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Design of a β-detector for TITAN-EC and the first electron-capture branching ratio measurement in a Penning trap

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Abstract. At TRIUMF's ion trap for atomic and nuclear science (TITAN) a new experimental technique is being developed to measure electron-capture branching ratios of intermediate nuclei in double-β decays. The key feature of this novel technique is the use of an open access Penning trap. Radioactive ions are stored inside the trap while their decays are observed. X-rays following an electron capture are detected by x-ray detectors radially installed around the trap. Electrons originating from β-decays are guided out of the trap by the Penning trap's strong magnetic field where they are then detected by a Si-detector. Detailed simulations have been performed to determine the size and characterize the efficiency of this detector. During a beam time with radioactive ^{107}In this β-detector has been used and for the first time an electron capture branching ratio has been determined with this novel technique of in-trap decay spectroscopy.

1. Introduction

With the observation of neutrino oscillations evidence has been found that the neutrino is a massive particle. One possibility to investigate the neutrino's nature is the search for $0\nu\beta\beta$ decays. This special decay violates lepton number conservation and is thus forbidden within the standard model. If it were to be observed reliably one could derive the effective Majorana neutrino mass,

$$|\langle m_\nu \rangle| = \left(T^{0\nu}_{1/2} \, M^2_{0\nu} \, G(Q_{\beta\beta}, E) \right)^{-1/2} , \tag{1}$$

from the half life $T^{0\nu}_{1/2}$ of the decay, a phase-space factor $G(Q_{\beta\beta}, E)$ and the transition matrix element $M_{0\nu}$ [1, 2]. This matrix element is purely based on theoretical calculations and is currently determined within the frameworks of pn-QRPA [3], shell model calculations [4] and the interacting boson model [5]. Recently, calculations have been published applying projected

Hartree-Fock-Bogoliubov in limited configuration spaces and schematic interactions [6] as well as density functional methods using the Gogny D1S functional [7]. But a comparison between calculated matrix elements from different models shows variations of up to a factor of 5 [3]. In order to determine the neutrino mass with sufficient accuracy this nuclear matrix element (NME) needs to be known with an uncertainty of less than 20% [8]. One possibility to probe these nuclear theories is by comparing them with experimental data from $2\nu\beta\beta$ decays. Another possibility is by measuring the branching ratios of the intermediate nuclei in $\beta\beta$ decays. This measurement directly gives access to the transition via the lowest intermediate state in $2\nu\beta\beta$ decays and thus directly probes the Gamow-Teller strength that enters the $2\nu\beta\beta$ NME. A special case is ^{100}Tc in which single-state dominance appears to be present, i.e. the transition via the lowest 1^+ state in ^{100}Tc accounts for the total matrix element $M_{2\nu\beta\beta}$. Typical electron capture branches are of the order of 10^{-5} ($(2.6 \pm 0.4) \cdot 10^{-5}$ for ^{100}Tc [9]) and therefore difficult to measure due to the dominant β background. At TITAN a new technique has been developed to measure these NMEs deploying a Penning trap [10].

2. TITAN-EC

During an electron-capture branching ratio (ECBR) measurement radioactive isotopes are produced by TRIUMF's ISOL-type facility ISAC. These isotopes are then delivered to TITAN [11] (see Fig. 1a) where they are first cooled and bunched in a buffer-gas-filled linear Paul trap. Afterwards, these bunches are sent to the open-access Penning trap where they are stored.

This spectroscopy Penning trap is the central component of the ECBR measurements at TITAN [12] (see Fig. 1a). In the trap, ions are radially confined by a strong magnetic field of up to 6 T while static electric fields confine the ions axially. A pair of superconducting coils in a quasi-Helmholtz configuration provides the magnetic field. This special coil configuration and cavities in the magnet bore allow direct visible access to the central trap electrode. This electrode is eight-fold segmented with slit apertures between each segment. These slits provide direct access to the trap center, hence x-rays originating from the trap center can be observed by detectors installed at these view ports. X-ray detectors can either be installed directly inside the vacuum in the bore cavities or outside the vacuum vessel at Be windows serving as vacuum barrier with minimal x-ray attenuation.

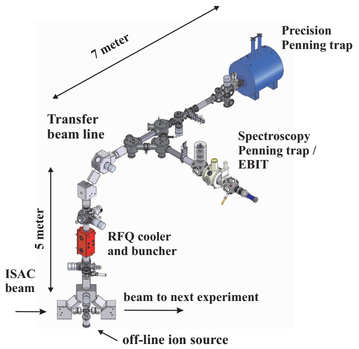
While the ions are stored inside the Penning trap the products of their radioactive decays are observed. X-rays following an electron capture are isotropically emitted and detected by x-ray detectors. These detectors are installed radially around the trap center with direct visible access to the trap center via view ports. Betas are guided out of the trap center by the strong magnetic field onto a β-detector. The β-detection is then used to monitor the number of isotopes injected into the Penning trap. A schematic view of the experimental setup is illustrated in Fig. 1b.

Downstream of the Penning trap, after the last trap electrode, a detection chamber is installed. It houses the Si-detector that can be moved onto the beam axis. When the β-detector is placed on axis it detects electrons originating from radioactive decays of ions stored inside the trap. Since the electrons follow the field lines of the strong magnetic field it is impossible for them to reach the x-ray detectors. Therefore, one can measure x-ray spectra almost without any β-background contribution.

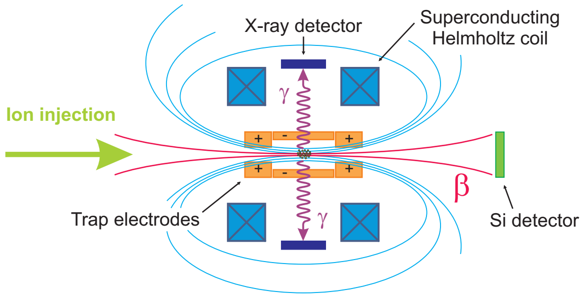
This application of a Penning trap for ECBR measurements provides spatial separation of x-ray and β-detection. With the novel technique of in-trap decay spectroscopy it is possible to measure very weak electron capture branches.

3. Beta-detector

At the exit of the spectroscopy Penning trap a Si-detector is installed to detect electrons originating from β-decays of stored ions. It is a 500 µm thick Si-waver (PIPS detector from Canberra) with 600 mm^2 active area that is mounted on an especially designed ceramic board.



(a) The TITAN facility.



(b) The TITAN-EC setup.

Figure 1: Schematic of (a) TITAN and (b) the TITAN-EC setup. Ions are injected from the left side while electrons are detected by the Si-detector on the right side.

This detector is mounted on a linear feedthrough and operates in ultra-high-vacuum condition with a residual magnetic field of $\sim 0.8\,\mathrm{T}$. The electrical connection is made via a flexible circuit board. The whole assembly is retractable in order to place a multi-channel plate or the electron gun at its position. The electron gun is used when the trap is operated as an electron-beam ion trap (EBIT [13]) instead of being operated as a spectroscopy Penning trap. A picture of the mounted Si-detector assembly is displayed in Fig. 3b. In order to determine the minimal size required to detect all βs, extensive simulations with the program SIMION [14] have been performed.

Note that during a previous experiment experiment a 500 µm thick Si-detector mounted on a ceramic board with an active area of $300\,\mathrm{mm}^2$ has been tested for vacuum compatibility and β-counting in an on-line experiment [12]. During the experiment ^{8}Li was implanted on an Al foil installed in front of the Si-detector. Betas originating from the decays of ^{8}Li were successfully counted and used to identify the isotope by its half life. This detector with an active area of $300\,\mathrm{mm}^2$ is not sufficient to detect all electrons from β-decays leaving the trap so a larger detector has been developed.

3.1. Simulations

In these simulations electron trajectories were calculated for various ion-cloud distributions in typical magnetic field strengths of 4 T, 5 T and 6 T. The ion cloud was assumed to be Gaussian distributed with a constant width σ_z along the beam-axis and varying radial distributions $\sigma_x = \sigma_y$. For the electrons originating from β decays a Gaussian kinetic energy distribution was used centered at 1.282 MeV with a standard deviation of 750 keV. This distribution was adjusted to resemble a β-spectrum with a Q_β-value of 3 MeV. This is a typical Q_β-value of intermediate transition nuclei in $2\nu\beta\beta$-decays. In all simulations the detector was placed 284 mm downstream from the trap center where it is installed in the experiment.

The number of electrons reaching the β-detector was simulated for varying ion-cloud distributions $\sigma_x = \sigma_y$ for different magnetic field strengths. The simulated fraction of electrons impinging onto the detector is displayed in Fig. 2a. These simulations show that the fraction of electrons leaving the trap depends on several factors:

- The Helmholtz-coil configuration is not ideal because the coils are further apart than their radius [13]. This creates a local magnetic field minimum at the trap center and thus a magnetic bottle inside the trap. Electrons that are emitted with a pitch angle, i.e. the angle between particle velocity and the magnetic field, larger than the critical angle α_c stay trapped and cannot reach the detector. This critical angle depends on the mirror ratio, that is the ratio between the magnetic field B_{min} at the origin of the electron to the maximal magnetic field B_{max} and is given by

$$\frac{1}{\tan \alpha_c} = \left(\frac{v_{||}}{v_{\perp}}\right)_{crit} = \sqrt{\frac{B_{max}}{B_{min}} - 1}. \tag{2}$$

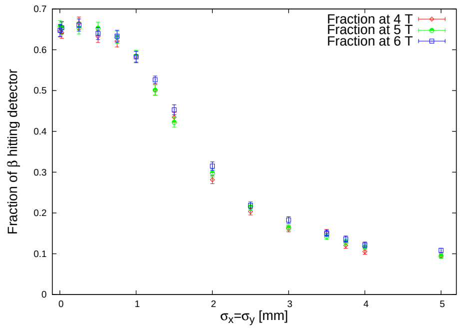
At the trap center the critical angle is calculated to be about 73° but it decreases further away from the trap center. Therefore, the number of electrons trapped in the magnetic bottle increases with increasing radial ion-cloud distributions. This effect limits the maximal number of electrons that can leave the trap. If all electrons would originate from the trap center only about 77% of them could leave the trap. Since a β-detector is installed at only one side of the trap only electrons emitted in one hemisphere are detected.

- With increasing ion-cloud diameter the extraction trap electrode, which has a diameter of 5 mm, acts as an aperture. Electrons that are emitted further away from the trap's central axis hit the electrode while following the field lines and are lost (see Fig. 2a).
- For electrons that are emitted radially with an energy larger than about 3.5 MeV the magnetic field strength is not sufficient anymore to confine the electrons. Thus, they can leave the trap center radially where they hit the central trap electrode. This does not affect ECBR measurements of transition nuclei in $\beta\beta$ decays because the largest Q_β value is 3.278(4) MeV in the case of ^{116}In [15].
- The result presented in Fig. 2a shows that the fraction of electrons reaching the β-detector is independent of the magnetic field strengths ranging from 4 T to 6 T. This fact allows one to perform in-trap decay spectroscopy measurements with a magnetic field setting that allows for the best ion storage.

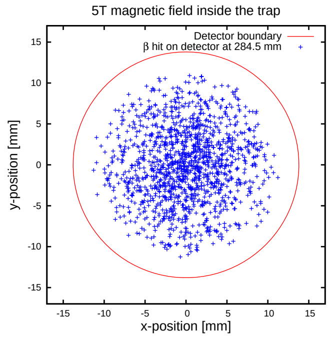
Based on these simulations it can be concluded that electrons being emitted from ion-cloud distributions with a radial extension smaller than $\sigma_x = \sigma_y \approx 0.8$ mm will be guided to the detector by magnetic field lines. For larger ion-cloud distributions the extraction electrode limits the number of electrons reaching the detector. Hence, this electrode determines the required size of the detector. No matter how large the ion cloud inside the trap is the β-distribution on the Si-detector cannot be larger than $\sigma_r \approx 3.8$ mm. The maximal spatial electron distribution on the β-detector is displayed in Fig. 2b. Also displayed in this figure is the outer edge of an area of 600 mm^2. This detector size is sufficient to detect all electrons that leave the trap as shown by the SIMION simulations. Based on these simulations a Si-detector of this dimension was built and is used in the experiment. It is noted that β-particles from ions lost inside the trap cannot reach the detector.

3.2. Experimental test of the β-detector

During the ^{107}In experiment the Si-detector with 600 mm^2 active area was used in combination with an Al foil to identify the delivered isotope by its half live [16]. Therefore, ion-bunches were implanted onto the Al foil and the count rate was recorded. The measured half life agrees with the literature value and ^{107}In could be identified with less than 10% contamination. For the measurement the Si-detector was mounted at its designated position after the Penning trap 284 mm away from the trap center. Fig. 3a displays the measured β^+ spectrum while Fig. 3b shows the detector prior to its installation. Due to the long half life of ^{107}In and its daughter ^{107}Cd this Si-detector was blocked for the second part of the experiment described in the following section. In future measurements this β-detector will be used without the Al foil to directly count βs originating from the trap center.

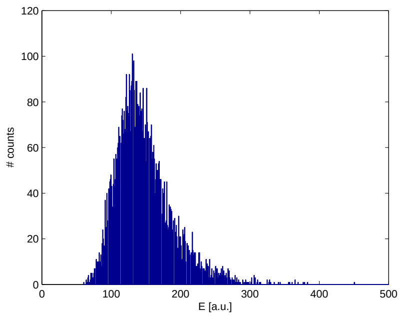


(a) Fraction of electrons emitted in one hemisphere reaching the β-detector depending on the ion cloud size. The simulation was performed for a magnetic field of 4 T, 5 T and 6 T.

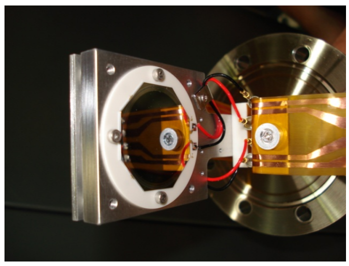


(b) Distribution of hits on the β detector.

Figure 2: SIMION simulation of betas being emitted from the trap center.



(a) Recorded energy spectrum of electrons from ^{107}In decays of ions implanted onto an Al foil.



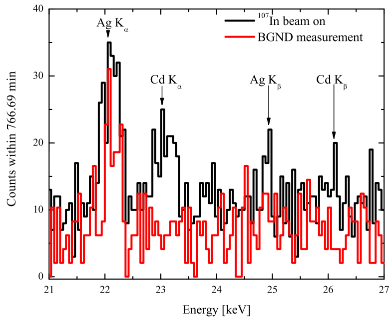
(b) Picture of the Si-detector without Al foil.

Figure 3: Measured energy deposition of electrons passing through the Si-detector and picture of the detector.

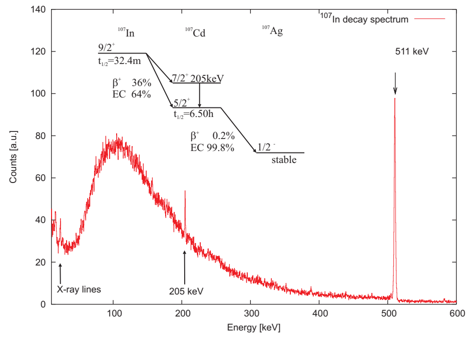
4. Electron-capture branching ratio measurement in a Penning trap

This novel technique of in-trap decay spectroscopy has been applied for the first time to determine the electron capture branching ratio of ^{107}In. This isotope has been chosen because of its rather large electron capture branching ratio of 64(3)% [15] to its daughter ^{107}Cd. In the experiment ^{107}In ion-bunches were injected into the spectroscopy Penning trap, where they were stored for 1 s. During this time their radioactive decays were observed with two Ge detectors. After the measurement period the trap was emptied, the ions were extracted into the beam line and a new ion bunch was injected into the trap for spectroscopy. The data acquisition was gated to only record data while the ions were stored inside the trap. Background spectra were taken before and after the ECBR measurement of ^{107}In.

During the ^{107}In ECBR measurement a coaxial REGe detector (Canberra reverse electrode coaxial Ge detector, model no. GR2018) was used to detect x-rays and γs from decays occurring inside the trap. This detector was mounted outside the vacuum vessel after two Be windows with a total thickness of 525 µm. This detector covered a solid angle of about 0.7%. Additionally, a planar low-energy Ge detector (Canberra planar Ge detector, model no. GUL0110P) with a



(a) LeGe x-ray spectrum. The black spectrum was recorded while ions were stored inside the trap. The red spectrum displays the background with no ions stored in the trap.



(b) Total spectrum recorded with the REGe detector.

Figure 4: Photon spectrum of LeGe and REGe detector that was taken during the ECBR measurement of ^{107}In.

geometrical detection efficiency of $\epsilon_{geo} \approx 0.02\%$ was installed inside the vacuum chamber close to the trap center. Both detectors were mounted in locations with fringe fields up to $\sim 0.8\,$T present. The influence of the magnetic field on detection efficiency and detector performance was investigated prior to the experiment but no influence could be found. This agrees with results reported in [17].

In order to determine the electron capture branching ratio of ^{107}In the 205 keV photopeak with a well know intensity of 47.2% [15] was used to determine the total number of decays. Considering the fluorescence yield ω_K [18, 19], the yields of conversion electrons emitted from the K-shell [15] and the probability f_K that an electron capture leaves a vacancy in the K-shell the number of EC is determined from the measured Cd x-ray intensity. The measured branching ratio is BR(EC)=$52 \pm 20\%$. The result of this independent analysis agrees with the previous analysis of this data presented in [16] ($55 \pm 20\%$) and also agrees with the literature value of 64(3)% [15]. Nevertheless, the result presented here must be treated with caution. This value results from the analysis of one hour of data that was taken with the REGe detector. In the spectrum of the LeGe detector that was recorded at the same time x-ray lines from Ag are visible besides the Cd x-ray lines (see Fig. 4a). This indicates ion losses occurring in the trap. The origin of these losses needs to be investigated. One possibility would be that Cd leaves the trap due to the recoil of the decay. However, In could also get lost inside the trap due to charge-exchange reactions during its storage.

5. Conclusion

Experimental input is needed to benchmark theoretical models of $2\nu\beta\beta$ decays. This input can be provided by measuring ECBRs of intermediate nuclei in double-β-decay nuclei. At TITAN a novel technique of measuring these branching ratios has been developed. The feasibility of this method has successfully been demonstrated with the ECBR measurement of ^{107}In. Due to the strong magnetic field almost no β-induced background is present at the x-ray detector.

For the future, further systematic studies are planned as well as an upgrade of the x-ray detectors. This upgrade will provide a geometrical detection efficiency of 2.1%. With the ECBR measurement of ^{100}Tc the first intermediate nucleus in a $\beta\beta$ decay will be measured with this technique.

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