An Experiment for the Measurement of the Bound β-decay of the Free Neutron

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The H hyperfine state population after the neutron bound β decay yields directly the neutrino left- handedness or a possible right- handed admixture, and small scalar and tensor contributions to the weak force. Using the through-going beam tube of a high flux reactor, a background free H rate of ca. 3 s^{-1} can be obtained. The detection of the neutral hydrogen atoms and the analysis of the hyperfine states is accomplished by Lamb shift source type quenching and subsequent ionisation.

After the two-body neutron beta-decay

$$n \rightarrow H + \bar{\nu} \tag{1}$$

the hyperfine population of the emerging hydrogen atom has to be measured at the very small branching ratio BR $= 4 \cdot 10^{-6}$ of the total neutron β decay rate [1]. According to the n^{-3} law only nS H atoms with zero angular momentum l are generated via the reaction 1 , i. e., the 1S and the metastable 2S state with 83.2% and 10.4% probability, respectively. The residual 6.4% nS states with n > 2 decay within nanoseconds mainly into the 1S state.

Using standard V-A theory the possible spin configurations emerging from this bound beta decay and the resulting hyperfine states of the emitted hydrogen atom are given in table 1.

Table 1: Spin projections i in the neutron bound β decay. As a convention, the H moves to the right, the $\bar{\nu}$ to the left. W_i are the populations according to pure V-A interaction (cf. eqs. 2-4 [1] [2]), F is the total spin (with hyperfine interaction) and m_F the F projection.

i	$\bar{\nu}$	n	p	e^-	$W_i(\%)$	F	m_F
1	$\leftarrow$	$\leftarrow$	$\leftarrow$	$\rightarrow$	$44.174 \pm .017$	0,1	0
2	$\leftarrow$	$\leftarrow$	$\rightarrow$	$\leftarrow$	$55.211 \pm .013$	0,1	0
3	$\leftarrow$	$\rightarrow$	$\rightarrow$	$\rightarrow$	$.615 \pm .003$	1	1
4	$\rightarrow$	$\leftarrow$	$\leftarrow$	$\leftarrow$	0.	1	-1
2'	$\rightarrow$	$\rightarrow$	$\rightarrow$	$\leftarrow$	0.	0,1	0
1'	$\rightarrow$	$\rightarrow$	$\leftarrow$	$\rightarrow$	0.	0,1	0

According to [1] the population probabilities W_i of the various configurations i are given by

$$W_1 = 2C((1-\lambda) + g_S + 2g_T)^2 \tag{2}$$

$$W_2 = 8C(\lambda - 2g_T)^2 \tag{3}$$

$$W_3 = 2C((1+\lambda) + g_S - 2g_T)^2 \tag{4}$$

with a coefficient C determined by $\sum_{i=1}^{3} W_i = 1$. λ is the ratio $\lambda = g_A/g_V = -1.2675 \pm .0009$ [2]. g_A, g_V, g_S, g_T are the axial, vector, scalar and tensor coupling constants, respectively. The V - A contribution to the emission of H in one of its hyperfine spin states with F = 1 and $m_F = 1$ (config. 3 of table 1) is suppressed by about two orders of magnitude (cf. eq. 4). Therefore, by measuring the population of this configuration in relation to the configurations 1 and 2 (both $m_F = 0$), the existence of S, P, T weak interaction variants can be verified. While the states $F = 1, m_F = \pm 1$(conf. 3 and 4) are pure eigenstates of the Hamiltonian describing the p - e^- interaction in an external magnetic field B_1, linear combinations of the configuration 1 and 2 states with coefficients depending on B_1 yield the other two eigenstates. Therefore, the configurations 3 and 4 are separated in any case from configurations 1 and 2, whereas a separation of configurations 1 and 2 is only possible, if the decays occur within a magnetic field B_1.

A possible small contribution of negative helicity to the $\bar{\nu}$ would be manifested, if a nonzero value of config. 4 (table 1)is measured. The population of configuration 4 predicted by a left- right symmetric V + A model, is given by

$$W_4 = 2(\eta - \xi + \lambda(\eta + \xi))^2,$$

where η is the mass ratio squared of the two intermediate vector bosons and ξ the boson mass eigenstate mixing angle [3].

In a model independent scheme W_4 becomes

$$W_4 = \eta^2(1+\lambda)^2/(2(1+3\lambda^2))$$

and the antineutrino helicity $H_{\bar{\nu}} = 1 - 2\sqrt{\eta}$, respectively [4].

A certain background to the configurations 1 - 4, 1', 2' comes from originally populated nS states with n > 2 which decay into the 1S and 2S states by spontaneous emission of photons, where the e^- spin quantum number is changed. The contribution $W(4s \rightarrow 2s)$ is given by

$W(4s \rightarrow 2s) = 2 \cdot W(4s) \cdot W(4s \rightarrow 3p) \cdot W(3p \rightarrow 2s) \cdot W(\pi)W(\sigma) = 3.07 \cdot 10^{-4}$. W(4s)=1.3% is the original 4S population,

$W(4s \rightarrow 3p) = A_{4s3p}/(A_{4s3p} + A_{4s2p}) = .416$ and $W(3p \rightarrow 2s) = A_{3p2s}/(A_{3p2s}+A_{3p1s}) = .118$ is the $4s \rightarrow 3p$ and $3p \rightarrow 2s$ transition probability, respectively, with A_{4s3p} being the corresponding $4s \rightarrow 3p$ Einstein transition coefficient [5] etc. Assuming the transition probabilities for linear polarized ($\pi, \Delta j = 0$) and circular polarized($\sigma, \Delta j = \pm 1$) photons to be equal, where $j = l + s$ is the realized spin orbit coupling, the probability for π and σ $P \to S$ photons is given by the multiplicities of the Zeeman split P and S levels to be $W(\pi) = 2/5$ and $W(\sigma) = 3/5$.

Correspondingly, the background contribution from the 5S state is given by
$W(5s \to 2s) = 2 \cdot W(\pi) W(\sigma) \cdot W(5s)(W(5s \to 4p) \cdot W(4p \to 2s) + W(5s \to 3p) \cdot W(3p \to 2s)) = 2.18 \cdot 10^{-4}$, with

$W(5s \to 4p) = A_{5s4p}/(A_{5s4p} + A_{5s3p} + A_{5s2p}), W(4p \to 2s) = A_{4p2s}/(A_{4p2s} + A_{4p3s} + A_{4p1s})$ and

$W(5s \to 3p) = A_{5s3p}/(A_{5s3p} + A_{5s4p} + A_{5s2p}), W(3p \to 2s) = A_{3p2s}/(A_{3p2s} + A_{3p1s})$.

If only the 2S state is used for the spin analysis, 44.17% of the sum $W(4s \to 2s) + W(5s \to 2s) = 5.25 \cdot 10^{-4}$, i. e., $2.32 \cdot 10^{-4}$ would be the background of config. 4 and 55.21% of the sum, i. e., $2.90 \cdot 10^{-4}$ would show up in config. 3 being already 45% of W_3. Therefore, extracting the e^- spin flip background from W_4 and W_3, W_4 yields the negative $\bar{\nu}$ helicity contribution and W_1, W_2, W_3 the g_S and g_T ingredients, respectively.

In fig. 1 the suggested setup is sketched. Hydrogen atoms from the neutron bound β decay have a kinetic energy of $T_H = 326.5$ eV which corresponds to a velocity v with $v/c = 0.83 \cdot 10^{-3}$. They are produced in the high neutron flux from an intense neutron source and extracted from a throughgoing beam pipe.

During their passage in the beam tube the H atoms move to the right, the hyperfine spin states $F = 1, m_F = 0, \pm 1$ states are kept in a longitudinal magnetic quantization field B_1 which extends from the n-decay volume to the analysing station. For separating the configuration 1 and 2 states, B_1 should be at least as large as the critical field B_c of the 2S level. I. e., B_1 must be $B_1 \geq 63.4\,\text{Gauss}$.

The hyperfine analyzing part starts with a transverse magnetic field $B_2 = 10$ Gauss. Within the $\vec{B_2}$ field region of 5.4 mm extension the $2S, F = 1, m_F = 0, \pm 1$ states are rotated adiabatically by $\pi/2$ into the same states, however, with the quantization axis being perpendicular to the direction of flight and parallel to the magnetic field $\vec{B_3}$ with $B_3 = 575$ Gauss, immediately following the $\vec{B_2}$ field region.

Fig.2 depicts the Breit- Rabi diagram of the $2S_{1/2}$ hyperfine states in a magnetic field also showing the corresponding $2P_{1/2}$ states [6].

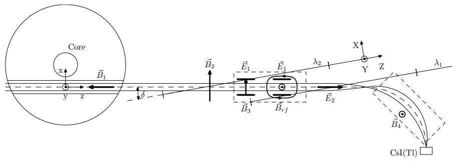

Fig. 1: Sketch of the experimental setup for measuring n bound β H atoms in the FRMII. The through-going beam tube with the magnetic quantization field $\vec{B_1}$ is drawn. Furthermore, a spin rotating by $\pi/2$ field $\vec{B_2}$, a level splitting field $\vec{B_3}$ with transverse electric field $\vec{E_1}$ and a transverse rf magnetic field $\vec{B_{rf}}$ inside, a longitudinal accelerating and focussing electric field $\vec{E_2}$ and a bending and focussing magnetic field $\vec{B_4}$ are denoted. By means of the $\lambda_2 = 243\,nm$ and the $\lambda_1 = 364\,nm$ laser the H atoms are excited from 1S to 2S and ionized, respectively. They are detected using a small CsI(Tl) crystal.

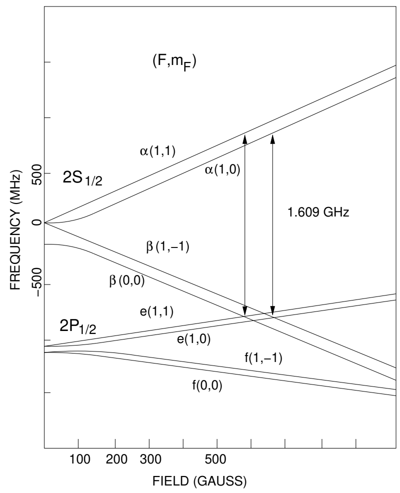

Fig. 2: Breit-Rabi diagram of the hyperfine splitting of the 2S and 2P states in a magnetic field

One of the two remaining α states can be selected by the spin filter method using a simultaneous interaction of the α, β and e levels at B_3 [6]. Owing to the static transverse electric field $\vec{E_1}$ (fig. 1) β and e are mixed. Then, we apply an rf field of 1.609 GHz causing the α states to interact with the coupled $\beta - e$ levels. At $B_3 \approx 538$ Gauss the $\alpha(1,0)$ will be quenched and the $\alpha(1,1)$ state will be selected, whereas with the same frequency at $B_3 \approx 605$ Gauss the $\alpha(1,0)$ will remain, and the $\alpha(1,1)$ be removed.

References

[1] L.L. Nemenov, Sov. J. Nucl. Phys. **31** (1980) 1
[2] B.G. Yerozolimsky, Nucl. Instr. Meth. in Physics Research **A440** (2000) 491
[3] J. Byrne, Eur. Phys. Lett **56(5)** (2001) 63
[4] D. Dubbers, private communication, February 2005
[5] W.L. Wiese *et al.*, National Standard Reference Data Series, National Bureau of Standards 4, Category 3- Atomic and Molecular Properties, 1966
[6] W. Haeberli, Ann. Rev. Nucl. Sci. **17** (1967) 373 and references quoted therein