An experiment to measure the bound- β - decay of the free neutron

W. Schott · T. Faestermann · P. Fierlinger ·
F. J. Hartmann · R. Hertenberger · A. R. Müller ·
S. Paul · J. Schön · T. Udem · A. Ulrich

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Abstract The two-body neutron β -decay into a hydrogen atom and an electron antineutrino is investigated. The hyperfine-state population of the monoenergetic hydrogen atoms (326.5 eV) yields the neutrino left-handedness or a possible right-handed admixture and possible small scalar and tensor contributions to the weak force. The constraints on the neutrino helicity and the scalar and tensor coupling constants of weak interaction can be improved considerably.

Keywords Two-body neutron β -decay · Hydrogen atom · Electron antineutrino

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1 Introduction

The neutron decay is for many years subject of intense studies, as it reveals detailed information about the structure of the weak interaction. Using the two-body neutron β -decay into a hydrogen atom (H) and an electron antineutrino ($\bar{\nu}$)

$$n \rightarrow H + \bar{\nu} \quad (1)$$

W. Schott (✉) · T. Faestermann · F. J. Hartmann · A. R. Müller · S. Paul · J. Schön · A. Ulrich
Physik-Department Technische Universität München, 85748 Garching, Germany
e-mail: wolfgang.schott@ph.tum.de

P. Fierlinger
Excellence Cluster Universe, Technische Universität München, 85748 Garching, Germany

R. Hertenberger
Sektion Physik, Ludwig- Maximilians- Universität München, 85748 Garching, Germany

T. Udem
Max- Planck- Institut für Quantenphysik, 85748 Garching, Germany

Table 1 Spin projections i in the neutron bound- β decay

Configuration i	$\bar{\nu}$	n	p	e^-	trans.	$W_i(\%)$	F	m_F	$ m_S m_I\rangle$
1	$\leftarrow$	$\leftarrow$	$\leftarrow$	$\rightarrow$	Fe/GT	$44.14 \pm .05$	0,1	0	$ +-\rangle$
2	$\leftarrow$	$\leftarrow$	$\rightarrow$	$\leftarrow$	GT	$55.24 \pm .04$	0,1	0	$ --\rangle$
3	$\leftarrow$	$\rightarrow$	$\rightarrow$	$\rightarrow$	Fe/GT	$.622 \pm .011$	1	1	$ ++\rangle$
4	$\rightarrow$	$\leftarrow$	$\leftarrow$	$\leftarrow$	Fe/GT	0.	1	-1	$ --\rangle$
2'	$\rightarrow$	$\rightarrow$	$\rightarrow$	$\leftarrow$	Fe/GT	0.	0,1	0	$ --\rangle$
1'	$\rightarrow$	$\rightarrow$	$\leftarrow$	$\rightarrow$	GT	0.	0,1	0	$ +-\rangle$

As a convention, the H moves to the right, the $\bar{\nu}$ to the left. Fe and GT mean Fermi and Gamov-Teller transition, respectively. W_i are the populations according to pure V-A interaction, F the total spin and m_F the F projection. m_S and m_I denote the e^- and p spin quantum numbers (+ means $+1/2$, i.e. spin points to the right). The population probability W_i is $W_i = N_i/N$ with N_i being the configuration i state population and $N = \sum_{i=1}^3 N_i$

the hyperfine population of the emerging hydrogen atom can be investigated [1]. The challenge lies in the very small branching ratio $BR = 4 \cdot 10^{-6}$ of the total neutron β -decay rate. Hydrogen atoms from this decay have 326.5 eV kinetic energy corresponding to $\beta = 0.83 \cdot 10^{-3}$. Only states with zero angular momentum in the hydrogen atom are populated, the 1s and the metastable 2s with 83.2% and 10.4% probability, respectively. The residual 6.4% ns states with $n > 2$ decay within nanoseconds into the 1s and 2s states.

Using standard V-A theory the possible spin configurations emerging from this bound- β decay emitted hydrogen atom are given in Table 1.

According to [2, 3] for a purely left-handed V-A interaction, the population probabilities W_i of the first three configurations i can be deduced to be

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

depending only on one variable $\chi = (1 + g_S)/(\lambda - 2g_T)$, with $\sum_{i=1}^3 W_i = 1$. λ is the ratio

$$\lambda = g_A/g_V = -1.2695 \pm .0029$$

Eidelman et al. [4] g_A, g_V, g_S, g_T are the axial, vector, scalar and tensor coupling constants, respectively. Thus, by means of W_i only a combination of g_S and g_T can be measured. g_S is obtained from W_i only if g_T is known from somewhere else and vice versa.

While the states $F = 1, m_F = \pm 1$ (configurations 3 and 4) are pure eigenstates, linear combinations of the configuration 1 and 2 states with coefficients depending on B_1 yield the other two eigenstates.

The last three configurations 4, 2' and 1' in Table 1 can only be populated by the emission of right-handed neutrinos, where only configuration 4, namely $|--\rangle$, is a pure state. The configuration 2' is mixed with 2, and 1' with 1.

A possible small contribution of negative helicity to the $\bar{\nu}$ would manifest itself by a non-zero value of W_4 in Table 1. The population of configuration 4, predicted by a left-right symmetric V+A model, is given by [5]

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

with $x = \eta - \zeta$ and $y = \eta + \zeta$, where η is the mass ratio squared of the two intermediate charged vector bosons and ζ the boson mass eigenstate mixing angle, η and ζ being $\eta < 0.036$ [6] and $|\zeta| < 0.03$ (C.L. 90%) [7], respectively. In this model the antineutrino helicity $H_{\bar{\nu}}$ becomes

$$H_{\bar{\nu}} = \frac{1 + 3\lambda^2 - x^2 - 3\lambda^2 y^2}{1 + 3\lambda^2 + x^2 + 3\lambda^2 y^2}. \quad (4)$$

A certain background to the configurations 1–4, 1', 2' comes from originally populated ($n > 2$)s states which subsequently decay into the 1s and 2s states by spontaneous emission of photons, where the spin quantum number m_s of the e^- can be changed. Since only the 2s state is used for the spin analysis, the 4s and higher-state population yield a 2s background from ($n > 2$)s states slowly converging with n ; as a m_s changing example $W(4s \rightarrow 2s) = 3.07 \cdot 10^{-4}$ and $W(5s \rightarrow 2s) = 2.18 \cdot 10^{-4}$. From the sum $W(4s \rightarrow 2s) + W(5s \rightarrow 2s)$ a fraction of 44.2% (that is $2.32 \cdot 10^{-4}$) would contribute to configuration 4 as background, and 55.2% of the sum ($2.90 \cdot 10^{-4}$) would show up in configuration 3. The latter background constitutes already 47% of the resulting W_3 rate, which according to $W(2s) \cdot W_3$, contributes $6.2 \cdot 10^{-4}$ to the 2s population.

In order to improve the present g_S , g_T and $H_{\bar{\nu}}$ accuracies, the background due to optical m_s changing transitions from ns states with $n > 2$ into the 2s-state analyzed must be eliminated, e.g. by ionizing these ns H-atoms prior to their decay using a $\lambda = 1.46 \mu\text{m}$ laser.

2 Experiment

Using the through-going FRMII beam tube (Fig. 1) a background free hydrogen rate of ca. 3 s^{-1} can be obtained. The small axial $\mathbf{B}_1$ field keeps the initial e^- and p spin directions of the H atom. The neutron β -decay protons are shielded by the axial counter $\mathbf{E}_3$ field. Other charged and neutral particles moving in transverse directions are suppressed by diaphragm collimators on both sides of the maximum neutron flux. Only the metastable H(2s) atoms are analyzed by a Lamb shift spin filter selecting the four hyperfine states, subsequently excited to a Rydberg state within two crossed perpendicular curved mirror laser resonators and ionized by the axial $\mathbf{E}_2$ field by means of which the resulting protons are accelerated and focused by the transverse $\mathbf{B}_4$ field (magnet with wedges) onto a CsI(Tl) detector. The β -decay electrons are deflected by the $\mathbf{B}_4$ field away from the detector.

Fig. 1 Sketch of the experimental setup for measuring hydrogen atoms from neutron bound- β - decay at FRMII. The through-going beam tube with the axial spin holding magnetic field $\mathbf{B}_1$ and an axial electric counter field $\mathbf{E}_3$ for suppressing the neutron β - decay protons are drawn. The spin filter consists of an axial quantization $\mathbf{B}_3$ with a Stark mixing transverse electric field $\mathbf{E}_1$ and an azimuthal magnetic rf field $\mathbf{B}_{rf}$. After the spin filter there are two transverse laser beams with wavelengths λ_1 and λ_2 , a longitudinal accelerating and focussing electric field $\mathbf{E}_2$ and a bending and focussing magnetic field $\mathbf{B}_4$

2.1 H(2s) excitation

Downstream of the spin filter the remaining state-selected H atoms (e.g., $2s_{1/2}$, $F = 1$, $m_F = 1$, config. 3) are excited by two CW lasers with $\lambda_1(2s \rightarrow 10p) = 379.68 \text{ nm}$ and $\lambda_2(10p \rightarrow 27d) = 10.56 \mu\text{m}$.

The Doppler shifted frequency is given by

$$\nu' = \nu \frac{\sqrt{1 - \beta^2}}{1 + \beta \cos \phi}, \quad (5)$$

where ϕ is the angle between the H atom and the photon. For $\phi = \pi/2$ the second order Doppler shift $\nu' = \nu \sqrt{1 - \beta^2}$ results. The relative shift due to the H(2s) velocity $\beta = 0.83 \cdot 10^{-3}$ is $\Delta\nu'/\nu = \beta^2/2 = -3.44 \cdot 10^{-7}$. The relative width due to the velocity spread $d\beta = 0.73 \cdot 10^{-5}$ because of the thermal motion of the decaying neutrons is

$$\frac{d\nu'}{\nu} = -\frac{\beta d\beta}{\sqrt{1 - \beta^2}} = -6.06 \cdot 10^{-9} \quad (6)$$

yielding an absolute width $d\nu' = -4.785 \cdot 10^6 \text{ s}^{-1}$ for $\nu_{2s-10p} = 7.896 \cdot 10^{14} \text{ s}^{-1}$ which corresponds to a single mode laser width. Thus, using the second order Doppler effect H(2s) atoms with a large velocity spread can be excited. However, the angular width, within which the excitation occurs, is very small being $d\phi = (d\nu'/\nu)/\beta = -7.3 \cdot 10^{-6}$. The divergence of the H atoms in our experiment, which must correspond to the divergence of the photons within the laser resonator, is 1000 times larger. Therefore, the resonator mirrors must be curved.

Figure 2 shows the Monte Carlo calculated level occupations for various laser 2 positions. The 2s occupation is rather constant and high, the 10 p always low. There is a position, where 27 d occupation is 45% which is quite efficient.

Fig. 2 2s, 10p and 27d level occupation vs. laser 2 position relative to laser 1 for thermal decaying neutrons and $7.3 \cdot 10^{-3}$ H atom divergence. The power within the resonators is 20 kW and 100 W for laser 1 and 2, respectively

Fig. 3 Neutron bound- β - decay H(2s) yield measurement. The setup contains a transverse magnetic $\mathbf{B}$ field, two collimators with diaphragms, an axial electric $\mathbf{E}$ field and a photon detector

2.2 Pre- experiment

In a preceding experiment the yield of neutron bound- β -decay H(2s) atoms will be measured at a through- going reactor beam line by a transverse $\mathbf{B}$ field (Fig. 3) deflecting the charged particles from the beam tube axis followed by an axial $\mathbf{E}$ field,

where the H(2s) are quenched resulting in the emission of Lyman α photons which will be detected perpendicularly to the axis by a photon detector (e.g., LAAPD).

3 Experimental constraints on g_S , g_T and $H_{\bar{\nu}}$

A small g_S or g_T contribution including the sign may be measured via the population probability W_3 . In [8] a 1σ confidence level upper limit for the absolute value of g_S is quoted to be $g_S \leq 6 \cdot 10^{-2}$. The statistical error for g_S can be written as

$$\begin{aligned} (\delta g_S)_{\text{stat}} &= \left| \left(\frac{\partial g_S}{\partial W_3} \right)_{g_S=6 \cdot 10^{-2}, g_T=0} \right| \cdot (\delta W_3)_{\text{stat}} \\ &= \left| \frac{\lambda(\chi^2 + 3)^2}{-\chi^2 + 2\chi + 3} \right| \cdot \sqrt{\frac{W_3}{N}}. \end{aligned}$$

With $(\delta g_S)_{\text{stat}} = 6 \cdot 10^{-3}$ ($\chi \approx 1/\lambda$, $W_3 = 3.683 \cdot 10^{-3}$) $N = 4.4 \cdot 10^4$ results, which corresponds to 40 h measuring time. This reduces the present g_S upper limit by a factor of ten. The statistical error of $H_{\bar{\nu}}$ is

$$(\delta H_{\bar{\nu}})_{\text{stat}} = \frac{4(1 + 3\lambda^2)}{(1 + \lambda)^2} \cdot \sqrt{\frac{W_4}{N}}. \quad (7)$$

yielding with $(\delta H_{\bar{\nu}})_{\text{stat}} = 1 \cdot 10^{-3}$, $\eta = 0.036$, $W_4 = 8.1 \cdot 10^{-6}$ and $H_{\bar{\nu}} = 0.997 N = 8.3 \cdot 10^5$, i.e., 770 h measuring time.

4 Conclusion

The present values of the scalar and tensor coupling constants g_S and g_T , the intermediate boson mass ratio squared η and the mixing angle ζ are $|g_S| \leq 6 \cdot 10^{-2}$ (C. L. 68%), $|g_T/g_A| \leq 9 \cdot 10^{-2}$ (C. L. 95%) [9], $\eta \leq .036$, $|\zeta| \leq .03$ (C. L. 90%).

By measuring the neutron bound- β - decay, the g_S or g_T upper limits can be reduced by a factor 10 and $H_{\bar{\nu}}$, which is given by $\lambda = g_A/g_V$, η and ζ , can be obtained with 10^{-3} accuracy.

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References

1. Nemenov, L.L.: Sov. J. Nucl. Phys. **31**, 115 (1980)
2. Nemenov, L.L., Ovchinnikova, A.A.: Sov. J. Nucl. Phys. **31**, 659 (1980)
3. Schott, W., et al.: Eur. Phys. J. A **30**, 603 (2006)
4. Eidelman, S., et al.: Phys. Lett. B **592**, 1 (2004) and 2005 partial update for edition 2006
5. Byrne, J.: Eur. Phys. Lett. **56**, 633 (2001)
6. Gaponenko, A., et al.: Phys. Rev. D **71**, 071101 (2005)
7. Musser, J.R., et al.: Phys. Rev. Lett. **94**, 101805 (2005)
8. Adelberger, E.G., et al.: Phys. Rev. Lett. **83**, 1299 (1999)
9. Boothroyd, A.I., Markey, J., Vogel, P.: Phys. Rev. C **29**, 603 (1984)