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Tritium ion blocking and detection in the KATRIN experiment

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Abstract.
The aim of the KATRIN experiment is to determine the absolute neutrino mass scale in a model independent way by measuring the electron energy spectrum shape near the endpoint of molecular tritium beta decay. The beta electrons are guided from the source to the spectrometers by a high magnetic field. The beta decays and ionisations of the beta electrons in the source produce a variety of positive tritium ions that are not allowed to reach the spectrometers. Therefore they will be blocked by a positive potential and removed by dipole electrodes in the beam transport system. Various ion detection methods (Faraday cup, FT-ICR and ionisation of the residual gas in the spectrometers) will be used to test the ion blocking and removal efficiency.

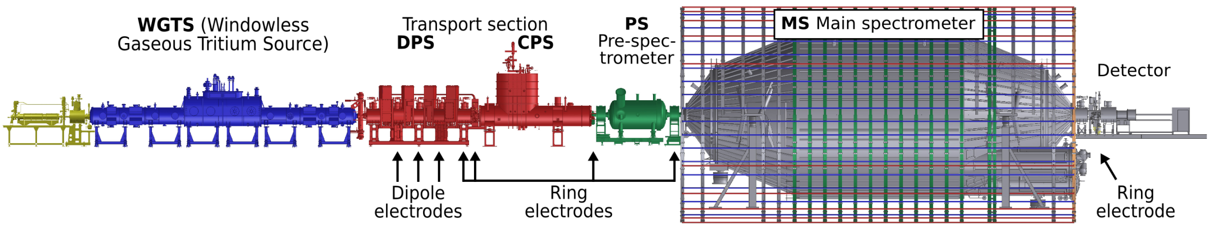

Figure 1. The KATRIN beamline. Ring electrodes are used for ion blocking and dipole electrodes are used to remove ions.

1. The KATRIN experiment

The KATRIN experiment is designed to determine the absolute neutrino mass scale with a sensitivity of 200 meV (90% CL) by measuring the integral electron energy spectrum close to the endpoint (~ 18.6 keV) of molecular tritium β decay. For this purpose, KATRIN (Fig. 1) uses a high resolution MAC-E filter [1] and a high intensity Windowless Gaseous Tritium Source (WGTS). The beta electrons from the WGTS are guided to the spectrometers by a high (up to 5.7 T) magnetic field. The neutral tritium gas will be prevented to reach the spectrometers by the differential and cryogenic pumping sections (DPS and CPS). The energy analysis takes place at the central plane of the main spectrometer (MS), where there is a small magnetic field on the order of 1 μT. The purpose of the pre-spectrometer (PS) is to reduce the background from ionisation by beta electrons. The planned background level of the KATRIN experiment is 10 mcps. For further details see references [1, 2, 3].

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2. Ion production in the Windowless Gaseous Tritium Source (WGTS)

About $2 \cdot 10^{12}$ tritium ions / s are produced in the WGTS by beta decays of tritium molecules and ionisation of the tritium gas by the beta electrons. The ions include $^3\mathrm{HeT}^+$, $^3\mathrm{He}^+$, T^+ and T_2^+. The T^+ and T_2^+ ions are transformed quickly to T_3^+ ions due to exchange reactions in collisions with T_2 molecules, e.g.: $\mathrm{T}_2 + \mathrm{T}_2^+ \to \mathrm{T}_3^+ + \mathrm{T}$. The T_3^+ ions can also be transformed to T_5^+ cluster ions by the reaction: $2\mathrm{T}_2 + \mathrm{T}_3^+ \to \mathrm{T}_5^+ + \mathrm{T}_2$. Even larger cluster ions like T_7^+, T_9^+, etc. can be produced by collisions. Those positive ions can recombine with thermalised secondary electrons that are created from ionisations of the beta electrons. The dissociative recombination reaction of the T_3^+ ions is: $\mathrm{T}_3^+ + \mathrm{e}^- \to \mathrm{T}_2 + \mathrm{T}$. The cluster ions have large dissociative recombination coefficients. According to calculations, the expected flux from the WGTS towards the transport section is about $2 \cdot 10^{11}$ positive tritium ions / s. In addition, a rate of $2 \cdot 10^{10}$ T^- ions / s is expected to be created in the WGTS by associative attachment.

3. Impact of ions on the KATRIN neutrino mass measurements

In contrast to neutral tritium, ions are not pumped off the beamline because they follow the magnetic guiding field in the transport system, similar to the beta electrons. Without blocking the positive ions, they would enter the spectrometers (PS and MS). There they would cause a tritium contamination that is a million times higher than the acceptable level. In addition, ionisation by the positive ions in the residual gas of PS and MS would produce an extremely large background on the order of 10 kcps in a 10^{-11} mbar vacuum. This is also a million times higher than the background specifications.

The positive ions can be blocked in the transport system by applying a positive blocking potential. In this case, however, these ions will be stored between the blocking potential and the gas flow at the detector end of the WGTS. The resulting high-density ion plasma could increase the space charge potential in the WGTS. Possible plasma instabilities could change the energy of the beta electrons moving through this plasma. Also, the end point energies of beta decays of the various tritium ions is different from neutral tritium molecules. Hence, the stored ions could cause non-negligible systematic effects for the KATRIN neutrino mass measurement. Therefore, the ions need to be removed from the transport system by $E \times B$-drift, as described in the following section.

4. Ion blocking and removal in the transport section

Positive ions can be blocked due to their thermal energies of about 10 meV with two ring electrodes (Fig. 2) in the transport section. Set to +100 V, each ring electrode forms a potential wall for positive ions and a potential well for the measured > 18 keV electrons which remain unaffected. One of these ring electrodes is designed to serve in the experiments with the FT-ICR unit (Fourier Transform Ion Cyclotron Resonance, see section 5.2). Three more ring electrodes are placed in the spectrometer section (see Fig. 1).

There are three dipole electrodes (Fig. 3) in the differential pumping section (DPS) between the WGTS and the ion-blocking ring electrodes. One electrode of each dipole will be set to -100 V while the other electrode remains grounded. This causes an electric dipole field $\vec{E}$ transverse to the magnetic field $\vec{B}$ and an ion drift with velocity $\vec{v} = \vec{E} \times \vec{B}/|\vec{B}|^2$. The blocked ions leave the flux tube due to this drift after less than one second: after moving a few times through the dipole electrodes, they are neutralised when they hit the dipole electrode surfaces or the beam-tube walls. The neutralised tritium atoms and molecules will be pumped off.

5. Ion detection in the KATRIN beamline

Successful ion blocking is confirmed by detecting the residual ion flux behind the transport section with Faraday cups and via ionisation in the spectrometers. Analysis of the ion composition is possible with a FT-ICR unit in the transport section.

Figure 2. Ring electrodes block ions.

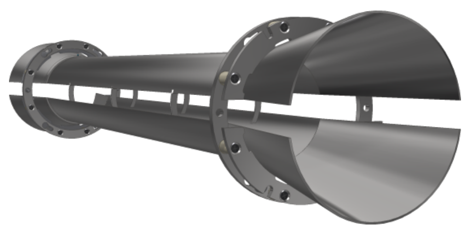

Figure 3. Dipole electrodes drift out ions.

5.1. Faraday cups in the transport section (CPS)
Two Faraday cups at the Forward Beam Monitor (FBM) in the CPS can measure an ion flux of at least 10^7 ions / s and 10^8 ions / s. The larger Faraday cup is optimised on flux sensitivity. The smaller measures the radial ion flux distribution to validate the ion source model. The Faraday cups will be used only during KATRIN commissioning since their detector board needs to be exchanged for the monitoring board of the FBM.

5.2. Fourier Transform Ion Cyclotron Resonance (FT-ICR) in the transport section (DPS)
The FT-ICR unit [4] also has an ion sensitivity of 10^7 ions / s. The FT-ICR method can be used to further distinguish between ion species, e.g. T^+, T_3^+ and T_5^+. Due to its location in the transport section, the FT-ICR unit can be used to investigate the ion composition in the WGTS and yield important information about the physical processes in the source.

5.3. Ionisation in the spectrometers (PS or MS)
An ion flux of 500 ions / s can be measured via ionisation of residual gas in the spectrometers according to simulation (see section 3). Secondary electrons from ionisation are detected when either the MS or the PS is set to -18.6 kV while the other remains grounded. For ion detection, the spectrometers will be filled with He gas at 10^{-7} mbar. Setting the PS to a high negative potential has the advantage that a possible flux of tritium ions will not reach the MS and will thus not contaminate it. These measurements with the spectrometers will only start when the Faraday cups and the FT-ICR unit measure no residual ion flux downstream from the ion-blocking ring electrodes. If either measurement with the spectrometers then shows a significant ion flux, the valve between CPS and PS will be closed on a time scale of 10 s.

6. Outlook: First tests of ion blocking and detection
First tests with ions in the KATRIN beamline are scheduled for November 2016. A pencil beam of 5 mm diameter and up to 10^9 deuterium ions / s will be sent through the KATRIN beamline with the ELIOTT ion source [5]. This allows a proof of principle of the ion blocking and drifting (section 4) and of ion detection with the spectrometers (section 5.3).

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