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Study of weak magnetism by precision spectrum shape measurements in nuclear beta decay

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Abstract. Nuclear beta decays play an important role in uncovering the nature of the weak interaction. The weak magnetism (WM) form factor, $b_{\rm WM}$, is generally a small correction to the beta decay rate that arises at first order as an interference term between the dominant Gamow-Teller and the magnetic dipole contributions to the weak current. This form factor is still poorly known for nuclei with higher atomic number. We performed a careful analysis of the measured beta spectrum shape for Gamow-Teller transitions in ^{114}In and ^{32}P nuclei. The precision spectrum shape measurements were carried out using the miniBETA spectrometer consisting of a low-mass, low-Z multi-wire gas tracker and a plastic scintillator energy detector. The preliminary results for the weak magnetism extraction for ^{114}In and ^{32}P nuclei are presented.

1. Introduction

High precision β-spectrum shape measurements in nuclear beta decay are very important, as they allow exploring still poorly known effects in the Standard Model (SM) and hypothetical effects not included in it (BSM). Accurate studies of beta-decays have been exploited in various applications of fundamental physics. These studies are carried out in the low-energy regime and by using of effective field theory they can be compared to direct searches for exotic couplings performed at large hadron colliders. The precision experiments in the low-energy research are significantly smaller in size and less expensive, making a perfect complement to large-scale research.

At the sensitivity level of new generation experiments, reaching a precision of the order of 1% and below, it is expected that the so-called recoil order effects in the hadronic weak current and radiative corrections will have a sizable contribution and cannot be neglected when interpreting results in terms of BSM physics. The recoil terms in nuclear beta decay originate from QCD effects in the weak interaction of a bound quark, and folds with nuclear structure effects in heavier nuclei [1, 2]. The most important of these induced currents, the weak magnetism term, is directly related to the difference of the magnetic moments of the proton and the neutron and can be determined in precision measurements of the beta spectrum shape in selected transitions. Most of the available data mainly concern the allowed and first forbidden transitions. Knowledge about induced terms in higher forbidden transitions is very limited though crucial for ongoing research, such as dark matter studies investigations of the anti-neutrino anomaly in the observed antineutrino event rate at nuclear reactors. An overview of current experimental and theoretical knowledge of the most important recoil term, i.e. the weak magnetism, for both the $T = 1/2$ mirror beta transitions and a large set of beta decays in higher isospin multiplets can be found in Ref. [1]. The experimental information on weak magnetism is only available for beta transitions of nuclei with masses up to $A = 75$. Hence, an experimental result for this quantity is badly needed for isotopes with higher masses (e.g. ^{114}In) as well as for higher Ft value transitions (e.g. ^{32}P).

Furthermore, the shape of the beta spectrum reveals also a high sensitivity for exotic scalar and tensor coupling contributions to the weak interaction contained in the Fierz term b_{F}. In order to reliably assess both the weak magnetism form factor and the Fierz term one needs to consider a number of spectrum shape corrections, such as atomic effects - screening and exchange processes, radiative corrections, finite size of the nucleus etc. The full analytical description of the allowed beta spectrum shape, including most of them with a relative precision of a few parts in 10^{-4}, is presented in Ref. [3].

For a Gamow-Teller transition, the leading order expression for the beta energy spectrum is given by:

$$N(W)dW \propto \frac{F(\pm Z, W)}{2\pi^3} pW(W_0 - W)^2 \left(1 + \frac{m_e}{W} b_{\mathrm{F}} \pm \frac{4}{3}\frac{W}{M_n}\frac{b_{\mathrm{WM}}}{Ac}\right) dW, \quad (1)$$

where $F(\pm Z, W)$, p, W and W_0 are the Fermi function, β particle momentum, its total energy and total energy at the spectrum endpoint, respectively. m_e and M_n are the electron and nucleon masses, A corresponds to the nuclear mass number, the upper (lower) sign is for electron (positron) emission, and b_{WM}/c is the ratio of the weak magnetism and Gamow-Teller form factors in the Holstein formalism [4]. b_{WM} appears in the spectrum as a term linear in energy with the slope of, typically, $\pm$ 0.5% MeV^{-1} [2]. In experiments measuring b_{WM}, the dominant systematic uncertainties come from incomplete deposit of electron energy in the detectors due to backscattering, partial transmission and Bremsstrahlung. Monte Carlo (MC) simulation of these effects is helpful, however, it introduces its own uncertainty as the input parameters are known with limited accuracy. For extraction of the WM form factor from the beta spectrum shape, we developed a position sensitive spectrometer that allows for identification and three-dimensional (3D) tracking of electrons while maintaining minimal electron energy losses.

2. Experimetal setup

The multi-wire gas electron tracker with electron energy detector, named miniBETA spectrometer, was built for studying experimental effects that must be controlled in β spectrum

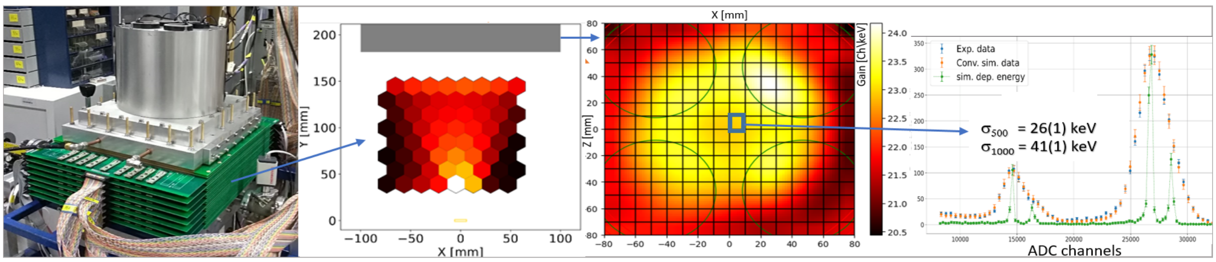

Figure 1. The miniBETA spectrometer with beta sources located in the middle of the chamber. (a) photograph of the setup, (b) illumination of the chamber with the cell colors indicating density of hits, (c) gain map of the plastic scintillator and (d) sample of measured ^{207}Bi-spectrum used for calibration.

shape measurements. The current version of miniBETA is a combination of a plastic scintillator, serving as energy detector and a trigger source, and a hexagonally structured multi-wire drift chamber (MWDC), filled with a light gas mixture of helium and isobutane at a pressure of 600 mbars. The gas electron tracker is responsible for efficient identification of electrons emitted from β decay sources. Having precise information about the electron track, it is possible to identify electrons backscattered from the energy detector and eliminate those not originating from the β source. Additionally, the coincidence condition between signals from the gas tracker and energy detector suppresses background from gamma emission typically accompanying β decays. The low-mass construction of the MWDC and optimized geometry help reducing background from secondary radiation created inside the chamber due to collisions with wires and mechanical support structures. The hexagonal cell configuration was chosen to assure maximum transparency of the detector in order to minimize electron scattering on wires. Inside the MWDC the electrons are traced in three dimensions. The measured drift time is used to determine the XY- coordinates of the closest approach of the electron track to the anode wires, while ZY-coordinates are determined by the charge division process on the signal wires. The energy detector is made of a plastic scintillator embedded in the gas detector and is connected via a lightguide with four photomultiplier tubes (PMT) installed outside the chamber. The digitized pulse height of the PMT signals carry the electron energy information. Additionally, the PMT signals provide the time reference for the drift time measurement. In Fig. 1 the experimetal setup, the hit illumination of the chamber, the gain map of the scintillator and a sample of the measured ^{207}Bi spectrum are presented. More information about the spectrometer can be found in Ref. [5–8].

3. Weak magnetism extraction from β spectra shapes

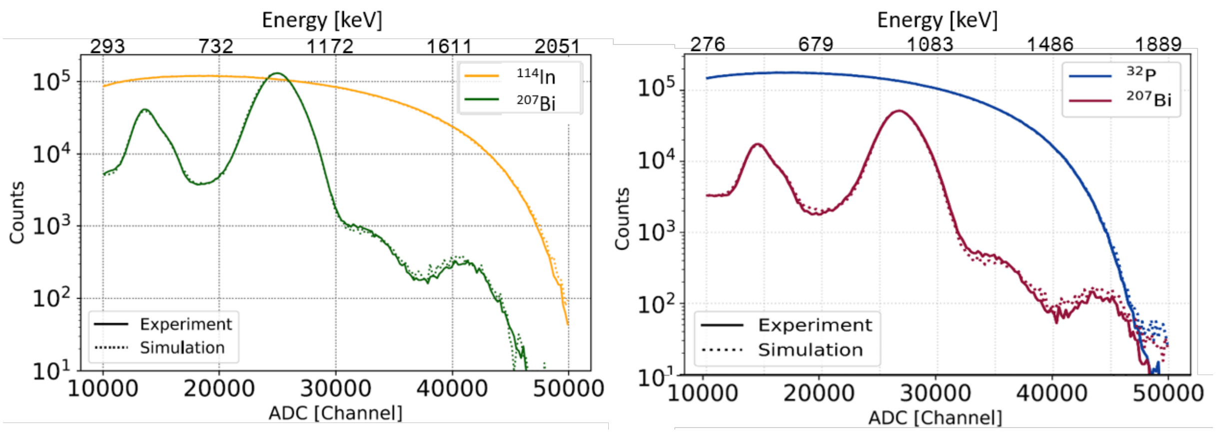

Figure 2. A comparison of the recorded experimental and simulated spectra of ^{207}Bi conversion electrons with ^{114}In (left) and ^{32}P (right).

The beta spectrum shape measurements were performed for the pure Gamow-Teller transitions ^{114}In $\rightarrow$ ^{114}Sn and ^{32}P $\rightarrow$ ^{32}S. The miniBETA spectrometer was fully modelled in MC simulations [7]. The total experimental and simulated β spectra of ^{207}Bi used for online energy calibration with the corresponding measurements of ^{114}In and ^{32}P (assuming b_{F} and b_{WM} to vanish) are shown in Fig. 2. In the ^{207}Bi spectrum, the corresponding peaks of the measured conversion electrons from K, L and M shells are reproduced by the simulation at the 10^{-2} level. The comparison of the measured and simulated ^{114}In spectra exhibit a slope difference on the 10^{-2} level in the energy region 730 – 1700 keV, which can be explained by a non-zero b_{WM} term. In case of ^{32}P, the energy region of 1150 – 1570 keV was explored.

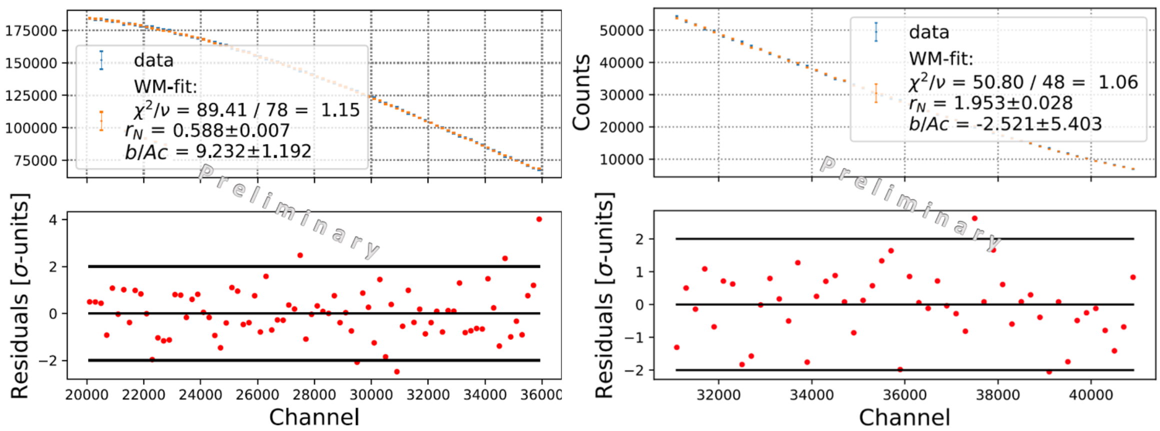

Figure 3. Results for $b_{\rm WM}/Ac$ extracted from ^{114}In spectrum [7] (left) and from ^{32}P spectrum (right). The systematic error is not included.

In both cases, the MC simulations and the calibration with the ^{207}Bi conversion spectrum were used to obtain a complete detector response. Consequently, a simulated beta spectrum can be generated for a particular choice of b_{WM}, by convoluting the corresponding theoretical β spectrum [2] with the response. Hence, by means of a minimization algorithm a central value for b_{WM} can be estimated for which a 'best fit' with the experimental spectrum is observed. The preliminary result of this procedure reveals a $b_{\rm WM}/Ac = 9.2 \pm 1.2\,({\rm stat})$ for ^{114}In and $b_{\rm WM}/Ac = -2.5 \pm 5.4\,({\rm stat})$ for ^{32}P, as demonstrated in Fig. 3. The main contribution to the systematic errors is coming from the gain map and energy resolution uncertainties. The maximum of the systematic error is currently estimated to be around 5. The detailed systematic error analysis is still ongoing.

4. Summary and outlook

Experimental studies of the beta spectrum shape with the lowest possible uncertainty are essential to constrain and validate the theoretical predictions. Weak magnetism is a part of the SM, which is still poorly known and new measurements of this quantity with accuracy of about 10% or better are welcome. The use of a 3D gas electron tracker with a plastic scintillator for beta spectrum shape measurements reveals promising results. The measurements for ^{114}In and ^{32}P isotopes are completed. Providing sensitive electron tracking, extensive 2D energy calibration and MC simulation, miniBETA allowed, for the very first time, the extraction of the weak magnetism term from the ^{114}In and ^{32}P β spectra shape. The detailed systematic error analysis is in progress.

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