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WEAK-INTERACTION STUDIES WITH LIGHT RADIOACTIVE IONS*

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We present an experimental plan to study the weak interaction by measuring the electron–neutrino angular correlation from radioactive β-emitter atoms, ^{6}He being the first case. Radioactive atoms, produced by a neutron-induced reaction, will diffuse to an electron beam ion source that ionizes, bunches and then injects them into an electrostatic ion beam trap where the angular correlation will be measured. We have tested the trap with stable ions and found the storage time to be 0.6 to 1.2 s for different ions. We have also performed the production experiment for ^{6}He with a production rate of $\sim 10^5$ atoms/s. We present the current status of this project and future plans.

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1. Introduction

Within the Standard Model for weak interaction, the scalar- and tensor-type components, being very small, are excluded. This leads to the value of the β–ν angular correlation coefficient ($\alpha_{\beta\nu}$) equal to 1 for a pure Fermi transition (FT) and $-1/3$ for a pure Gamow–Teller (GT) transition. Measuring a precise value of $\alpha_{\beta\nu}$ allows one to search for minute signals that possibly originate from tensor- or scalar-type interactions, thus probing the physics beyond the Standard Model [1, 2]. An ion trap can play an important role in these precision measurements since the position of the incoming ion bunch, the energy and position of the decay products can be precisely measured. We have embarked on an experimental program to measure $\alpha_{\beta\nu}$

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from the decay of trapped, light, radioactive ions inside an electrostatic ion beam trap (EIBT) [3]. Electrostatic traps have been developed since the late 90s [4] for solving problems in atomic physics but it is a novel approach to use such traps in β-decay studies. Our scheme provides a complementary solution to other techniques of trapping.

^{6}He has some interesting properties that make it a good starting candidate for our quest. It is almost a pure beta emitter (GT decay) [5] with a sufficiently long half-life of 806.89 ± 0.11 ms [6] for production, ionizing, and trapping. It also has a large Q value (~ 3.5 MeV), and being a noble gas, does not react with residual gas. There have been a few experiments reported with high precision measurements of $\alpha_{\beta\nu}$ in the decay of ^{6}He [7–9]. Our scheme aims at reducing the systematic errors and achieving higher precision in the measurement.

The experimental plan is to produce light radioactive atoms using neutron-induced reactions that will be piped into an electron beam ion source (EBIS) for ionization and bunching. After some time, the bunch will be ejected from the EBIS by switching the voltages on its drift tubes, thereby injecting it into the EIBT where they are trapped. The recoiling nucleus and the electron from the β decay of the trapped ions will be detected in a large area position-sensitive microchannel plate detector with a resistive anode encoder (MCP-RAE) [10] and a large area position-sensitive plastic scintillator (LAPS) [11] outside the trap, respectively. Thus, the $\alpha_{\beta\nu}$ value can be calculated from the known kinematics of the electrons and the recoils. The block diagram showing this scheme is presented in Fig. 1. In this report, we present the current status of this project along with the near future plans.

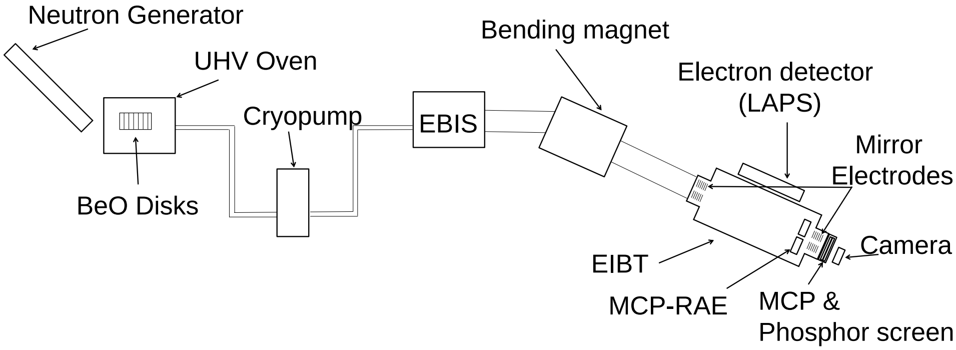

Fig. 1. Block diagram of the experiment for measurement of angular correlation coefficient ($\alpha_{\beta\nu}$). See the text for details.

2. Electrostatic ion beam trap

The EIBT, developed at the Weizmann Institute of Science, Israel, is useful for trapping low-energy ions in the range of several seconds. Its storage time is dependent on the residual gas pressure in the chamber [12]. The residual gasses interact with ion bunches and neutralize them or scatter them from stable trajectories. The EIBT used in our experiment has been specifically designed for efficient detection of the decay products from the trapped radioactive ions. The length of the ion trap was chosen to accommodate the MCP at a distance from the center of the LAPS that provides high detection efficiency for the case of ^{6}He β decay. The increase in detection efficiency is not confined to a single ion species because the distance of the detector can be varied to get better efficiency for other radioactive ions.

Two electrostatic mirrors form the EIBT, each mirror having eight electrodes. The retarding field produced by these electrodes acts as a lens that reflects the beam back along its path and also focuses it transversely. Because the innermost electrodes of each mirror are grounded, the region between the mirrors is field-free. In this region, the energy and direction of the ion bunch are well-defined. A small RF voltage can also be applied to one of the electrodes for re-bunching the ion beam. A LabVIEW-based control program defines the timing configuration of the EIBT. Prior to injection of the ion bunch, the peak potential in the mirror is lowered to a value less than the accelerating voltage of the bunch to enable the bunch to enter. The potentials on the entrance electrode are raised quickly, thus constraining the bunch to oscillate between the two mirrors. A capacitive pickup is used to detect the passage of the ion bunch. The innermost (grounded) electrode of each mirror was modified to incorporate a capacitive pickup and another pickup was installed adjacent to the MCP for beam diagnostic purposes. The mirrors, MCP, and pickups are mounted on a precision optical table on the base of trap chamber, to ensure their precise alignment and minimize the systematic errors.

The stable ions used in the trapping test were generated by the EBIS purchased from Dreebit GmbH, Germany. Foreseeing a low production yield of radioactive atoms, the ionization efficiency of the EBIS has been improved by modifying the drift tube assembly to allow direct injection of the atoms [13]. Different ion species, *viz.* CO^+, O^+ and $^4\mathrm{He}^+$, with $\sim 4.2\,\mathrm{keV}$ energy, were ionized by the EBIS and mass-selected by a 30° bending magnet placed before the trap. SIMION® was used to find the optimal voltages for the operation of the EIBT and the same voltages were used in the trap. The decay of the trapped ions was measured by recording the neutrals hitting an MCP detector located outside the trap after the exit mirror. The base pressure of the trap was $\sim 7 \times 10^{-10}\,\mathrm{mbar}$, and the storage time for the heavier ion species was found to be $\sim 1.2\,\mathrm{s}$ and $\sim 0.6\,\mathrm{s}$ for $^4\mathrm{He}^+$ ions. The decay curve of $^4\mathrm{He}^+$ ions inside the trap is shown in Fig. 2.

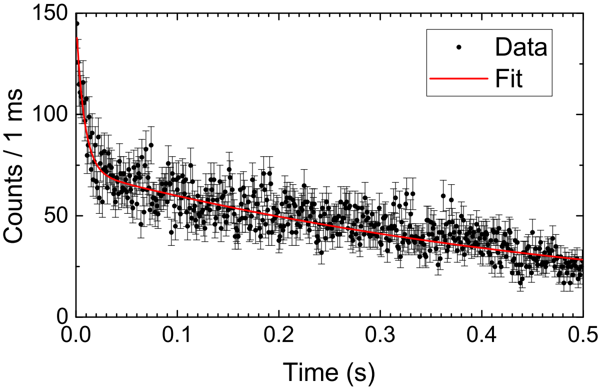

Fig. 2. Decay of 4.2 keV $^{4}\mathrm{He}^{+}$ ions inside the electrostatic ion beam trap. Data has been fitted with double-exponential decay. Initial fast decay is due to the loss of ions that entered the trap on unstable trajectories. The slow decay corresponds to the decay time of the ion bunch, which is termed the storage time. The storage time from the fit is ~ 0.6 s.

3. Production of ^{6}He

The production experiment of ^{6}He radioactive atoms was performed at the Weizmann Institute of Science. ^{6}He atoms were produced in an UHV oven (production chamber) and from which they diffused to a six-way cross made of stainless steel (measurement chamber), both of which were maintained at $\sim 10^{-8}$ mbar. The EBIS and the EIBT were not used in this part of the measurement. The radioactive atoms were produced in porous BeO disks using the $n(^{9}\mathrm{Be},\alpha)^{6}\mathrm{He}$ reaction. The neutron source was a commercial neutron generator (NG) producing isotropic neutrons with an average kinetic energy of 14 MeV and a flux of $\sim 10^{9}$ neutrons/s [14]. The temperature dependence of the diffusion rate of ^{6}He from the BeO disks was measured in a previous measurement [15]. In the present configuration, 38 BeO disks, ⌀38 mm × 2 mm, were placed inside the oven that was heated to 1400°C while maintaining a pressure of $\sim 10^{-8}$ mbar. The diffusing ^{6}He passed through a cryopump on its way to the measurement chamber in order to freeze out all impurities coming from the BeO. The decay of ^{6}He was measured in a plastic detector placed outside the measurement chamber. The measurement chamber was pumped with a turbopump for maintaining the vacuum. The measurement was performed in cycles with each cycle consisting of *(i)* 2.5 s of NG operation, *(ii)* 100 ms for the ^{6}He to diffuse to the measurement chamber, and *(iii)* 10 s of data acquisition from the plastic detector. A total of 900 cycles was performed. The background was also recorded for the same time, and the background-subtracted final decay curve along with the fitted simulation curve are shown in Fig. 3.

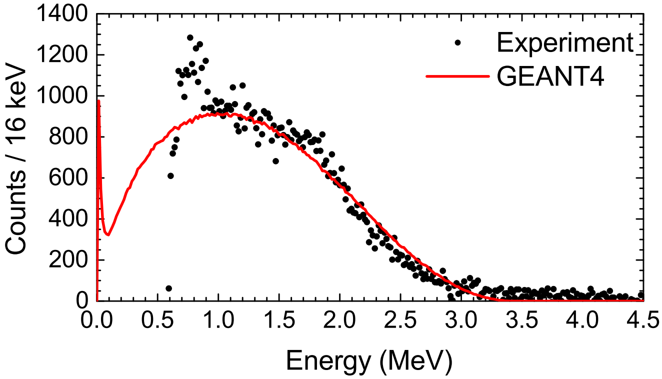

Fig. 3. Spectrum of ^{6}He decay inside the measurement chamber and the Geant4 simulated spectrum.

Simulation package Geant4 [16] was extensively used in our analysis. It was used to calculate the production probability of ^{6}He, giving $1.45\ \times 10^{-4}$ atoms/neutron for the present geometry of the NG and the oven. Geant4 was also used to simulate the production yield in the measurement chamber that was essential for calculating the system efficiency. The experimental system efficiency was found to be nearly 4.0%. This includes the corrections for the decay of ^{6}He atoms during the production and its diffusion to the measurement chamber. The system efficiency was also simulated using another Monte Carlo code and was found to be nearly 3.8%, which agrees with that obtained experimentally.

4. Future plans

The complete experimental setup is being moved to the newly constructed target room at the Soreq Applied Research Facility (SARAF) [17] at the Soreq Nuclear Research Centre, Israel. SARAF phase I provides a high neutron yield using 5 MeV deuterons on a Liquid Lithium Target (LiLiT), developed in-house [18]. The neutron source at SARAF will be replacing the NG for our experiment. SARAF-I is expected to help in increasing the production rate of ^{6}He to at least two orders of magnitude more than in the current experiment. With this expected rate of ^{6}He and the improved efficiency of our setup, we expect to achieve sub-decimal precision in our measurement. The full experiment is expected to be performed in the second quarter of 2018.

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