EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH

INTC-P-111-ADD-2
CERN-INTC-2012-024

Addendum to proposal P111
to the ISOLDE and Neutron Time-of-Flight Committee

SEARCH FOR NEW PHYSICS IN BETA-NEUTRINO CORRELATIONS USING TRAPPED IONS AND A RETARDATION SPECTROMETER – IS433

January 2012

M. Breitenfeldt[1)], T. Porobic[1)], M. Tandecki[1)], S. Van Gorp[1)], N. Severijns[1)], G. Soti[1)], V. De Leebeeck[1)], P. Friedag[2)], Ch. Weinheimer[2)], D. Zakoucky[3)], V.Yu. Kozlov[4)], F. Glück[4)], M. Beck[5)], X. Fléchard[6)], E. Liénard[6)], G. Ban[6)], C. Couratin[6)], A. Herlert[7)]

----

1) Instituut voor Kern- en Stralingsfysica, Katholieke Universiteit Leuven, B-3001 Leuven, Belgium
2) Institut für Kernphysik, Universität Münster, D-48149 Münster, Germany
3) Nuclear Physics Institute, Academy of Sciences of Czech Republic, Rez-near-Prague, Czech Republic
4) Karlsruhe Institute for Technology, Karlsruhe, Germany
5) Institut für Physik, Johannes Gutenberg Universität, Mainz, Germany
6) LPC Caen, ENSICAEN, Université de Caen, CNRS/IN2P3, Caen, France
7) FAIR GmbH, Darmstadt, Germany

Spokesperson: N. Severijns, nathal.severijns@fys.kuleuven.be
Contact person: M. Breitenfeldt, martin.breitenfeldt@cern.ch

Experiment keyword: WITCH

CERN-INTC-2012-024/INTC-P-111-ADD-2
06 January 2012

Abstract

The WITCH set-up is a combination of two Penning traps and a retardation spectrometer for recoil ion energy detection from beta decay. The aim of the experiment is to deduce with a high precision the $\beta-\nu$ angular correlation parameter in allowed transitions to study the structure of the weak interaction. Since the last addendum in 2008 the set-up was further optimized and extended. In this addendum the present status and important upgrades of the experiment are discussed. Furthermore, the first online results for ^{35}Ar and the plan until the long shutdown in 2013 are presented.

Requested shifts: We request 10 shifts of ^{35}Ar beam using a nano-structured CaO target with a VADIS ion source and a cold transfer line, for a single run.

1. Introduction

The main components of the WITCH (Weak Interaction Trap for CHarged particles) set-up are a double Penning ion trap system and a retardation spectrometer. The system is designed primarily to measure the energy distribution of the recoil ions from beta decay in a Penning trap. The shape of this distribution is sensitive to the β-ν angular correlation coefficient *a* [JAC57], which depends on the fundamental properties of the weak interaction. The WITCH experiment [BEC03a, BEC03b, KOZ04, TAN11a] thus allows to probe the existence of physics beyond the Standard Model such as, e.g., scalar and tensor weak currents. A relative precision of about 0.5 % or better on *a* is aimed at. With such a precision the sensitivity to scalar weak currents is similar to the present 95% upper limit of $|C_S/C_V| < 0.07$ [SEV06], and equal to the presently most precise result that was obtained in a β-ν correlation measurement with ^{38m}K in a Magneto Optical Trap at TRIUMF [GOR05].

Presently two ion trap based set-ups for β-ν correlation measurements exist: the LPCTRAP system was set up by the LPC-Caen group at GANIL [ROD06] to search for tensor weak currents in the pure Gamow-Teller β^- decay of ^{6}He. The ions are stored in a Paul trap and the β-ν correlation is extracted from β-recoil coincidence measurements, determining the position and energy of the β particles with a plastic scintillator and a position-sensitive Si detector, and measuring the position and time of flight of the recoil ions with a micro-channel plate detector. First results of the experiment have been published [FLE11] and a more extended data set is currently being analyzed.
The other set-up is the WITCH experiment at ISOLDE (IS433). The proof of principle of this experiment was demonstrated [KOZ08] and a first recoil ion energy spectrum has been measured [COE08, BEC11]. The WITCH experiment concentrates on scalar weak currents. In parallel our team is searching for tensor currents in beta-asymmetry measurements with polarized nuclei at NICOLE (experiment IS431).
Here we give a status report and ask for additional beam time to perform further measurements with WITCH. Note that we have recently started a collaboration with the group from LPC Caen, both on WITCH and on the LPCTRAP experiment.

2. Lay-out and principle

An overview of the WITCH set-up [BEC03, TAN11a] is shown in Fig. 1. In a first step the ions produced by ISOLDE are accumulated with REXTRAP at 30 keV. The ion bunches are then transported through the horizontal beam line and through an electrostatic 90° bender into the Pulsed Drift Tube (PDT) of WITCH [COE07a], where the energy of the ion bunch is reduced to about 100eV with respect to the ground potential. Afterwards the ions are guided by electrostatic potentials into the magnetic field of the trap magnet. In this field of about 6T two Penning traps are installed. In the first one, the cooler trap, the ions are cooled to an energy below 1eV by collisions with the atoms of a helium buffer-gas at a pressure of about 10^{-4}mbar. A pumping diaphragm is separating the cooler trap from the second Penning trap, the decay trap, where a pressure below 10^{-8}mbar is required. After a few 100ms, the ions are transferred and stored in the decay trap, where they form a scattering-free source of radioactive ions. After decay, the daughter ions can escape the trap thanks to the recoil energy, if only 1eV is picked up in the axial direction. Those ions which have a momentum in upwards direction will be leaving towards the spectrometer where a 0.1T magnetic field guides them and a set of electrodes is used to analyse their axial energy. Hereby it is important to have a slow drift over the magnetic field gradient from the high to the low field region for an adiabatic conversion of the radial energy component into axial energy. The degree of conversion is determined by the magnetic fields ratio of the trap and the spectrometer magnets, i.e. 6T/0.1T. Ions that pass the analysis voltage barrier are reaccelerated towards the main detector, a micro channel plate (MCP) detector with a delay-line anode, used to count the ions as a function of the analysis voltage and to measure their positions as redundant information to cross check for systematic uncertainties.

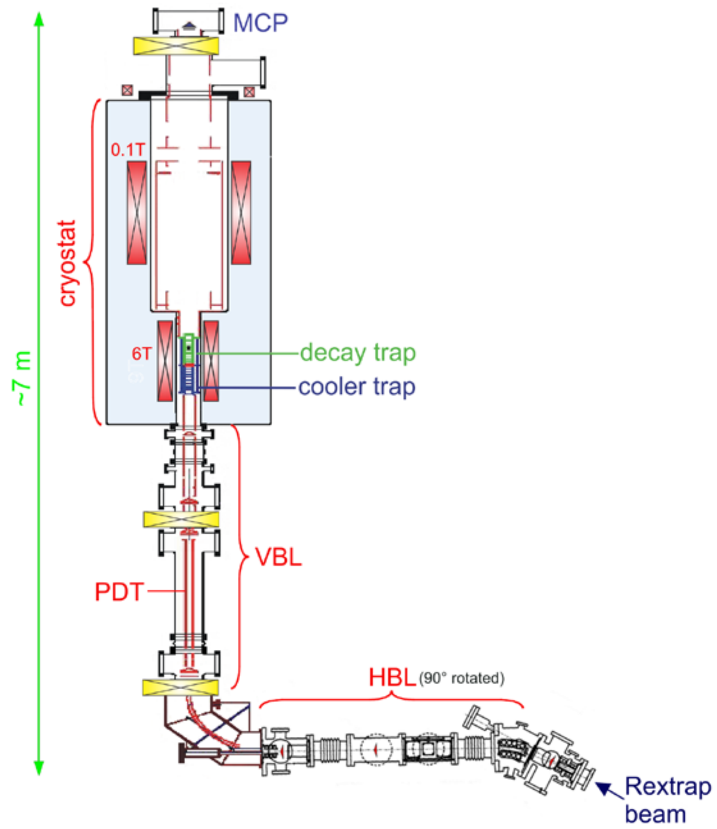

Figure 1: Schematic overview of the WITCH set-up at the ISOLDE/CERN facility.

3. Upgrades and Status

In the last addendum [SEV08] several upgrades were suggested, which in the meantime have been mostly incorporated into the WITCH set-up. In the following the major improvements which led to the first data with ^{35}Ar are summarized.

3.1 Control System

Since the commissioning experiment with ^{124}In in 2006, the hardware of the experiment has been upgraded. Computer controlled power supplies for the beam line electrodes and the trap electrodes as well as pulse pattern generators for the timing have been implemented in the system and integrated into a LabVIEW based control system (CS) [TAN11b]. The underlying framework has been developed at GSI and is also in use at ISOLTRAP. The application of the CS resulted in a high reproducibility of beam-line tunes and a faster set-up time for the system. Furthermore a state of the art graphical user interface allows a systematic and careful investigation of dependencies in the system (e.g. axial and total energy of the ions after transfer to the decay trap as a function of the cooling time in the cooler trap).

In future, the implementation of a simplex algorithm as well as upgrades for the acquisition hardware of the beam line monitoring are planned. This would allow a more efficient optimization of the ion-beam transport.

3.2 Offline ion source, compact RFQ and magnetic shielding of the REX beam line

In the last few years the request for REX beam times has increased, REX is now the working horse at ISOLDE. This advance has some drawbacks for the WITCH experiment: first REXTRAP and its offline ion source are now less frequently available to provide ions for the WITCH setup to test improvements and to characterize the entire setup, such as determining the energy straggling in the decay trap and tuning transfer efficiencies between certain parts of the setup. Second, the WITCH

stray magnetic field is affecting the highly charged ions travelling between the REXEBIS and the REXLINAC. For this reason it had been kindly requested to leave the WITCH magnets switched off during REX setup, online experiments, and machine development shifts. Consequently, in 2010 second half of the experimental year there was a maximum of 4 weeks in which the WITCH magnets and the REXTRAP offline ion-source could be used. This is far too few for efficient optimization of a complex system as WITCH.
To circumvent these limitations, a surface ion source (similar to the REXTRAP offline ion source) combined with a compact RFQ ion beam cooler and buncher [TRA11] have been installed at WITCH, which can produce bunches comparable in intensity and time structure as those delivered by REXTRAP.
Furthermore, to reduce the influence of the WITCH magnetic stray field on the REX beam a big effort has been done by our collaboration, after consulting the REX machine specialists, to install a cage made of mu-metal (Fe-Ni alloy with good magnetic properties, very high permeability and a very narrow hysteresis cycle in weak magnetic fields) around the beam line between the REXEBIS cage and the magnetic bender from the vertical to the horizontal beam line, including the benders. In this way a comparable transmission of the ions to the one obtained when the magnetic field is switched off could be achieved when the WITCH magnets are switched on. In addition, with small adjustments it is possible to use for different *A/q* the scaling of voltages and magnetic fields as used for the set-up of radioactive beams. The transfer of the ion beam and the application of the scaling have been tested between REXTRAP and a Faraday cup at the end of the REXLINAC for ^{39}K [BRE11]. Beginning of the year 2011 it was agreed to use this as a lower mass limit since it is not completely clear how the WITCH magnetic stray field is influencing the ion transport between REXTRAP and REXEBIS for masses below A = 39.

3.3 Charge exchange: Vacuum upgrade and stacking in WITCH

The online experiment in 2007 with ^{35}Ar showed a charge exchange half-life of 8 ms in the WITCH Penning traps and a high contamination / ion-of-interest ratio. The contamination of ^{35}Cl has been successfully tackled by the target group by the using a special cleaning procedure when producing the nano-structured target material [RAM11]. On the WITCH side the charge exchange rate has been decreased by several implementations:
NEG coating of the beam-line vacuum-chambers between the PDT and the cryostat has been implemented, and two SAES getter pumps were installed to improve the vacuum background. In the trap and the spectrometer volume NEG coated stainless steel foils have been introduced. In addition, the buffer-gas system has been upgraded to an all-metal system with a SAES getter pump for further purification of the buffer gas because commonly available He5.7 with a pressure of $3x10^{-4}$mbar would provide already as many impurities as the number of atoms present in the rest gas at 10^{-9}mbar. With these improvements no charge exchange in the WITCH system has been observed anymore in the online experiments performed at the end of 2011.
Nevertheless the accumulation in REXTRAP is still a bottle neck: here charge exchange half-lives of about 70ms have been observed during several tests [DEL04b, WUR11]. It has been observed that Ar/Kr ions are charge exchanging with the Ne gas that is used as buffer gas in REXTRAP, most probably due to high cyclotron radii during the cooling processes when using quadrupolar excitations. For this reason using Ne of a better quality to improve the charge-exchange half-life has not shown the desired results. For the 2012 online period, we will try to improve the injection by also using the simplex algorithm which is available for beam tuning at ISOLDE. Combining this with the stacking of pulses from REXTRAP in WITCH, the charge exchange losses in REXTRAP can be minimized. To allow for this stacking, a new piece of software for the REX timing has been provided by E. Piselli and the PDT can now be switched with 5Hz instead of 1Hz.

3.4 Background Ionization: Compensation magnet and wire in the spectrometer

Already during the commissioning experiment in 2006 [BEC11] it has been found that not all electrodes could be used at their design values because spontaneous discharges lead to a tripping of the power supplies. In addition, this ionized particles created somewhere in the system is guided

towards the detector and thus creating background counts. This issue has been discussed in detail in the PhD thesis of M. Tandecki [TAN11a]. Stepwise these effects have been discovered and reduced/solved afterwards. A compensation magnet has been installed to reverse the magnetic field lines in the einzel lens of the reacceleration section. Like this the unwanted Penning trap created by the magnetic field lines and the potential maximum has been destroyed (comp. Fig.2).
A similar solution is not applicable for the second unwanted Penning trap that has been found in the spectrometer, where the potential barrier of the analysis voltages is intrinsically a potential minimum for negatively charged particles, i.e. electrons. Based on the observed charge build-up times at WITCH a static wire perpendicular to the magnetic field axis has been added, to collect mainly electrons from the unwanted trap volume and thus prevent amplification reactions which lead to background ionization as was found in November 2009 with ^{35}Ar ions in WITCH. Note that this effect could only be studied with radioactive sources in our system and thus was only discovered during online measurements.

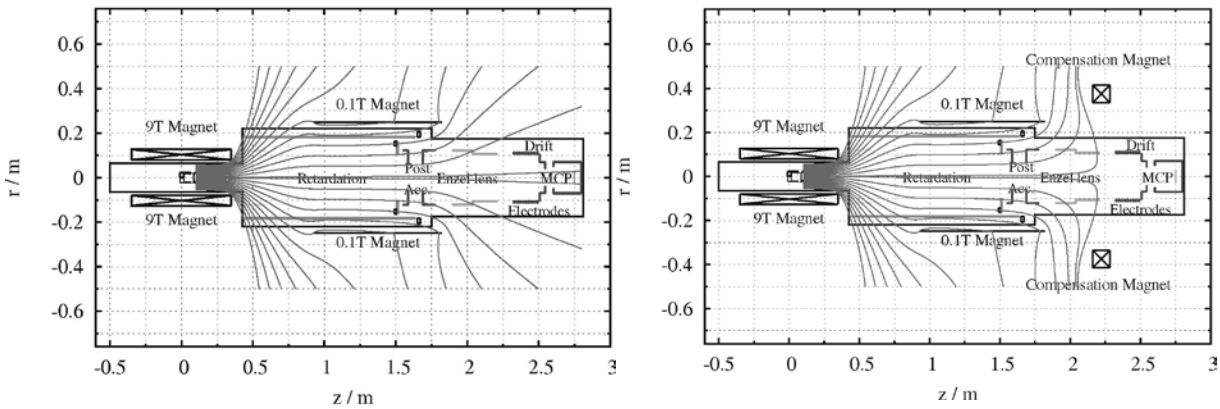

Fig. 2 Scheme of the vacuum vessel of the WITCH cryostat and the detector chamber including electrodes. Superposed is a map of magnetic field lines, at left without compensation magnet, at right with the compensation magnet.

3.5 Main Detector

In the WITCH experiment the ions are counted as a function of the applied retardation spectrometer voltage, which ideally would allow already the extraction of the beta-neutrino angular-correlation coefficient *a*. Nevertheless, having redundant information available, such as position and pulse height distributions for different classes of events, strengthens the analysis of the acquired data [BEC11]. For this reason counting is done using a micro channel plate detector with delay line anode. For higher detection efficiency and no charge state dependency the old detector with a 4 cm diameter, which was borrowed from the LPC Caen group, has been replaced by a similar one but now with an 8 cm diameter active surface.
Between mid-2010 and end-2011 the detector setup has been improved and the efficiency of the plates has been calibrated as a function of the position using an alpha source. In fig. 3 such a distribution is shown.

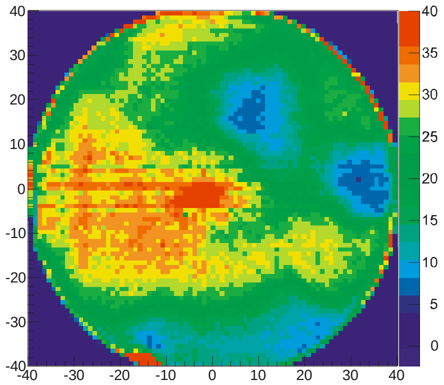

Fig.3 Colour coded the position distribution of events created by an alpha source about 11cm away from the surface of the MCP.

3.6 Simulation codes

In order to understand the set-up and its systematic effects, it is important to characterize it as well as possible. Therefore, the variation of several parameters and their influence on the count rate in the diagnostics MCPs and on the position distribution of the events on the main detector can be studied. A deeper understanding is provided by comparison with results of numerical simulations. For WITCH two packages have been developed: SIMBUCA, a code using the parallelism of processing on a graphics card for calculation of Coulomb interactions of many particles in a trap [VGO11], and SIMWITCH, a particle tracking routine [FRI08] based on programs created by F. Glueck for the KATRIN experiment [GLU11a,GLU11b].
SIMBUCA is used to study space charge effects in the Penning traps and to determine how ion-ion interactions can change the intuitively assumed energy and position distribution in the decay trap after transfer. The results are used as input data for SIMWITCH, which determines the trajectories of daughter nuclei from the traps towards the main detector. Combining the results of the two programs, systematic effects such as charge state or energy dependent transfer efficiencies can be investigated. Furthermore, these codes helped significantly to identify the background ionization and to test possible solutions. Also the decision to install the 8 cm diameter MCP detector was based on results of particle tracking.

4. Experimental results

In the period from January 2008 till the end of 2011 several online experiments using different nuclides and with different objectives have been performed as shown in Tab. 1.

Table 1. List of online experiments since the last addendum [SEV08] at the beginning of 2008 including the nuclides of interest and the achievements of each experiment.

Date	Nuclide	Achieved
July 2009	^{124}In	Test of modifications
November 2009	^{35}Ar	Discovery of the low intensity background ionization due to unwanted Penning traps in the spectrometer
June 2010	^{144}Eu, ^{140}Pm	Problems with space charge due to beam impurities; too few ions of interest
November 2010	^{35}Ar	Cancelled due to both GPS and WITCH problems
June 2011	^{35}Ar	First recoil energy spectrum of ^{35}Ar with about 5000 counts
October 2011	^{35}Ar	Recoil energy spectrum with several 10000 counts
November 2011	^{35}Ar	Many recoil energy spectra using different measurement sequences to study systematic effects and corresponding to a statistical precision of 2% to 3% on '*a*'.

1) After spending several years on debugging and improving WITCH it was finally possible to acquire the first sets of data, meaning recoil spectra of ^{35}Ar ions. In the June 2011 run a recoil spectrum with about 5000 events had been recorded. In this case 'events' refer to missing counts

because ions are blocked by the voltage that is applied to the spectrometer electrodes. The spectrum was obtained in a measurement of 3 hours by applying a sequence of four different voltages (i.e. 150 V, 250V, 350 V and 600 V) for 50ms and separated by 50ms of 0V as a reference (see Fig. 4). This first spectrum has been analysed with the help of the simulation programs and under consideration of the charge state distribution, which has been determined at LPCtrap/GANIL. The result is a value of a = 0.78(42) which is compatible with the literature value for ^{35}Ar of 0.904(16) [SEV08b].

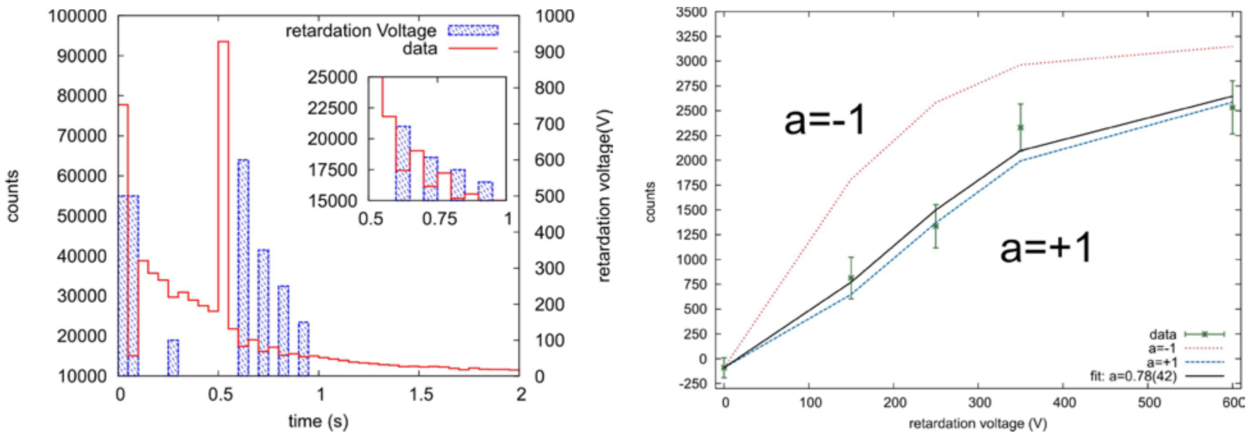

Fig. 4 Left: Spectrum (red) and voltages applied (blue) of the June 2011 run. Right: Extracted “counts” as a function of the retardation voltage with the fit to the correlation coefficient *a*.

2) In autumn 2011 two runs with different targets have been performed. The first run at the end of October was performed with a target unit which was already used twice for WITCH (Nov. 2009 and June 2011). For this reason, the yield was still a factor of 5 lower than requested and, as the transmission efficiency at WITCH was not optimal, old values could not be achieved. Nevertheless, the statistics from June has been surpassed after only half an hour of measurement. In this run several different sequences of voltages have been used to produce a spectrum. I.e. the spectrometer voltages have been switched from low towards high voltages, and vice versa, to study potentially present rest gas ionization effects (Fig. 5 Left). These data are still under analysis by the Münster group.

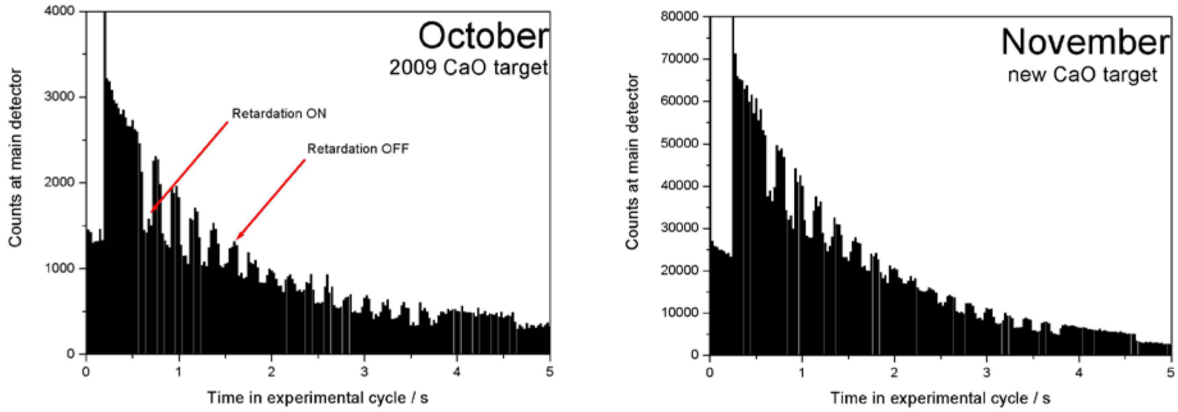

Fig. 5: Set of “V” measurements, the retardation voltages are varied within one cycle. Left: as performed in October and right: as in November.

The second autumn run was scheduled by the coordinator only one week after the October run to compensate for the low yield from the ISOLDE side in the first run (Fig. 5 Right, comparable measurement time). Furthermore, on the WITCH side it has been possible to improve the transmission, which had been moderate due to a mismatch of voltages produced by an old power supply as compared to those applied by the newly installed one and a shortage of preparation time with having REXTRAP available.

Also, in this second run several sequences of voltages have been used for scanning the recoil energy distribution. In addition to the previously used schemes also an ON-OFF sequence has been used. Part of these data is shown in figure 6. Here, ON refers to the spectrometer voltage having been set to some nominal value (at times between 0.8 s to 2.4 s in the experimental cycle; see figure 6) and OFF refers to 0V (during the remainder of the cycle, except for a period of 0.5s at the end of the cycle, where always 600V was applied). The part of the spectra for values of 0V and 600V are being used for normalization. In principle the plot is an exponential decay curve with some parts missing for the ON and the 600V periods. In the case of the November measurement there is also an oscillation with the magnetron frequency superposed. This together with some other tests hints to a misalignment of the geometrical axis of the trap electrodes with respect to the magnetic field axis. This is being investigated now.

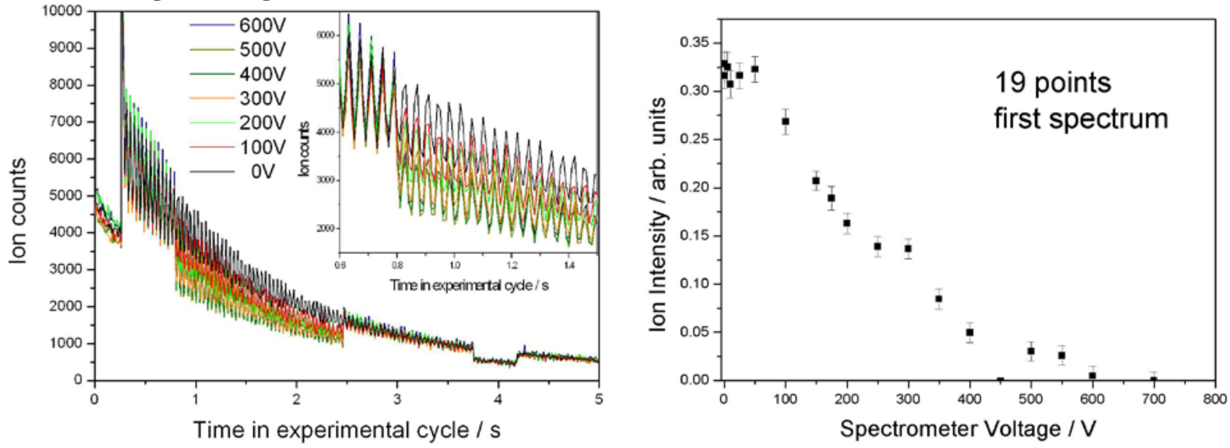

Fig. 6 Left: Set of ON-OFF measurements as described in the text, the count rate is varying between 0.8s and 2.4s. Right: First rough analysis of the ON-OFF measurements.

5. Offline improvements

Beginning of 2012 the geometrical misalignment which produced oscillations in the data has to be taken care of. In addition, maintenance operations have to be performed. Furthermore, some systematic studies concerning the behaviour of the ions in the traps have to be studied to determine more precisely the input parameters for the simulations so as to reduce the systematic uncertainties originating from them. Also significant time will be spent on analysing the data.

6. Summary of requested shifts

In order to study systematic effects and improve statistics by measuring the recoil ions energy spectrum for ^{35}Ar, we ask for 10 shifts with ^{35}Ar. In combination with the still available 10 shifts we would ask for 2 experiments in 2012. The first run will be used to check whether the improvements of the setup, such as e.g. fixing the misalignment, provide the required effect. The second run will be dedicated to acquire more statistics.

Table 2. Beam time request.

Run	Beam	Min. intensity	Target material	Ion source	Shifts	Available from last addendum
1	^{35}Ar	1 x 10^7/s	CaO	VADIS cold transfer line	10	Yes
2	^{35}Ar	1 x 10^7/s	CaO	VADIS cold transfer line	10 New request = 10	No

Appendix - Safety

Description of the proposed experiment:
The experimental setup comprises: the WITCH fixed installation with no additions and the use of **REXTRAP**

Part of the Choose an item.	Availability	Design and manufacturing
WITCH fixed installation	☒ Existing	☒ To be used without any modification
[Part 1 of WITCH fixed installation]	☒ Existing	☒ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing

Hazards generated by the experiment:
Hazards named in the document relevant for the fixed WITCH installation. No additional hazards that were not mentioned in that document.

Additional hazards:
No additional hazards that were not mentioned in the above mentioned document.

References (a '*' indicates a WITCH paper or Ph.D. thesis)

*[BEC03a] M. Beck et al., Nucl. Instr. and Meth. A503 (2003) 567.
*[BEC03b] M. Beck et al., Nucl. Instr. and Meth. B204 (2003) 521.
*[BEC11] M. Beck et al., Nucl. Instr. and Meth.
*[BRE11] M. Breitenfeldt et al., Report on WITCH magnetic shielding, 2011.
*[COE04] S. Coeck and N. Severijns, WITCH Internal Report 01-10-2004.
*[COE06] S. Coeck et al., Nucl. Instr. and Meth. A 557 (2006) 516.
*[COE07a] S. Coeck et al., Nucl. Instr. and Meth. A 572 (2007) 585.
*[COE07b] S. Coeck et al., Nucl. Instr. and Meth. A 574 (2007) 370.
*[COE07c] S. Coeck, Ph.D. thesis, Katholieke Universiteit Leuven (2007).
*[COE08] S. Coeck et al., submitted to Phys. Rev. Lett.
*[DEL04a] B. Delauré, Ph.D. thesis, Katholieke Universiteit Leuven (2004).
[DEL04b] P. Delahaye et al., Nucl. Phys. A 746 (2004) 604c–607c.
[FLE11] X. Fléchard et al, J. Phys. G: Nucl. Part. Phys. 38 (2011) 055101.
*[FRI08] P. Friedag, diploma thesis, WWU Münster, 2008
[GLU11a] F. Glück, Progress In Electromagnetics Research B 32 (2011) 319.
[GLU11b] F. Glück, Progress In Electromagnetics Research B 32(2011) 351.
[JAC57] J. D. Jackson, S. B. Treiman and H.W. Wyld, Nucl. Phys. 4 (1957) 206.
*[KOZ05] V. Kozlov, Ph.D. thesis, Katholieke Universiteit Leuven (2005).
*[KOZ06] V. Kozlov et al., International Journal of Mass Spectrometry 251 (2006) 159.
*[KOZ08] V. Kozlov et al., Proc. of the EMIS Conference, Deauville (France), 2007, to be published in Nucl. Inst. and Meth. B.
[LIE05] E.Liénard et al., Nucl. Instr. And Meth. A 551 (2005) 375.
*[KOZ04] V. Kozlov et al., Physics of Atomic Nuclei, 67 (2004) 1112.
[ROD06] D.Rodriguez et al., Nucl. Inst. and Meth. A 565 (2006) 987.
[RAM11] J.P. Ramos, Master thesis, University of Aveiro (2011).
*[SEV06] N. Severijns, M. Beck and O. Naviliat-Cuncic, Rev. Mod. Phys. 78 (2006) 991.
[SEV08] N. Severijns et al, INTC-P-111-ADD-1
[SEV08b] N. Severijns et al, Phys. Rev. C 78 (2008) 055501.
*[TAN07] M. Tandecki, WITCH Internal Report 27-03-2007.
*[TAN11a] M. Tandecki, PhD thesis, Katholieke Universiteit Leuven (2011).
*[TAN11b] M. Tandecki et al., Nucl. Instr. and Meth. A 629 (2011) 396-405.
*[TRA11] E. Traykov et al., Nucl. Instr. and Meth. 648 (2011) 1-14.
*[VGO11] S. van Gorp et al., Nucl. Instr. and Meth. A 638 (2011) 192-200.
*[WUR11] E. Wursten, summer student report, IKS KU Leuven (2011).