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(Neutron decay retardation spectrometer)

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Summary:

We developed a retardation spectrometer for protons in neutron decay. In a test beam time we gave a proof of principle, but background instabilities were serious enough to prevent us from presenting a new value for the correlation coefficient a. Several approaches to an optimization of the spectrometer have been realized. Major improvements are i) the usage of a different detector type at significantly reduced detector HV, ii) the improvement of the UHV conditions, and iii) the redesign of parts of the electrodes system. In a recent beam time we demonstrated that we are able to perform a high precision measurement of a.

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Report for the TRAPSPEC JRA-11 in EURONS
on task T-J11-8
(Neutron decay retardation spectrometer)

Motivation

The neutron decay spectrometer *a*SPECT has been built to perform a precise measurement of the proton spectrum shape in the decay of free neutrons. Such a measurement allows a determination of the neutrino electron angular correlation coefficient a. The present best experiments have an uncertainty of a $\Delta a / a = 5\%$; and since the seventies there is no substantial improvement. With *a*SPECT, we aim for an uncertainty which is lower by more than an order of magnitude, thus enabling us to perform several precise tests of the Standard Model.
In our first beam time at the particle physics beam MEPHISTO at the Forschungsneutronenquelle Heinz Maier-Leibnitz, we studied the properties of the spectrometer. The most serious problem turned out to be situation- and time-dependent behavior of the background.

In a recent beam time performed at the Institut Laue-Langevin during April / May 2008 we reached a statistical accuracy of about 2% per 24 hours measurement time. Several systematic effects were investigated experimentally. We expect the total relative uncertainty to be well below 5%.

Introduction

The decay of the free neutron allows one to determine the coupling constants of the weak interaction and can be used to search for physics beyond the standard model of elementary particle physics [Sev06, Abel08]. The decay rate for unpolarised neutrons can be described as [Jack57]:

$$d\Gamma \propto \left(1 + a\frac{\vec{p}_e \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e}\right) d\Omega_e d\Omega_\nu dE_e$$

Where me is the mass of the electron and $\vec{p}_e$, $\vec{p}_\nu$, E_e and E_μ are the momenta and energies of electron and antineutrino, respectively.

Within the standard model, where neutron decay is described as a V-- A type interaction, the antineutrino electron angular correlation coefficient a depends only on the ratio of the axial vector and vector coupling constants $\lambda = g_A / g_V$:

$$a = \frac{1-\lambda^2}{1+3\lambda^2}$$

Since λ describes the renormalisation of the axial vector current by the structure of the nucleon, it cannot be calculated well enough from first principles and thus has to be determined experimentally.

From λ and the neutron lifetime, the element V_{ud} of the Cabibbo-Kobayashi-Maskawa matrix can be derived. Furthermore, the determination of λ from different observables (e.g. from a and the beta asymmetry A [Jack57]) permits cross-checks of the theory and searches for non-V-A couplings [Sev06].

The Spectrometer

The neutrino is hard to detect, hence we infer a from the shape of the proton recoil spectrum. *a*SPECT is a retardation spectrometer. This means, the spectrum is measured by counting all decay protons that overcome a potential barrier. By varying the height of the barrier the shape of the proton spectrum can be reconstructed.

Fig. 1. *a*SPECT setup at beam line PF1B during the beam time performed at the Institut Laue-Langevin (April / May 2008).

A beam of cold, unpolarised neutrons passes through the spectrometer, where about 10^{-8} of the neutrons decay in the decay volume (see fig.1). This region is held at ground potential. From here the decay protons are guided to the proton detector by a strong magnetic field. About half of the protons are emitted in the opposite direction. These are reflected by an electrostatic mirror and thus finally all protons are directed towards the detector. The endpoint energy of the proton spectrum is about 751eV, therefore a voltage of U_M = 820 V at the electrostatic mirror reflects all protons. Before the protons can reach the detector, they have to overcome a potential barrier, which is maximal at the so-called analysing plane. The barrier potential is generated by a 54cm long cylindrical electrode, held at a voltage U_A. In the analysing plane the magnetic field is about 5 times lower than in the decay volume. Protons travel from the decay volume to the analysing plane, gyrating about a magnetic field line. As a result of the adiabatic invariance of the magnetic moment, part of the proton's momentum transverse to the field line is transferred into parallel momentum. In the adiabatic approximation, the probability that a proton overcomes the potential barrier can be analytically calculated as a piecewise function:

$$F_{tr}(T) = \begin{cases} 0 & ;T < eU_A \\ 1 - \sqrt{1 - \left(1 - \frac{eU_A}{T}\right) / r_B} & ;Otherwise \\ 1 & ;T > eU_A \end{cases}$$

where *T* is the kinetic energy and *e* the charge of the proton. This transmission function $F_{tr}(T)$ depends only on U_A and the ratio of the magnetic fields in the analysing plane and the decay volume, $r_B = B_A/B_0$. Further details of the spectrometer design and systematic effects may be found in [Glueck, Bae08].

After the electrostatic barrier the magnetic field increases to focus particles that overcome the barrier onto the proton detector. The detector is held at a high negative potential to post-accelerate the protons to detectable energies, and to ensure that the protons overcome the magnetic mirror created by the increasing field.

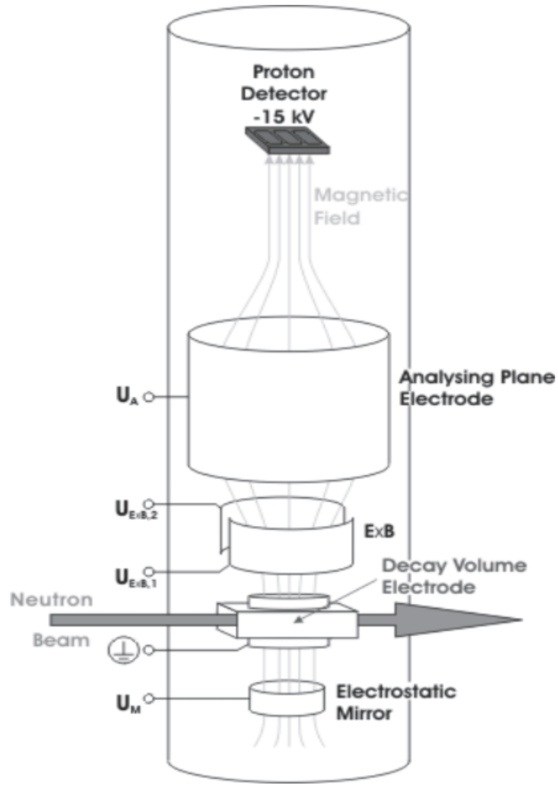

Fig. 2. Sketch of the *a*SPECT spectrometer.

Test Beam-time at the beam–line MEPHISTO at the Forschungsneutronenquelle Heinz Maier-Leibnitz. {Subtask T-J11-8.1 Retardation spectrometer / TJ11-8.4 Beam time}

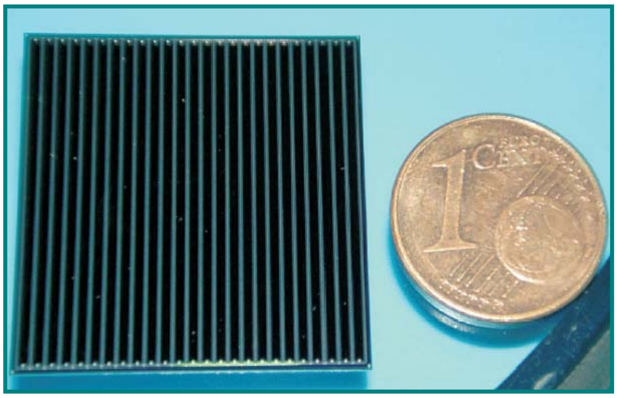

Fig. 3. Segmented PIN diode proton detector. Custom built for our experiment by Detection Technology Inc., Finland. The detector has a thin entrance window of 40 nm Si3N4, followed by 27 nm SiO2, followed by the active layers.

The proton detector used was a segmented PIN diode. It consists of 25 parallel segments with a surface area of 25 mm x 0.8 mm each, separated by a non-active region of 0.2 mm width oriented perpendicular to the neutron beam.

A typical pulse height spectrum is shown in fig. 4. During data taking, each single measurement lasted about 60 s. Data-taking cycles typically started with a measurement at U_A = 50 V, followed by a measurement at an intermediate analyzing plane voltage, then a background measurement at U_A = 780 V, and finally a measurement at U_A = 0 V in order to remove trapped particles. This sequence was then repeated with a different intermediate analyzing plane voltage.

The optimization of the sequence of measurement cycles for statistical sensitivity is performed in [Zim00] and would encourage a different sequence. We chose to use this sequence to get detailed information on the background.

As one can infer from fig. 4, the proton peak decreases as the analyzing plane voltage U_A is ramped up and disappears at U_A = 780 V. If we subtract the data at U_A = 780 V from the data at other analyzing plane voltages, we remove beam-related and environmental background, provided that the background is stable and does not depend on the analyzing plane voltage, fig. 5.

The total proton count rate is determined by summing up the number of events from the pulse height spectrum in the so-called Proton Peak region, which extends from the pulse height channels 40 to 120, and which is symmetric around the proton peak position.

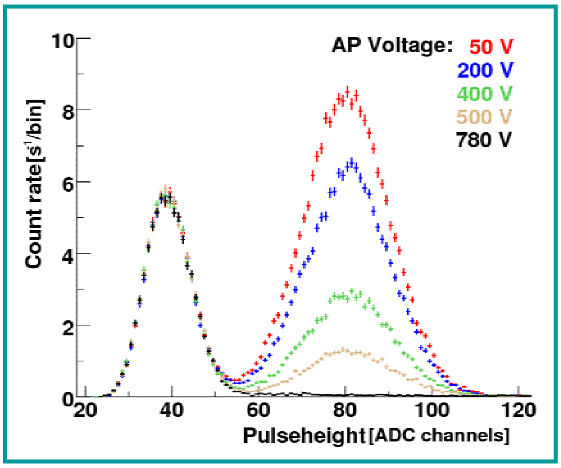

Fig. 4. Pulse height spectrum for detector PIN diode detector: The left peak is due to electronic noise, the right peak is due to protons. The count rate in the proton peak decreases as the analyzing plane voltage is ramped up.

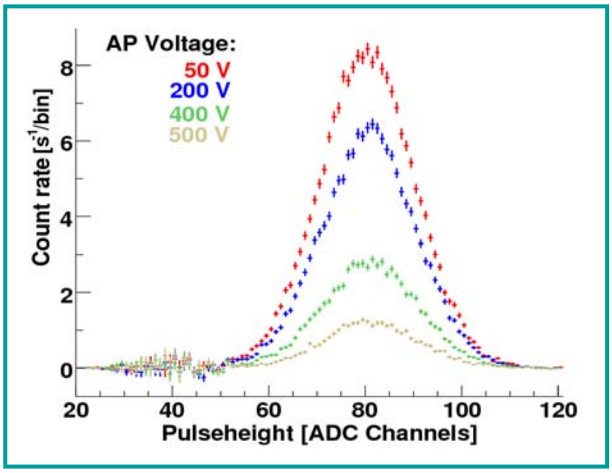

Fig. 5. Proton pulse height spectrum after subtracting the background.

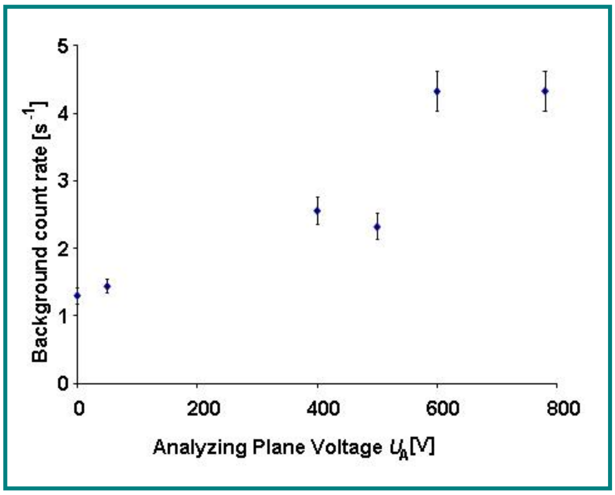

Fig. 6 Voltage dependence of the background count rate in the Proton Peak region in a period without neutron beam. In these count rates, the (stable) contribution from the electrons from neutron decay is absent

In the Proton Peak region and with the analyzing plane voltage set to U_A = 50 V, the proton count rate on the entire detector was about 500 s^{-1} in the data-taking period.

During the beam time, we sometimes found that there is a proton-like peak in the background spectra measured at an analyzing plane voltage U_A =780 V. Its position was sometimes the same as the proton peak, and sometimes the peak was shifted to lower pulse heights by about 10 channels. In the first case, its shape was indistinguishable from the proton peak. Once we had a proton-like peak, it persisted, even for days. Only ramping down the voltage on all electrodes including the detector high voltage, or ramping down the magnetic field, made it disappear. Furthermore, even when there is no visible proton-like peak, the background count rate changed with time and showed non-statistical variations.

What is worse is that the excess background rate depends on the analyzing plane voltage U_A. In our analysis we had to assume that the background rate in either window at U_A = 780 V is equal to the background rate at any other analyzing plane voltage U_A. In fig. 6 a measurement without neutron beam is shown. The measurement clearly demonstrates the voltage dependence of the background.
Trapped particles in our electrode system could cause this background. Protons or other positive ions can be trapped between the electrostatic mirror and the analyzing plane electrodes. The magnetic field prevents them from moving radially, and the electric potential limits possible movements along the axis. But it is unlikely that this trap causes the background fluctuations: The lower ExB drift electrode was just installed to remove positive ions from this trap.

However, the situation is different for electrons. Possible traps for electrons are the electrostatic mirror electrode, the analyzing plane electrode, and the region close to the detector high voltage electrode.

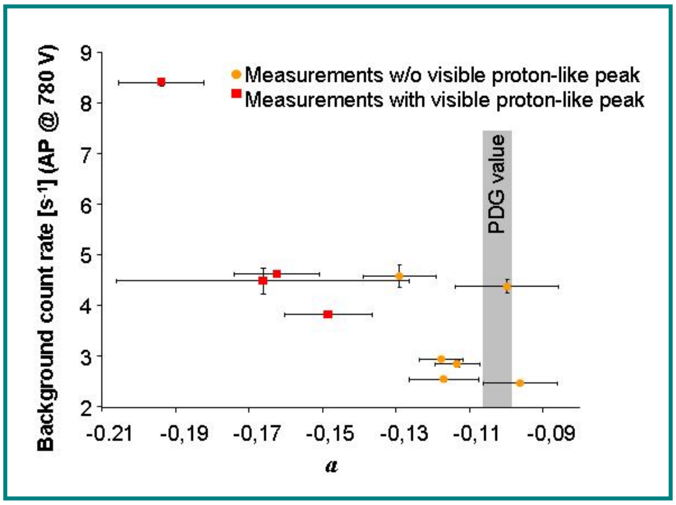

Fig. 7. Calculated value of a for different measurements runs with and without visible proton-like peak.

We presume, the primary source of electrons is field emission from the high voltage electrodes of the proton detector or a Penning-type discharge between electrodes. These electrons are accelerated by the high voltage towards the bottom of the spectrometer. A small portion of them can have ionizing collisions with residual gas particles or the electrode walls. In such a way, secondary electrons are created that can be trapped and, in turn, are able to produce many positive ions. These positive ions give similar signals in the detector than the

protons coming from neutron decay. The observation that there is more background at higher analyzing plane voltages points to the trap in the analyzing plane being our problem. This trap in the analyzing plane is deeper if the analyzing plane voltage is increased. Therefore, the secondary electrons can ionize more residual gas atoms. In addition, in test measurements after the beam time an increase of the background rate could also be observed at a fixed analyzing plane voltage by making the potential of both half cylinders of the ExB electrode more negative. Here again, the relative trap potential for secondary electrons is deeper.
Background due to electron trapping in the analyzing plane explains, at least qualitatively, our findings.

Positive residual gas atoms from the trap in mirror electrode e1 will only pass the potential barrier in the analyzing plane if the latter is lower than the potential at which they are produced. For these ions, the count rate would not raise with increasing analyzing plane voltage U_A.

The third penning trap in the HV electrodes should not produce background which depends on the analyzing plane voltage. On the other hand, it can explain the memory of our system of past periods with high leakage currents.

Optimization of the spectrometer {Subtask T-J11-8.3 Optimization}

In our first beam time we gave a proof of principle of this spectrometer. We found limitations in the accuracy to determine the electromagnetic fields in the regions of interest and showed ways to overcome them. Beam related background was no problem, but background instabilities due to particle trapping and the electronic noise level of the proton detector were serious enough to prevent us from presenting a new value for the neutrino electron correlation a from this beam time.

We decided to face the background instability problems by a significant reduction of the field emission current of the HV electrodes (lower setting of the high voltage, new polishing of the detector cup), improved UHV conditions (usage of getter pumps installed in the cold bore of the magnet), and a redesign of part of the upper electrode system which avoids a trap at this place, see figures 8-10. A better separation of the electronic noise from the proton peak in the pulse height spectrum is also needed. The proton detector was replaced by a silicon drift detector with the additional advantage that the high voltage of the HV electrode is reduced to about -15 kV, which decreases the field emission from that electrode considerably.

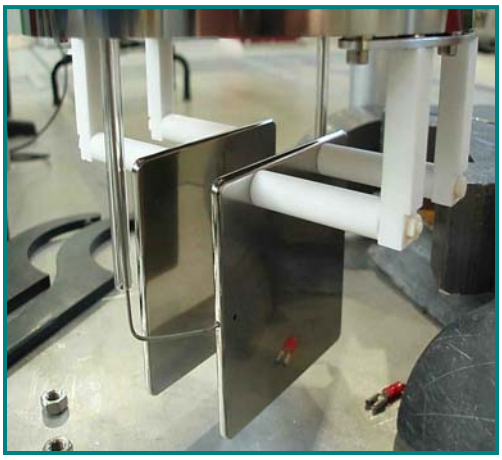

Fig. 8. upper ExB electrode used on the test beam-time at the beam–line MEPHISTO at the Forschungsneutronenquelle Heinz Maier-Leibnitz.

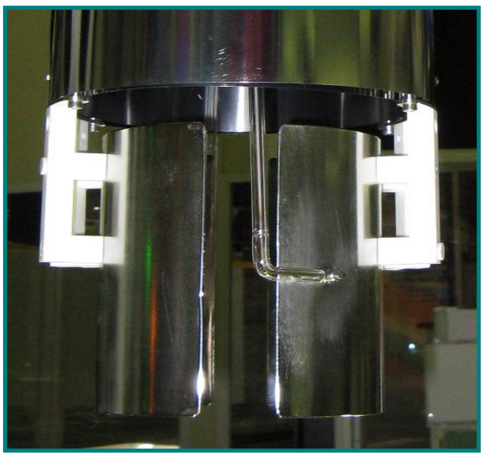

Fig. 9. ExB used during the beam-time performed at the Institut Laue-Langevin (April / May 2008).

Fig. 10. Left: detector HV electrode used on the test beam-time at the beam–line MEPHISTO at the Forschungsneutronen-quelle Heinz Maier-Leibnitz. **Right** detector HV electrode used during the beam-time performed at the Institut Laue- Langevin (April / May 2008).

Beam time performed at the Institut Laue-Langevin (April / May 2008) {Subtask T-J11-8.4 Beam time}

The detector used was a Silicon Drift Detector (SDD), fig. 11. A SDD is a semiconductor detector based on the principle of sideward depletion [sdd], which allows the depletion of a large detector volume with a small readout anode. In the spectrometer, one chip with 3 detector pads (10 x 10 mm^2 each) is used. The first amplifying transistor, as well as a diode for temperature measurement, is implemented on the chip. (Results with a smaller test detector have been published in [sim07])

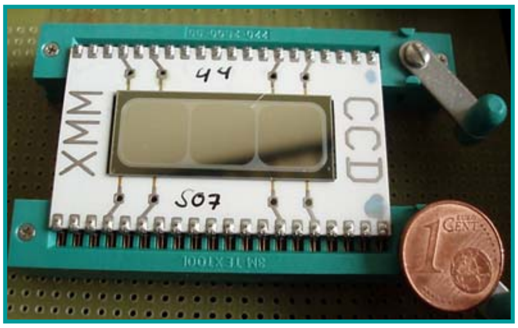

Fig. 11. Silicon Drift detector. In the spectrometer one chip with 3 detector pads (10 x 10 mm^2 each) is used.

The SDD allowed us to significantly reduce the acceleration voltage, compared to the previously used silicon PIN diode detector. Thus we avoided problems like electrical breakdowns or instabilities of the background due to field emission. During the beam time post-acceleration voltages from -10 to -15 kV were used. Some pulse-height spectra with different acceleration voltages are shown in fig. 12.

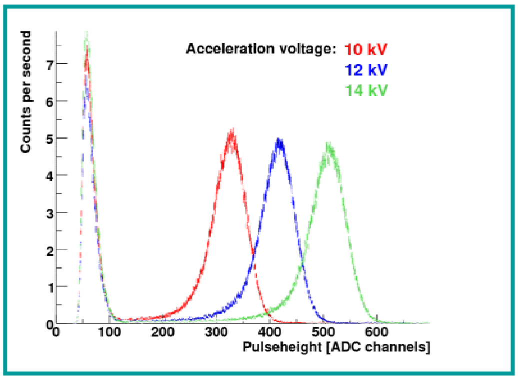

Fig. 12. Typical pulse-height spectra from the beam time, taken with the silicon drift detector at different acceleration voltages. By increasing the acceleration voltage the proton peak (right peak) is shifted to higher ADC channels, whereas the position of the electronics noise (left peak) is not influenced.

On the recent beam time we showed that our spectrometer is capable of measuring the proton recoil spectrum with high precision. Compared to a previous beam time, the major improvements were the new proton detector, the redesign of several electrodes, and a better vacuum. From the investigated systematic effects and the collected statistics, we expect a total error well below 5%. No clear dependence of the background with the analysing plane voltage has been observed, fig 13.

Investigation of systematic effects {Subtask T-J11-8.3 Optimization}

The proton spectrum was determined by setting the analysing plane electrode to 7 different voltages U_A. 50 V is used for the normalisation of the count rates, 400 V approximately provides the best statistical sensitivity towards a [Zim00]. The background was quantified by measurements with 780 V. Most of the background is caused by beam-related electrons from neutron decay which are also guided towards the detector. At 780 V no proton can overcome the barrier, whereas the background is only marginally influenced. To learn about systematic effects and to gain a more precise knowledge of the shape of the spectrum 0 V, 50 V, 250 V, 400 V, 500 V, 600 V, and 780 V were measured, fig 14 and 15.

Typically, about 470 events per second with pulse-heights in the integration window from 160 to 900 ADC channels (fig. 9.) at 50 V analysing plane voltage were counted on one detector pad. At U_A = 780 V the count rate in the same window was about 7 counts per second. This means, approximately 460 protons per second were detected. With closed neutron shutter the count rate dropped to 0.2 counts per second in the integration window.

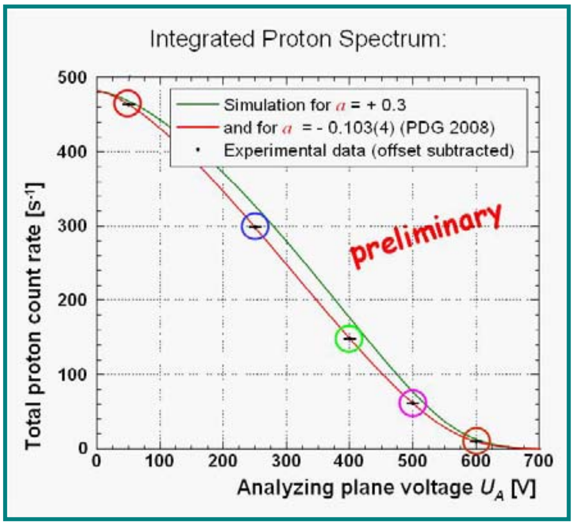

Fig. 15. Preliminary integral proton spectrum obtained with the *a*SPECT spectrometer.

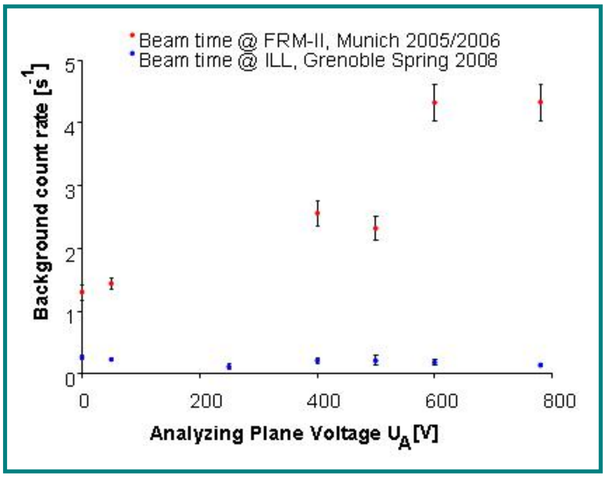

Fig. 13 Voltage dependence of the background count rate in the Proton Peak region. Comparison between both beam-times.

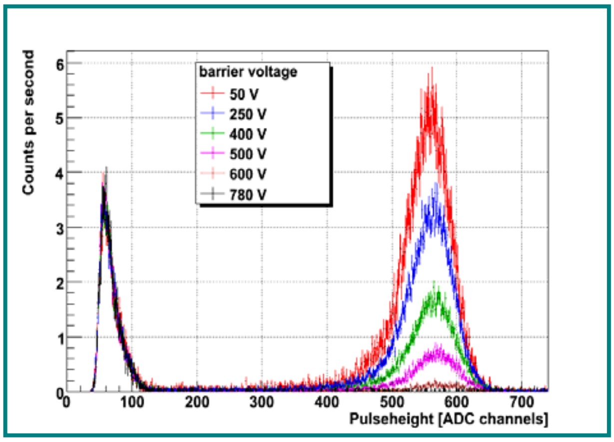

Fig. 14. Typical pulse height spectrum.

In our previous beam time, the background count rate without neutron beam at U_A = 780 V was higher than at U_A = 50 V by several Hz [Bae08]. For this beam time, changes were made to the detector high voltage and the rest of the electrodes system to suppress the dependence of the background count rate on the analysing plane voltage. So far, such dependence was not clearly identified in the present beam time.

The absolute height of the potential barrier has to be known precisely to determine the transmission function.

The voltage applied to the electrode was monitored by a precise multimeter (Agilent 3458A). The accuracy of the voltage settings was better than 5 mV, limited by the multimeter calibration. Stability and reproducibility of the voltage were much better. However, the electrostatic potential inside the electrode is affected by the work function of the electrode surface. In a cylindrical sample electrode at room temperature, a variation of up to 100 mV was found. To investigate this effect, further measurements with a Kelvin probe are ongoing.

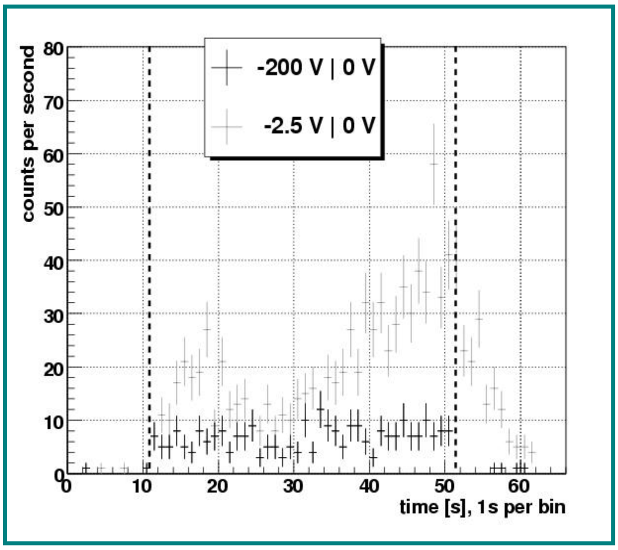

Fig. 16. Background count rate in the integration window for two different settings of the ExB electrode. The dashed lines show where the neutron shutter was opened (after 11s) and later closed again (52s).

Protons and positive ions with too low energy to overcome the potential barrier are trapped between the electrostatic mirror and the analysing plane. They are removed by a ExB electrode implemented between the decay volume and the analysing plane. This electrode consists of two half cylinders set to different voltages $U_{ExB,1}$ and $U_{ExB,2}$. Trapped particles oscillate between the mirror and the analysing plane. Every time they pass the electrical field produced by the ExB electrode they drift into the same direction, perpendicular to both ExB.

In addition, as explained above, electrons and negative ions may be trapped in the region of the analysing plane electrode.

These trapping effects were investigated with two methods:

- For each analysing plane voltage U_A, the measurement started with closed neutron shutter during a time t1, then the shutter was opened for t2, and closed again for t3. This mode allowed us to investigate the environmental, not beam-related background and possible differences in the background count rate before and after the shutter was opened. A higher count rate in the last part would point to either trapped particles inside the spectrometer or activation of some material.

- The analysing plane was set to 780 V so that no protons should be able to overcome the barrier and the ExB drift potential was reduced from the standard setting of $U_{ExB,1}$ / $U_{ExB,2}$ = -1000 / -50 V on the two half cylinders of the electrode in several steps down to -2.5 ,V / 0 V. A comparison of two measurements with -2.5 V / 0 V and -200 V / 0 V is shown in fig 16. For the lowest drift voltage of 2.5 V there are only some counts before the shutter is opened, this is the environmental background. As soon as the shutter is opened, protons are trapped and the count rate starts to fluctuate. Even after the shutter is closed again, there are still particles that reach the detector. Already a potential of -10 V / 0 V reduces this behaviour strongly, and with -200 V / 0 V the count rate is stable as long as the shutter is open and drops back to the environmental background count rate immediately after the shutter is closed again.

Calibration Source {Subtask T-J11-8.2 Electron source}

In order to achieve the desired accuracy, we need to know the potential-difference between the analysing plane and decay volume with an accuracy of 10mV. Surface charges at the surface of these electrodes can change the value of the potentials independently of the applied voltage. Therefore we need a direct measurement of the potential. A calibration source which can operate in a strong magnetic field and which provides a monochromatic beam of charged particles with known energy and energy spread of 10meV is suitable to carry out such a measurement.

An electron source, based on the idea that the energy of photo- electrons is given by the energy of the photons minus the work function, turned out not to fulfil this requirements due to the difficulty of obtaining gold surfaces with a work function which is homogeneous enough. Inhomogeneities in the work function cause a spread on the electron beam energy and as a result increase the uncertainty in the measurement of the potential. In test measurements we obtained an energy resolution of ~0.5eV (FWHM). In Fig.17 It is shown a picture of the test setup, built up in collaboration with the group of Prof. Schönhense at the University of Mainz.

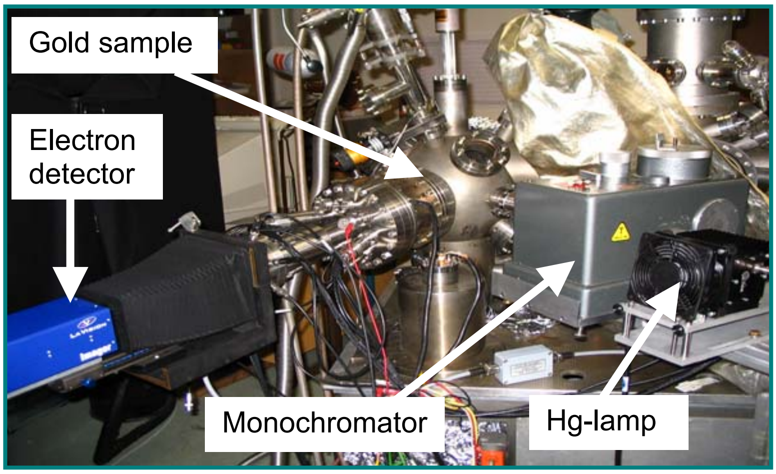

Fig. 17. Test setup of the *a*SPECT electron source.

Therefore we decided to concentrate on an ion source, which is as well need for detector tests. A He^+ source, also based on the idea of extracting charged particles with a very well defined energy, is presented in figures 18 and 19. The source is an electron impact ionization using pure helium gas as medium, (the setup also allows the use of hydrogen to produce protons). Fig. 17 shows the main components of the source: ^4He atoms are flowing through a thin bended stainless steel tube with a very low flux, so the helium atoms have nearly no momentum. Electrons coming from a BaO-Cathode (heated with tungsten wires) can pass through a small hole in the stainless steel tube (1mm of diameter) and ionize the ^4He atoms by impact. The ionized helium is then extracted by a set of electrodes in direction of the applied magnetic field of the spectrometer.

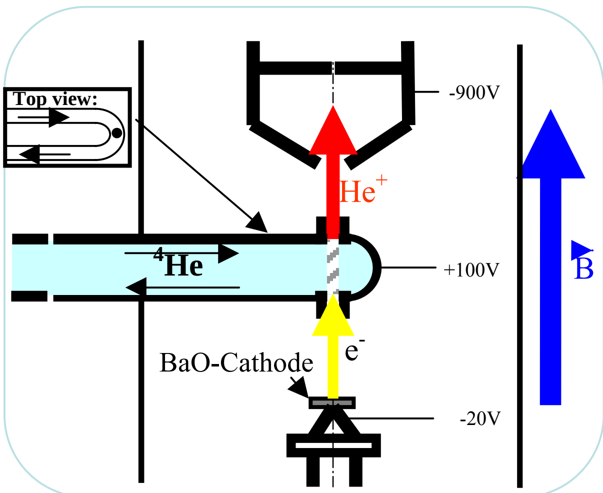

Fig. 18. Sketch of the main parts of the *a*SPECT Proton Source

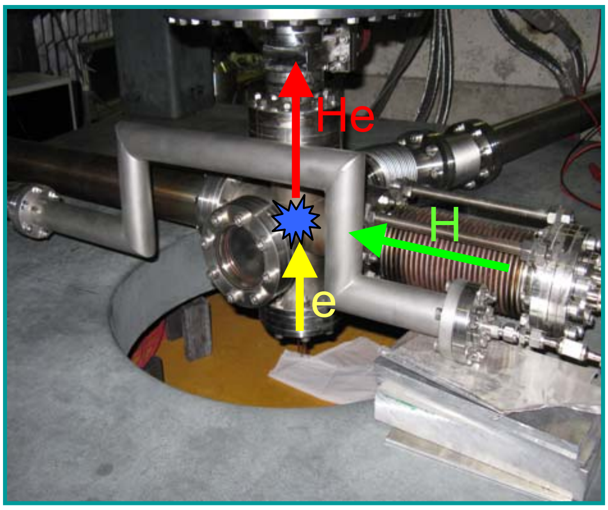

Fig. 19. Proton Source setup at *a*SPECT spectrometer.

In order to guarantee narrow proton spectra, the potential along the ionization volume has to be very homogeneous (the spatial variation of the field, relative to its absolute value has to be on the order of 10^{-4}).

The Proton Source has already been tested on the *a*SPECT spectrometer, fig. 18). Spectra for different extraction potentials is shown in Fig. 20. More tests where performed during last beam-time at the ILL in 2008, the source is now fully operational, only small improvements should be implemented in the source concept in near future.

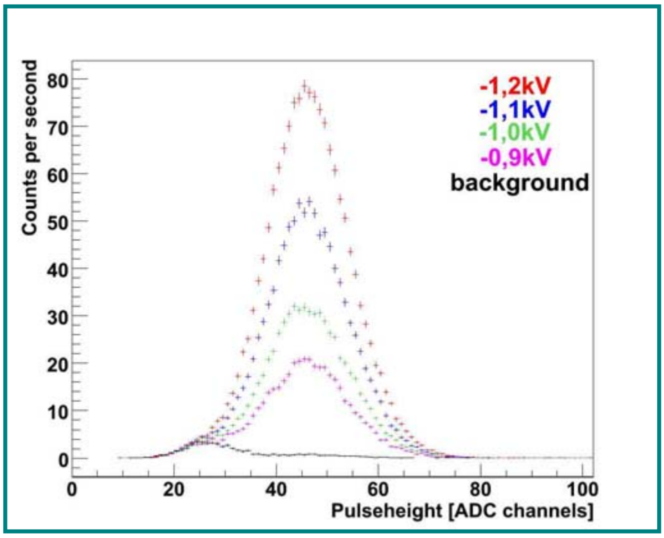

Fig. 20. Energy spectrum for different extraction potentials.

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Recent publications

[1] *R. Muñoz Horta*, **First measurements of the *a*SPECT spectrometer**, doctoral thesis, Johannes-Gutenberg-Universität Mainz, in progress

[2] *G. Konrad et al.*, **The Proton Spectrum in Neutron Beta Decay: Latest Results with the *a*SPECT spectrometer**, Proceedings of the Conference "PANIC08", to be published in Nuclear Physics A

[3] *M. Simson et al.*, **Measuring the proton spectrum in neutron decay – latest results with *a*SPECT**, submitted to NIM

[4] *S. Baeßler et al.,* **First Measurements with the Neutron Decay Spectrometer *a*SPECT**, Eur. Phys. J. A **38**, 17-26 (2008)

[5] *R. Muñoz Horta et al.,* **The Proton Spectrum in Neutron Beta Decay - First Results with the *a*SPECT Spectrometer,** Proceedings of the "14th International seminar on interaction of neutrons with nuclei", Dubna, Russia (2006)

[6] *S. Baeßler et al.,* **The Proton Spectrum in Neutron Beta Decay - First Results with the *a*SPECT Spectrometer**, Proceedings of the Conference "CIPANP 2006"

[7] *F. Ayala Guardia*, **First tests of the neutron decay spectrometer aSPECT**, diploma thesis, Johannes Gutenberg-Universität Mainz (2005)