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The WITCH Experiment: towards weak interactions studies. Status and prospects

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Abstract Primary goal of the WITCH experiment is to test the Standard Model for a possible admixture of a scalar or tensor type interaction in β -decay. This information will be inferred from the shape of the recoil energy spectrum. The experimental set-up was completed and is under intensive commissioning at ISOLDE (CERN). It combines a Penning trap to store the ions and a retardation spectrometer to probe the recoil ion energy. A brief overview of the WITCH set-up and the results of commissioning tests performed until now are presented. Finally, perspectives of the physics program are reviewed.

Keywords Weak interactions · Penning trap · Retardation spectrometer

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1 Introduction

The most general interaction Hamiltonian for nuclear β -decay which includes all possible interaction types consistent with Lorentz-invariance [1,2] contains 5 different terms, so-called Scalar (S), Vector (V), Tensor (T), Axial-Vector (A) and Pseudoscalar (P) contributions. The Standard Model (SM) of the weak interaction excepts only V and A interactions which leads to the well-known V - A structure of the weak interaction. However, the presence of scalar and tensor types of weak interaction is today ruled out only to the level of about 8% of the V- and A-interactions [3].

A possible admixture of a scalar or tensor type weak interaction in β -decay can be studied by determining the $\beta - \nu$ angular correlation. This correlation for unpolarized nuclei can be characterized by the $\beta - \nu$ angular correlation coefficient a [4] which is for instance for pure Fermi transitions given by:

$$a_F = \frac{|C_V|^2 + |C_V'|^2 - |C_S|^2 - |C_S'|^2}{|C_V|^2 + |C_V'|^2 + |C_S|^2 + |C_S'|^2}$$
(1)

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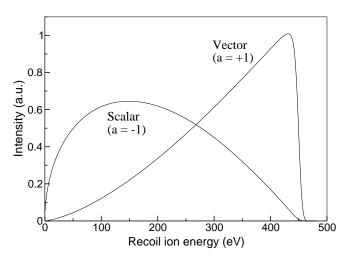


Fig. 1 Differential recoil energy spectrum for a = 1 (pure V interaction) and a = -1 (pure S interaction).

Since the Standard Model assumes only V- and A- interactions $a_F^{SM} = 1$ ($a_{GT}^{SM} = -1/3$ for pure Gamow-Teller). Any admixture of S- to V- (T to A) interaction in a pure Fermi (Gamow-Teller) decay would result in a < 1 (a > -1/3). It can be shown that the two leptons in β -decay will be emitted preferably into the same direction for a V (T) interaction and into opposite directions for an S (A) interaction leading to a relatively large energy of the recoil ion for a V (T) interaction and a relatively small recoil energy for an S (A) interaction (Fig. 1). The WITCH experiment as a primary goal aims to measure the shape of the recoil energy spectrum in nuclear β -decay with high precision in order to deduce the parameter a which will give information on a possible scalar or tensor type interaction. Similar experiments were recently performed at TRIUMF [5] and at Berkley [6], while another experiment is ongoing at GANIL [7].

2 Experiment

In order to fulfill the goal of the experiment the WITCH set-up was built and installed in ISOLDE (CERN). The main feature of this set-up is a combination of a double Penning trap structure to store the β -decaying radioactive ions and a retardation spectrometer to probe the energy of the daughter recoil ion (Fig. 2).

The radioactive ions are produced by the ISOLDE facility [9] and are then first trapped, cooled and bunched by REXTRAP [10]. The ion bunches ejected from REXTRAP have 60 keV (optionally 30 keV) energy and are guided into the WITCH set-up. They are decelerated from 60 keV to about 80 eV in the vertical beamline by means of the pulsed drift cavity [11] and thus can be trapped in the first Penning trap, the cooler trap. This trap serves to cool the ions further down in energy by buffer gas collisions and to prepare the ion cloud to be injected into the second Penning trap, the decay trap. Both traps are placed in a 9 T magnetic field. After β -decay ions leave the decay trap and those emitted in the direction of the spectrometer (upper half hemisphere) are probed for their energy by an electrostatic retardation potential. The magnetic field in the region of the retardation analysis plane is 0.1 T. The working principle of the retardation spectrometer is based on the principle of adiabatic invariance of the magnetic flux and similar to the β -spectrometers used for the neutrino rest-mass measurements. The ions that pass the retardation plane are re-accelerated to ~10 keV and focused onto the micro-channel plate (MCP) detector which is equipped with delay line anodes for position sensitivity. Changing the retardation potential over the necessary range allows to measure a recoil ion spectrum with high precision.

Simulations performed show that for a reasonable measurement time one can reach a precision for the $\beta - \nu$ angular correlation parameter $\Delta a = 0.005$ which corresponds to $|C_S| \leq 9\%^{-1}$ at C.L.=95%.

¹ More detailed information on scalar constraints can be found in [8,3]

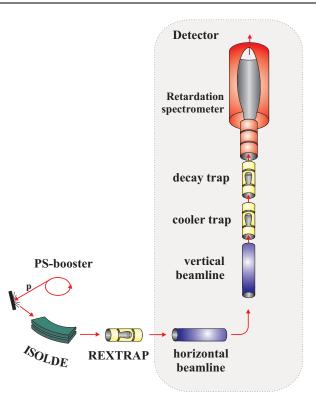


Fig. 2 General schematic view of the WITCH set-up (not to scale).

Further improvements in order to push the limit down to $\Delta a = 0.002$, or $|C_S| \lesssim 6\%$ at C.L.=95\%, should be possible.

More details about the WITCH set-up can be found in [12, 13].

3 Present status

Tests performed to check the beam transport, to confirm the functionality of pulsing down the ions and to verify the basic operation of the Penning traps are described in [13,11]. Here we present only the most recent results.

3.1 Traps

The main purpose of the cooler trap is to prepare the ion cloud for the measurement. This involves buffer gas cooling, cleaning from possible contaminates, better centering and cooling of the magnetron motion to prevent the cloud from expanding. The last three tasks can be achieved by *sideband cooling* [14]. This technique was tested by measuring the signal on the MCP detector installed in the middle of the retardation spectrometer as a function of the applied frequency near the true cyclotron frequency. The isotope used is ¹³³Cs. In a first step all ions in the cooler trap were driven out of the center with dipole excitation and then the quadrupole excitation was applied (Fig. 3, square data points). Only ions which can be re-centered can reach the detector because they have to pass the 3 mm diameter pumping diaphragm (see Fig. 5). As can be seen from Fig. 3 a nice resonance curve is obtained with $\Delta\nu$ (FWHM)=346 Hz corresponding to a mass resolving power $R = \nu/\Delta\nu$ (FWHM) \approx 2000. This is enough to completely remove isotopic contaminations which can be present in the incoming beam. A pure quadrupole excitation without prior dipole excitation was applied as well. As one can see from Fig. 3 (triangle data points) it has a similar effect as sideband cooling meaning that the initial injection into the cooler trap was not ideal, e.g. ions were injected off center and/or they had a too large magnetron component. However, using the quadrupole excitation still allowed to correct for this.

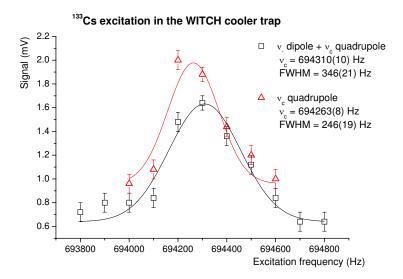


Fig. 3 Cooling resonances for 133 Cs as obtained from the MCP ion signal as a function of the applied frequency. Ions are ejected from the cooler trap. The B-field was 6 T.

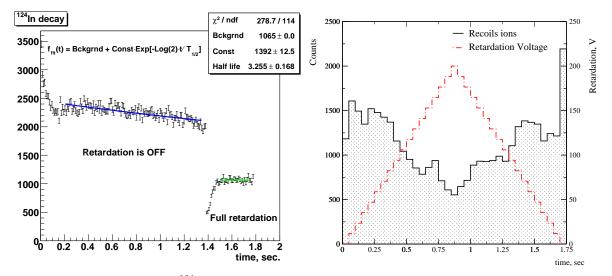


Fig. 4 Retardation spectra for 124g,m In β -decay. *Left*: simple On-Off measurement; *Right*: 35 retardation steps are used in total, first rising from 0 to 200 V then going back to 0 V (retardation steps are indicated).

It has to be noted here that the magnetic field homogeneity allows to improve the mass resolving power up to $R = 10^4 \div 10^5$.

3.2 First recoil ions

In June 2006 the WITCH experiment observed first recoil ions following the β -decay of trapped ¹²⁴In (Fig. 4). The incoming beam was a mixture of ^{124g}In ($t_{1/2}$ =3.11 s) and ^{124m}In ($t_{1/2}$ =3.7 s). As a first step a simple on-off measurement was performed: for 1.4 s no retardation was applied thus measuring the total signal and then for 0.4 s 400 V retardation was used stopping all recoil ions and thus providing the background signal (Fig. 4, left). As expected the count rate drops down when the retardation is On. The data were fitted and a half-life of 3.3(3) s was found which is in a good agreement with the incoming mixed beam of ^{124g,m}In. The latter confirms that the ions trapped in the decay trap are ^{124g,m}In. As a next step different retardation schemes were used. However, strong discharge in

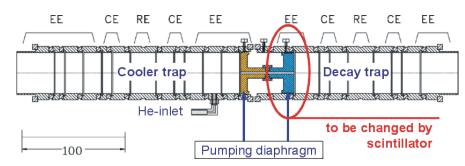


Fig. 5 WITCH double Penning trap structure. Part of the pumping diaphragm to be changed is indicated.

the re-acceleration part of the set-up (see Sect. 2) was observed. Thus the acceleration voltages were significantly reduced which, however, caused a focusing effect, i.e. recoil ions were focused differently depending on their energy and could miss the detector. Nevertheless, a correct general behavior of the spectrometer was observed (Fig. 4, right): increasing the retardation leads to lower count rate on the detector while decrease of the retardation corresponds to higher count rate.

3.3 Position sensitivity

Recently a position sensitive MCP of 4 cm diameter was installed as the main detector in the system. This MCP allows to detect a larger beam spot and to study a number of systematic effects like a possible dependence of the beam size on the ion energy, the focusing problem which already played a role during the beam time (see Sect. 3.2) and the effect of the β -background. This MCP is of the same type as described in [15]. Position sensitivity is realized by delay line anodes, i.e. the one-dimensional position of the ion hit is deduced from the difference of the propagation times to both ends of the corresponding wire. The position sensitivity read-out was tested by installing a special mask in front of the detector. Reading back the timing signals and reconstructing the hit positions allowed to reproduce the shape of the mask, thus confirming the functionality of the system. Presently achieved position resolution is of the order of 1 mm. This MCP is located in the magnetic field of about 30 G, but no dependency of the MCP resolution on B-field was studied yet.

4 Outlook

As for technical improvements we currently investigate the possibility to change part of the pumping diaphragm to a β -detector (optionally to a scintillator detector)(Fig. 5). This will allow to have an additional normalization between different trap loads, to have a start signal for TOF measurements and to evaluate the β -background on the main MCP detector on-line.

The WITCH physics program is not limited to the search for exotic scalar or tensor currents. If one assumes that the Standard Model is correct measuring the $\beta - \nu$ correlation parameter *a* yields information about the Fermi to Gamow-Teller mixing ratio. Due to the properties of the retardation spectrometer different charge states will appear at different positions in the spectrum thus allowing to study the charge state distribution after nuclear β -decay. Also, ions from β -decay and from electron capture (EC) can be separated in the WITCH spectrometer. This opens the possibility to determine the EC/ β^+ -branching ratio. However, for this one has to include the charge state distribution as a parameter and has to measure the whole recoil spectrum. One can also study the possibility to search for heavy neutrinos. The presence of these neutrinos can be indicated by subtle kinks in the recoil spectrum.

5 Conclusion

The WITCH experiment has as the primary goal to measure exotic scalar or tensor currents in the weak interaction. The set-up is installed in ISOLDE (CERN). All major components of the set-up including

beamline transport, double Penning trap system and the retardation spectrometer are checked for their functionality and show good or acceptable efficiency (Table 1). The overall efficiency of the setup was improved by up to a factor of 30 in comparison with 2004 (see [13]). This allowed to detect first recoil ions in the WITCH set-up. A number of systematic effects still has to be studied and certain improvements have to be made in order to further increase the efficiency and to perform precise measurement of the recoil ion spectrum.

Table 1 Efficiencies for the ideal WITCH set-up and currently best achieved values (for parameters that were not yet studied the values of an ideal set-up are taken to calculate the total efficiency).

Description	ideal set-up	Best achieved 2004-2006
Beamline transfer $+$ pulse down	50%	$\sim 50\%$
Injection into B-field	100%	10%
Cooler trap efficiency	100%	$\sim 60\%$
Transfer between traps	100%	${\sim}80\%$
Storage in the decay trap	100%	100%
Fraction of ions leaving the decay trap	40%	not studied
Shake-off for charge state $n=1$	10%	not studied
Transmission through the spectrometer	100%	$\sim 50\%$
MCP efficiency	60%	52.3(3)% [15]
Total efficiency	${\sim}1\%$	$\sim \! 2.5 \cdot 10^{-2} \%$

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