A novel method for fundamental interaction studies with an electrostatic ion beam trap

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Abstract. We present the first steps towards the realization of a novel experimental scheme to measure $\beta-\nu$ correlations in the $\beta$ decay of $^6$He, for the purpose of Fundamental Interaction studies. Our method is based on a novel use of an ion trapping device, the Electrostatic Ion Beam Trap (EIBT) coupled to a d+t neutron generator. The EIBT which has not been previously considered for Fundamental Interaction studies, exhibits potentially very significant advantages over other state of the art experimental schemes aimed at precision measurements of the $\beta-\nu$ angular correlation coefficient.

1. Introduction
Trapped radioactive atoms present exciting opportunities for the study of fundamental interactions and symmetries. For example, detecting beta decay in a trap can probe the minute experimental signal that originates from possible tensor or scalar terms in the weak interaction. Such scalar or tensor terms affect, e.g., the angular correlation between a neutrino and an electron in the beta-decay process, thus probing new physics of “beyond-the-standard-model” nature [1].

We propose an innovative experimental scheme for beta-decay studies using a practically “table-top” experiment, featuring an Electrostatic Ion Beam Trap (EIBT) [2]. Such a trap has not been previously considered for Fundamental Interaction studies and exhibits potentially very significant advantages over other experimental schemes (e.g. Magneto Optical Traps []). The long (~seconds) storage time of the ion beam is perfectly suitable for beta decay studies for relatively short lived species. Other advantages include high injection efficiency of the radionuclide under study, an extended field-free region, ion-beam kinematics for better efficiency, ease-of-operation and the potential for a much larger solid angle for the electron and recoiling atom counters.

In the following we briefly present the theory of beta decay formalism, with special emphasis on the case of radioactive $^6$He (half life 807 ms). The subsequent sections include a brief method description and preliminary simulation results. We conclude with a brief summary.

2. Theory
The $\beta$-decay transition rate $W$ (inverse lifetime) in case of non-oriented nucleus is given by [3]

$$dW \propto \frac{\xi}{1 + \frac{p_e}{E_eE_\nu} \cdot \cos \theta_{e\nu}} \left( 1 + a \frac{p_e}{E_e} \cdot \sin \theta_{e\nu} \right)$$

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The most general way to write the beta decay Hamiltonian \([3]\) is:

\[
H_{\beta}^{6He} = \sum_{i=S,P,V,A,T} (6Li)_{i}^{6He} [\bar{\nu} \hat{O}_{i} (C_{i} + C'_{i} \gamma_{5}) \nu_{e}] + h.c.
\]

where S,P,V,A and T stands for Scalar, Pseudo-scalar, Vector, Axial-vector and Tensor respectively. The \(\beta-\nu\) correlation coefficient can be expressed by means of the Gamow-Teller (GT) and Fermi (F) matrix elements together with eight coupling constants \(C, C'\) \([3]\):

\[
a_{i} = F \left[ |C_{i}|^{2} - |C_{S}|^{2} + |C'_{i}|^{2} - |C'_{S}|^{2} \right] + \frac{|GT|^{2}}{3} \left[ |C_{T}|^{2} - |C_{A}|^{2} + |C'_{T}|^{2} - |C'_{A}|^{2} \right]
\]

and

\[
\xi = F \left[ |C_{i}|^{2} + |C_{S}|^{2} + |C'_{i}|^{2} + |C'_{S}|^{2} \right] + |GT|^{2} \left[ |C_{T}|^{2} + |C_{A}|^{2} + |C'_{T}|^{2} + |C'_{A}|^{2} \right]
\]

The \(^{6}\text{He}\) beta decay is a \(J^{P}=0^{-}\) to \(J^{P}=1^{+}\) pure Gamow-Teller decay. In that case the beta-neutrino correlation coefficient can be expressed only by Axial and Tensor coupling constants in the Hamiltonian, since the Fermi matrix element is zero. In the Standard Model (SM) only the V-A interactions can occur, therefore only the axial coupling constants remain \([3]\):

\[
|C_{T}|^{2} = |C'_{T}|^{2} = 0 \quad |C_{A}|^{2} = |C'_{A}|^{2} = 1
\]

Consequently the transition rate for pure Gamow-Teller decays in the SM frame has the following simple form (with \(a=-1/3\)),

\[
dW_{SM}(\theta_{e\nu}) \propto \left( 1 - \frac{\frac{p_{e}}{3} \cos \theta_{e\nu}}{E_{e}} \right)
\]

where the squared GT matrix element can be brought out of brackets, hence its absolute value is not important. On the contrary, in a general case, beta decay may be neither a pure Gamow-Teller nor a pure Fermi decay. As a result any beta decay coefficient in the transition rate equation would be matrix elements depended, thus nuclear structure theory depended.

3. Method

The main purpose of the experiment is a high-precision measurement of the beta decay coefficients (a). In the following we present a novel approach – that of using an Electrostatic Ion Beam Trap (EIBT). Following the pioneering work at the Weizmann Institute of Science \([2]\), the EIBT is being used worldwide (Germany, France, India, Japan and USA) in atomic and molecular physics experiments and even a cryogenic EIBT operated at 2K has been recently commissioned \([4]\). However, injecting and trapping radioactive nuclei for Fundamental Interaction studies in an EIBT device is an entirely novel direction that has never been tried before. This direction offers significant improvements in detection efficiency (paramount consideration when working with radioactive beams of limited intensity) and ease of operation.
The EIBT was developed at WI in 1996 [2] for storing ions at typical energy of few keV. The principle of operation of an EIBT [5] is based on the analogy with the classical optical resonator: it is possible to store a beam of photons between two spherical mirrors separated by distance $L$ if the focal length $f$ fulfills the stability condition, namely: $L/4 < f < \infty$ and the potential on the mirrors is larger than the ion beam kinetic energy. A scheme of the EIBT setup is shown in figure 1. The basic EIBT consist of 2 sets of eight electrodes both acting as an electrostatic mirror and as a lens by producing a retarding field which reflects the beam along its path and focuses it on the lateral direction. The typical distance between the electrostatic mirrors is 500 mm.

Ions with kinetic energy of ~10 keV are injected through the grounded entrance mirror, once the ions fill the trap; potentials on the entrance mirror are quickly raised (< 10 ns) so that the ions bounce back and forth between the mirrors. For the $^6\text{He}$, the revolution time is \( \sim 4 \) microseconds. Shortly after injection the trapped beam is bunched using RF fields. A pickup electrode, located in the trap center is used to continuously monitor the bunch location (in the new set up two pickup electrodes will be located as a part of the ground electrode in the mirrors). Therefore, the position of the decay is known. The products of the decay (recoil Li nuclei and electron) are detected by a set of dedicated detectors. Two annular position sensitive Multi-Channel-Plate (MCP) detectors are situated along the main trap axis with the purpose of counting the recoil Li. These MCPs have central holes which allow the stable trajectories of the stored ions (such technology was demonstrated before [6]). The electrons are counted by two detectors located above and below the optical axis. The detectors are composed of plastic scintillators coupled to double sided silicon strip detectors (DSSD), thereby obtaining both energy and position of the beta particle.

4. Preliminary simulations results
Simulations are crucial to demonstrate the concept validity and, later on in the project itself, to optimize both the bunch dynamics and the detection geometry. The construction of the dedicated setup of an EBIT for beta-decay studies should naturally follow such simulations and take advantage of the gained insight. This process is currently ongoing and we present below first and preliminary results. The observable parameters (recoil time of flight, position of the ion bunch, position of particles on detectors, electron energy), allow the full reconstruction of the momentum of the undetected neutrino particle in the beta decay. Thus the angular correlation between electron and the neutrino upon decay can be studied.

The accuracy of the neutrino momentum is mainly limited by the certainty of the position of the decay, which can occur anywhere inside the ion bunch. While only the location of the bunch is measured. Previous works on the subject show that under special trapping conditions (“self bunching”) [7], the ion bunch size can be reduced to few cm. We plan to investigate this issue further in the hope of achieving bunch size of typically 1 cm. Moreover, a study of the influence of the bunch...
size (e.g. the uncertainty of the decay within the bunch) on the sensitivity of our measurement is now underway and preliminary results are shown in figure 2 for different bunch sizes. As we can see small bunch sizes (~<2 cm) are almost identical to a point-like beta decay occurrences. Further simulations, aimed at a better understanding of the detailed characteristics of the particles in the bunch, as far as the correct labeling of the corresponding energy and momentum (and hence the ensuing $\beta$–$\nu$ angle) are presently being carried out.

![Figure 2. GEANT4 [8] simulation of the beta-neutrino correlation with different bunch sizes.](image)

As a consequence of these simulations, we are presently embarking on a R&D effort to investigate the efficient bunching of the ion beam as an input to the EIBT. For that purpose, we are using $^4$He stable ions from an rf source (shown in figure 3).

![Figure 3. A picture of the initial experimental setup, with the rf source, beam-lines and analyzing magnet. The d+t neutron generator will be placed next to the ion source](image)
5. Summary and future plans
This research direction is also closely related in turn to the intensive R&D efforts that are currently under way in our laboratory to facilitate the production and extraction of such radioactive nuclei (\(^6\)He and \(^8\)Li, for example) in record yields, using neutron-induced reactions [9]. We are planning to use an intense d+t commercial neutron generator that provides \(14\) MeV neutrons at fluxes reaching \(10^9 - 10^{10}\) n/s. The purchase of such a generator has recently been approved by the WI. At a later stage, we envisage taking advantage of uniquely high yields of radioactive nuclei that will become available at the new and modern SARAF accelerator at Soreq.

It is also imperative to use an appropriate buncher-cooler device, such as an RFQ buncher-cooler as a pre-injection device into the EBIT. Simulations regarding design option to this effect are presently being examined in detail. Another subject under initial considerations is the electron and ion detection system, consisting of a positive sensitive Micro Channel Plate (MCP) device and for the recoiling \(^6\)Li ions and a set of silicon strip detectors for the electrons’ position and energy determination.

Though the research program is only at the beginning, it seems robust and promising in the light of the recent calculations and our growing understanding of the system.

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