IMPROVEMENT OF THE PERFORMANCE OF A COMPTON-SUPPRESSION SPECTROMETER BY MINIMIZING THE DEAD LAYER OF THE CENTRAL Ge DETECTOR

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The performance of a Compton-suppression spectrometer is investigated for two different Ge crystals as central detector; a 126 cm^3 Ge(Li) with a dead layer of 1.0 mm and a 90 cm^3 HPGe with a dead layer of 0.22 mm. The thin dead layer HPGe gives a 32% improvement in the overall Compton suppression. Predictions of the influence of the dead-layer thickness by means of Monte Carlo calculations are in good agreement. The spectrometer is further tested with radioactive sources of ^{88}Y and ^{152}Eu and the in-beam reaction ^{24}Mg + (45 MeV)^{16}O.

1. Introduction

During the last few years there has been an increasing interest in the use of Compton-suppression spectrometers for in-beam γ-ray spectroscopy with heavy-ion induced reactions, since the γ-ray spectra produced in these reactions are rather complex and therefore demand spectrometers with high resolution and low background.

In a Compton-suppression spectrometer (CSS) the background, which normally almost completely originates from Compton-scattered γ-rays, is reduced by surrounding the primary Ge detector with a scintillator, like NaI(Tl) or plastic. Only events in the central detector which occur without simultaneous observation of scattered quanta in the surrounding shield are accepted.

The inherent lower absolute efficiency of such a spectrometer, due to the required larger minimum distance between the target and central detector, would generally be a serious disadvantage for in-beam γ-ray spectroscopy. However, heavy-ion induced reactions show a reasonably large γ-ray yield and a large solid angle is not always very desirable in view of the Doppler broadening of the peaks. In practice the lower efficiency can be compensated for by the use of a higher beam intensity.

The actual performance of a CSS is, apart from the dimensions of the anticoincidence shield, mainly determined by the quality of the central detector and the amount of non-detecting material between the central detector and the surrounding shield. As far as the transmission is concerned the dead Ge layer around the central Ge crystal is the main source of non-detecting material and in the present paper its effect on the background is investigated by comparing CSS performance for a conventional Ge(Li) crystal with a 1.0 mm dead layer and a high-purity germanium (HPGe) crystal with a 0.2 mm thick Li-diffused outer contact.

To investigate the effect of a continuous variation of the thickness of the dead layer, Monte Carlo calculations have been performed.

2. Monte Carlo calculations

A Monte Carlo program has been written to simulate the histories of photons in a CSS configuration shown in fig. 1. A 115 cm^3 cylindrical closed-end Ge crystal with a dead core as an inner contact and a dead layer of variable thickness on the outside is used as a central detector. The Ge crystal is surrounded by a 1.0 mm thick aluminium cap. The influence of the MgO reflector and of the aluminium cover of the NaI can be neglected in the calculations since their contribution is relatively small. Multiple processes and an appropriate angular distribution for Compton scattering [1] are taken into account. It is assumed that in the absorption processes no second-

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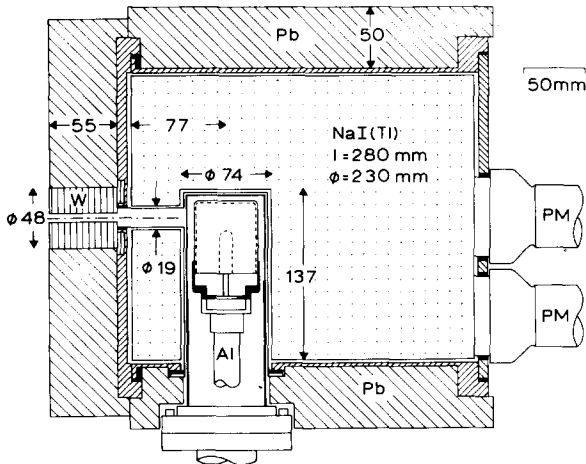
Fig. 1. Schematic drawing of the Compton-suppression spectrometer. The γ-rays enter the system through a collimator at the left side. At the right hand side two of the six multipliers are indicated. All dimensions are in mm.

ary electrons or bremsstrahlung escape from the central crystal, so that the validity of the calculations is restricted to not too small Ge volumes and not too high-energy γ-rays ($E_\gamma \leqslant 3$ MeV),

In the Monte Carlo calculations spectra of ^{60}Co are generated. To obtain a spectrum, 10^5 photons for each energy (1.17 and 1.33 MeV) are emitted from a point source in front of the collimator. The signal from the central detector is vetoed when the energy

absorbed in the NaI shield exceeds a lower level of 50 keV.

In fig. 2 we show the calculated Compton suppression averaged over the energy region 100–1100 keV. The curve is relative and normalized to unity for a dead layer of 1.0 mm.

For a reduction of the dead layer from 1.0–0.22 mm, the Monte Carlo calculation predicts an improvement of about 35% for the overall Compton suppression.

In the next section the Monte Carlo prediction is compared with test measurements.

3. Experimental results

The geometry of the NaI(Tl) anticoincidence shield is shown in fig. 1. The shield has been used in studies of high-spin states in the sd shell as reported in ref. [2].

Two crystals have been compared as central detectors; a 126 cm^3 Ge(Li) crystal with a dead layer of 1.0 mm and a dead core and a 90 cm^3 HPGe crystal with a dead layer of 0.22 mm and a hollow core. More specific properties of both detectors are given in table 1.
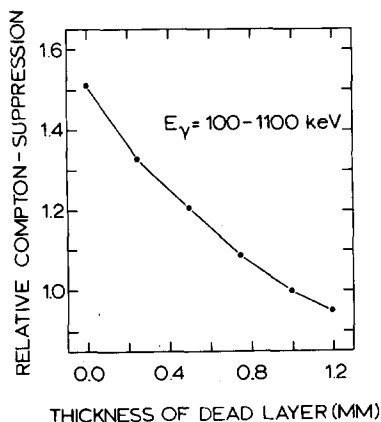

Fig. 2. Result of the Monte Carlo calculation for the relative Compton suppression as a function of the thickness of the dead layer of the central detector. The curve is normalized to unity for a dead-leayer thickness of 1.0 mm. The statistical errors are smaller than the points.

Table 1
Properties of the two detectors used as central crystal in a CSS

Manufacturer	Philips Nederland BV	Harshaw Chemie BV Holland
Type	Ge(Li)	HPGe
Active volume	126 cm^3	90 cm^3
Core	Inactive germanium	Hollow
Thickness dead layer	1.0 mm	0.22 mm
Thickness Al-cap: front side	0.5 mm 0.5 mm	0.5 mm 0.8 mm
Operating voltage	4500 V	3000 V
Efficiency	27%	20%
fwhm (1.33 MeV, ^{60}Co)	2.4 keV	1.9 keV
Peak-to-Compton ratio	46	50

3.1. The thickness of the dead layer of the HPGe detector

The thickness of the dead layer of the HPGe detector was obtained from the observed area ratio of the (79.6 + 81.0) keV complex and the 53.1 keV γ-rays from a collimated ^{133}Ba source, in the way as shown in fig. 3.

With this method the thickness of the dead layer is given by

$$d_{Ge} = \left[\ln\left(\frac{A_{(80+81)}}{A_{53}}\right) - \ln\left(\frac{I_{(80+81)}}{I_{53}}\right) - pd_{Al} \right] / q \quad (1)$$

with d_{Ge} = the thickness of the Ge dead layer in cm, $A_{(80+81)}/A_{53}$ = the observed ratio of the area of both the (80 + 81) keV and 53 keV peaks, $I_{(80+81)}/I_{53}$ = ratio of the intensities of the (80 + 81) keV and 53 keV incoming radiation,

$$p = \mu_{Al}(53 \text{ keV}) - \mu_{Al}(81 \text{ keV}) = 0.376 \text{ cm}^{-1}$$

(the difference of the linear attenuation coefficients for aluminium, see ref. [3]), d_{Al} = the thickness of the aluminium can in cm and

$$q = \mu_{Ge}(53 \text{ keV}) - \mu_{Ge}(81 \text{ keV}) = 10.62 \text{ cm}^{-1}$$

(ref. [3]). The term pd_{Al} in eq. (1) is practically negligible for the present case with d_{Al} = 0.08 cm.

The intensity ratio $I_{(80+81)}/I_{53}$ is given by Gehrke et al. [4] as 14.8 ± 1.1.

Because this value is rather inaccurate, the intensity ratio has been measured with a 5 cm³ low-energy photon spectrometer (LEPS) with a 250 μm thick Be entrance window, an ion-implanted 0.3 μm thick front contact and 10 mm depletion depth. The data are given in fig. 4. They lead to $I_{(80+81)}/I_{53}$ = 16.6 ± 0.2. Corrections due to self-absorption in the source, entrance window, front contact and depletion depth are taken into account. Their combined influence is less than 1%. Measurements of the irradiation at different angles also give consistent results.

With $I_{(80+81)}/I_{53}$ = 16.6 ± 0.2 and the present d_{Al} = 0.08 cm, eq. (1), reduces to

$$d_{Ge} = \left[\ln\left(\frac{A_{(80+81)}}{A_{53}}\right) - (2.839 \pm 0.012) \right]$$

$$\times 0.0942 \text{ cm} . \quad (2)$$

This relationship is depicted by the curve in the lower part of fig. 3.

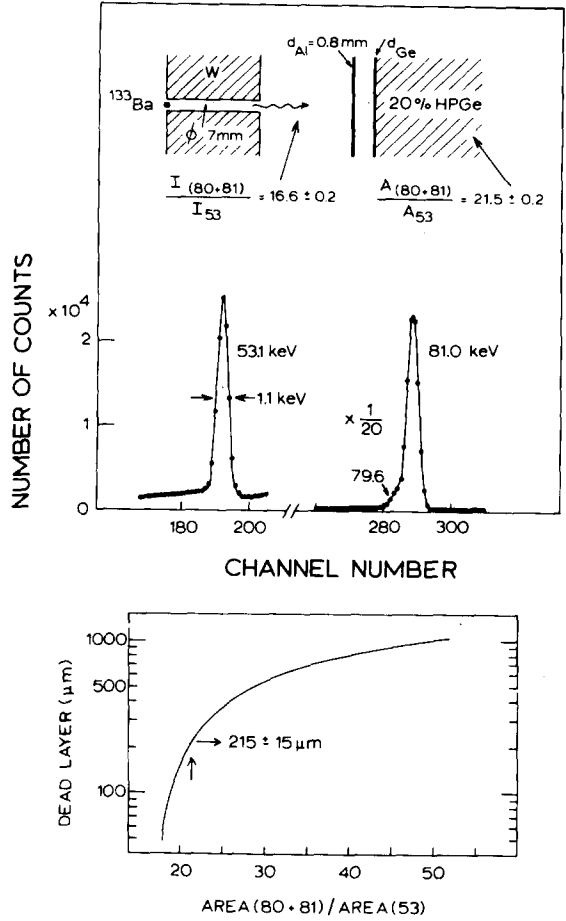The measured area ratio $A_{(80+81)}/A_{53}$ = 21.5 ± 0.2

Fig. 3. Method to measure the dead-layer thickness of a Ge detector. The method is based on the difference in transmission of the dead layer for the (80 + 81) keV complex and the 53 keV γ-ray of a ^{133}Ba source. For the present HPGe detector the area ratio amounts to $A_{(80+81)}/A_{53}$ = 21.5 ± 0.2. The lower part gives the thickness of the dead layer as a function of the measured area ratio.
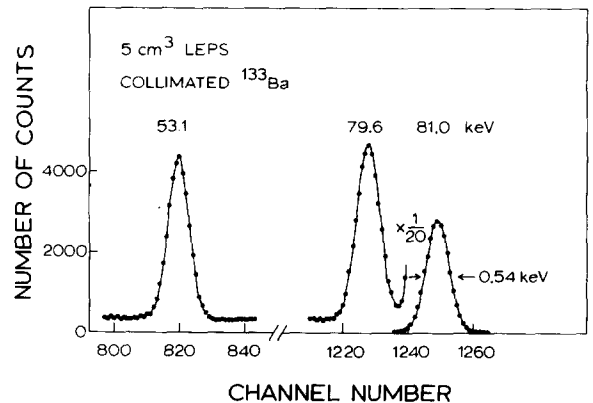

Fig. 4. The 53.1, 79.6 and 81.0 keV γ-rays from ^{133}Ba as measured with a 5 cm³ LEPS.

implies a thickness of (215 ± 15) μm for the dead layer of the HPGe detector.

For the 126 cm³ Ge(Li), the area ratio is measured as 48.3 ± 1.1, which corresponds to a dead-layer thickness of (980 ± 25) μm.

From the data of fig. 4 follows as a byproduct $I_{81.0}/I_{79.6} = 12.5 \pm 0.2$ for the intensity ratio of the 81.0 and 79.6 keV γ-rays from ^{133}Ba.

3.2. Experimental performance of the CSS for two different crystals as the central detector

With the HPGe crystal as the central detector a ^{60}Co spectrum has been recorded with a PDP 11/40 computer. The HPGe–NaI anti-coincidence pulse is used to gate two ADCs, such that two spectra, one coincident and one anti-coincident with the NaI pulse, are recorded simultaneously. The results are shown in fig. 5. The upper spectrum is the sum of the two recorded spectra and represents the result without Compton suppression (i.e. the normal HPGe spectrum). The lower spectrum is with Compton-suppression. The insert gives the ratio between the number of counts in the upper and lower spectrum,

i.e. the Compton suppression as a function of energy. The loss of pulses in the photopeak due to random veto's is less than 2%. The average Compton suppression between 100–1100 keV amounts to 11.2. The Compton edges are reduced to little bumps due to the small diameter of the entrance hole in the NaI(Tl) shield. Their shape differs appreciably from that of a normal peak. The single-escape peak of the 1332 keV γ-ray is suppressed with the same factor as the background while the double-escape peak disappears due to the absence of collinear holes in the NaI(Tl) shield.

The areas of the 1173 and 1332 keV peaks taken together amount to 65% of the total number of registered counts for the suppressed spectrum and 18% for the non-suppressed spectrum.

The Compton suppression for ^{60}Co with the 1.0 mm dead layer Ge(Li) crystal as the central detector is obtained similarly as described above. The result is shown in the middle part of fig. 6. The average Compton-suppression between 100 and 1100 keV is now 8.4. The upper part of fig. 6 again shows the Compton suppression for the 0.2 mm dead layer HPGe.
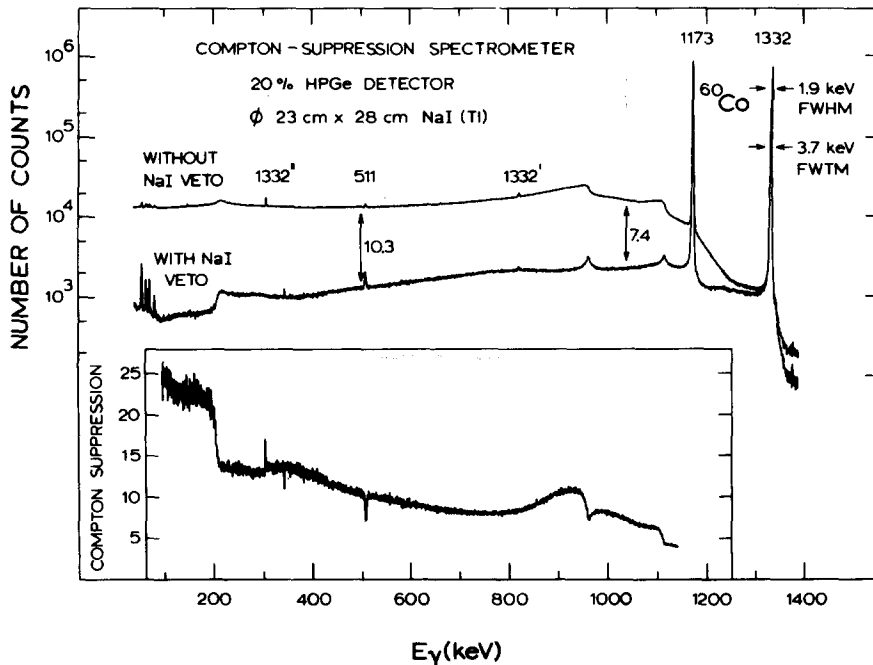

Fig. 5. Spectra of ^{60}Co for a 90 cm³ HPGe crystal as central detector. The upper spectrum is without Compton suppression, the lower spectrum is with Compton suppression. The insert shows the ratio between the number of counts in the upper and lower spectrum, i.e. the Compton suppression as a function of the energy.
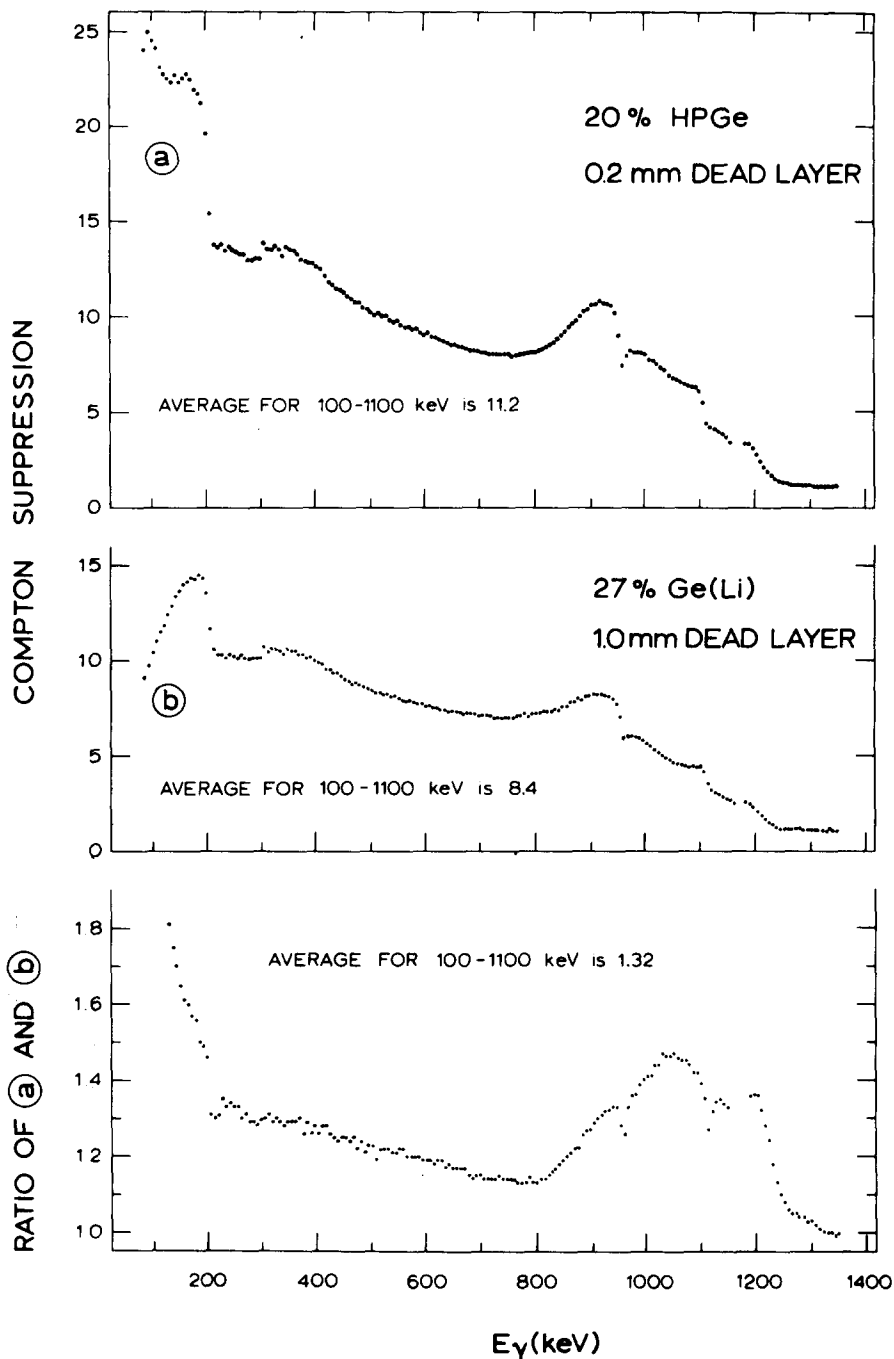
Fig. 6. Comparison of the Compton suppression for ^{60}Co for the 1.0 mm dead layer Ge(Li) and the 0.2 mm dead layer HPGe crystals as the central detector. The differences for $E_\gamma < 200$ keV between the top and the middle curve are probably due to different timing properties.

The lower parts of fig. 6 gives the ratio of the two Compton suppressions and thus shows the improvement in performance of the spectrometer as a function of energy. The improvement is especially notable for the (high-background) region around the Compton edges (800–1150 keV), i.e. the energy
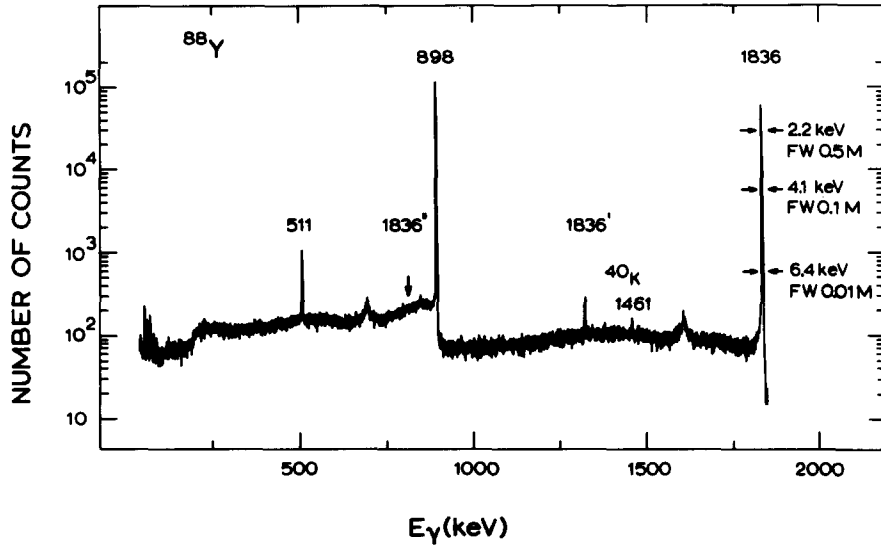
Fig. 7. Compton-suppressed spectrum of a ^{88}Y source.

region corresponding to the escape of Compton-scattered photons of low energy from the central detector. Reduction of the dead layer surrounding the central detector makes it more transparent for these low-energy γ-rays, which can now reach the surrounding shield more easily to produce a veto signal.

The average improvement for 100–1100 keV is 32% in good agreement with the Monte Carlo prediction of 35%.

3.3. Performance of the CSS with the thin-dead-layer HPGe as central detector for radioactive sources ^{88}Y and ^{152}Eu and the in-beam reaction $^{24}Mg + (45\,MeV)^{16}O$

In fig. 7 we give the spectrum from a ^{88}Y source. The peak-to-Compton ratio for the 1836 keV peak is 650, i.e. the residual Compton background is lower by almost three orders of magnitude. The sum of the
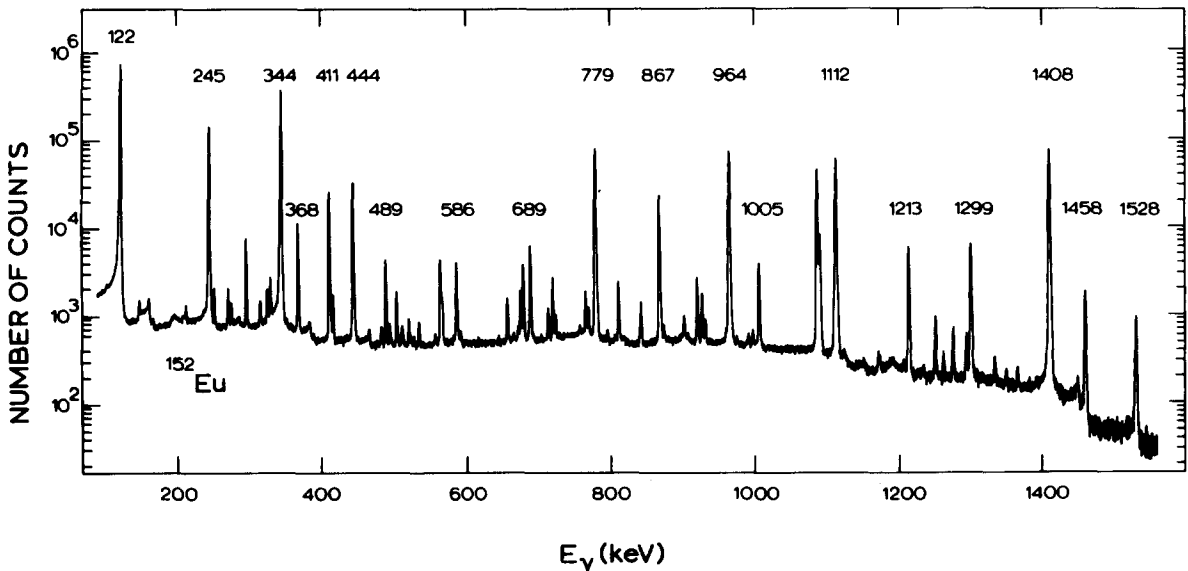

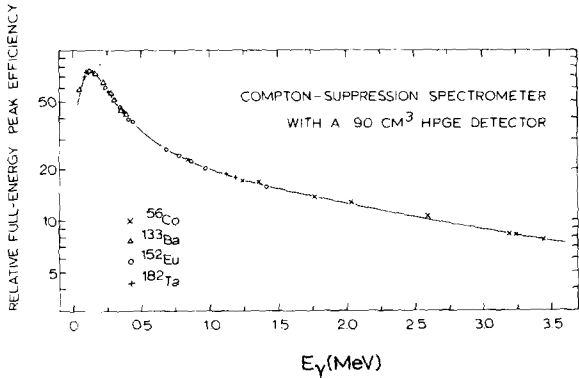Fig. 8. Compton-suppressed spectrum of a ^{152}Eu source.

Fig. 9. The relative full-energy peak efficiency for the CSS with the 90 cm³ HPGe crystal as the central detector.

^{56}Co (ref. [5]), ^{133}Ba (ref. [4]), ^{152}Eu (ref. [5]) and ^{182}Ta (ref. [4]). The relative intensities are taken from the references indicated. The result is shown in fig. 9. The slope of the efficiency curve for higher energies is less steep, when compared with the HPGe detector outside the NaI shield. This reflects the thickness (48 mm) of the selectively irradiated part of the central detector (see fig. 1).

In fig. 10 we show the low-energy part ($E_\gamma < 2$ MeV) of a singles γ-ray spectrum of the heavy-ion reaction ^{24}Mg + ^{16}O at $E(^{16}$O$) = 45$ MeV and $\theta_\gamma = 90°$. The measuring time was 5 h with a ^{16}O^{6+} beam current of 100 nA (electrical) on a 320 μg · cm^{-2}, 99.94% enriched, ^{24}Mg target on thick Au. The upper spectrum is without the NaI veto. The lower one is the Compton-suppressed spectrum. The suppression varies from about 7 to 12.

This spectrum clearly shows the advantage of a CSS for in-beam γ-ray spectroscopy.

Weak and hardly visible peaks in the upper spectrum stand out clearly in the lower spectrum, see e.g. the 350 and 1400 keV regions.
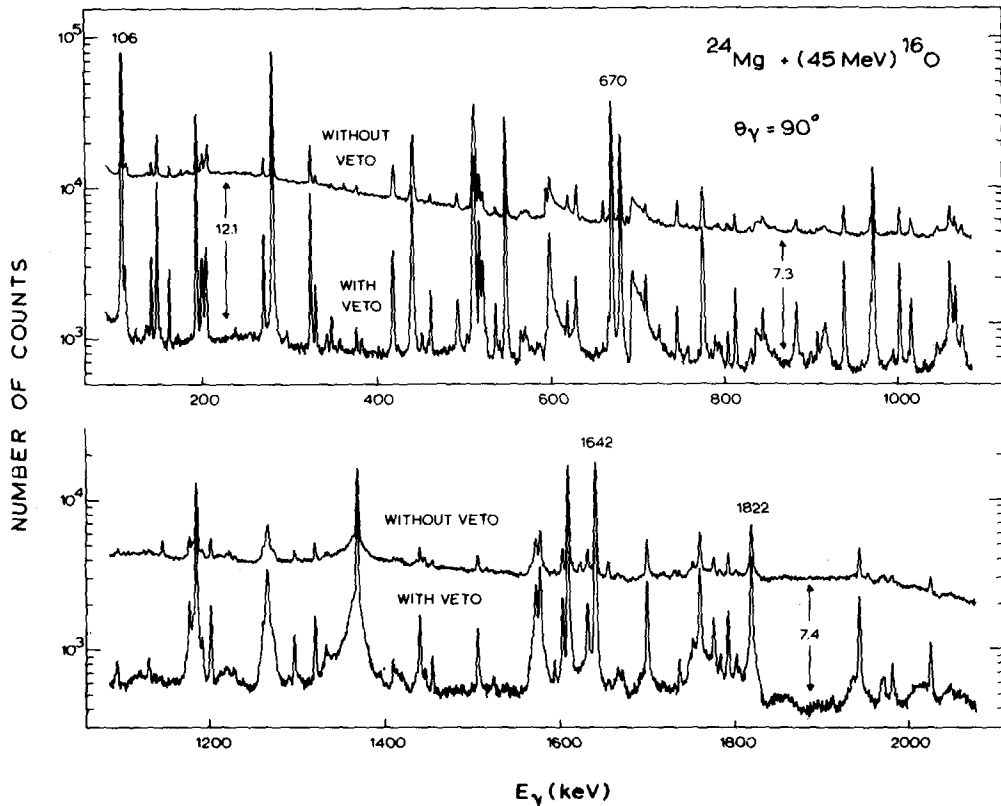
areas of the 898 and 1836 keV peaks amount to 62% of the total number of registered counts.

In fig. 8 we show the more complicated γ-ray spectrum of a ^{152}Eu source. The relative full-energy peak efficiency for the CSS has been measured with

Fig. 10. Suppressed and non-suppressed γ-ray spectrum observed with the CSS at $\theta_\gamma = 90°$ in the bombardment of a 320 μg cm^{-2}, 99.94% enriched, ^{24}Mg target on thick Au with a 45 MeV, 100 nA, ^{16}O^{6+} beam after 5 h measuring time.