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# A detector setup to study the decay properties of exotic nuclei

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**Abstract**

General features of a detector setup for decay studies at on-line mass-separators are discussed. The detection system was used for measurements of β-decay properties of exotic nuclei with $A \approx 70$. Results of GEANT Monte-Carlo simulations of the detector setup generally confirm the measurements. Both measurements and simulations show that even in case of low multiplicity events the Ge detector efficiency and peak to total ratio of γ-lines are reduced by large factor due to summing. Steps to improve the detection system are discussed. 

*Keywords:* Exotic nuclei; β-decay; Mass separators

## 1. Introduction

For decades, nuclei far from the line of stability have been studied at on-line mass separators [1]. The main difficulty of these experiments is the low production rate and the high isobaric contamination with yields which are sometimes orders of magnitude higher than the yield of the nuclei of interest. To overcome some of these problems a laser ion source selectively ionizing the reaction products of interest was developed at the LISOL mass-separator [2,3]. By exploiting this laser source, decay properties of $^{68-74}$Ni isotopes were recently studied by utilizing proton-induced fission of $^{238}$U [4]. One of the ultimate goals of this experimental program is to investigate the decay properties of the doubly-magic $^{78}$Ni and nuclei in its neighbourhood, which is of great interest for both nuclear physics and astrophysics [5,6]. The estimated production rate for $^{78}$Ni is of the order of a few atoms per day [7]. Even with further improvements of the laser source efficiency one cannot observe the decay of $^{78}$Ni without a significant improvement of the detection setup. Ideally a detection system should have a high detection efficiency and effective background suppression.

Exotic nuclei in this region of the chart of nuclei typically decay by emission of $\beta^-$-particles eventually followed by neutrons and/or γ rays. An effective way to suppress the background from the

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primary beam reactions and the room background is the detection of γ-rays gated by β-particles from the same decay cascade.

However, there are other "internal" sources of background associated with the decay cascade itself. For example, the high-energy β-particles can leave energy in a germanium γ-ray detector either by direct interaction or via emission of Bremsstrahlung radiation. The signal originating from the β-particles can sum up with the signal of detected γ rays belonging to the same cascade which resulting in a displacement of the energy position. This we call "true" summing. For the high-energy β-particles this background spreads to the high-energy part of the spectrum creating severe problems for the detection of high-energy γ transitions of very weak intensities, which are expected in the decay of many of the neutron rich Cu–Ni–Co isotopes. An "ideal" beta detector, hence, should also be able to reject (veto) those true summing events.

Another problem, is related to the "true" summing in the Ge detector of the γ-rays belonging to the same decay cascade. The Ge detectors are usually placed as closed as possible to the source, leading to an unwanted increase of the "true" summing probability. The situation is even worse for $\beta^+$ radioactive nuclei with positrons annihilating to two 511 keV γ-rays increasing the effective γ multiplicity. The "true" summing of γ-rays and β-particles not only causes "internal" background, but also hinders the correct determination of the efficiency of Ge detector which is essential for assigning decay branching ratios. The single transition efficiencies have to be corrected for the summing probabilities for each individual decay cascade. In many cases it is very difficult to measure the "true" summing effects of the γ-rays and β particles and the efficiencies of the β- and the γ-detectors with commercially available radioactive sources. One can perform simulations using the Monte-Carlo code, GEANT[1], which was initially developed for high-energy physics and has proven recently to be very useful for low-energy nuclear-physics applications as well. It is likely that as the sophistication of γ-ray detectors and β triggers grows one will have to rely on GEANT simulations to understand the detector response. It is therefore necessary to perform various tests with off-line radioactive sources and on-line measurements of nuclei with well-known decay properties to confirm the reliability of GEANT simulations.

The present paper, therefore, is divided in two closely related parts:

1. In the first part we will describe a new detector setup and demonstrate the suppression of the true summing of β-particles with γ-rays in the detectors.
2. The second part is devoted to a comparison of different tests with GEANT simulations using off-line as well as on-line radioactive sources and recent results obtained with the new detector setup.

## 2. Experimental setup

Recently, decay studies of neutron rich $^{67-71}$Co isotopes were performed at the LISOL separator. Details on the results will be published in future publications [8,13], here we concentrate on the experimental setup. After mass separation, the radioactive ions were implanted into a tape, which periodically was moved taking the daughter activity away with a time cycle optimized for the life times of the investigated nuclei. The main features of the detection system are presented in Fig. 1. Two Ge detectors with a relative efficiency of 70% and 75% ("left", $\Gamma_L$, and "right", $\Gamma_R$) were used for the γ-ray detection. The typical solid angle of the Ge detector from the implantation point is of order of 30% of 4π. Three thin plastic scintillators (1.3 mm thickness) were used for the detection of the β-particles. In front of each of the Ge detectors 28 mm diameter plastic "veto" scintillators, denoted as $V_L$ and $V_R$, respectively, were placed. The areas of the veto detectors were chosen to have the same solid angle with respect to the source as the Ge detectors. An additional third plastic detector, labelled as *B*, was placed close to the implantation point. The plastic detectors serve as a β trigger only and the energy information was not registered. The small thickness of the plastic detectors is needed to

[1] http://wwwinfo.cern.ch/pl/geant.

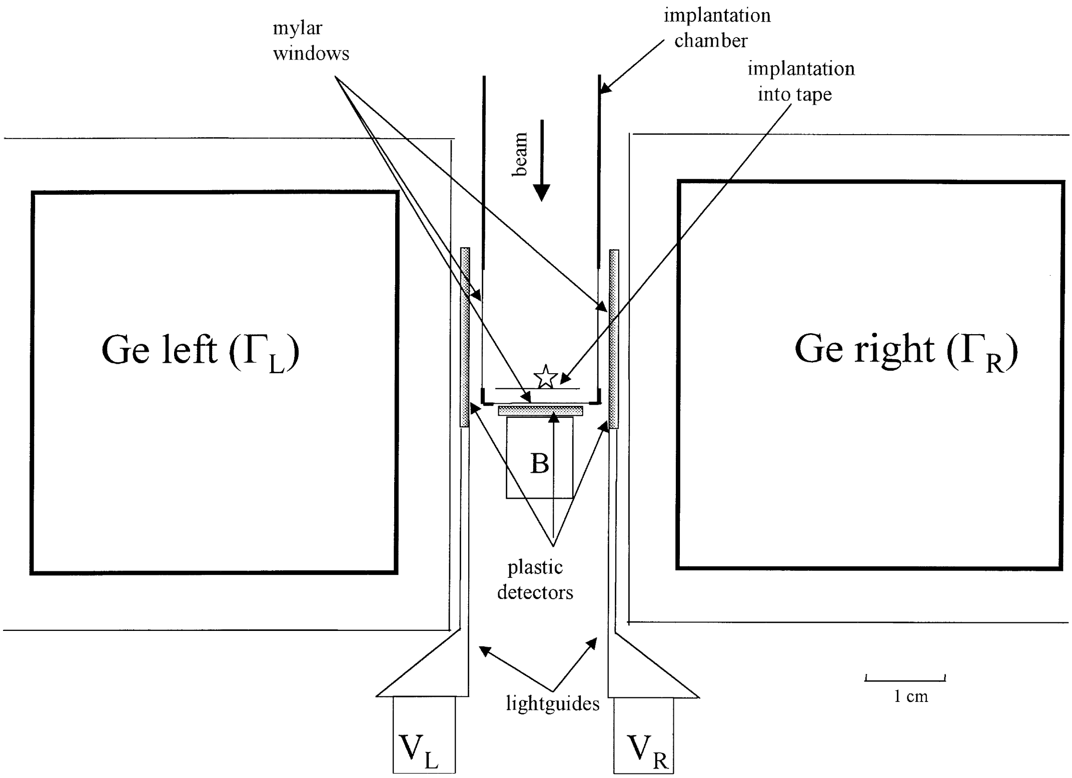


Fig. 1. The schematic drawing of the detection setup. Two Ge $\gamma$ detectors ($\Gamma_L$ and $\Gamma_R$) and three plastic detectors (B, $V_L$ and $V_R$) are indicated.

minimize its sensitivity to neutrons and $\gamma$-rays and to have the Ge detectors as close as possible to the source. Thus, each of the Ge detectors, say $\Gamma_L$, could be triggered by the *B* and/or the opposite veto detector ($V_R$) with an opportunity for $\beta$ suppression in case of a $V_L$–$\Gamma_L$ coincidence event. In the case of low-energy $Q_\beta$-value decay, when most of the beta particles are stopped in the plastic detector, the aluminum cap or the dead layer of the Ge detector without emission of a Bremsstrahlung radiation, the $V_L$ can be used as trigger detector for $\Gamma_L$ rather than as veto suppressor.

The veto plastic detectors were glued by an optical glue to lightguides. The detectors and lightguides were wrapped by a 15 μm thin aluminum reflective foil to increase the light collection efficiency. For all three plastic detectors the light signals were detected by two small photomultiplier tubes (PM) with 6 mm cathode diameters. These PM tubes were coupled to the light guides of the veto detectors and, in the case of the *B* detector, directly to the plastic scintillator. The signal-to-noise ratio for each individual PM is poor due to the thin plastic scintillator, the small area of the PM cathodes, and the loss of light in the lightguides. However, a coincidence condition between the two PMs of each detector strongly suppresses the noise (uncorrelated signals in the two PMs) even for the lowest threshold settings of the PM constant fraction discriminators, and does not effect the $\beta$-particles counting rate (correlated signals in the two PMs). To prove this experimentally the $\beta$ detection efficiency and signal-to-noise ratio have been compared with a similar plastic scintillator coupled by a lightguide with a large area PM of 4 cm cathode diameter. The comparison shows, that the two detectors had the same detection efficiency (close to 100%) while signal-to-noise ratio was at least an order of magnitude better for the two small PMs configuration.

Tests showed that these plastic detectors have an efficiency for γ-ray detection of the order of 1%–2% depending on the γ-ray energy. This was confirmed by GEANT simulation. This limits to a certain extent the use of these detectors for β gating.

The background rate of the plastic detectors is of order of 0.5 count/s. The origin of these prompt coincidence events is not well understood. The rate is much higher than the flux one expect from cosmic rays and is not due to external radiation or light leaks.

## 3. Experimental results

The data acquisition was triggered when one of the following coincidence conditions are met: $\Gamma_L$–$\Gamma_R$, $\Gamma_L$–$V_L$, $\Gamma_R$–$V_R$, $\Gamma_L$–$V_R$B and $\Gamma_R$–$V_L$B (see Fig. 1). The efficiency of the β detectors were measured by comparing the intensities of γ rays measured in singles Ge spectra and those gated by the individual β detectors. These on-line measurements were done by implanting into the tape system a beam of known radioactive nuclei, produced in the proton-induced fission reaction of $^{238}$U. In such way, it is ensured that a pure radioactive source (≈1000 Bq) is placed at the position corresponding to exact geometry of the target spot. The results of the efficiency measurements, based on the strongest 787 keV ($^{98}$Nb, $Q_\beta = 4.6$ MeV) and 1223 keV ($^{98}$Y, $Q_\beta = 8.8$ MeV) γ transitions are summarized in Table 1. One can see from Table 1, that detector efficiencies based on the measurement of the 1223 keV transition are slightly higher compared to those based on the 787 keV line measurement. This decrease in β efficiency for the lower $Q_\beta$-values was confirmed for other cases and is due to the larger fraction of low-energy particles that are absorbed in the 50 μm mylar windows of the implantation chamber, in the light reflective layer of aluminum and in the light protection black tape wrapped around the plastic detectors. One can also see from Table 1, that the sum of the efficiencies of the individual detectors, $\eta_{V_R} + \eta_B + \eta_{V_L}$, is slightly larger than the total efficiency of three detectors together, $\eta_{V_L V_R B}$. This is due to scattering of β-particles, which leaves a simultaneous signal in more than one detector. All β and γ detector efficiencies were simulated by GEANT code (see the next chapter).

The effectiveness of the β trigger was studied in a recent measurement of the β decay of $^{67}$Co [13] ($Q_\beta = 8.4$ MeV and $T_{1/2} = 425$ ms), which consists essentially of a single β decay followed by a single 694-keV γ ray. This simple scheme allows one to perform various tests in well-controlled conditions. These tests are not possible with off-line radioactive sources and on-line sources with more complicated decay schemes. Fig. 2 shows four spectra collected at mass 67 and observed in $\Gamma_L$ for different gating conditions: (1) singles spectrum; (2) all possible trigger conditions (see above); (3) the same as (2) but without γ–γ coincidences between $\Gamma_L$ and $\Gamma_R$ detectors; (4) same as (3) with additional veto suppression of events with $\Gamma_L - V_L$ coincidences. The ratios of the 694-keV line intensity to the total number of counts in the spectrum are 0.002, 0.025,

Table 1
The results of the β efficiency measurements based on comparison of intensities of 787-keV and 1223-keV γ transitions from decay of $^{98}$Nb ($Q_\beta = 4.6$ MeV) and $^{98}$Y ($Q_\beta = 8.8$ MeV), respectively. The results of GEANT simulations are also shown

| $Q_\beta$-value | $\eta_{V_L}$ | $\eta_{V_R}$ | $\eta_B$ | $\eta_{V_L V_R B}$ | $\eta_{V_R} + \eta_B + \eta_{V_L}$ |
|---|---|---|---|---|---|
| 4.6 MeV($^{98}$Nb) | | | | | |
| Experimental | 0.16(1) | 0.165(10) | 0.210(15) | 0.51(2) | 0.54(3) |
| GEANT | 0.17 | 0.17 | 0.24 | 0.59 | 0.61(2) |
| 8.8 MeV($^{98}$Y) | | | | | |
| Experimental | 0.175(15) | 0.170(15) | 0.26(2) | 0.57(3) | 0.61(2) |
| GEANT | 0.19 | 0.19 | 0.27 | 0.64 | 0.65 |

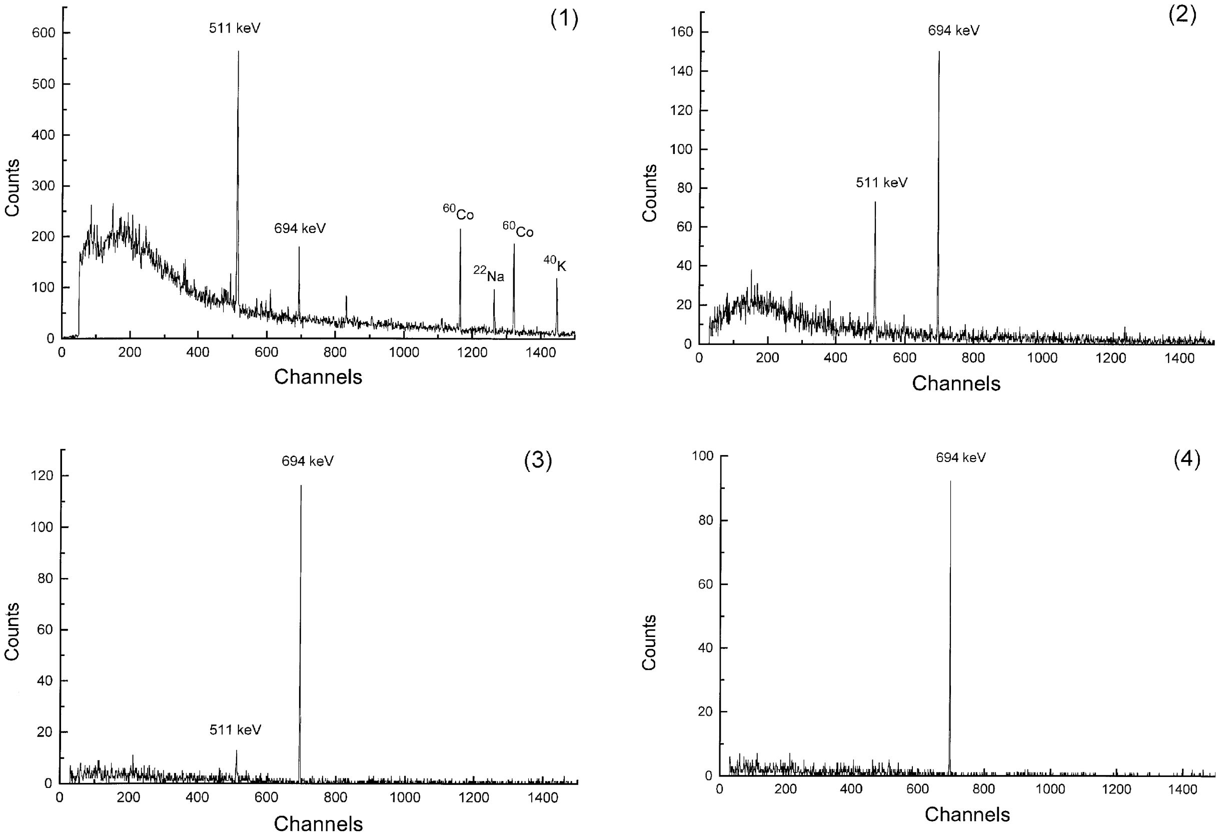


Fig. 2. Four energy spectra ($\Gamma_L$) obtained at mass 67 and using different triggering conditions: (1) singles spectrum; (2) with all possible triggers conditions; (3) the same as 2. but without $\gamma$–$\gamma$ coincidences between $\Gamma_L$ and $\Gamma_R$ detectors; and (4) the same as 3. but with additional veto suppression of the events with $V_L$ $\Gamma_L$ coincidences.

0.114 and 0.146 for the four spectra in Fig. 2, respectively. A background 511-keV transition appears in the spectra due to electron–positron pairs produced by the high-energy Bremsstrahlung radiation and high-energy $\gamma$-rays from neutron-induced reactions.

The application of the veto suppression procedure is more significant in the case of very weak transitions. To demonstrate this we show, in Fig. 3, spectra of the $\Gamma_L$ detector gated by the single strong 694-keV transition of $^{67}$Co in the opposite $\Gamma_R$. The spectrum exhibits a very weak 313.1-keV transition, which corresponds to a l-forbidden beta decay of the $^{67}$Co to a second excited state of the $^{67}$Ni daughter nucleus (the estimated branching ratio is 3%). This excited state has been previously observed in in-beam experiments [9]. The peak-to-total ratios for the spectra with and without the veto suppression are 0.04 and 0.02, respectively. Thus, in this particular case, veto suppression is quite important.

Moreover, the simple decay scheme of $^{67}$Co also provides a unique opportunity to measure the fraction of $\beta$ particles which leave a signal in the Ge detector. One can measure the number of counts in the 694-keV peak in, for example, the $\Gamma_L$ detector triggered by the $V_R$ or B detectors, $N_{L_{V_R B}}$, and compare it with the number of counts in the $\Gamma_L$ spectrum triggered by the $\Gamma_R$–$V_R$ coincidence condition, $N_{L_{V_R \Gamma_R}}$. Since the detection of the single 694-keV gamma ray is demanded in the $\Gamma_L$ detector, the only possibility to have the coincidence in $\Gamma_R$ and $V_R$ is due to the beta particle. Thus, the fraction of $\beta$ particles, $\Delta$, which are detected in the $V_R$ and also

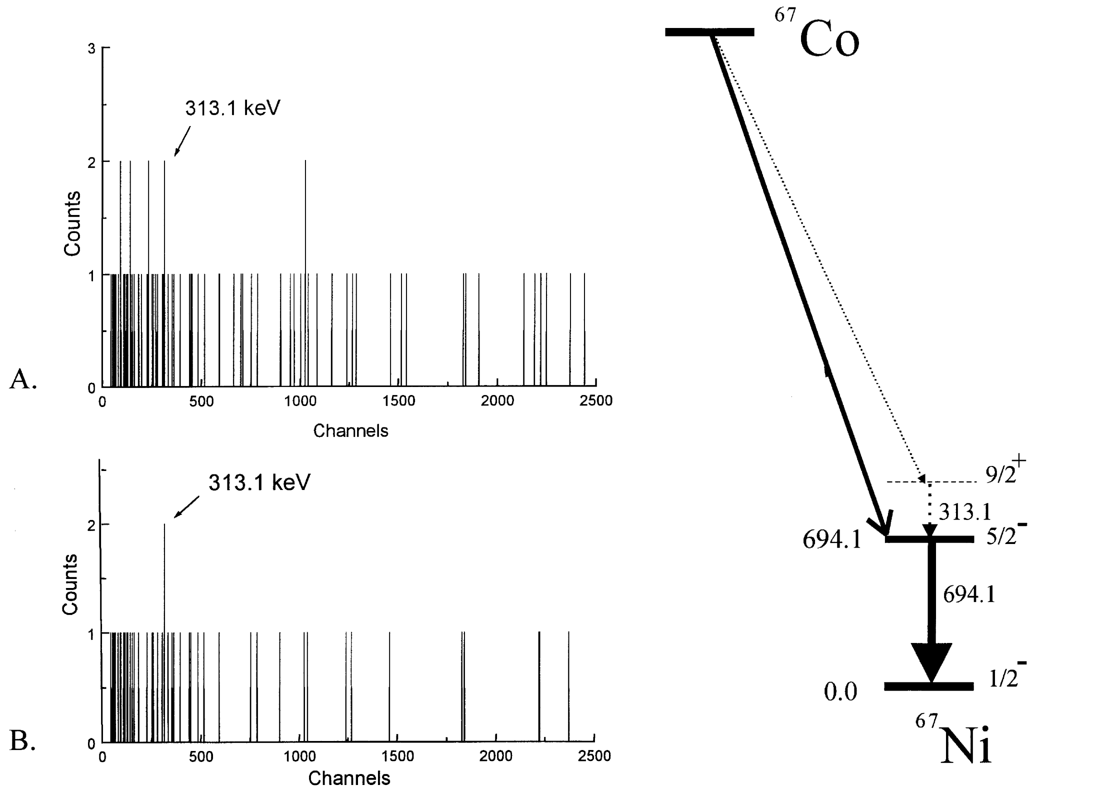


Fig. 3. The spectra of the $\Gamma_L$ gated by the 694-keV transition in the $\Gamma_R$ detector without (A) and with (B) the veto suppression. The 313.1-keV from the second excited state of $^{67}$Ni is observed.

leave signal in the $\Gamma_R$, is

$$\frac{N_{L_{V_R}\Gamma_R}}{N_{L_{V_R}B}} = \frac{\eta_{V_R}\Delta}{(\eta_{V_R} + \eta_B)},$$

where the symbol $\eta$ stands for efficiency of the $\beta$ detectors (Table 1). In a similar manner, the corresponding $\Delta$ is extracted for the $\Gamma_R$. The $\Delta$ factor for the $^{67}$Co electrons of 8.4 MeV end-point energy was found to be 0.37(3) and 0.40(3) for the $\Gamma_L$ and $\Gamma_R$ detectors, respectively. These results are also in a good agreement with GEANT simulations (see next chapter).

## 4. Results of GEANT simulations

To acquire confidence we compared the results of GEANT simulations with the results of various measurements. As a first step, we compared the $\gamma$-ray efficiency of the Ge detector measured with intensity calibrated $\gamma$ sources with GEANT simulations (Fig. 4). The nuclear level schemes, $\beta$ and $\gamma$ branching ratios, $I_\beta$ and $I_\gamma$, were introduced as input parameters in GEANT, which generate the expected spectra, taking into account the "true" summing effects for the case of the sources with larger than one $\gamma$ multiplicity, $M_\gamma$. Simulations show that the best result is obtained for the Ge detector's dead layer of order of 1 mm. This value is slightly larger compare to the manufacture's specification (0.5 mm) [10], probably due to the fact that the Ge detectors were kept warm for a long time. As it is seen from Fig. 4. the simulation is in a good agreement with the measurements.

During the on-line experiment a well-known nucleus with many $\gamma$-rays of various energy was used to measure the relative efficiency. In our case, we

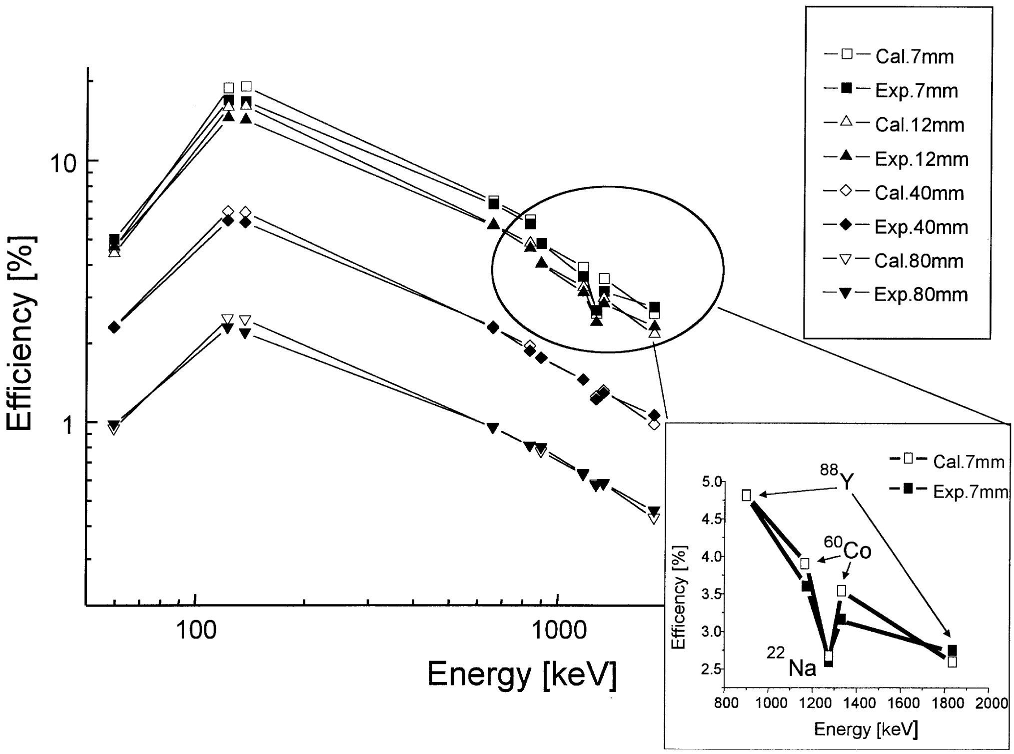


Fig. 4. The comparison of the GEANT simulation (solid lines) and the experimental data for 75% Ge detector efficiency, measured with the calibrated sources at various distances. The summing effects for $^{60}$Co and $^{22}$Na are shown in the inset.

have used an intense mass-separated beam of $^{96}$Y, which decays through a cascade of gamma rays ranging from 147 to 2226 keV (Fig. 5). One can introduce into GEANT the known level scheme and branching ratios of the $^{96}$Y transitions and obtain the absolute efficiency of the detector for each transition of the cascade. These absolute efficiencies can then be compared to the experimental relative efficiencies of $^{96}$Y transitions yielding the proper normalization factor for the latter ones. Absolute efficiencies of the single line transitions obtained by GEANT simulations are also shown in Fig. 5.

Knowing from the simulations the Ge detector response for any $\gamma$ ray energy and any geometry one can reconstruct the branching ratios and absolute $\gamma$-transitions intensities of a nucleus with a known level scheme. To demonstrate this, we have placed a $^{133}$Ba source on the Ge detector cap and compared the measured "raw" $\gamma$ intensities with the tabulated values [11]. As it is seen in Table 2, the measured intensities are much lower due to the strong summing effects (even at a modest $\gamma$ multiplicity). These summing probabilities can be

Table 2
Comparison of the "raw" absolute $^{133}$Ba $\gamma$ transitions intensities and intensities, corrected for summing effects. The summing correction were performed using GEANT simulations. The absolute intensities quoted in Table of Isotope [12] and average multiplicity of each transition are also shown

| $E$ (keV) | $M_\gamma$ | $I_{\gamma\text{raw}}$ | $I_{\gamma\text{corrected}}$ | $I_{\beta\text{TABLE}}$ |
|---|---|---|---|---|
| 53.2 | 2 | 1.55 | 2.2 | 2.2 |
| 80.0 | 2.5 | 22.4 | 36.2 | 36.8 |
| 160.6 | 2 | 0.44 | 0.63 | 0.65 |
| 223.2 | 3 | 0.33 | 0.47 | 0.45 |
| 276.4 | 3 | 5.07 | 7.24 | 7.16 |
| 302.9 | 2 | 14.47 | 17.02 | 18.33 |
| 356.0 | 2 | 50.93 | 60.0 | 62.0 |
| 383.8 | 1 | 8.94 | 8.94 | 8.94 |

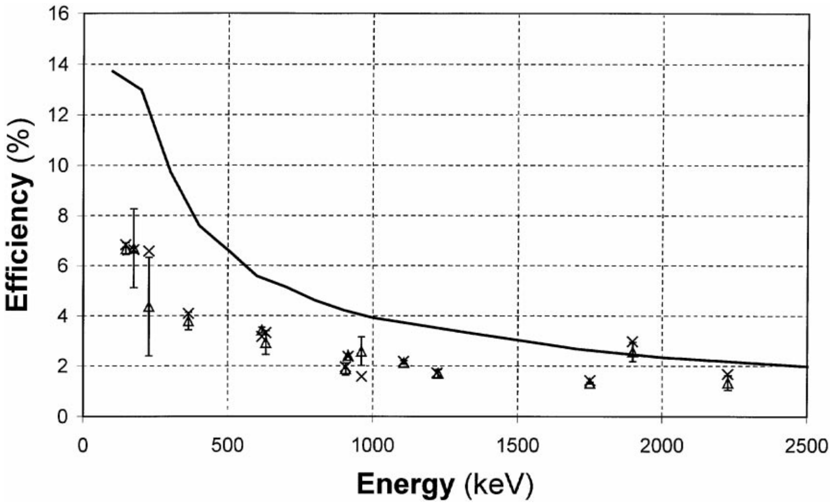


Fig. 5. The calculated absolute single transition efficiency (solid line) and, the corrected on summing effect, efficiencies (crosses) of the 75% Ge detector for $^{96}Y$ nucleus. The experimental efficiencies for $^{96}Y$ transitions are also shown (triangles). One can observe that single line efficiency value coincides with experimental value for 1897 keV line, which has $M_\gamma = 1$.

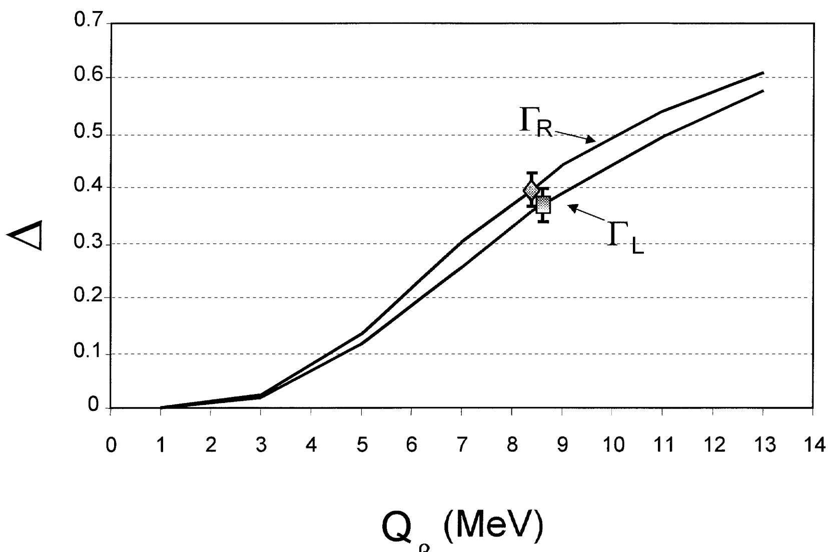


Fig. 6. The calculated β penetration factor, $\Delta$, as function of $Q_\beta$ value for two Ge detectors. The experimental values for $^{67}Co$ are also shown.

calculated by GEANT. After the corresponding corrections the absolute γ-ray intensities values are very closed to the tabulated ones (Table 2).

The efficiencies of the β detectors were calculated and compared with the experimental results. As seen from the Table 1, the GEANT simulations provide a reasonable agreement with the experimental values of the beta trigger detectors efficiencies for the both 8.8 and 4.6 MeV $Q_\beta$-values (1223 and 787 keV transitions, respectively, Table 1). The main source of the discrepancy between the simulations and the measurements comes from uncertainties in the position and size of the implantation spot.

And, finally, the β-particles "penetration" factor into γ spectrum , defined above as $\Delta$, measured in the $^{67}$Co decay could also be checked with the GEANT simulations. The results for $\Delta$ the simulation as a function of energy are shown in Fig. 6 together with measured values for $^{67}$Co. One can observe a good agreement between the simulation and measurements.

## 5. Conclusion

A new β trigger was designed for decay experiments. The total β-efficiency was found to be up to 56% for β decay with high-energy $Q$-values. Veto suppression was found to be especially useful in the case of high-energy $Q$-values and weak γ-ray transitions. GEANT Monte-Carlo simulations during various tests proved to be reliable and will be used for further simulations of more complicated experimental setups.

As a next step, we are currently designing a new tape system which will allow to implement more β detectors and increase the efficiency of the β trigger up to 80%. The utilization of a cluster of segmented Ge detectors [12] will reduce the "true" summing probability and increase the overall gamma efficiency. An implementation of a BGO Compton suppression for the Ge detector with veto suppression of the signal from the beta particle will reduce the "internal" background in the gamma spectra. All these improvements of the detection system together with improvements in the efficiencies of the laser source and ion transport will lead to new opportunities for the investigation of exotic nuclei.

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