

# Unrecognized backscattering in low energy beta spectroscopy

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## Abstract

We present studies on electron backscattering from the surface of plastic scintillator beta detectors. By using a setup of two detectors coaxial with a strong external magnetic field—one detector serving as primary detector, the other as veto-detector to detect backscattering—we investigate amount and spectrum of unrecognized backscattering. These are events where only one detector recorded a trigger signal. The implications are important for low energy particle physics experiments.

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## 1. Introduction

In the  $\beta$ -decay of the free neutron in proton, electron, and anti-neutrino,  $n \rightarrow p e^- \bar{\nu}_e$ , a number of interesting questions of particle physics and cosmology can be addressed [1]. These studies provide clean data and uncertainties due to nuclear structure do not arise. Main observables are correlations (emission asymmetry parameters) between neutron spin and the momenta of the decay products, or correlations between two of the latter. They are determined by measuring the emission direction of electrons and protons (e.g. Refs. [2–5]). Due to their small mass, electrons may be scattered from nuclei at large angles leading to electron backscattering out of the detector [6]. As generally in low-energy beta spectroscopy, this induces a systematic effect for neutron decay experiments since energy and angle dependent losses may falsify the asymmetry signal [7–9], a problem that has been discussed for many years now. In this paper, we present a method to directly determine the effect.

At present and in the near future, there will be several spectrometers employing a magnetic field to precisely

measure neutron decay parameters, such as aSPECT, PERKEO III, and a PNPI experiment in Europe, and UCNA, aCORN, abBA, Nab, and PANDA in the US [1,10,11]. Therefore it is of great interest to study electron backscattering in the framework of these experiments, to investigate how backscattering can be suppressed, and to determine the size of possible systematic effects. Especially for plastic scintillators that are widely used in these studies almost no data are available in the low energy range [8].

## 2. Experimental setup

We will focus on the rather simple setup of the electron spectrometer PERKEO II [12]. This is a quite general approach since many of the newly proposed experiments have a similar design. It features a strong magnetic field ( $B_{\max} = 1.03$  T) applied across a polarized neutron beam. The field is slightly decreasing and guides the electrons generated in neutron decay onto two opposite detectors. In this way, a  $2 \times 2\pi$  detection system is realized and no particles can miss the detectors (Fig. 1). This configuration is ideally suited to study backscattering effects from a primary detector which can be registered in the secondary detector on the opposite side (“veto detector”). The spatially varying magnetic field  $B$  also lowers electron backscattering considerably due to the magnetic mirror

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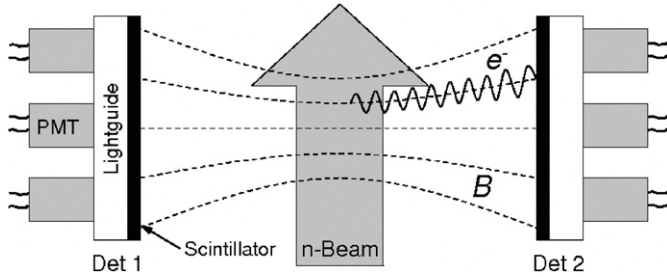


Fig. 1. The experimental setup of PERKEO II to study electron backscattering. Electrons from neutron decay are guided onto the detectors (plastic scintillator) by the magnetic field.

effect: The magnetic flux enclosed by the electron trajectories is an adiabatic invariant,  $p_t^2/B = \text{const.}$ , with the transversal momentum  $p_t$ . An electron moving in an increasing field can therefore be reflected. Many electrons scattered out of the detector are thereby returned to the same scintillator where they deposit their remaining energy.

The detectors consist each of a large area plastic scintillator ( $190 \times 130 \text{ mm}^2$ , 5 mm thick, Bicron BC 404, pulse width 2.2 ns), coupled to a 30 mm thick plexiglass light guide and six photomultiplier tubes (Hamamatsu R5504 mesh PMTs). These are read out by charge integrating ADCs (analogue to digital converter) to measure the energy. A trigger is generated, when at least two of the six photomultiplier signals of one detector have passed the discriminator threshold. The trigger probability is 90% at about 100 keV. Every trigger signal is sent to an individual TDC (time to digital converter) channel to determine which of the detectors were hit and to register timing information. A detailed description of the experimental setup can be found in Ref. [13].

Compared to solid state detectors, which have backscattering probabilities  $p_{BS}$  of up to 80% (NaI, [6]), plastic scintillators have the lowest  $p_{BS}$  in beta spectroscopy due to their low average atomic number  $Z$ . But with  $p_{BS} \approx 8\%$  ( $p_{BS} \approx 4\%$  for normal incident) this probability is still quite high [6] and has to be considered in the analysis of precision measurements.

In the experiments listed above, backscattering enters in an integral way, i.e., integrated over different angles of incidence  $\theta$  on the detector. In PERKEO II, the maximal angle  $\theta_{\text{max}}$  is around  $45^\circ$  as the decreasing magnetic field increases the electron momentum component parallel to the field lines. Most electrons hit the detector near  $\theta_{\text{max}}$ . Overall, the influence of the magnetic field reduces the backscattering probability to below 5%.

### 3. 2-Trigger backscattering

Whenever a trigger signal occurs, the ADCs of both detectors are read out simultaneously. With 180 ns, the integration time is much higher than the average time the backscattered electrons need to cover the distance between the detectors (800 mm), and we always obtain the full energy information of the event by summing up both

detectors. *2-trigger backscattering* occurs when an event generates a trigger both in the primary and the secondary detector. This allows to determine the chronological order of the two signals by using the timing information of the TDC. If its time resolution is smaller than the minimal flight time between the detectors, this assignment can be done without any uncertainty.

Fig. 2 shows the timing measurement of 2-trigger backscattering: The well separated peaks correspond to events where detector 1 (left) or detector 2 (right) was hit first. The separation is a measure of the system's time resolution which is given by the TDC-channel width of 0.8 ns. In between the peaks, where no first detector can be assigned properly, there are less than 0.2% of the backscatter events. Combined with the backscatter probability of below 5%, this fraction is negligible. The energy of the backscattered electrons is not distributed uniformly into primary and secondary detector (Fig. 3): Independent

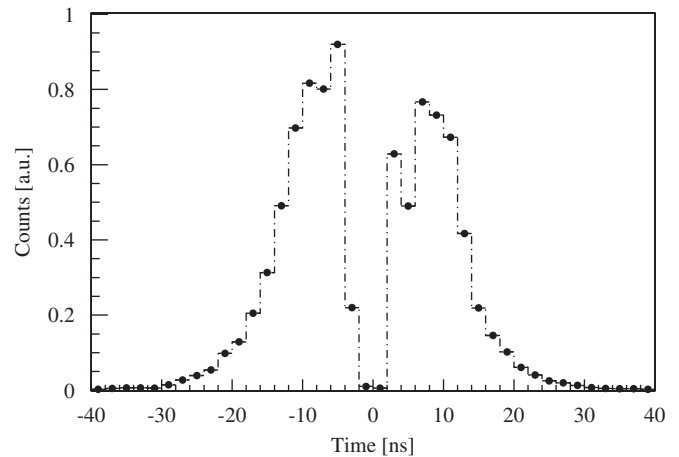


Fig. 2. Timing measurement of 2-trigger backscattering. The plot shows the time difference between triggers of detectors 1 and 2. Events where detector 1 triggered first are in the left peak. The peaks are well separated.

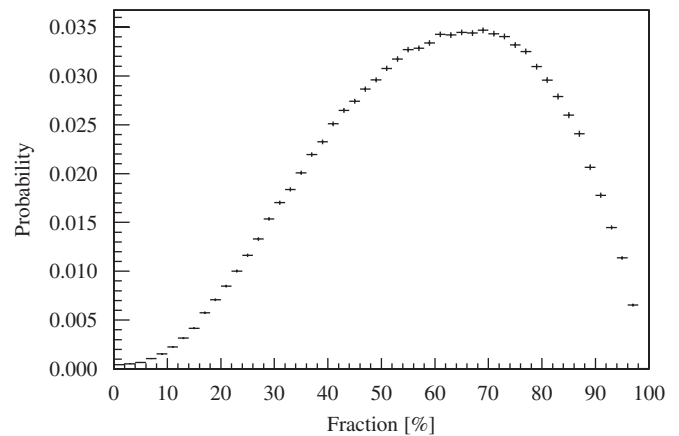


Fig. 3. Measurement of the probability that a backscattering event deposits a particular fraction of its energy in the primary detector. The distribution is asymmetric, i.e. there is a strong preference to deposit more energy in the primary detector.

of the overall signal size, it shows a strong preference to deposit more energy in the first.

In summary, 2-trigger backscattering can be fully reconstructed: The events are assigned to the correct detector with the correct energy.

#### 4. Unrecognized backscattering and wrongly assigned events

In order to analyze the effects of *unrecognized backscattering*, i.e., backscattering where we do not have two triggers and therefore cannot proceed as described above, we have to take a look at the decision tree shown in Fig. 4. We consider an electron hitting detector 1: If no backscattering occurs, it is not important whether detector 1 triggers or not. In the first case (a), we have the usual electron detection and in the second (b) nothing happens at all—but this case is limited to small energies and is described by the trigger function of detector 1.

Now consider the case with backscattering. When detectors 1 and 2 record a trigger (case c) we have 2-trigger backscattering as described above. For small energies it is possible that both detectors do not trigger and the event gets lost (f). When detector 1 triggers and detector 2 does not, we have unrecognized backscattering, but the event is assigned to the correct detector (d). Crucial is only case e, where the primary detector does not trigger but the secondary does. Here the event is assigned to the wrong detector—imposing a systematic error to the asymmetry parameter measurement. In the following, we will show how to identify unrecognized backscattering and how to discriminate between the cases d and e.

As the energy information is always available for both detectors (even if only one triggers) we can analyze the ADC content of the second: If the primary detector has triggered and the ADC of the secondary contains a signal above the pedestal threshold (the ADC signal without any energy deposition), we have identified an unrecognized backscatter event. This is illustrated in Fig. 5: Histogram  $H_1$  (solid circles) shows the energy content of detector 2, when detector 1 has created the primary and detector 2 a secondary trigger (2-trigger backscattering, case c).  $H_2$

(triangles) includes events where detector 1 has triggered first and the ADC content of the second is above the pedestal threshold. For energies high enough to generate a second trigger, the curves coincide. For low energies,  $H_2$  shows additional unrecognized backscattering where detector 2 has not triggered.

The trigger signatures of the cases:

- primary Det1 triggers, secondary Det2 triggers not;
- primary Det2 triggers not, secondary Det1 triggers;

are the same, whereas the signals belong to different “primary” detectors. Hence we have to discriminate between these cases.

The trigger function gives the probability  $T_i(E)$  that an electron of energy  $E$  generates a trigger signal in detector  $i$ . If this probability is unity for the whole energy range, we would not have any unrecognized backscattering. Thus we correct the 2-trigger spectrum  $H_1$  in Fig. 5 to obtain a trigger probability  $T_2(E) = 1$  for all  $E$  by dividing it by the measured trigger function of detector 2. The resulting

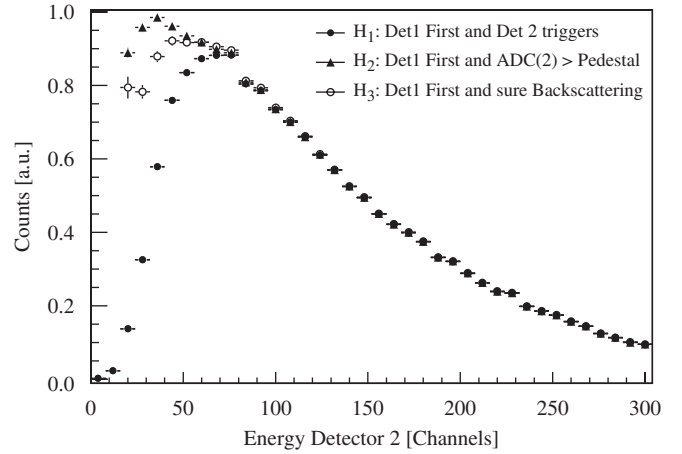


Fig. 5. Lower part of the energy spectrum of the second detector under the condition that detector 1 has triggered first (Det1First).  $H_1$  includes all backscatter events with two triggers. The difference between  $H_2$  and  $H_3$  are the events wrongly assigned to detector 1 (cf. text).

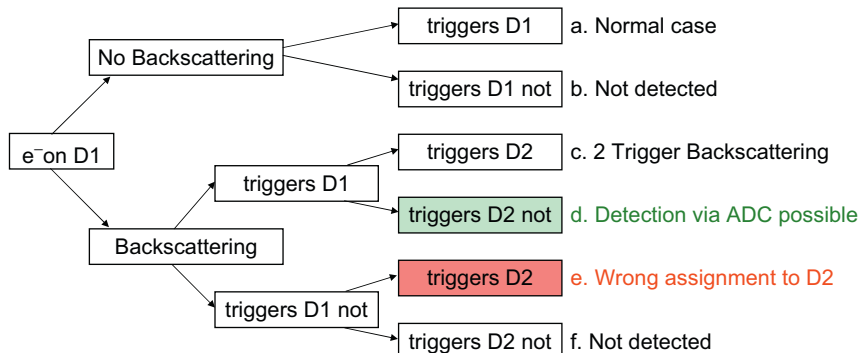


Fig. 4. Backscattering decision tree: The cases d and e are important for unrecognized backscattering, but only e alters the asymmetry parameter measurements.

spectrum  $H_3$  (open circles) contains all events where detector 1 has triggered first and the backscattered electron has reached detector 2.

The difference between the spectra  $H_2$  and  $H_3$  is the fraction of *wrongly assigned events* (case e). Here, the experimental signature suggests that the events belong to detector 1, in reality, however, the electrons have hit detector 2 first without depositing enough energy to create a trigger.

## 5. Size and spectrum of wrongly assigned events

In this section, we will show that the influence of wrongly assigned events (case e in Fig. 4) is negligible in a measurement if the region of interest starts at energies above a certain threshold. In order to analyze unrecognized backscattering quantitatively, it is necessary to extrapolate the energy spectra in Fig. 5 to lower ADC channels, as it is not possible to evaluate the spectra below a certain channel due to the pedestal threshold.<sup>1</sup> We have chosen two extreme extrapolation cases for the histograms  $H_2$  and  $H_3$ : In the first we assume no entries to be in the lowest bins, in the second we set them to the value of the lowest correctly determined channel.

We average over both extrapolation cases to obtain a value for wrongly assigned backscattering, and choose the difference between average and extrapolation to be the  $2\sigma$  error. This is a reasonable procedure to account for statistical errors, extrapolation, and a non-linear detector calibration in this energy region. Table 1 shows the results: Integration of  $H_1$  yields the 2-trigger backscattering, the integral of  $H_3$  (extrapolated as described above) gives the number of “true” backscattering events, where the correct detector has triggered first. The difference  $H_2 - H_3$  gives the fraction of wrongly assigned events: These are less than 5% of all backscattering events or  $\approx 0.2\%$  of all events.

For the analysis of a low-energy experiment it is important to know the energy of the events assigned to the wrong detector to check their influence. Fig. 6 shows the full energy spectrum of events in  $H_2 - H_3$ : Within the errors, there are no events above 240 keV. In general, however, this result depends on the trigger thresholds of the detectors. We think that this is the first time that size and spectrum of wrongly assigned events have been measured in this type of experiment.

The energy spectrum, Fig. 6, can also be modeled: We start with the normalized distribution  $P_{E^*}(E)$ , Fig. 3, giving the probability that a backscattered electron of total energy  $E^*$  deposits an energy fraction  $E$  in the primary detector. A low energy threshold (a step-function at  $x_0 = 39, 47$ , and 55 keV) is introduced to account for the trigger function of the first detector. The distribution is integrated for different electron energies  $E^*$  from 0 to  $x_0$  to determine the fraction of events not triggering the first detector. This is then

Table 1

Results for the general amount of backscattering (“true” BS) and for the fraction assigned to the wrong detector

	2-trigger (%)	“true” BS (%)	Wrong Det (%)
Detector 1 first	4.23 (1)	4.9 (2)	0.12 (1)
Detector 2 first	3.57 (1)	4.4 (2)	0.20 (2)

Since detector 1 had a slightly worse trigger function and a higher pedestal threshold, its number of wrongly assigned events is higher.

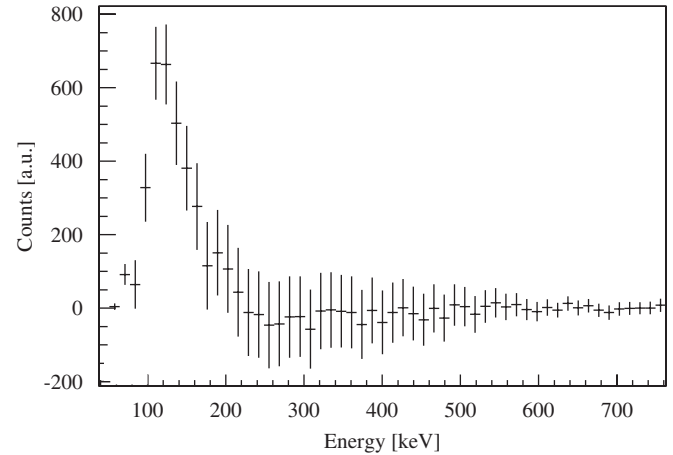


Fig. 6. Total energy of wrongly assigned events: These are registered as “detector 1 first” although detector 2 was hit first without generating a trigger. The plot shows that unrecognized backscattering is a low energy effect. Note that the energy scale is uncertain below 100 keV due to scintillation output non-linearities.

multiplied with the Fermi-spectrum  $F(E^*)$  to obtain an energy distribution similar to the situation in neutron decay. The model yields the spectrum  $H_2 - H_3$ :

$$s(E^*) = F(E^*) \int_0^{x_0} P_{E^*}(E) dE. \quad (1)$$

We neglect the trigger function of the secondary detector.

The model, Fig. 7, agrees well with the measurement, Fig. 6. Integration allows to estimate the fraction of wrongly assigned events in the spectra, Fig. 8: If the region of interest starts above 240 keV, the model predicts less than 6% ( $x_0 = 55$  keV) of wrongly assigned events to have higher energies. With overall 0.2% wrongly assigned events (Table 1), this yields a maximal correction in the order of 0.01% which is negligible in all ongoing experiments. This result is consistent with the measurement shown in Fig. 6 with no wrongly assigned events above 240 keV within the errors.

## 6. Conclusion

In this paper, we have presented a method—based on measured data only—to analyze electron backscattering quantitatively. Electrons backscattered from detector

<sup>1</sup>Below channel  $\sim 16$ , the pedestal prevents a correct identification of backscattering events, and the histogram  $H_2$  diverges.

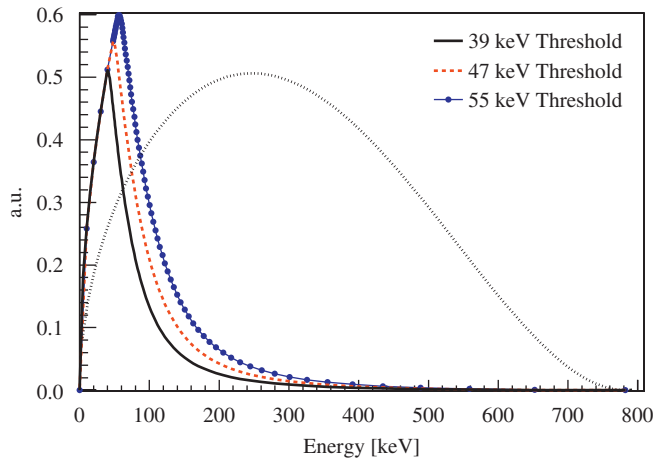


Fig. 7. Modeled energy spectrum of the events wrongly assigned to the first detector, for different trigger thresholds. The shape is consistent with the experimental data, Fig. 6. For comparison, the energy spectrum  $F(E)$  of electrons generated in neutron decay is also given; its endpoint energy is 782 keV.

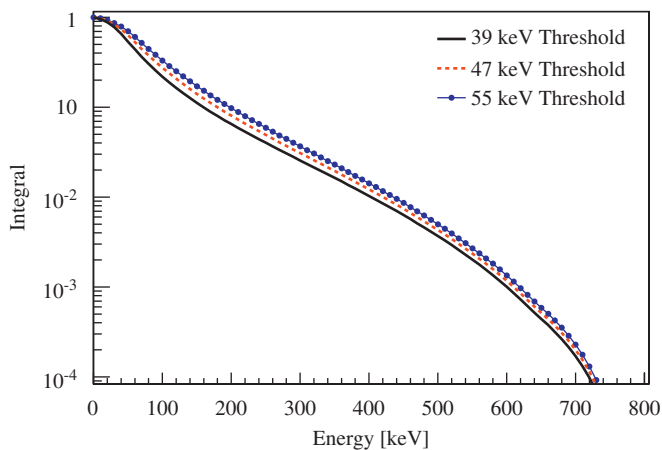


Fig. 8. Integral of the three model spectra of Fig. 7: Above 200 keV, the fraction of wrongly assigned backscatter events is below 10%.

surfaces might seriously affect beta spectroscopy. In a setup of two detectors coaxial with a magnetic field, electrons backscattered from one detector are guided to the opposite (“veto”) detector and backscattering effects are

well suppressed. In this setup, it is still possible that an event generates only a trigger in the veto detector and is therefore assigned to the wrong emission direction, which might give rise to systematic effects. We have shown that these effects only affect low energies. They are negligible when analyses of the electron spectra are performed only above an energy threshold. However, when the low energetic part of the spectrum shall be used as well, the effect of wrongly assigned events must be corrected using the method discussed in this paper.

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