PROCEEDINGS OF SCIENCE

Measurement of the electron-antineutrino angular correlation coefficient *a* in neutron β-decay with the spectrometer *a*SPECT

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A free neutron decays into a proton, an electron and an antineutrino. This is a weak interaction process described by the *V-A* theory within the Standard Model. The distribution of the decay products is parametrized by several measurable correlation coefficients which can be related to parameters of the Standard Model and are used to search for new physics. The spectrometer *a*SPECT was designed to measure the electron-antineutrino angular correlation coefficient *a* with an accuracy of 0.3% (previous measurements reached 5%). The value of this coefficient is inferred from the shape of the proton recoil spectrum. The principle is to measure with high precision the integral proton spectrum using magnetic adiabatic collimation and electrostatic retardation. Data acquisition for a 1% measurement was performed during a beam-time in 2013 at the Institut Laue-Langevin in Grenoble. Dedicated measurements or simulations were conducted to determine background, edge effect, magnetic and electric fields, etc. The analysis is ongoing. Preliminary results are presented here.

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1. Introduction

A free neutron decays, with a lifetime of 880.3 ± 1.1 s [1], into a proton, an electron and an antineutrino. Within the formalism of the Standard Model, this decay is described by the conversion of a *down* quark of the neutron into an *up* quark via the emission of a *W* boson which decays into the two leptons. This is a weak interaction process described by the *V-A* theory. Within the Standard Model (SM), it is governed by only two free parameters: the first element of the CKM matrix V_{ud} and the ratio of the weak coupling constants $\lambda = \frac{g_A}{g_V}$. The differential decay rate of neutrons can be written in terms of correlation coefficients [2]:

$$\frac{\mathrm{d}W}{\mathrm{d}\Omega_e \mathrm{d}\Omega_{\overline{\nu}} \mathrm{d}E_e} \propto 1 + b\frac{m_e}{E_e} + a\frac{\overrightarrow{p_e} \cdot \overrightarrow{p_{\overline{\nu}}}}{E_e E_{\overline{\nu}}} + \overrightarrow{P_\mathrm{n}} \cdot \left[A\frac{\overrightarrow{p_e}}{E_e} + B\frac{\overrightarrow{p_{\overline{\nu}}}}{E_{\overline{\nu}}}\right] + \ldots \tag{1.1}$$

where m_e is the mass of the electron, and $\overrightarrow{p_{\overline{\nu}}}$, $\overrightarrow{p_e}$, $E_{\overline{\nu}}$ and E_e are the momenta and energies of antineutrino and electron, respectively. $\overrightarrow{P_\mathrm{n}}$ is the polarization of the neutron beam. The electron-antineutrino angular correlation coefficient *a,* the beta asymmetry parameter *A*, the Fierz interference term *b* and the antineutrino asymmetry parameter *B* are related to the coupling constants of the weak interaction. Within the SM, the Fierz interference term becomes *b*=0 and the other coefficients depend on λ only, see e.g. [3]:

$$a = \frac{1 - |\lambda|^2}{1 + 3|\lambda|^2},\ A = -2\frac{|\lambda|^2 + \mathrm{Re}(\lambda)}{1 + 3|\lambda|^2},\ B = 2\frac{|\lambda|^2 - \mathrm{Re}(\lambda)}{1 + 3|\lambda|^2}. \tag{1.2}$$

The parameter λ accounts for the renormalization of the axial-vector current by the structure of the nucleon. The first element of the CKM matrix can be derived from the ratio λ and the neutron lifetime τ_n [4]:

$$|V_{ud}|^2 = \frac{(4908.7 \pm 1.9)\mathrm{s}}{\tau_\mathrm{n}(1 + 3\lambda^2)}. \tag{1.3}$$

This contributes to test the unitarity condition of the CKM matrix. Non-unitarity could indicate for example a new quarks generation. Beyond the Standard Model, the correlation coefficients depend on further coupling constants, for example scalar and tensor interactions. Precise measurements of these coefficients allow to search for new physics like possible contribution of leptoquarks, right-handed interactions, new gauge boson, etc [5, 6, 7, 8, 9].

2. Indirect measurement of the coefficient *a*

The aim of the experiment *a*SPECT is to measure the electron-antineutrino angular correlation coefficient *a* with an accuracy of 0.3% (previous measurements reached 5% [1]). Via kinematics *a* can be related to the shape of the proton recoil energy spectrum [10]:

$$W_p(T) \propto g_1(T) + a \cdot g_2(T), \tag{2.1}$$

where $g_1(T)$ and $g_2(T)$ are known functions of the kinetic energy T of the proton ($T_\mathrm{max} = 751.4\,\mathrm{eV}$). The shape of the proton energy spectrum is shown in Fig. 1-a for different values of the coefficient a including the present world average $a = -0.103(4)$ [1]. The relation between a and the proton spectrum can be understood as follows: if the electron and the antineutrino are emitted with parallel momenta, $a = +1$, the proton carries a maximal recoil momentum due to momentum conservation. In the opposite case, $a = -1$, the proton energy spectrum will be shifted towards lower energies.

3. The experiment *a*SPECT

*a*SPECT is a retardation spectrometer, see refs. [11, 12, 13, 14, 15, 16, 17] for details. The experiment (Fig. 1-b) took place at the cold neutron beam facility PF1b [18] of the Institut Laue-Langevin (ILL). A beam of unpolarized cold neutrons (mean energy about 10 meV) passes through

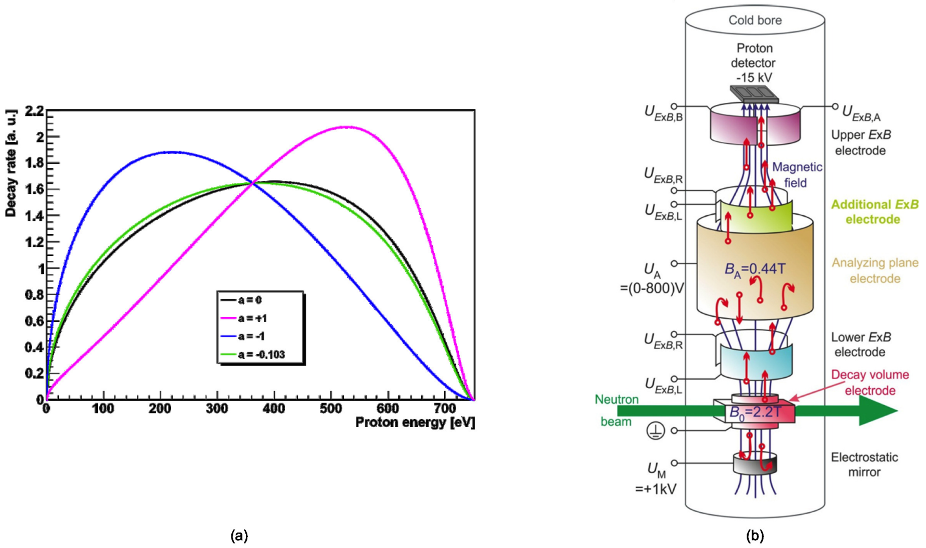

Figure 1: (a) The theoretical proton spectrum W_p calculated for different values of the coefficient a and for its actual world average value. (b) Sketch of the spectrometer: the green arrow represents the neutron beam, the blue lines the magnetic field and the red arrows decay protons.

the *a*SPECT spectrometer where about 10^{-8} of the neutrons decay in the Decay Volume (DV) (Fig. 1-b). Protons emitted into the lower hemisphere are reflected adiabatically by an electrostatic mirror enabling 4π acceptance for protons created in the DV. Protons moving upwards are guided to the Analysing Plane (AP) and collimated adiabatically by a strong and decreasing magnetic field (2 T in the DV, 0.4 T in the AP). They are energy-selected by a potential barrier, U_{A}, focused onto the detector by an increasing magnetic field (6 T) and post-accelerated by a high voltage potential, -15 kV, applied at the detector electrode. Rejected protons are trapped between the AP and the mirror and removed by an $\vec{E} \times \vec{B}$ drift. Another $\vec{E} \times \vec{B}$ electrode helps guiding selected protons to the detector.

The proton count rate is measured for different voltages U_{A} in order to build the integrated proton spectrum as shown in Fig. 2. The value of a is inferred by a fit:

$$\rho_{\mathrm{tr}}(U_{\mathrm{A}}) = N_0 \int_0^{T_{\max}} F_{\mathrm{tr}}(U_{\mathrm{A}}, T) \cdot W_p(T) \mathrm{d}T \tag{3.1}$$

where $F_{\mathrm{tr}}(U_{\mathrm{A}}, T)$ is the transmission function characterized by the shape of the magnetic field and the potential barrier voltage U_{A}. The free fit parameters are the normalization N_0, the correlation coefficient a and an offset to account for a constant background. This background is dominated by decay electrons and can be measured at $U_{\mathrm{A}} = 780\,\mathrm{V}$. Different systematic effects are investigated through measurements with different settings and through simulations in order to quantify the impact on the angular correlation coefficient.

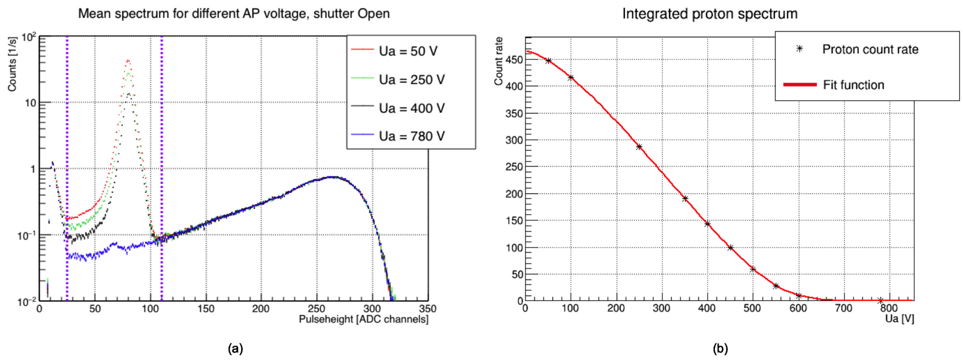

Figure 2: (a) Example of pulseheight spectra measured for different AP voltages $U_{\rm A}$. The proton integration window is indicated. The shape of the spectrum above the proton window is caused by a non-linear amplification. (b) Example of an integrated proton spectrum which represents the proton count rate as a function of the voltage $U_{\rm A}$.

4. Investigation of a systematic effect: the background

During the beam-time, the following time sequence was used for measurements (Fig. 3-a). The acquisition starts with the shutter closed (no neutron beam). The potential barrier is ramped

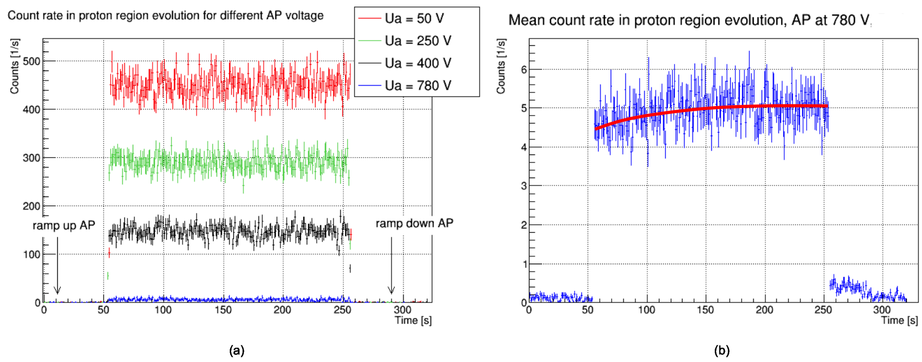

Figure 3: (a) Evolution of the proton count rate for different AP voltages $U_{\rm A}$ during the acquisition time sequence. (b) Zoom on the evolution of the proton count rate with $U_{\rm A} = 780\,$V: the red line represents the fit function in eq. 4.1.

from 0 V to a given voltage $U_{\rm A}$. The time between reaching $U_{\rm A}$ and opening the shutter is called "Close1", the period with open shutter "Open", and the period after closing the shutter and before ramping down the potential barrier "Close2". This structure allowed to highlight several details of the background [19]. Fig. 3-b shows data for 780 V (all decay protons rejected). The count rate is not constant during "Open" and the count rate in "Close2" is higher than in "Close1". This residual count rate is removed when the AP voltage is ramped down to 0 V. The time evolution in "Open" can be described by an exponential build-up function:

$$f(t) = p_0 + p_1 \cdot \left(1 - {\rm e}^{-(t-t_0)/\tau}\right), \tag{4.1}$$

where the parameter p_0 represents the constant part of the background, p_1 the saturation value of the variable contribution, τ the time constant and t_0 the start time of "Open". This increase of

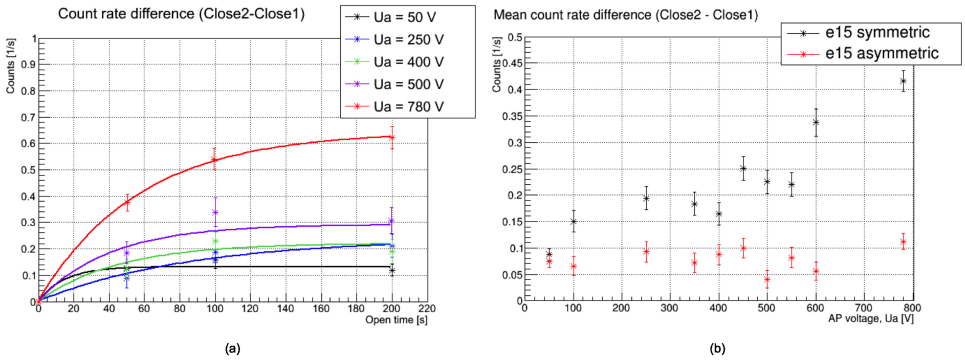

Figure 4: (a) Evolution of the residual proton count rate in function of the opening time of the shutter for different AP voltages U_A. (b) Residual count rate in function of the voltage U_A for two configurations of the electrode e15.

the count rate is related to the residual count rate in "Close2". Fig. 4-a shows this residual rate (rate "Close2" - rate "Close1") as a function of the duration of "Open". It can be described by the same exponential build-up function, eq. 4.1 and shows a significant dependence on U_A. These observations can be explained by a particle trap in the AP region.

In order to remove trapped particles, the electrode e15 above the AP electrode (Fig. 1-b) was designed as a dipole and can be used in an asymmetric configuration. The effect on the residual count rate is shown in Fig. 4-b. The variable background contribution can be estimated by integrating eq. 4.1:

$$BG(U_\mathrm{A}) = p_1(U_\mathrm{A}) \cdot \left(t_\mathrm{op} - \tau(1 - \mathrm{e}^{-t_\mathrm{op}/\tau}) \right) . \tag{4.2}$$

Here, t_op is the duration of "Open" and $p_1(U_\mathrm{A})$ describes the U_A-dependence. Different models (constant, linear, quadratic, exponential) were used for $p_1(U_\mathrm{A})$ (Fig. 4-b) and the corrections on the coefficient a calculated. Quadratic and exponential models described data (Fig. 5) best and result in consistent corrections on a.

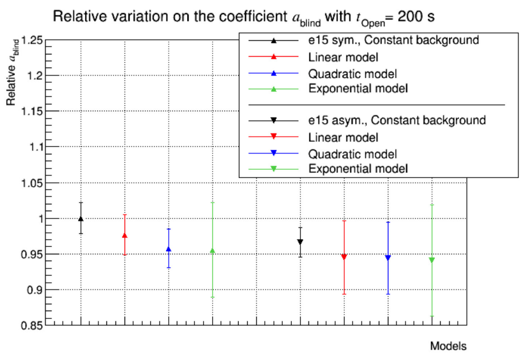

Figure 5: Relative impact of the non-constant background correction on the coefficient a.

5. Preliminary results and outlook

During the beam-time of 2013 at the ILL, the statistical sensitivity was 1.1% per day. Data were taken with different experimental settings (e.g. configuration for e15, a modified neutron beam profile, different times for "Open") [19]. The variations between different settings are of the order of expected systematic corrections. Preliminary results are encouraging for 1% final accuracy. Detailed simulations and the blinded final analysis are in progress.

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