The Proton Spectrum in Neutron Beta Decay: First Results with the *a*SPECT spectrometer

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Abstract. The purpose of the *a*SPECT spectrometer is a precision measurement of the proton spectrum in free neutron decay. Its shape depends on the angular correlation between the momenta of the antineutrino and the electron for kinematic reasons. Nowadays, a measurement of the antineutrino electron correlation coefficient a is of great interest in order to test the unitarity of the Cabibbo-Kobayashi-Maskawa-Matrix.

First measurements with the *a*SPECT spectrometer have been performed in a beam time at the beam line MEPHISTO of the neutron research reactor FRM-II in Garching, Germany. In this paper, a short description of the spectrometer is given and first raw analysis is shown.

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1. MOTIVATION

A precision measurement of the correlation coefficient a is of great interest for its possible use in testing the unitarity of the Cabbibo-Kobayashi-Maskawa-Matrix. Its upper left element, V_{ud}, is currently determined from superallowed beta decays (see [1, 2]). But these experiments need additional calculations due to nuclear structure corrections. Therefore, a determination of V_{ud} from free neutron decay experiments is desirable since it avoid such difficult corrections. Neutron beta decays are mixed superallowed weak transitions with accurately known Fermi and Gamow-Teller matrix elements. Here, one can determine the weak vector and axial vector coupling constants G_{V} and G_{A} with two independent measurements: the neutron lifetime τ_{n}, together with an observable sensitive to the ratio $\lambda = G_{\text{A}}/G_{\text{V}}$. The determination of λ in neutron decay can be done either with measurements of the beta asymmetry A or of the neutrino-electron angular correlation coefficient a. The dependence of these correlation coefficients on λ is:

$$A = -2\lambda \frac{\lambda+1}{1+3\lambda^2} \qquad \text{and} \qquad a = \frac{1-\lambda^2}{1+3\lambda^2} \tag{1}$$

So far, the beta asymmetry measurements have provided the best results. In fig. 1 (left) are shown different λ values from beta asymmetry measurements (the five squares) and indirect λ determinations (the three triangles) employing the unitarity condition of the CKM matrix, as follows (see [3]):

$$\sqrt{1-|V_{\rm us}|^2-|V_{\rm ub}|^2}=|V_{\rm ud}|=\frac{4908.7(1.9)s}{\tau_{\rm n}(1+3\lambda^2)} \tag{2}$$

The direct measurements of λ from beta asymmetry do not agree well with each other. The particle data group [1] inflates the uncertainties of the beta asymmetry measurements by a factor of 2.3. The indirect determinations using the unitarity depend on the measurement input used. In order to clarify the situation, an accurate measurement of the coefficient a would be very valuable as an independent check with entirely different systematics, besides improving the accuracy.

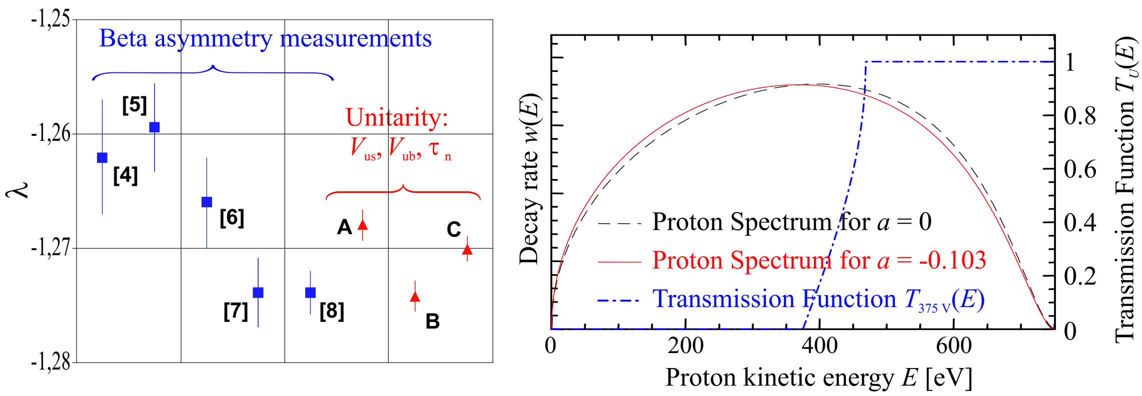

FIGURE 1. Left: Values of λ. The five squares are calculated from beta asymmetry measurements using eq. 1 and the following inputs: [4] $A=-1,262\pm0,005$, [5] $A=-1,2594\pm0,0038$, [6] $A=-1,266\pm0,004$, [7] $A=-1,2739\pm0,0030$ and [8] $A=-1,2739\pm0,0019$. The three triangles show the calculated value of λ using the unitarity condition of the CKM matrix and $V_{\rm us}$, $V_{\rm ub}$, $\tau_{\rm n}$ (see eq. 2) and: A) PDG 2004 data [9], B) $\tau_{\rm n}$ from Serebrov et al. [10] and λ from PDG 2004 and C) using PDG 2006 data which contains new Kaon data and new radiative corrections (see [1]). Right: Spectra of the decay protons for different values of the neutrino electron correlation coefficient a. The solid line shows the spectra for $a=0$, the dashed line for $a=-0.103$. In addition, the Transmission Function for a barrier voltage of $U=375$ V is plotted.

The neutrino electron correlation coefficient a in the decay of the free neutron is defined as

$$dw \propto \left(1+a\frac{v_{\rm e}}{c}\cos\left(\vec{p}_{\rm e},\vec{p}_{\nu}\right)\right) \tag{3}$$

where dw is the differential decay probability, $v_{\rm e}$ and $\vec{p}_{\rm e}$ are electron velocity and momentum and $\vec{p}_{\nu}$ is the momentum of the electron antineutrino. From eq. 3 can be inferred that the proton spectrum from neutron decay is sensitive to the coefficient a. Two extreme cases are distinguished: decay protons have maximum kinetic energy when electron and antineutrino have parallel momenta, and minimum when electron and antineutrino have antiparallel momenta. That means, a positive value of a would cause in average higher proton energies (see fig. 1, right) and vice versa.

In the Standard Model the proton spectrum $w(E)$ can be parametrized on a as

$$w(E) = g_1(E) + a \cdot g_2(E) \tag{4}$$

where g_1 and g_2 are independent of the correlation coefficient a and mainly given by the kinematics.

2. PRINCIPLE OF THE MEASUREMENT

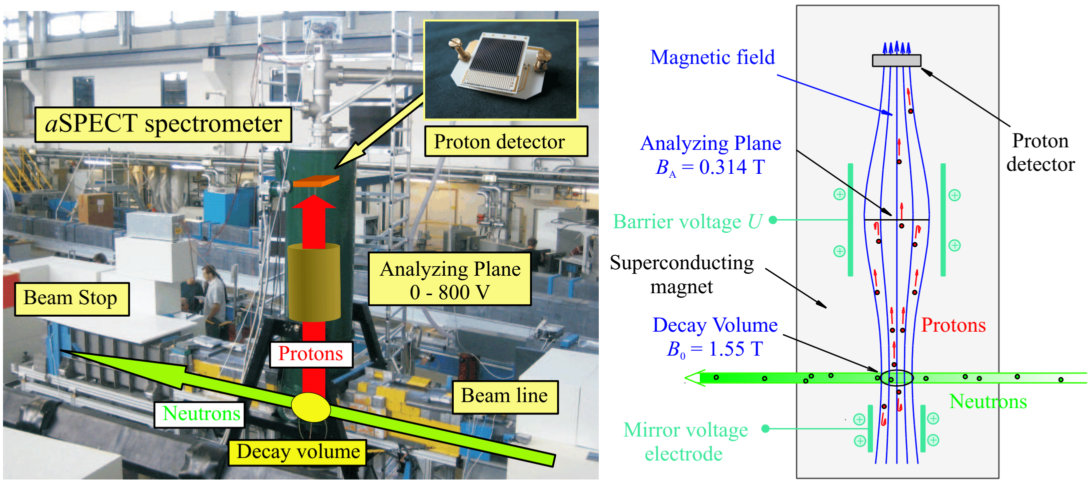

FIGURE 2. Setup of the experiment, at the left as a picture, at the right as a sketch. A neutron beam (the green arrow) is guided through the spectrometer. Some neutrons decay in the decay volume, and the decay protons are guided by a magnetic field to the proton detector.

The design of the retardation spectrometer *a*SPECT is based on Magnetic Adiabatic Collimation followed by an Electrostatic Filter (MAC-E-Filter) and consist of a set of electrodes and superconducting coils (see sketch on fig 2). It works as follows: a cold neutron beam is guided through the spectrometer to the so-called Decay Volume, placed in a strong magnetic field region. The protons produced in this region are guided towards the detector by magnetic field lines. The ones emitted in the hemisphere opposite to the detector are reflected back by an electrostatic mirror electrode held at 1 kV, a potential larger than the maximum proton kinetic energy (at about 750 eV), obtaining a 4π acceptance. On their way to the detector the protons are adiabatically collimated by crossing a weaker magnetic field. At the Analyzing Plane, an electrostatic potential barrier is applied. Protons with sufficient energy can overcome the barrier and are accelerated towards the detector held at a high negative voltage (-30 kV), where they are counted. By varying the barrier potential one can measure the integrated proton spectrum of free neutron decay.

The action of the potential barrier can be described with a transmission function $T_U(E)$, which is the probability that a proton with a definite starting kinetic energy E passes the Analyzing Plane (see fig. 1). An accurate knowledge of the transmission function is essential. For that purpose, the motion of the decay protons is kept adiabatic [11]. Then, protons moving into the low field region keep their orbital magnetic moment constant, provided the magnetic and electric field change is slow enough that the motion is adiabatic. Since also energy has to be conserved, an increase of their longitudinal momentum is required, while the energy in the gyration is decreased in the low-field region. This process is called the inverse magnetic mirror effect or magnetic adiabatic collimation. Under this condition, the initial kinetic energy needed to pass the potential barrier at the analyzing plane is

$$E = \frac{eU}{1 - B_{\mathrm{A}}/B_0} \sin^2\theta \tag{5}$$

where U indicates the applied barrier voltage and θ is the initial angle between the proton momentum and the magnetic field lines at the Decay Volume. B_0 and B_A are the magnetic field values at the Decay Volume and Analyzing Plane, respectively. In our spectrometer, the magnetic field in the Decay Volume (B_0 = 1,55 T) is larger by a factor 5 than the field in the Analyzing Plane (B_A = 0,314 T). The angular dependent transmission function $T_U(E,\theta)$ for a fixed emission angle θ can be written as:

$$T_U(E,\theta) = \begin{cases} 1 & \text{if } E > \frac{eU}{1-B_{\mathrm{A}}/B_0}\sin^2\theta \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

The proton recoil spectrum for unpolarized neutron decay is isotropic. Therefore, by averaging over all initial proton directions the transmission function can be given by:

$$T_U(E) =< T_U(E,\theta) >_\theta = \begin{cases} 0 & \text{if } E < eU \\ 1 - \sqrt{1 - \frac{B_0}{B_{\mathrm{A}}}\left(1 - \frac{eU}{E}\right)} & \text{otherwise} \\ 1 & \text{if } E > \frac{eU}{1-B_{\mathrm{A}}/B_0} \end{cases} \tag{7}$$

Then, the transmission function depends only on the electrostatic potential and magnetic field values in the Decay Volume and in the Analyzing Plane, and it is independent of the detailed shape of the electromagnetic field.

A segmented silicon PIN diode is the detector used to count the decay protons. It is divided into 25 strips with a total area of 26x26 m^2, providing spatial resolution in one dimension. The segmentation is mainly needed to reduce the capacitive noise of the detector. The detector has a thin entrance window with a total dead layer of 67 nm of SiO_2 that produces an approximate energy loss of 8 keV for 30 keV energy protons.

The observable in the *a*SPECT experiment is the dependence of the count rate $N(U)$ on the barrier voltage, which is given by:

$$N(U) = N_0 \int T_U(E) w(E) dE \tag{8}$$

By fitting the measured count rates, one extract the total proton decay rate N_0 and the correlation coefficient a.

3. PRESENT RESULTS

In the first aSPECT beam time, the data acquisiton system allowed to record the pulse shape signal of each event (see fig. 3). For our preliminary analysis the pulse height of

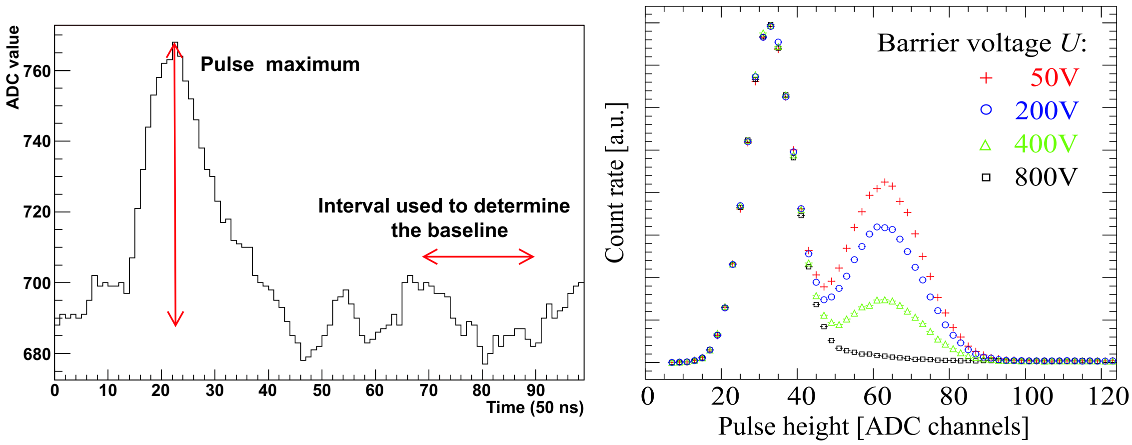

FIGURE 3. Left: Pulse shape signal for one event. Here the maximum value of the signal and the interval of time used to determine the baseline (mean value of the interval taken at the tail of the signal) are marked. The difference between them is the proton pulse height. Right: Pulse height spectrum of the proton detector for different barrier voltages U in the Analyzing Plane. The signal to background ratio is better than 10:1 below the proton peak.

each pulse event is taken by getting the difference between the maximum value of the pulse event and its respective baseline. The baseline for each pulse event is defined by taking the mean value of some points at the tail of the signal. In fig. 3 left, the pulse height spectrum in nearly one hour run of the detector for different analyzing plane voltages is shown. At about channel 65, the protons are seen. The proton count rate decreases by increasing the Analyzing Plane voltage. Since the endpoint of the proton spectrum is at about 750 eV, by setting the analyzing plane voltage to 800 V no protons are detected. The peak at channel 30 is due to electronic noise of the detector. The remaining background comes from decay electrons and gamma radiation generated in the neutron beam.

For the background subtraction one has to take into consideration the problem of correlated background, i.e., the distinction between the electron and proton coming from the same neutron decay. For that purpose, above the Decay Volume, an electric field is applied perpendicular to the magnetic field which allows to shift the protons respect the electrons. The detector's spatial resolution permits to detect them in different channels. The events during a time interval between two consecutive signals can be seen in fig. 4. Electrons and protons from the same neutron decay are temporally (protons are slower on their way to the detector) and spatially (by channel distance) separated. The accumulation of events seen at 10 μs in fig. 4, shows the typical time interval between electron and proton from the same neutron decay (the decay electron spectrum has a maximum energy of about 750 keV and part of the decay electrons are guided, like the protons, along the magnetic field to the detector). This accumulation in fig. 4 disappears by applying 800 V at the analyzing plane, because then no proton can reach the detector. Furthermore, one can also see that the dead time after detecting the first event for the same channel is about 6 μs, small enough to distinguish between electron and proton from the same decay event.

Once the background (i.e., 800 V pulse height) has been subtracted (see fig. 4, right)

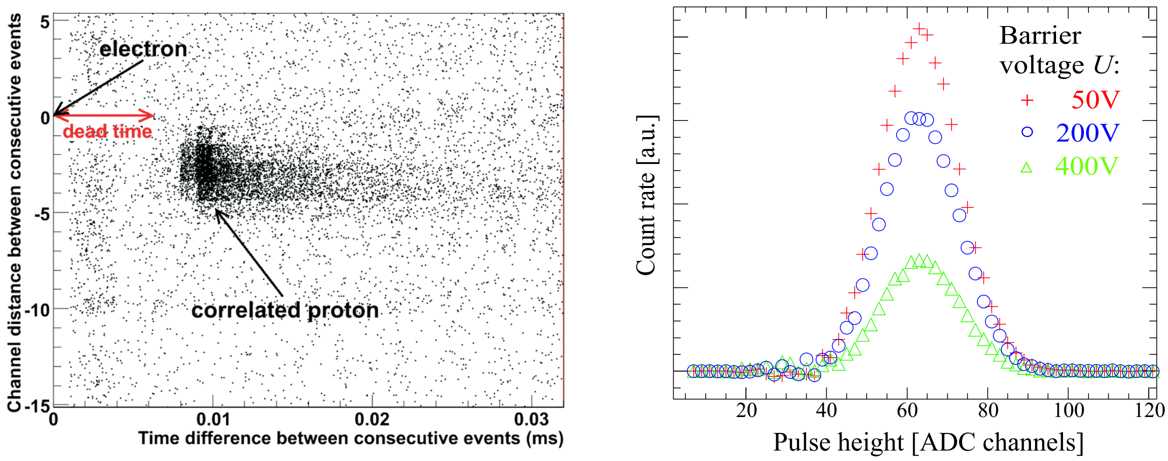

FIGURE 4. Left: Plot of the channel and time difference of two consecutive events. One can distinguish an accumulation of events with a channel difference of -3 channels and in a time difference of 10 μs. This accumulation corresponds to protons and electrons produced in the same neutron decay. One can also extract from this plot that the detector's time and spatial resolution are big enough in order to differentiate between these events. Right: Free background pulse height spectrum of the Proton Detector for different barrier voltages U in the Analyzing Plane. Small fluctuations on the left side of the pulse height have been observed due to time-instabilities of the electronic peak. A better separation of the electronic peak from the proton peak is needed.

the proton peak is not completely separated from the electronic noise. This effect due to electronic noise instabilities introduces an additional error to the integrated proton pulse height. By increasing the high voltage in the detector we should be able to improve the situation, because then the proton peak is shifted to higher ADC channels. However, during our measurements stability problems with the high voltage of the proton detector did not allow us to get the proton peak completely separated of the electronic noise. That will limit the accuracy of the data taken.

We integrate over the background-free proton peak to obtain the total proton count rate for each barrier potential. The total measured proton count rate amounts to about 500 Hz. The dependence of the proton count rate $N(U)$ on the barrier voltage is fitted with the function in equation 8 to extract our measured number for the correlation coefficient a, fig 5. The dataset shown is consistent with the recommended value in [1].

Tests of the Transmission Function, as discussed thoroughly in [12], were performed. The electric potentials and magnetic fields in Analyzing Plane and Decay Volume were measured with sufficient accuracy. However, the analysis of the data taken in the first run has to be done with one modification: in order to take into account a possible voltage offset in the potential due to surface charges on the electrodes, a third fit parameter ΔU will be introduced. For the future runs, an electron calibration source will be used in order to measure directly such voltage offset on the electrodes.

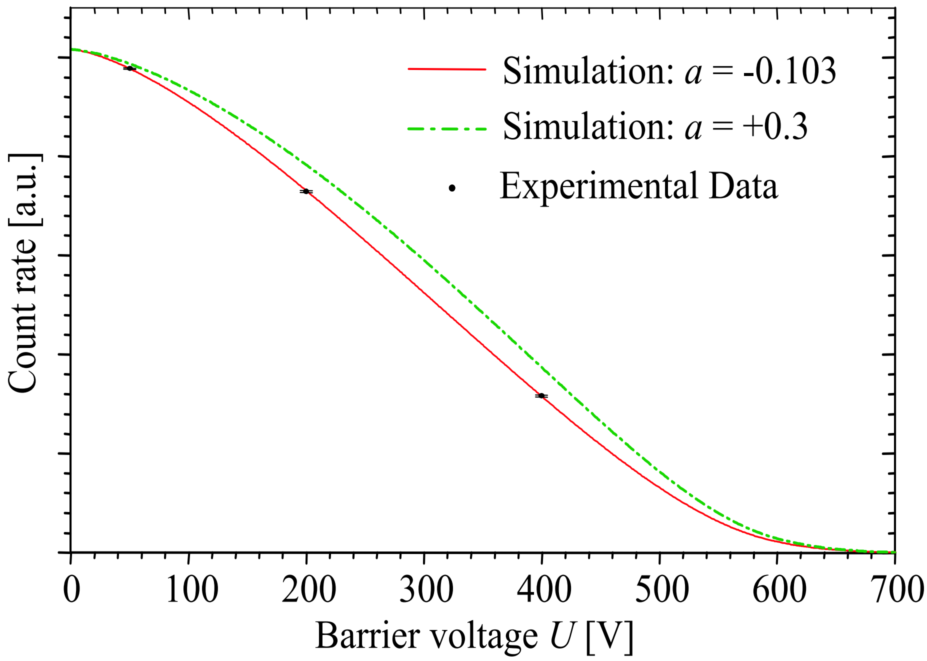

FIGURE 5. Total proton count rate vs. barrier voltage after the subtraction of the background. The solid line is the prediction from the Standard Model with the recommended value for *a*, the dashed line shows how a deviation from that would look like.

4. SUMMARY AND OUTLOOK

An accurate measurement of the neutrino-electron correlation parameter in free neutron decay is important in order to determine precisely the element V_{ud} of the CKM quark-mixing matrix. A unitarity test of this matrix is of great interest for being fundamental in the Standard Model of particle physics. A short description of the neutron decay *a*SPECT spectrometer has been given in this paper. The first tests at the beam line MEPHISTO at the neutron research reactor FRM-II showed that the spectrometer fulfills the requirements expected. However, further improvements of the temporal stability of the detector and its functionality at high voltages in combination with strong magnetic fields should be implemented. Besides, a better separation of the proton peak from the electronic noise from the detector is needed. A more thorough analysis of the data taken is underway. We expect to obtain a result with an uncertainty that matches the currently best measurement of *a* or even improve it.

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