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## Bound beta-decay of the free neutron: BoB

J. McAndrew<sup>a,\*</sup>, S. Paul<sup>a</sup>, R. Engels<sup>b</sup>, P. Fierlinger<sup>c</sup>, E. Gutzmiedl<sup>a</sup>, Johannes Schön<sup>a</sup>,  
Wolfgang Schott<sup>a</sup>

<sup>a</sup>Technische Universität München, 85748 Garching bei München, Germany

<sup>b</sup>Institut für Kernphysik, Forschungszentrum Jülich, 52425 Jülich, Germany

<sup>c</sup>Excellence Cluster „Universe“, TUM, 85748 Garching bei München, Germany

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### Abstract

For many years neutron decay has been investigated as a possible pathway to the exploration of new physics. One such example is the bound beta-decay (BoB) of the neutron into a hydrogen atom and an anti-neutrino. This two-body decay mode offers a very elegant method to study neutrino helicities, just as the Goldhaber experiment has done. However, this rare decay has not yet been observed so far owing to the challenges of measuring a decay involving only electrically neutral particles with an estimated branching ratio of only  $10^{-6}$  of the three-body decay mode. Specifically an intense source of thermal neutrons would be required for such an experiment, such as the FRMII in Garching, the ILL in Grenoble or the ESS in Lund. This paper provides a summary of the novel experimental scheme that we propose to observe the BoB neutron decay, addressing all necessary problems in a very coherent way.

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### 1. Introduction

In 1947 Daudel, Jean and Lecoin predicted the existence of a two-body beta-decay mode in which the daughter nucleus and the electron remain bound (Daudel, Jean and Lecoin (1947)). For the beta-decay of the free neutron, this is referred to as “bound beta-decay” or “BoB” and is the two-body neutron decay mode:  $n \rightarrow H + \bar{\nu}_e$ . Many

\* Corresponding author. Tel.: +49-89-289-12569  
E-mail address: [j.mcandrew@tum.de](mailto:j.mcandrew@tum.de)

theoretical studies of this decay mode have been published (Bahcall (1961), Kabir (1967), Nemenov (1980), Song (1987), Byrne (2001), Faber (2009)), although it has never been observed experimentally. The main challenges in observing this decay and studying its properties lie in the small predicted branching ratio  $\sim 4 \times 10^{-6}$  of the three-body decay mode (Nemenov (1980), Faber (2009)) and in the detection of low-energy, electrically neutral particles in the final state.

Experimentally, the decay signature is a hydrogen atom of energy 325.7 eV, corresponding to a velocity  $\sim 10^5$  m/s. As the weak interaction is a short-range force, it is also expected that only hydrogen atomic states with zero angular-momentum will be populated, with 83.2% of atoms in the 1s state and 10.4% in the 2s state and the remainder in an  $ns$  state where  $n \geq 3$ .

## 2. Physics Motivation

As this decay results in a two-body final state, the spin state of the anti-neutrino is mirrored by the outgoing hydrogen atom. A careful and precise study of the hyperfine spin state of the hydrogen atom would therefore contain full information regarding the momentum direction of the anti-neutrino. The observation and study of the bound beta-decay of the neutron is therefore a novel and exciting opportunity to directly observe neutrino helicity.

Table 1 shows the possible combinations of spin states in this decay along with the spin state populations as predicted by V-A theory. In this theory, Configurations 4, 1' and 2' cannot be populated as the emission of a left-handed anti-neutrino would be required. Therefore a genuine non-zero value measured for populations  $W_4$ ,  $W_{1'}$  or  $W_{2'}$  would imply a left-right symmetric V+A theory.

Table 1. The six possible spin configurations,  $i$ , in the neutron bound-beta decay (Schott (2006)). By convention the neutron,  $n$ , is in the rest frame, the anti-neutrino,  $\bar{\nu}_e$ , goes to the left and the hydrogen atom,  $H$ , goes to the right. The spins of all the particles, including the electron,  $e^-$ , are indicated by arrows. The spin population of each of the spin configurations,  $W_i$ , is also given.  $F$  is the total spin with hyperfine interactions, its projection being  $m_F$ .  $|m_s m_l\rangle$  are the Paschen-Back states where  $m_s$  and  $m_l$  represent the  $e^-$  and  $p$  quantum numbers respectively.

Configuration, $i$	$\bar{\nu}_e$	$n$	$p$	$e^-$	$W_i$ (%)	$F$	$m_F$	$ m_s m_l\rangle$
1	←	←	←	→	44.14±0.05	0,1	0	+>
2	←	←	→	←	55.24±0.04	0,1	0	+>
3	←	→	→	→	0.622±0.011	1	1	++>
4	→	←	←	←	0.0	1	-1	->
1'	→	→	→	←	0.0	0,1	0	+>
2'	→	→	←	→	0.0	0,1	0	+>

The population probabilities of Configurations 1 to 3 are given by (Nemenov and Ovchinnikova (1980)):

$$W_1 = \frac{(\chi - 1)^2}{2(\chi^2 + 3)}, \quad W_2 = \frac{2}{\chi^2 + 3}, \quad W_3 = \frac{(\chi + 1)^2}{2(\chi^2 + 3)}$$

where

$$\chi = (1 + g_s)/(\frac{g_A}{g_V} - 2g_T) \text{ and } \frac{g_A}{g_V} = -1.2695 \pm 0.0029 \text{ (Eidelman (2004))}$$

and where  $g_A$ ,  $g_V$ ,  $g_S$  and  $g_T$  are the axial, vector, scalar and tensor coupling constants respectively. Therefore, by measuring  $W_i$ , a combination of  $g_S$  and  $g_T$  can be obtained. The current best limits for  $g_S$  and  $g_T$  are  $|g_S| < 6 \times 10^{-2}$  (68% C.L.) obtained from  $e^+ - \nu_e$  correlation measurements in  $0^+ \rightarrow 0^+$  nuclear beta-decay (Adelberger (1999)) and  $|g_T/g_S| < 9 \times 10^{-2}$  (95% C.L.) obtained from the complete set of nuclear beta-decay correlations (Boothroyd (1984)).

A more exciting possibility would be the observation of a non-zero value of Configuration 4. Here, V+A theory predicts the population probability to be (Byrne (2001)):

$$W_4 = \frac{(x + \lambda y)^2}{2(1 + 3\lambda^2 + x^2 + 3\lambda^2 y^2)}$$

with  $x = \eta - \xi$  and  $y = \eta + \xi$ . Here  $\eta < 0.036$  (Gaponenko (2005)) is the mass-ratio squared of two intermediate charged-vector bosons mediating the left and right-handed interactions and  $\xi < 0.020$  (90% C.L.) (Bayes (2011)) is the boson mass eigenstate mixing angle.

From the Goldhaber experiment in 1957 (Goldhaber, Grozins and Sunyar (1958)) which laid the foundations of V-A theory, to the present day, no experimental investigations into the beta decay of the neutron,  $\mu$  and  $\pi$  and also into  $W$  and  $Z^0$  production have shown any deviations from a pure V-A interaction. However, the observation of finite neutrino mass (deduced from the observation of neutrino oscillations), the large violation of CP-symmetry linked to the asymmetry of matter over anti-matter in the Universe and the mass hierarchy problem make it obvious that our present Standard Model is not yet complete and a higher symmetry may exist which could allow for a left-right symmetric description of nature leaving room for the right handed boson sector contributing to the interactions. As the bound beta-decay of the neutron has never been studied experimentally, this provides a new, un-explored pathway to directly search for such physics beyond the Standard Model.

### 3. Experimental concept

Figure 1 shows a schematic diagram of the experimental concept. The neutrons decay into hydrogen atoms inside the through-going beam tube and within a longitudinal magnetic field,  $B_1$ , which preserves the original hyperfine spin state of the H atoms in the metastable 2s state and its spin projection on the axis. Assuming the experiment were located at the FRMII, 0.1 H(2s) per second will exit the beam tube (Schott (2006)). The atoms then pass through the collimator followed by the Lamb-Shift Spin Filter which separates out the hyperfine spin states. A transverse magnetic field,  $B_3$ , then removes the large number of charged three-body-decay protons and electrons from the beam line to reduce background radiation at the hydrogen detector. The H(2s) atoms now pass through an array of electric field grids where they are periodically quenched at a frequency of  $\sim 25$  MHz in a field of 500 V. This allows for measurement and assessment of background measured in the hydrogen detector, as well as velocity-selection of the H(2s) of interest, thus acting as a “beam chopper”. Finally the H(2s) with an energy of 325.7 eV enter the hydrogen-detection stage where they are detected through Lyman- $\alpha$  detection or via a charge-exchange reaction.

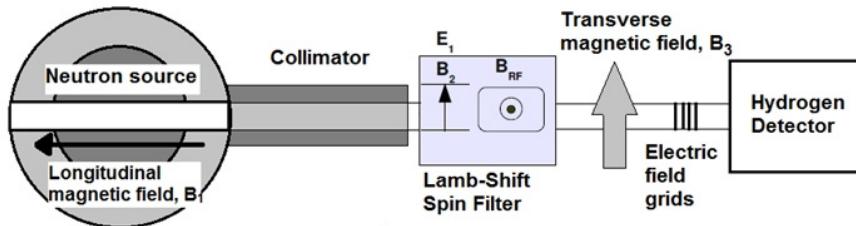


Fig. 1. Schematic diagram showing the main concept of the experiment to measure the bound-beta decay of the neutron.

In the Lyman- $\alpha$  detection method, although hydrogen atoms in the 2s state are metastable ( $\tau_{1/2} \sim 0.1$  s), the presence of a moderate electric field allows the 2s state to mix with the 2p state, resulting in decay in  $\sim$  ns with the emission of a Lyman- $\alpha$  photon ( $\lambda = 121.6$  nm). The photon can then be detected by e.g. a photomultiplier tube.

A second method explored by our group has been the charge-exchange reaction of hydrogen atoms in argon gas with subsequent detection of the charged reaction H-atom:  $H + Ar \rightarrow H^- + Ar^+$ . Here hydrogen atoms pass through a gas cell containing argon and the resulting  $H^-$  are energy-selected by an electric counter-field. From binding energy calculations we can show that a ground state H of 325.7 eV will form an  $H^-$  of 309.9 eV whereas an H(2s) of 325.7 eV will form an  $H^-$  of 320.1 eV. This is due to the 2s state lying 10.2 eV above the 1s state. The  $H^-$  can then be deflected by  $90^\circ$  through a dipole magnet and accelerated to a detector such as a CsI(Tl) crystal.

#### 4. Suitable sources of neutrons

A further important consideration for the BoB experiment is the source of neutrons. The first requirement is an intensive thermal neutron source due to the very small expected branching ratio for the decay. A second requirement is a through-going beam tube to reduce neutron background in the detector (essentially to prevent the hydrogen detector from “seeing” the source) as the experiment will be very sensitive to neutron background. There are currently two facilities which meet these requirements: the FRMII in Garching (neutron flux  $\sim 10^{14} \text{ cm}^{-2} \text{s}^{-1}$ ) and the H6-H7 beam tube at the ILL in Grenoble (neutron flux  $\sim 5 \times 10^{14} \text{ cm}^{-2} \text{s}^{-1}$ ). A further option would be the European Spallation Source (ESS) in Lund, where the possibility of constructing through-going beam tube is currently under discussion. For a through-going beam tube passing below the internal Be reflector and thus reducing the flux at the other beam ports by less than a few percent, it is estimated that the integrated thermal neutron flux at the centre of this beam tube would be  $\sim 2 \times 10^{13} \text{ cm}^{-2} \text{s}^{-1}$  (Klinkby (2013)). Although the flux would be lower than at the FRMII or the ILL, the ESS has the further advantage of a pulsed beam. This would significantly benefit the BoB experiment allowing for measurement of background in the detector without using the electric field grids to chop the beam and, in the process, removing a certain proportion of H(2s) from the beam.

#### 5. Summary

An experiment to measure the bound beta-decay of the neutron has been outlined. The experiment will rely on the detection of H(2s) atoms in order to measure the branching ratio of this so-far unobserved decay for the first time. A measurement of the hyperfine spin state populations of these atoms will then be measured, providing a novel method to directly observe the helicity of the neutrino and thus open up a new pathway to look for physics beyond the Standard Model. Our previous calculations (Schott (2006)) have shown that in the proposed experiment the upper limits of  $g_s$ ,  $g_T$ ,  $\eta$  and  $\zeta$  can be reduced by a factor of ten. In addition to the sensitive detection of hydrogen atoms in the 2s state at 325.7 eV, another key requirement of this experiment will be an intense source of thermal neutrons with a through-going beam tube. In addition to the FRMII in Garching and the ILL in Grenoble, the ESS will provide such a facility having the further advantage of combining a high neutron flux with a pulsed beam.

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