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High-precision efficiency calibration of a high-purity co-axial germanium detector

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ABSTRACT

A high-purity co-axial germanium detector has been calibrated in efficiency to a precision of about 0.15% over a wide energy range. High-precision scans of the detector crystal and γ-ray source measurements have been compared to Monte-Carlo simulations to adjust the dimensions of a detector model. For this purpose, standard calibration sources and short-lived online sources have been used. The resulting efficiency calibration reaches the precision needed e.g. for branching ratio measurements of super-allowed β decays for tests of the weak-interaction standard model.

1. Introduction

Many spectroscopic studies in nuclear physics require only modest precisions (typically of the order of 1–10%) simply because nuclear-structure or astrophysical models are limited in their precision and therefore in their predictive power due to the lack of a high-precision standard model in nuclear physics. However, studies at the interface between nuclear and particle physics, where the nuclear β decay is used as a probe, require precisions which go well beyond the above mentioned level. Nuclear $0^+ \rightarrow 0^+$ β decay is presently the most precise means to determine the weak-interaction vector coupling constant g_V which, together with the coupling constant for muon decay, allows the determination of the V_{ud} matrix element of the Cabibbo–Kobayashi–Maskawa (CKM) quark mixing matrix. To determine this matrix element, the half-life and the super-allowed $0^+ \rightarrow 0^+$ branching ratio have to be measured with a relative precision of about 0.1%, whereas the β-decay Q value has to be determined with a relative precision of 0.02%, as it enters in the calculation of the statistical rate function f with a power of 4–5. High-precision Q-value determination is done today basically exclusively with Penning-trap mass spectrometry where precisions well below 1 keV, equivalent to some 10^{-4} relative precision, are now routinely reached for most of the nuclei of interest. The half-life is usually determined by β-particle or γ-ray counting and precisions of the half-lives well below 10^{-3} are obtained [1].

In these measurements, the precise determination of the branching ratio remains the tricky part, in particular in more exotic nuclei (e.g. nuclei with an isospin projection $T_z = -1$) where the non-analogue branches, i.e. the branches other than the $0^+ \rightarrow 0^+$ β–decay branch, are of the same order of magnitude as the analogue branch. As, due to a continuous spectrum, it is extremely difficult to determine these branching ratios by a measurement of the β particles, the branching ratios are usually determined by detecting γ rays de-exciting the levels populated by β decay by means of germanium detectors. Therefore, in order to determine a branching ratio with a precision of the order of 0.1%, one needs to know the absolute efficiency of a germanium detector with a similar or better precision.

To our knowledge, there is presently one germanium detector which is efficiency calibrated to such a precision [2–4]. A lot of similar work has been carried out in the past, however, never with a comparable precision or only for relative efficiencies (see e.g. [5,6] for recent work). The calibration of a single-crystal high-purity co-axial germanium detector we present here will therefore follow to some extent the procedure used by Hardy and co-workers.

The aim of the present work is to construct a detector model using a simulation tool able to calculate detection efficiencies in different environments for any radioactive source or γ-ray energy.

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For this purpose, we have used a 3D detector scan and 23 different radioactive sources to calibrate our detector in full-energy peak as well as in total efficiency and we have tuned our detector model to match the source measurements. As will be laid out in detail below, we used 10 sources to determine the total-to-peak (T/P) ratio, and 14 sources for the peak efficiency determination, a dedicated ^{60}Co source being used in both series of measurements. For the simulations, we used mostly the CYLTRAN code [7] which was upgraded to allow for the simulation of complete decay schemes of radioactive sources. We also added the process of positron annihilation-in-flight originally not present in the code. In a later stage of our work, we implemented our detector model also in GEANT4 [8] and found perfect agreement between the two codes, with the CYLTRAN code being much faster than GEANT4 and GEANT4 allowing for more flexibility of the geometry of the problem simulated.

2. Detector, electronics, and data acquisition

The detector we purchased for the present work is an n-type high-purity co-axial germanium detector with a relative efficiency of about 70%. An n-type detector is important in particular for detecting low-energy γ rays, as the thick dead zone for an n-type detector is on the inner surfaces of the detector and, in particular, not on the front surface facing the radioactive sources. We have chosen an aluminum entrance window instead of a much more fragile beryllium window, because the detector will travel to different laboratories. A large dewar ensures an autonomy of the detector of close to four days.

A X-ray photography of the detector (Fig. 1) shows a slight tilt of approximately 1°of the detector crystal in the aluminum can. GEANT4 simulations lead us to the conclusion that this tilt has no influence on the results of the present work. The initial manufacturer characteristics of the detector, used as a starting point for the simulations, are given in Table 1.

As in the work of Hardy and co-workers, we used a fixed source-detector distance of 15 cm. This distance allows us to reach a positioning precision below 10^{-3} even in more difficult online conditions with radioactive sources deposited on a tape transport system. The precision is achieved by means of a position sensor which is aligned with respect to either the source position or the transport tape in our mechanical workshop. The displacement is done with a 5 μm precision optical encoders with a digital readout. The alignment procedure was performed several times with results well within the required precision of 0.1 mm.

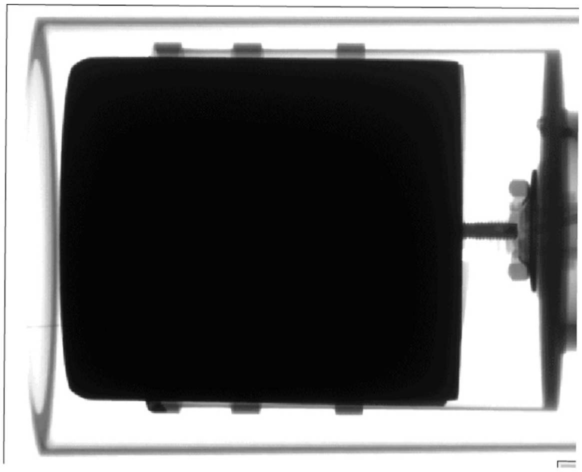

Fig. 1. X-ray photograph of the germanium detector. The slight tilt of the crystal with respect to the detector housing (about 1°) is visible.

Table 1
Detector characteristics used in the modelling of the germanium detector. The vendor specifications are compared to the finally adopted characteristics.

Detector parameter	Specifications	Parameters
Length of crystal	79.2 mm	78.10 mm
Radius of crystal	34.8 mm	34.84 mm
Length of central hole	70.0 mm	68.5 mm
Radius of central hole	5.0 mm	6.1 mm
External dead zone	< 1.0 μm	8.5 μm
Internal dead zone	0.5 mm	2.2 mm
Back-side dead zone	0.5 mm	0.8 mm
Distance window–crystal	5 mm	5.7 mm
Entrance window thickness	0.7 mm	0.7 mm

The experiment electronics consists mainly of an ORTEC 572A spectroscopy amplifier, an ORTEC 471 timing filter amplifier, and an ORTEC 473A discriminator. The signal from the discriminator is then sent to a LeCroy 222 gate generator (gate length typically a few micro-seconds) which then triggers the data acquisition (DAQ). The measurement duration is determined with a high-precision pulse generator (relative precision of 10^{-5}) fed into a CAEN VME scaler (V830) in the DAQ.

The data acquisition is a standard GANIL data acquisition [9] using VME modules. In addition to the scaler, we use a V785 ADC from CAEN for the energy signals and the TGV trigger unit built by LPC Caen [10].

The dead-time correction is performed by means of a 1 kHz pulser sent directly to the scaler and passed through a veto module (Phillips 758), where the veto is generated by the BUSY signal of the DAQ. The live-time (LT) is the ratio between the second and the first scaler values and the dead-time (DT) is equal to 1 − LT. To test the dead-time correction, a radioactive source (^{137}Cs) was mounted on the source holder at 15 cm from the detector entrance window. A measurement yielded a first result for the counting rate in the detector. We then added other triggers from a pulse generator. Thus the trigger rate of the DAQ was steadily increased without affecting the number of γ rays emitted from the ^{137}Cs source hitting the detector. Without dead-time correction, the apparent counting rate from the source decreases with increasing total trigger rate. When corrected for the acquisition dead time as described above, we recover the source counting rate without dead-time. We performed similar tests also with a ^{60}Co source (twice higher γ-ray energies) and found equivalent results.

Another concern when aiming for very high detection efficiency precision is the pile-up of radiation in the detector. Due to summing of signals from different events, counts are removed from the full-energy peak of a γ ray and moved to higher energy. We correct this by assuming a Poisson distribution of the events around a measured average count rate. With this assumption, we can determine the pile-up probability once we have defined a “pile-up time window” [11]. This time window was determined in a similar fashion as the dead-time correction. The full-energy peak counting rate was determined for a fixed source (^{137}Cs or ^{60}Co). In a second step, a low-energy source (^{57}Co) was approached more and more to increase the trigger rate, but also the pile-up. In the analysis, the pile-up time window was varied to achieve a full-energy peak rate of the fixed source independent from the total counting rate of the detector. The results of this procedure are shown in Fig. 2. It was found experimentally that the pile-up time window depends, as expected, linearly on the shaping time of the amplifier (2.75 × shaping time) and is, at least in the limit of the precision we achieved, independent of the γ-ray energy. This last finding is not necessarily expected, as, e.g. in a too large acquisition window, a larger signal coming after a smaller one will “erase” this smaller signal in our peak-sensing ADC.