The Larmour radii, R_L, for the ejected protons of interest (having energy E_p) shown are calculated for the 7 T magnetic field of TAMUTRAP.

Nuclide	Lifetime (ms)	E_p (MeV)	R_L (mm)
^{20}Mg	137.05	4.28	42.7
^{24}Si	147.15	3.91	40.8
^{28}S	180.33	3.70	39.7
^{32}Ar	141.38	3.36	37.8
^{36}Ca	141.15	2.55	33.0
^{40}Ti	72.13	3.73	39.9
^{48}Fe	63.48	1.23	22.9

TAMUTRAP will observe this angular distribution between β and ν for β-delayed proton emitters in order to take advantage of the benefit these particular decays have on the experimental procedure. In such a case, the β-decay yields a daughter nucleus that is unstable, and can result in the subsequent emission of a proton with significant probability. As discussed in Ref. [4], the great advantage to utilizing β-delayed proton emitters for such a study is that this proton energy distribution contains information about $\theta_{\beta\nu}$. If the β and ν are ejected from the parent nucleus in the same direction, they will impart a maximum amount of momentum to the daughter nucleus, which will be inherited by the proton. Conversely, if the β and ν are emitted in opposite directions, the proton inherits measurably less momentum. By determining the proton energy distribution at TAMUTRAP the value of $a_{\beta\nu}$ will be deduced, which can then indicate the existence of a scalar current if it exists [8].

1.2. Cylindrical penning traps

A Penning trap is a type of ion trap that employs a well-shaped static electric field and a linear magnetic field to spatially confine charged particles in a small, well-known volume. Such a trap can be implemented using a variety of electrode geometries, most commonly in either a cylindrical or hyperbolic configuration, to determine the electric field, which is used for axial confinement [9]. The magnetic field, which achieves the radial confinement of the ions, is typically generated by a solenoidal magnet in which the electrode structure is placed.

Penning traps that take advantage of a cylindrical electrode geometry allow for efficient access to the trapped ions, a large trapping volume compared to the common hyperboloid trap geometry, and an electric field that can be described analytically, which is of particular importance during the design process. Additionally, cylindrical electrodes are more easily manufactured with higher precision, a result of the inherently cylindrical turning or milling machining techniques typically employed in fabrication [9]. For these reasons, Penning traps with a cylindrical geometry have been used widely in nuclear physics research experiments ranging from precision mass measurements [10] to the production of anti-hydrogen [11].

Precision β-decay experiments are well served by a cylindrical geometry due to the fact that the magnetic field employed to trap the ions radially may simultaneously be used to contain charged decay products [12] such as β's and protons with up to 4π acceptance in an appropriately designed trap. The strong magnetic radial confinement in combination with the weak electrostatic axial confinement direct the decay products of interest to either end of the trap for detection with negligible affect on the energy of the particles. At the same time, features of a cylindrical trap geometry can be useful for other nuclear physics experiments, such as maintaining a line of sight to the trap center for spectroscopy, an easily tunable and orthogonalized electric field for experiments requiring a harmonic potential (such as mass measurements), and unrivaled access to the trapped ions due to a geometry that does not require confining electrodes that follow the desired equipotential surfaces.

2. Design of TAMUTRAP

For the reasons mentioned in Section 1.2, a cylindrical geometry has been chosen for the TAMUTRAP measurement Penning trap [13]. This particular geometry has been optimized to create a design that is suitable both for the precision β-decay experiments of interest, as well as a wide range of nuclear physics experiments as discussed. Specifically, the trap must display a large-bore for containment of decay products, it should allow for the placement of biased detectors at both ends for observation of these products, and it should exhibit a tunable and orthogonalized geometry in order to achieve a harmonic electric field.

2.1. Electrodes with large inner diameter

For $\beta-\nu$ correlation measurements, the trap must have a free diameter large enough to contain the decay products of interest within the electrodes via the Lorentz force imposed by the trapping magnetic field. The initial program of measuring $a_{\beta\nu}$ will investigate the $T=2$ nuclei shown in Table 1, by observing the proton energy distribution. To contain protons of interest with full 4π acceptance the trap radius is set to twice the Larmour radius of the most energetic expected proton within the 7 T magnetic field provided by the Agilent 7 T 210 ASR magnet [14]. The inner radius of the electrode structure was chosen to be 90 mm, which will fully contain protons of up to 4.75 MeV. This radius will be the largest of any existing Penning trap and will easily contain the protons of interest, as well as the less magnetically rigid β's, for the initial $a_{\beta\nu}$ studies.

2.2. Endcaps

The other primary requirement for performing the mentioned correlation measurements is that the design must ultimately accommodate position sensitive strip detectors at either end of the trap. The charged decay products (β, p, recoil ion) exhibit Larmour precession contained completely within the bore of the Penning trap until they are detected by such a detector. These detectors have been simulated separately as disk-shaped "endcap electrodes". Such an approximation satisfies the need to bias the detectors at some arbitrary potential not necessarily equal to that of the cylindrical end electrodes. The impact of the endcap electrodes on the solution to the complete electric field is discussed in detail in Section 2.3.