Development of a radiofrequency linear ion trap for β decay study

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Abstract

A Beta decay Paul Trap (BPT) has been constructed at Argonne National Laboratory for the precise measurement of beta decay. We have demonstrated the capability of producing and transferring a low-energy, bunched, and isotopically pure ions beam. In BPT the ions are cooled to sub-eV energies, and confined in a volume of less than 1 mm^3.

The trap has an open geometry which allows four sets of radiation detectors covering a substantial potion of solid angle. In combination with versatile detectors, BPT is able to precisely determine the entire decay kinematics of many isotopes.

1. Introduction

In the Standard Model, five types of interaction are allowed due to Lorentz invariance: Scalar (S), Vector (V), Axial-Vector (A), Pseudo scalar (P) and Tensor (T). Experimental data suggest a strong dominate of two interactions "Vector - axial vector" which is the so called (V-A) theory in weak interaction. However, the precisions of these experiments are not very high, contributions from scalar and tensor interactions of as large as 5%-10%

vector and axial-vector terms have not been excluded [1]. The existence of scalar and tensor interaction is accessible by high precision beta-neutrino angular correlation measurement in beta decay. Such small effect requires extremely strict experimental conditions like pure ions sample, almost at rest, located in a very limited space, without interaction with other material, good resolution of detectors, etc. Therefore the BPT is constructed to study the weak interaction of $^{8}Li^{+}$ ions.

For allowed transitions of unpolarized ions, the decay rate takes the following form:

$$W = W_o(E_e)\left(1 + \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} a + \frac{m_e}{E_e} b\right) \quad (1)$$

where $W_0(E_e)$ is a function of the β energy including the phase space and the coulomb interaction, $\mathbf{p}_e$ and $\mathbf{p}_\nu$ are the momenta of β particle and ν respectively, E_e and E_ν are the energy of β and ν respectively, *b* is the Fierz interference term which is very small and *a* is the β-ν angular correlation coefficient. For a pure Gamow-Teller transition, the coefficient *a* take the form:

$$a_{GT} = -\frac{1}{3}[1 - \frac{|C_T|^2 + |C'_T|^2}{C_A^2}] = -\frac{1}{3}, \text{ if } C_T = 0 \quad (2)$$

where C_T and C_A are tensor and axial-vector coupling constant respectively. A deviation of a_{GT} from the predicted value -1/3 will indicate the existence of tensor currents, and new physics beyond stand model. [2]

The β decay of ^{8}Li ($^{8}Li \rightarrow \beta^{-} + \nu_e^{-} + {}^{8}Be^{*} + 16.09$ MeV) (Fig. 1) is a nearly pure Gamow-Teller decay which is very sensitive to tensor interaction. The daughter nucleus ^{8}Be immediately breaks up into two α particles. The complete decay kinematics can be determined by measuring the momenta of two α's and the direction of the β with four sets of Double-sided Silicon Strip Detectors (DSSD). Future upgrade includes installing plastic scintillator behind DSSD which will measure the energy of β particle, so the decay kinematics will be over constrained.

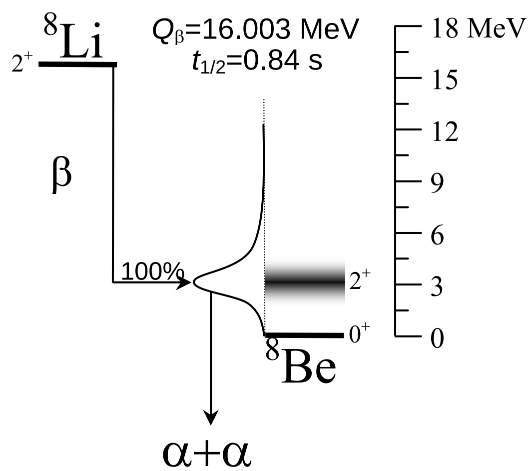


Figure 1 Decay scheme of $^8Li \rightarrow \beta^- + \nu_e^- + {}^8Be^* + 16.09$ MeV

2. Ion Trap System

The ^{8}Li is produced at the Argonne Tandem Linear Accelerator System (ATLAS) via the prolific d(7Li,8Li)p reaction. The deceleration, cooling and bunching of the $^8Li^+$ ions are performed at Canadian Penning Trap injection system (Fig. 2) [3,4]. $^8Li^+$ ions are efficiently loaded (> 90%) to BPT (Fig. 3.1, 3.2), where the measurement is taken.

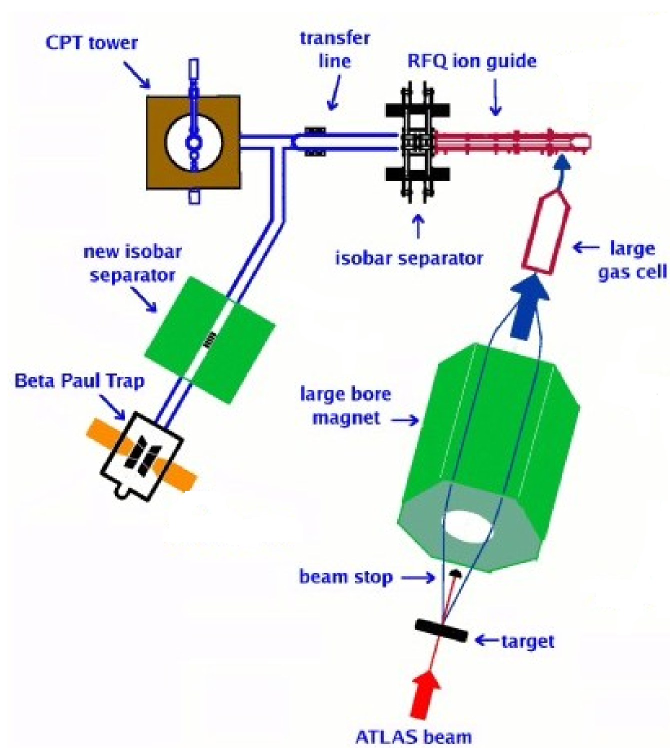


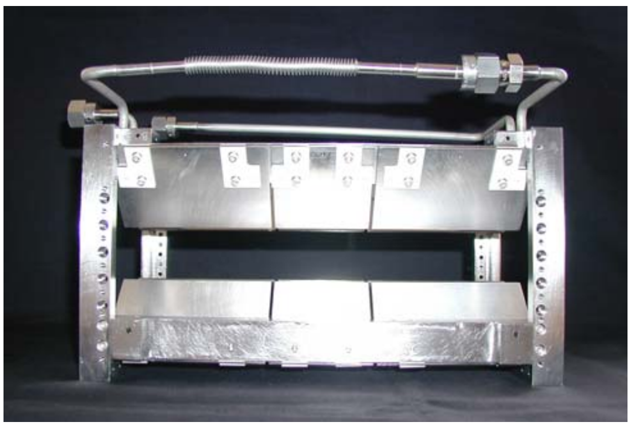
Figure 2

System overview

2.1 The Beta-decay Paul Trap

2.1.1 Ions confinement

The cooled, bunched, and purified $^{8}Li^{+}$ ions are loaded to BPT efficiently. Ions are confined with the combination of DC and RF field. In the axial direction, a DC potential well of -90 V are applied on the segmented electrode plates (Fig. 3.1). The depth of the potential well is 2V at the central 1cm region according to the simulation by Simion 7. In the radial direction, the ions are confined by an RF field with peak-to-peak amplitude of 1 kV at frequency of 2 MHz (Fig. 3.2). A PseudoPotential [5] Well of 5V over 1cm at the center is achieved under such RF conditions.



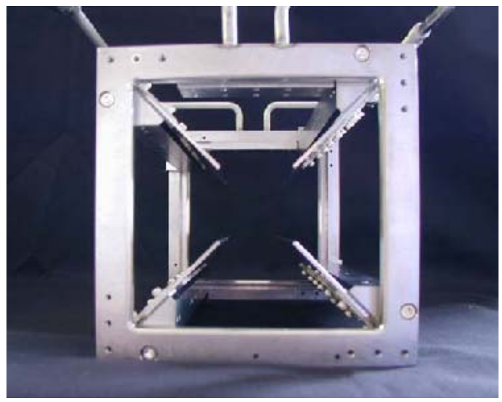


Figure 3.1 electrodes view of axial direction **3.2** electrodes view of radial direction

2.1.2 Cooling

High purity ^{4}He buffer gas is injected to the trap maintaining a pressure ~ 10^{-5} torr in the vacuum chamber to cool the $^{8}Li^{+}$ ions. Liquid nitrogen circulates in the trap frame to reduce the thermal energy of ^{4}He and $^{8}Li^{+}$ below 0.1 eV, which is low enough to let ions be confined within 1mm^{3} by electrical potential well. According to the simulation, ions cloud shrinks to 1mm^{3} within 100 ms after capture.

2.1.3 Storage

By adjusting the time interval between capture and ejection of ion bunches, and measuring the decay rate of ejected ^{8}Li by Si detector, the storage time of the trap is determined to be >10 sec. Compared to the 0.8 sec short half-life of ^{8}Li, almost all ions will decay within the trap.

2.2 The Detection Setup

The detector system consists of four sets of silicon detectors (Fig. 4). Each set of detectors has a DSSD of 300 μm thick, 16 strips on each side, 50×50 mm^2 active area, backed by 3 silicon wafers of 1mm thick, which record part of β energy. The DSSDs are 55 mm apart from the trap center, in a symmetrical geometry. They cover 35% solid angle; therefore the detection efficiency of a β-β-α coincidence is about 10%. An event is triggered by a signal on one DSSD, and all signals from DSSD and silicon wafers are recorded. For each event, two α's momenta, and β position information are recorded. The measurement of the coefficient a_{GT} can be extracted by measuring the counts of events with different angles between β and ν.

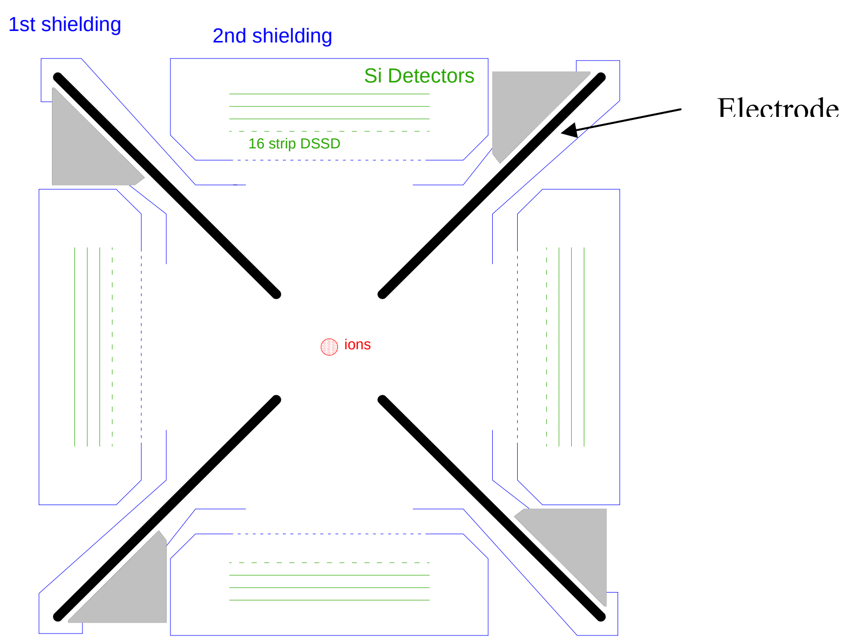


Figure 4 Detector system

3. Conclusion and outlook

During the June 2009 beam time, $\sim 10^4$ α-α coincidence were observed. β particle was not detected because of high RF pick-up from electrodes. Since then the noise has been reduced greatly and the resolution of DSSD is good enough to allow recording β information now. We expect to get a preliminary result with 10^6 α-α-β event during May 2010 beam time, which will allow a careful study of the systematic effect. Also the detector system will be upgraded by installing DSSD with high angular resolution and installing plastic scintillator behind DSSD to measure β energy. On the long term, BPT will be used to measure the β-ν angular correlation with other isotopes, and measure the neutron spectroscopy in β-delayed neutron decay.

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