

## A NEW METHOD IN GAMMA-RAY SPECTROSCOPY: A TWO CRYSTAL SCINTILLATION SPECTROMETER WITH IMPROVED RESOLUTION

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A new method has been developed to measure the spectra of gamma radiation emitted in cascade disintegrations. Use is made of a two-crystal scintillation spectrometer and a gated multi-channel analysing device. The pulses produced by summing the outputs of the two crystal-photomultiplier combinations are selected by a single-channel differential discriminator. The output of this differential discriminator gates the multi-channel analyser whenever the sum pulse corresponds to the release in the crystals of the full energy available in the cascade. The spectrum displayed is that of either of the two detectors.

The most important features of the technique are:

- (a) only "full-energy" peaks are detected;
- (b) improved resolution is obtained especially at higher gamma-ray energies;
- (c) one  $\gamma$ - $\gamma$  or p- $\gamma$ - $\gamma$  angular correlation experiment determines the angular correlation of the gamma rays of all double cascades deexciting a given level.

Details of operation and typical spectra are presented. It is suggested that the technique be called the "sum-coincidence" method.

### 1. Introduction

In a normal single-crystal gamma-ray scintillation spectrometer the pulse-height distribution produced by monoenergetic gamma radiation is rather complicated because of the different processes which arise in the conversion of the gamma-ray energy into an electric pulse. Therefore, since the beginning of gamma-ray scintillation spectroscopy there has been a tendency to simplify the observed spectra by using more than one crystal. In the two-crystal coincidence spectrometer developed by Hofstadter and McIntyre<sup>1)</sup> Compton-scattering processes are selected by a coincidence arrangement between the incident radiation and the radiation scattered at a certain angle. In the two-crystal anticoincidence spectrometer introduced by Albert<sup>2)</sup> only those pulses from one crystal are accepted which are not in coincidence with a pulse in a large crystal surrounding the first one. In the three-crystal triple-coincidence spectrometer constructed by Johansson<sup>3)</sup>, and independently by Maienschein and Bair<sup>4)</sup>, only those pair processes are accepted which are in coincidence with the detection of both annihilation

quanta in lateral crystals. All these solutions suffer from the disadvantage that if the resolution is good the efficiency becomes very small and vice versa. This is especially serious if the gamma-ray spectrum is complicated and contains a number of coincident lines. It is almost impossible to use one of these spectrometers to measure  $\gamma$ - $\gamma$  coincidence spectra or  $\gamma$ - $\gamma$  angular correlations.

In the present paper a new type of scintillation spectrometer is described especially suited to measure  $\gamma$ - $\gamma$  coincidence spectra and  $\gamma$ - $\gamma$  angular correlations. The new spectrometer combines good resolution with a relatively high efficiency for both low and medium gamma-ray energies. The main features are:

- (a) The pulse distribution shows only one peak, the "full energy" peak, for one specific gamma transition. There is no contribution to the spectrum from processes in which only part

<sup>1)</sup> R. Hofstadter and J. A. McIntyre, *Phys. Rev.* **78** (1950) 619.

<sup>2)</sup> R. D. Albert, *Rev. Sci. Instr.* **24** (1953) 1096.

<sup>3)</sup> S. A. E. Johansson, *Nature* **166** (1950) 794.

<sup>4)</sup> F. C. Maienschein and J. K. Bair, *Phys. Rev.* **82** (1951) 317 (A).

of the available gamma-ray energy is absorbed.

(b) The absolute half-widths of the peaks due to coincident gamma rays are, to first approximation, equal.

(c) The detection efficiencies of coincident gamma rays are equal.

## 2. Principle of operation

In many cases (e.g. in all  $(p,\gamma)$  reactions) a complicated nuclear decay scheme can be subdivided into a number of cascades starting all at one single level and ending at the ground

tillation counters. If both scintillation counters have the same energy calibration the sum of their output pulses is proportional to the sum of the energies absorbed in the two crystals. Therefore, if both gamma quanta of a cascade are fully absorbed, this sum pulse as obtained from a linear adding network corresponds to the release of the total energy involved in the cascade. Pulses from one of the scintillation counters which are in coincidence with these special sum pulses all belong to processes of full-energy absorption of one or both gamma

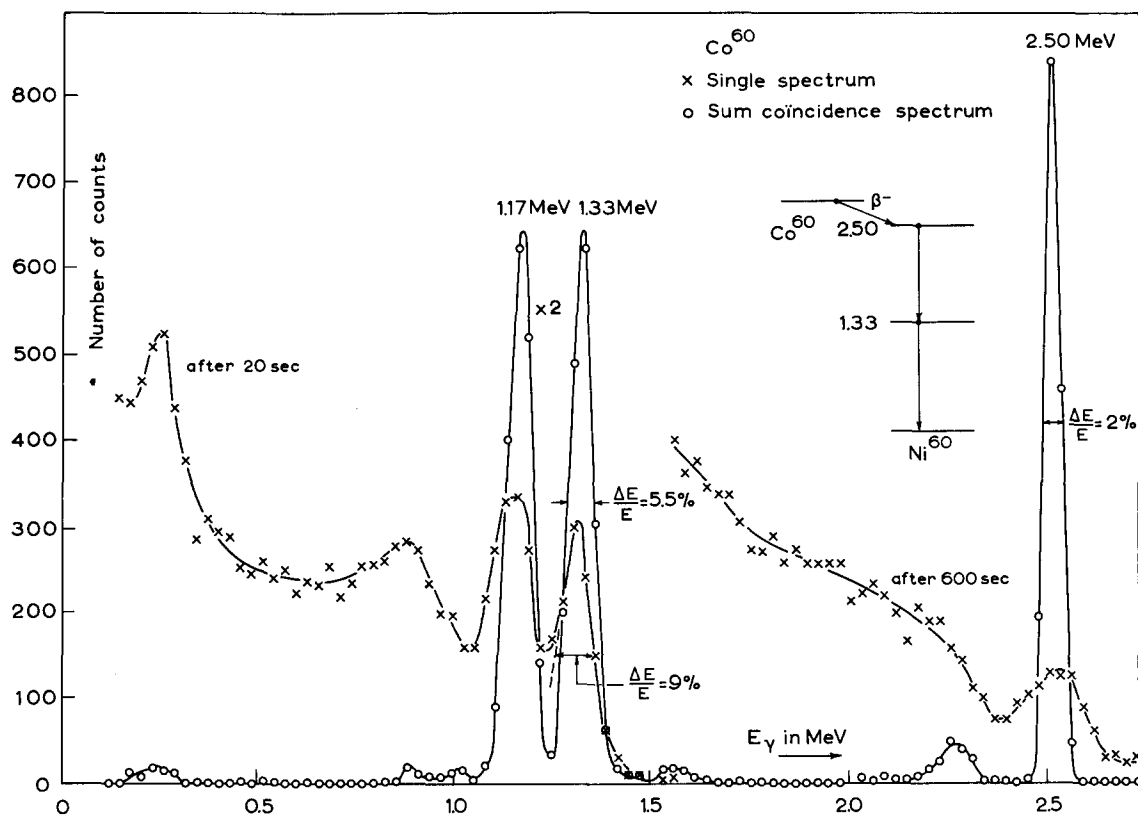


Fig. 1. Single and sum-coincidence spectrum of  $\text{Co}^{60}$  using 2" crystals. The single spectrum indicated by crosses is on an arbitrary scale. The sum-channel setting is at 2.50 MeV. In this measurements no lead shielding was applied between crystals. The small peaks at 0.25, 1.0, 1.6, and 2.30 MeV are due to back-scattering.

state of a nucleus. The principle of operation is based on the fact that the total energy involved in different cascades is the same. For simplicity the discussion will be limited to cascades of two gamma rays only.

The two gamma rays of one of these cascades can be detected in coincidence with two scin-

quanta in this crystal. Thus this coincidence spectrum shows only the full-energy peaks of the gamma rays of the cascade, accompanied by a peak due to the absorption of both gamma quanta in one crystal. In practice this "sum-coincidence" spectrum is obtained by gating a multi-channel pulse-height analyser. The gate

pulse is selected from the spectrum of sum pulses by a differential discriminator.

The sum-coincidence method will be elucidated by a simple example of a single cascade. The nuclide  $\text{Co}^{60}$  decays by  $\beta^-$  emission to the 2.50 MeV level in  $\text{Ni}^{60}$ . The 2.50 MeV level is deexcited by a cascade of 1.17 and 1.33 MeV gamma rays to the ground state. No cross-over is observed. In fig. 1 the pulse spectrum is shown obtained by applying the sum-coincidence method. In this case the channel of the differential discriminator of 2% width was set at 2.50 MeV. A further explanation of fig. 1 is given in section 5.

In the next section a description will be given of the necessary apparatus.

### 3. Apparatus

In this section a description is given of a sum-coincidence scintillation spectrometer. A schematic diagram is shown in fig. 2. The crystals CR1 and CR2 are shielded from each other by lead cones. About 7 cm of lead is put around the crystals to reduce background. The pulses from the cathode followers CF1a and CF2a are fed to the amplifiers 1 and 2, and to the linear adding network. The linear adding network comprises the cathode followers CF1b and CF2b, the resistors  $R_1$  and  $R_2$ , and a potentiometer RV1. The values of  $R_1$  and  $R_2$  are about 10 times the output impedance of the cathode followers. As mentioned in the preceding section the energy calibration of both detectors has to be the same. This is done by adjusting the high voltage of one of the multiplier tubes. The potentiometer RV1 serves as a fine adjustment. After amplification the sum pulses are fed into a differential discriminator to select the sum channel. The multi-channel analyser is gated with these selected pulses.

In fig. 2 no special coincidence arrangement is included. Actually the adding network acts as a slow coincidence circuit with a time resolution of about 3  $\mu\text{sec}$ . However, at high counting rates a coincidence circuit between CF1a and CF2a will be necessary. The extension to a system for high counting rates comprises also a

second coincidence circuit between the output pulse from "D.D. sum" and the output pulse from the first coincidence circuit.

The output of amplifier 2 can be used as a monitor in angular correlation experiments.

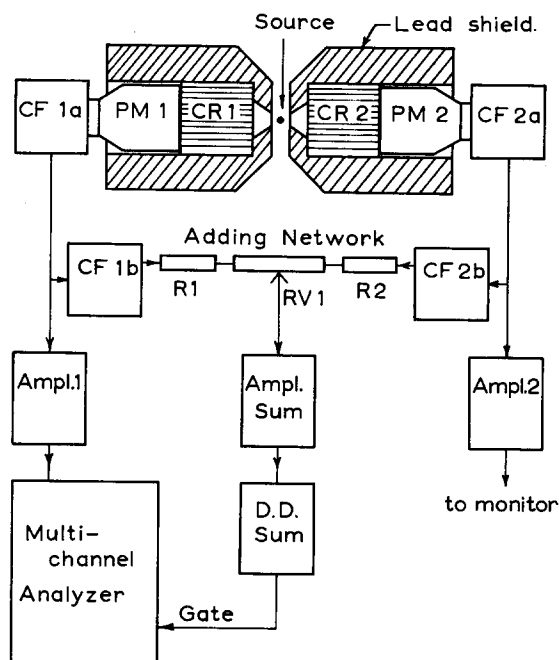


Fig. 2. Experimental arrangement of the sum-coincidence method. CR1 and CR2 are the two crystals, PM1 and PM2 indicate photomultipliers. The four cathode followers are labelled CF1a and b and CF2a and b. The pulses summed in the adding network are amplified by the amplifier "Sum". The sum-channel is chosen with the differential discriminator "D.D.sum".

The bias and channel width of the differential discriminator "D.D. sum" influence the shape of individual gamma-ray peaks. This is discussed in the next section.

### 4. Resolution and Efficiency

It is assumed that the gamma rays  $\gamma_1$  and  $\gamma_2$  with energies  $E_{01}$  and  $E_{02}$  respectively, are in cascade, and that the pulse distributions  $f_1(E_1 - E_{01})$  and  $f_2(E_2 - E_{02})$  corresponding to the "full-energy" peaks are gaussian with half-widths (full width at half maximum) of  $\Gamma_1$  and  $\Gamma_2$ , respectively. For mathematical simplicity the sum channel will also be assumed to have a gaussian transmission  $f_s(E_1 + E_2 - E_{0s})$

with a half-width  $\Gamma_s$ . The bias of the sum channel is set such that  $E_{0s} = E_{01} + E_{02}$ . The functions  $f_1$  and  $f_2$  are normalized such that the total numbers of pulses in the corresponding full-energy peaks equal  $\varepsilon_1$  and  $\varepsilon_2$ , where  $\varepsilon_1$  and  $\varepsilon_2$  are the full-energy efficiencies (including solid angle) for detection of  $\gamma_1$  and  $\gamma_2$ , respectively. The area under  $f_s$  amounts to  $\Gamma_s$ .

By multiplying  $f_1$ ,  $f_2$ , and  $f_s$ , and by integrating over  $E_2$  one obtains the pulse distribution in the sum-coincidence spectrum of the peak corresponding to  $\gamma_1$ . The half-width  $\Gamma_{s1}$  of this peak is given by:

$$\Gamma_{s1} = \Gamma_1 \sqrt{\Gamma_2^2 + \Gamma_s^2} / \sqrt{\Gamma_1^2 + \Gamma_2^2 + \Gamma_s^2}. \quad (1)$$

This proves that a peak in the sum-coincidence spectrum is always narrower than the corresponding peak in the single spectrum.

The best energy resolution is obtained, of course, if the sum channel is made vanishingly narrow ( $\Gamma_s \ll \Gamma_1$  and  $\Gamma_s \ll \Gamma_2$ ). Then:

$$\Gamma_{s1} = \Gamma_{s2} = \Gamma_1 \Gamma_2 / \sqrt{\Gamma_1^2 + \Gamma_2^2}. \quad (2)$$

In this case the peaks in the sum-coincidence spectrum corresponding to  $\gamma_1$  and  $\gamma_2$  have the same width. Both peaks are narrower than the narrowest of the two peaks in the single spectrum. This especially serves to improve the resolution in the high-energy region. If a 1 MeV and a 6 MeV gamma ray are in cascade, both having full-energy peaks in the single spectrum of 6% width, the width of the high-energy gamma ray in the sum-coincidence spectrum will only be 1%. If  $\gamma_1$  and  $\gamma_2$  have about equal energies and widths (which applies to the  $\text{Co}^{60}$  case) the improvement in resolution will still be a factor  $\sqrt{2}$ . The improvement obtained is especially welcome when the single-spectrum resolution is low, which is the case e.g. for large crystals. In practice there is no advantage in making  $\Gamma_s$  smaller than the smallest of  $\Gamma_1$  and  $\Gamma_2$ .

If the bias of the sum channel is not set correctly ( $E_{0s} \neq E_{01} + E_{02}$ ) the peaks in the sum spectrum corresponding to  $\gamma_1$  and  $\gamma_2$  are still gaussian but they are shifted. This shift is not a constant percentage of the setting error

$E_{0s} - (E_{01} + E_{02})$  and thus the spectrum is distorted. Careful bias setting is thus necessary.

The efficiency  $\varepsilon_{s1}$  for detection of  $\gamma_1$  with the sum-coincidence method is easily found by integrating the corresponding pulse distribution over  $E_1$ . This yields:

$$\varepsilon_{s1} = 2\sqrt{\ln 2/\pi} \varepsilon_1 \varepsilon_2 \Gamma_s / \sqrt{\Gamma_1^2 + \Gamma_2^2 + \Gamma_s^2}. \quad (3)$$

As this is symmetric in the indices 1 and 2 the areas of the peaks corresponding to  $\gamma_1$  and  $\gamma_2$  have to be equal. Any deviation from equality, outside statistics, can only be caused by a wrong setting of the potentiometer RV1 in the adding circuit. The fact that (3) contains the product of the full-energy efficiencies means that the detection efficiency in the sum-coincidence spectrum does not depend strongly on gamma-ray energy.

In every sum-coincidence spectrum a "sum peak" appears corresponding to the energy  $E_{0s}$  chosen by the sum channel. The intensity of this peak contains contributions from:

- (a) the full-energy peak of the cross-over transition;
- (b) events in which the two gamma rays of one cascade both dissipate their total energy in crystal 1;
- (c) background.

If the experimental arrangement is symmetric (crystals of equal size at equal distance from the source) contribution (b) exactly amounts to one half the sum of the intensities of all other peaks in the sum-coincidence spectrum. Contribution (c) can easily be measured. In a symmetric arrangement the sum peak can thus be used as a sensitive measure to obtain the intensity of the cross-over transition relative to that of the cascades. With the analysis given above it is not difficult to deduce an expression relating this intensity ratio to the areas of the relevant peaks.

## 5. Measurements of spectra

To demonstrate the possibilities of the sum-coincidence method a number of gamma-ray spectra were measured. In the following discussion  $\gamma_1$ ,  $E_{\gamma_1}$ , and  $\Gamma_1$  will be used for the lower-energy gamma ray of a cascade.

## 5.1. SPECTRA MEASURED WITH TWO 2" CRYSTALS

The two 2" crystals used to measure the following spectra were both of medium quality giving about 10% half-width at  $E_\gamma = 1$  MeV and about 7% at 8 MeV.

5.1.1.  $\text{Co}^{60}$ 

The spectrum already mentioned in section 2 consists only of one cascade. As shown in fig. 1 this cascade gives rise to two well resolved peaks at 1.17 and 1.33 MeV. Because the energies of  $\gamma_1$  and  $\gamma_2$  are nearly the same while the sum channel is relatively narrow (2%) one has

$$\Gamma_{s1} \approx \Gamma_{s2} \approx \Gamma_1 / \sqrt{2}.$$

Fig. 1 also shows the single spectrum giving 9% half-width for the 1.33 MeV peak. Substitution of this value predicts a 6% half-width for this peak in the sum spectrum. This is in good agreement with the measured value of 5.5%.

somewhat smaller than that to crystal 2. Therefore the number of counts in the sum peak is higher than the number of counts in the 1.17 and 1.33 MeV peaks. The latter numbers are equal as they should be.

The small peaks at about 0.25, 1.0, 1.6, and 2.3 MeV originate from back-scattering of one detector to the other. In fig. 1 these peaks are relatively high because the lead shielding between the detectors was removed in order to show this effect clearly. Back-scattering can be avoided easily by only one centimeter of lead between the crystals in the way shown in fig. 2.

5.1.2.  $\text{Na}^{22}$ 

The decay of  $\text{Na}^{22}$  by  $\beta^+$  emission gives rise to two 0.51 MeV annihilation quanta emitted from the source in opposite directions and coincident with the gamma ray of 1.28 MeV from the first level in  $\text{Ne}^{22}$  to the ground state.

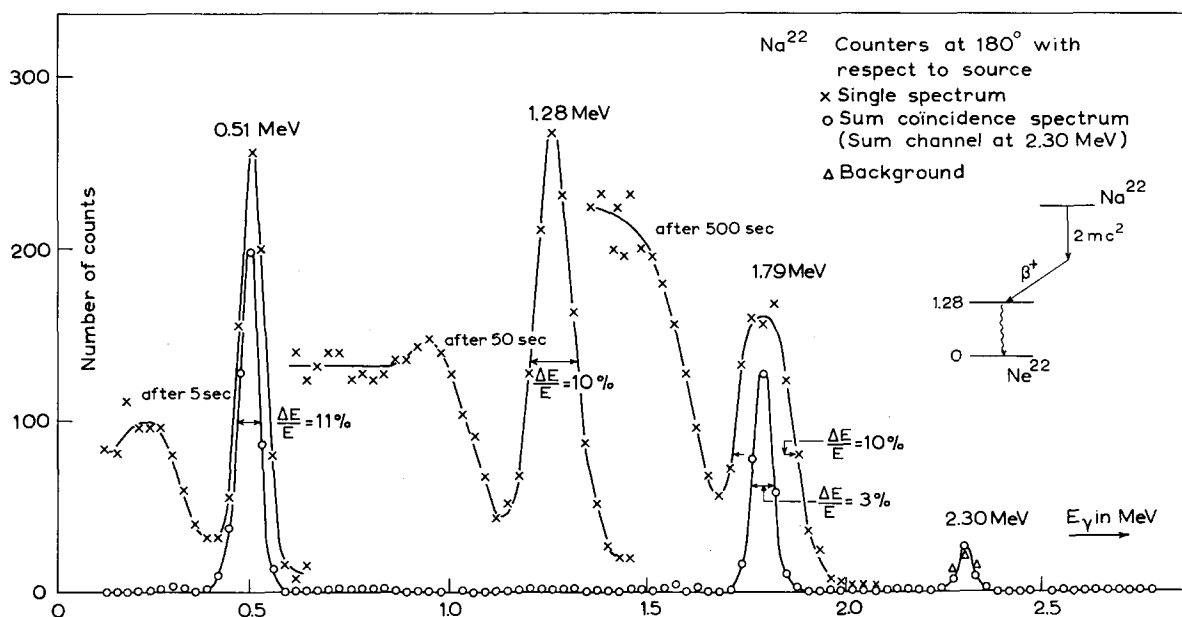


Fig. 3. Single and sum-coincidence spectrum of  $\text{Na}^{22}$  using 2" crystals. The counters are placed at  $180^\circ$  with respect to the source. The sum channel is set at 2.30 MeV. The single spectrum is given on an arbitrary scale. Note the back-ground measured near 2.30 MeV.

Because  $\text{Co}^{60}$  is known to emit no 2.50 MeV gamma ray the sum peak in this case is only due to events in which both gamma rays are absorbed in one crystal. In this measurement the distance from the source to crystal 1 was

Therefore, depending on the position of the counters and the setting of the sum channel, two different spectra can be obtained:

(a) Putting the counters at  $180^\circ$  with respect to the source gives the possibility of absorption

of one 0.51 MeV quantum in one crystal in coincidence with the absorption of the other 0.51 MeV quantum plus the 1.28 MeV quantum in the second crystal. In this case the sum of the energies involved amounts to 2.30 MeV. Fig. 3 represents a measurement with the sum channel set at 2.30 MeV. It clearly shows the impossibility of absorption of the two annihilation quanta

$\Gamma_s \ll \Gamma_2$ , and also  $\Gamma_1 \ll \Gamma_2$ . Using eq. (2) one finds for this case  $\Gamma_{s2} \approx \Gamma_1$ . Because also  $\Gamma_{s1} \approx \Gamma_1$  the absolute half-width of the peaks at 0.51 MeV and 1.79 MeV should be the same. The measurement gives  $\Gamma_{s1} = 55$  keV and  $\Gamma_{s2} = 54$  keV. This means a relative half-width for  $\gamma_2$  of only 3% compared with a 10% half-width in the single spectrum in fig. 3.

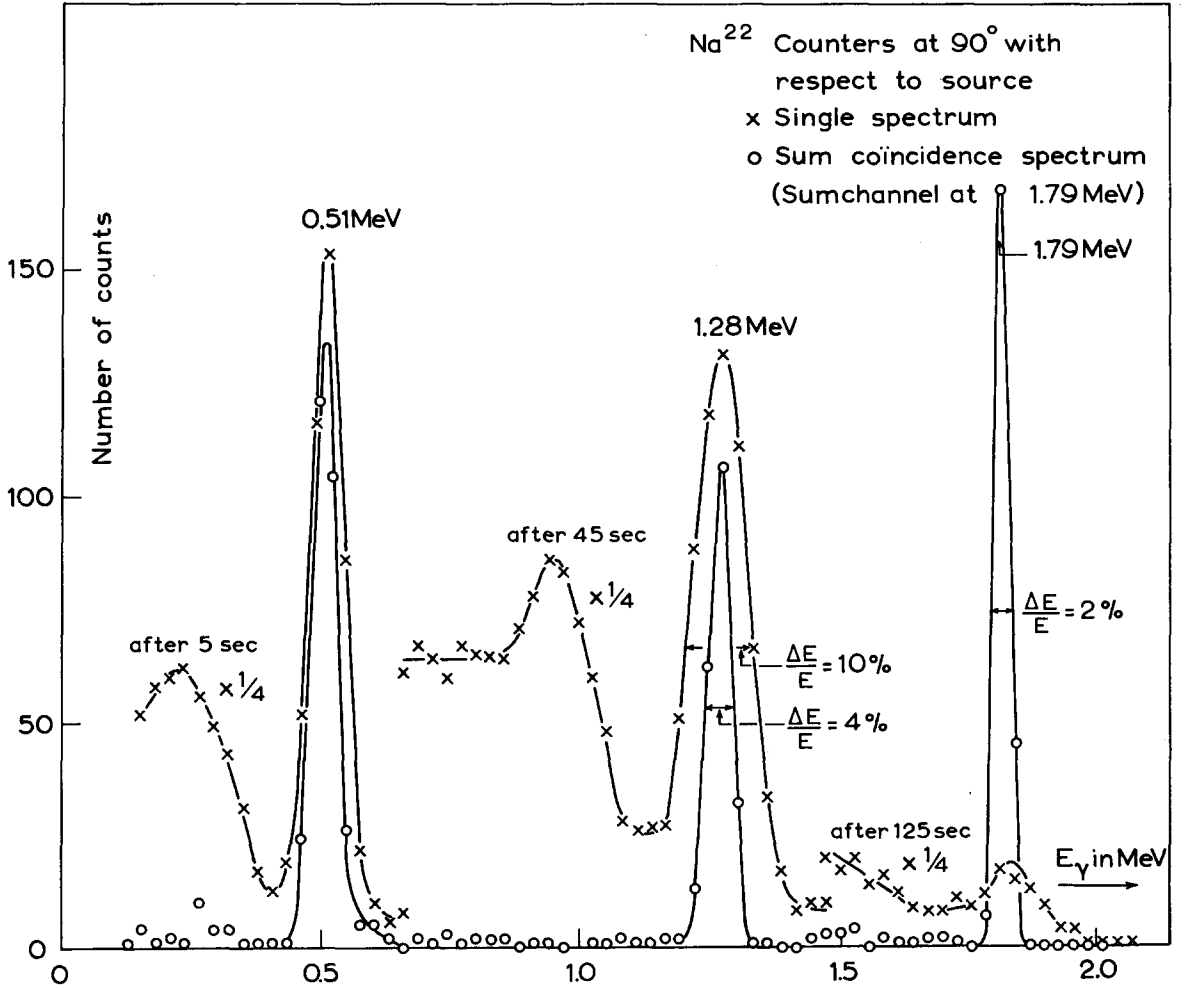


Fig. 4. Single and sum-coincidence spectrum of  $\text{Na}^{22}$  using 2'' crystals. The counters are placed at  $90^\circ$  with respect to the source. The sum channel is set at 1.79 MeV. The single spectrum is given on an arbitrary scale.

in one crystal by the complete absence of the 1.28 MeV line. For the same reason the height of the sum peak reduces to zero after subtraction of background. The width of the sum peak as determined by the channel width of the differential discriminator amounts to 1.5%. Therefore

Because in this measurement the source was nearer to crystal 2 than to crystal 1 the intensity of the 0.51 MeV peak is somewhat higher than the intensity of the 1.79 MeV peak.

(b) Putting the counters at  $90^\circ$  with respect to the source limits the sum of the energies of

the gamma rays absorbed in coincidence to 1.79 MeV. Therefore, setting the sum channel at 1.79 MeV one gets the spectrum of fig. 4 showing the 0.51 MeV and the 1.28 MeV gamma ray. Here the sum peak arises from the absorption of both gamma rays in one crystal. Substituting the values 125 keV for  $\Gamma_2$ , 50 keV for  $\Gamma_1$ , and 36 keV for  $\Gamma_s$ , as taken from the single spectrum and from the sum peak in fig. 4, into eq. (1), gives  $\Gamma_{s2} = 58$  keV. The measured value amounts to 53 keV or about 4%.

## 5.2. SPECTRA MEASURED WITH TWO 4" CRYSTALS

In this case the counters consisted of two 4" Harshaw crystals and two 5" Dumont 6394 photomultiplier tubes. These counters gave a relative half-width in the single spectrum of about 15% at 0.51 MeV and about 10% at 8 MeV.

spectrum of  $\text{Co}^{60}$  (taken to be equal to that of the 1.28 MeV line in  $\text{Na}^{22}$ ) amounts to  $\Gamma_1 \approx \Gamma_2 \approx 145$  keV. From fig. 5 one finds  $\Gamma_s = 100$  keV. Using eq. (1) one gets  $\Gamma_{s1} \approx \Gamma_{s2} \approx 110$  keV or about 8.5%. The measured value is 9%.

In this experiment the shielding between the crystals was rather good. Comparison of fig. 1 with fig. 5 indeed shows the suppression of the scattering peaks in the latter.

### 5.2.2. $\text{Mg}^{24}(\text{p},\gamma)\text{Al}^{25}$ resonance at $E_p = 222$ keV

The decay scheme of the resonance at  $E_p = 222$  keV in the reaction  $\text{Mg}^{24}(\text{p},\gamma)\text{Al}^{25}$  is shown in fig. 6. The relative intensities indicated are taken from the review article by Endt and Braams<sup>5</sup>). The spectrum comprises the two cascades 2.06, 0.45 MeV and 1.56, 0.95 MeV. The relative half-width of 5% found for the

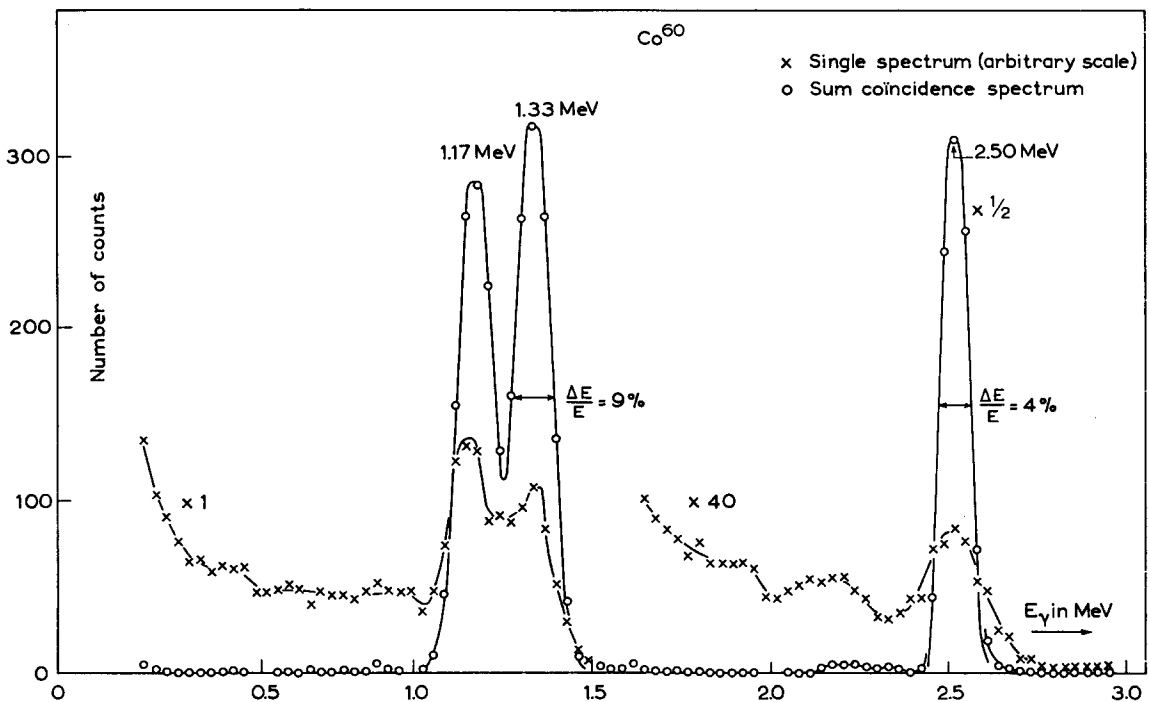


Fig. 5. Sum-coincidence and single spectrum of  $\text{Co}^{60}$  taken with 4" crystals. The sum channel is placed at 2.50 MeV.

### 5.2.1. $\text{Co}^{60}$

The peaks in the spectrum of fig. 5 are somewhat broader than the peaks in the  $\text{Co}^{60}$  spectrum of fig. 1 because of the lower quality of the large crystals. The half-width in the single

2.06 MeV line is in agreement with the calculated value from eq. (1) assuming a 10% relative half-width for the single spectrum and using the

<sup>5</sup>) P. M. Endt and C. M. Braams, *Revs. Mod. Phys.* 29 (1957) 683.

measured value of 100 keV for  $\Gamma_s$ . The widths of the lines corresponding to the 0.95 and 1.56 MeV gamma rays are also reduced. Because in this experiment the lead shielding between the

ground-state transition of about 6%. The spectrum of the 5.27, 0.69 MeV cascade represented in fig. 7 clearly shows the good resolution for two high-energy gamma rays having an

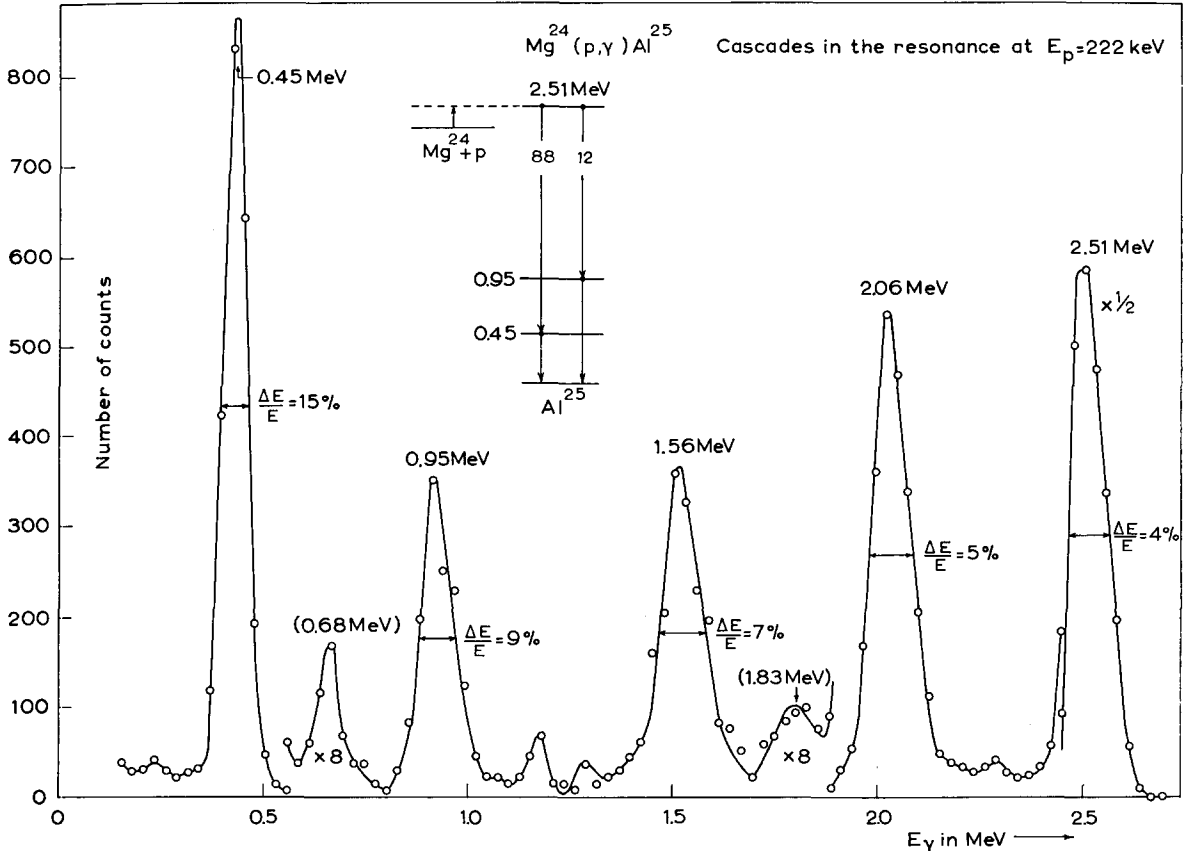


Fig. 6. Sum-coincidence measurement with 4" crystals showing cascades of 1.56, 0.95 MeV and 2.06, 0.45 MeV in the reaction  $\text{Mg}^{24}(\text{p},\gamma)\text{Al}^{25}$  at  $E_p = 222$  keV. The peaks at 0.68 and 1.83 MeV are explained in the text. The sum channel is put at 2.51 MeV.

crystals was partly removed the strong cascade 2.06, 0.45 MeV is accompanied by scattering peaks. The most evident scattering peak is observed at 0.68 MeV, whereas its complement is present as a small shoulder near 1.83 MeV. The low peaks in the 1.1 and 1.35 MeV region are not due to scattering because they appear with equal intensity in measurements with good lead shielding. They are unexplained at the present time.

#### 5.2.3. $\text{Si}^{29}(\text{p},\gamma)\text{P}^{30}$ resonance at $E_p = 414$ keV

This resonance decays primarily by a cascade of 5.27 and 0.69 MeV gamma rays. There is a

energy difference about equal to their single-spectrum half-width. The dotted line shows the single spectrum measured with the same 4" crystal. Even with the rather broad sum channel of 4%,  $\Gamma_{s2}$  is about 0.5  $\Gamma_2$ .

#### 5.2.4. $\text{Si}^{30}(\text{p},\gamma)\text{P}^{31}$ resonance at $E_p = 622$ keV

This resonance shows a very strong ground-state transition as can be seen clearly from the single spectrum given in fig. 8. The low-energy part (below 3 MeV) of this spectrum suggests the existence of two cascades by the appearance of the rather clear 1.27 MeV peak and the low peaks at 2.4 and 2.9 MeV. However, the



high-energy complements of these gamma rays are not resolved in the single spectrum. The sum-coincidence spectrum clearly shows 2.88, 5.01 MeV and 6.62, 1.27 MeV cascades. The intensities of these cascades relative to the ground-state transition amount to about 3% for each. The large intensity of the ground-state transition is

The complement of this peak appears as a small shoulder near 7.4 MeV.

At this strong resonance a background is visible resulting from random coincidences. A reduction by a factor of about 100 would be possible by the use of the fast-slow coincidence technique as indicated in section 3.

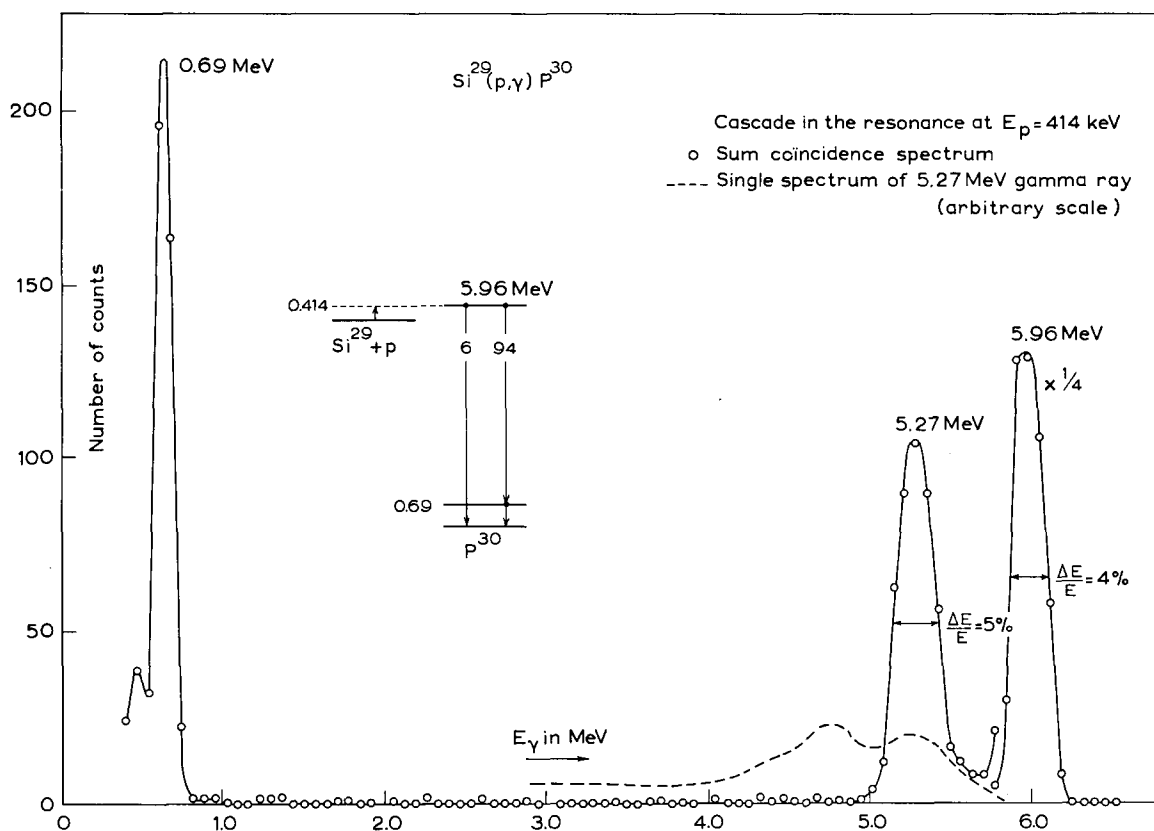


Fig. 7. Sum-coincidence measurement with 4'' crystals showing a cascade of 5.27, 0.69 MeV in the reaction  $\text{Si}^{29}(\text{p},\gamma)\text{P}^{30}$  at  $E_p = 414$  keV. The sum channel is set at 5.96 MeV. The dotted line represents the single spectrum.

apparent from the reduction factor of 1080 used in drawing the 7.89 MeV sum peak in fig. 8.

The decay scheme shown in fig. 8 was derived from the observed cascades using the known level scheme<sup>5)</sup> of  $\text{P}^{31}$ . Because it is known that there is no level at 2.88 MeV, it is concluded that the 2.88, 5.01 MeV cascade decays through a level at 5.01 MeV.

The peak at 0.51 MeV arises from pair formation by 7.89 MeV quanta in crystal 2 and detection of one of the annihilation quanta in crystal 1.<sup>7</sup>

#### 5.2.5. $\text{Si}^{30}(\text{p},\gamma)\text{P}^{31}$ resonance at $E_p = 675$ keV

The resonance at  $E_p = 675$  keV in the reaction  $\text{Si}^{30}(\text{p},\gamma)\text{P}^{31}$  presents a rather complicated decay scheme. The sum-coincidence spectrum showing the cascades in this decay is given in fig. 9. There are three strong cascades namely the 6.67, 1.27 MeV, the 4.81, 3.13 MeV, and the 4.43, 3.51 MeV cascade. Three known levels<sup>5)</sup> through which these three cascades can proceed are the levels at 1.27, 3.13, and 3.51 MeV. The relative intensities are given in the decay scheme

inserted in fig. 9. In this decay scheme three weak cascades are indicated as derived from this experiment. The corresponding relative intensities have not been corrected for possible strong triple cascades with two gamma rays of the three absorbed in one crystal. Therefore, triple coincidence measurements are necessary to confirm the results given.

relative intensities as derived from the sum-coincidence spectra have not been corrected for triple angular correlation effects. In the case of the 622 keV resonance no such effect could occur because the spin of the resonance level is  $\frac{1}{2}^5$ ). However, the spin of the 675 keV resonance is known to be  $\frac{3}{2}$ . For this resonance a correction would have been necessary.

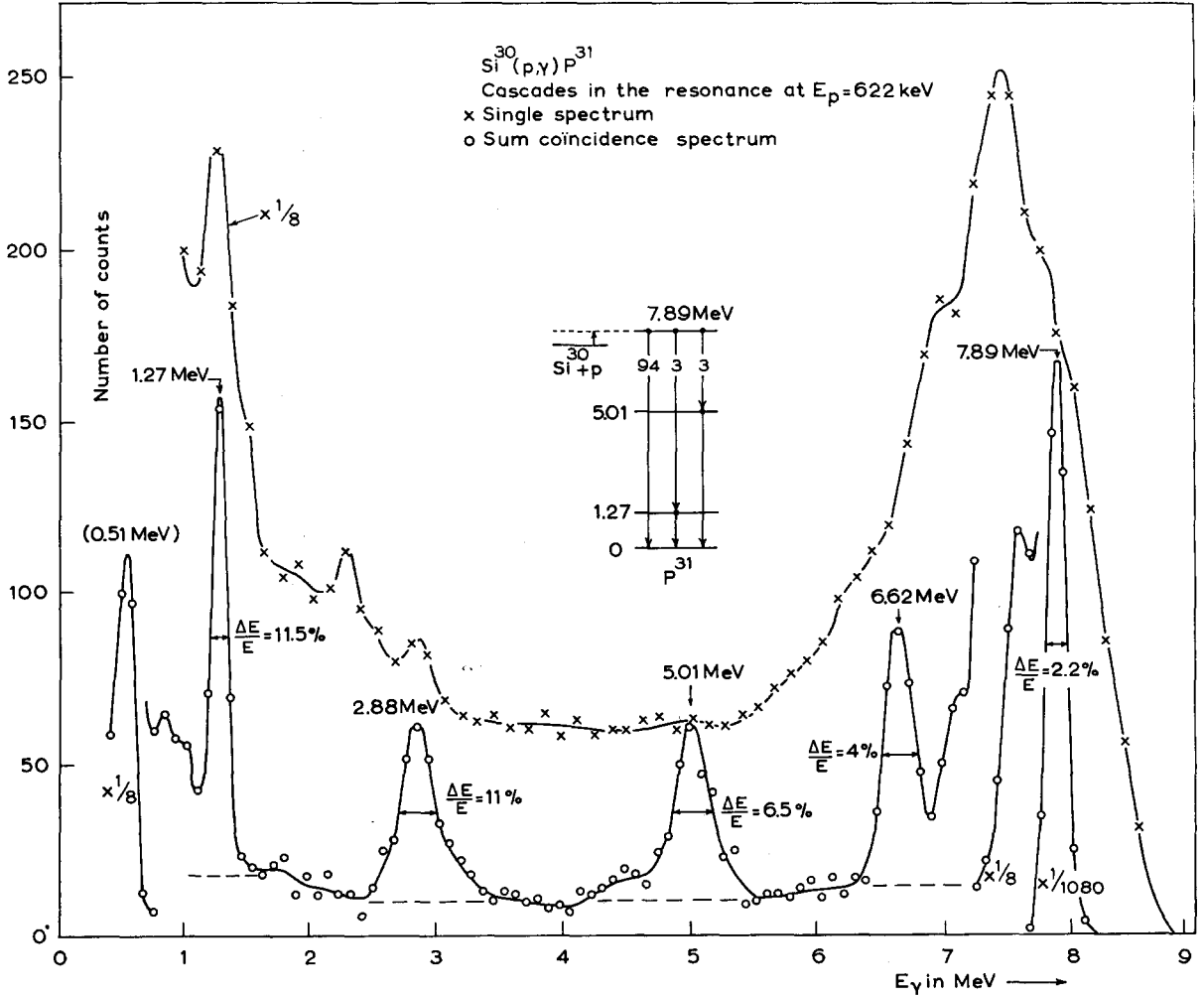


Fig. 8. Sum-coincidence measurement with 4'' crystals showing the cascades 6.62, 1.27 MeV and 2.88, 5.01 MeV in the reaction  $\text{Si}^{30}(\text{p},\gamma)\text{P}^{31}$  at  $E_p = 622$  keV. The sum channel is set at 7.89 MeV. Comparison with the single spectrum shows the gain in resolution obtained with the sum-coincidence method. Note the strong ground-state transition (the sum peak has a reduction factor of 1080).

## 6. Angular correlation measurements

In the  $\text{Si}^{30}(\text{p},\gamma)\text{P}^{31}$  experiments described above the detectors were placed at  $+90^\circ$  and  $-90^\circ$  with respect to the proton beam. The

The measurement of triple angular correlations serves as a tool to determine, in many cases uniquely, spins and parities of the levels involved. Therefore a description of the

application of the sum-coincidence method to a triple angular correlation measurement is included here.

The example chosen is the resonance at  $E_p = 760$  keV in the reaction  $\text{Si}^{30}(p,\gamma)\text{P}^{31}$ . In this experiment the detectors are placed at a

1.27 and 6.76 MeV gamma rays. The other gamma rays all are slightly anisotropic. The sum peak itself gives (after correction for back-ground and summing effects in crystal 1) the angular distribution for the ground-state transition. In the measurement the ground-state transition

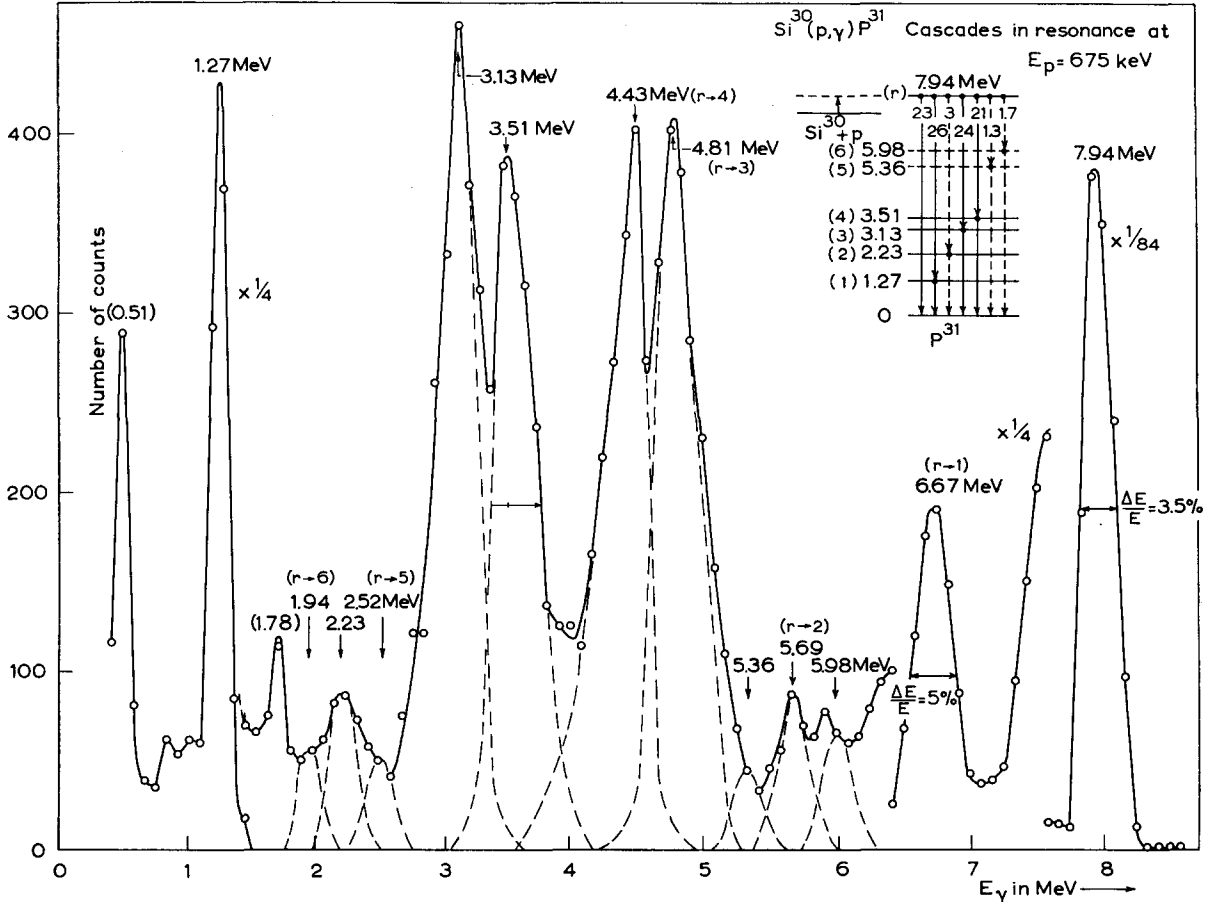


Fig. 9. Sum-coincidence measurement with 4'' crystals showing cascades in the reaction  $\text{Si}^{30}(p,\gamma)\text{P}^{31}$  at  $E_p = 675$  keV. The sum channel is set at 7.94 MeV. The decay scheme given in the insert can be derived from this measurement. An indication ( $r \rightarrow i$ ) above a peak points to the position of the corresponding transition in the decay scheme. The peak at 1.78 MeV is of analogous origin as the peak at 0.51 MeV (see § 5.2.4).

distance of 10 cm from the target. Crystal 1 can rotate in the plane determined by the proton beam and by crystal 2 as elucidated in the lower insert in fig. 10. The resonance level decays through a weak ground-state transition and through three cascades via the levels at 1.27, 2.23, and 3.51 MeV. The spectra given in fig. 10 are taken at angles of  $90^\circ$ ,  $45^\circ$ , and  $0^\circ$ , respectively. They show a strong anisotropy of the

appears almost isotropic. The implications of these measurements will not be discussed here.

## 7. Conclusions

In sections 4 and 5 theoretical and experimental results are given for the application of the sum-coincidence method to the measurement of cascades of two gamma rays. An extension of this method to cases where three

transitions determine a sequence is easily possible. It will not always be necessary to sum the signals from all three detectors involved. For example triple cascades having one transition  $\gamma_1$  in common (where  $E_{\gamma_1}$  is smaller than the energy of all other gamma rays) can be observed by detecting  $\gamma_1$  with a third crystal and requiring a coincidence between the signal from crystal 3 and the sum signal from crystals 1 and 2. The sum channel in this case has to be set at the total available energy minus  $E_{\gamma_1}$ .

the requirement that beta particles in a certain energy range be in coincidence with a sum pulse from the gamma detectors can select this special sequence. Thus all gamma cascades are observed deexciting the level fed by the selected beta transition.

## 8. Acknowledgements

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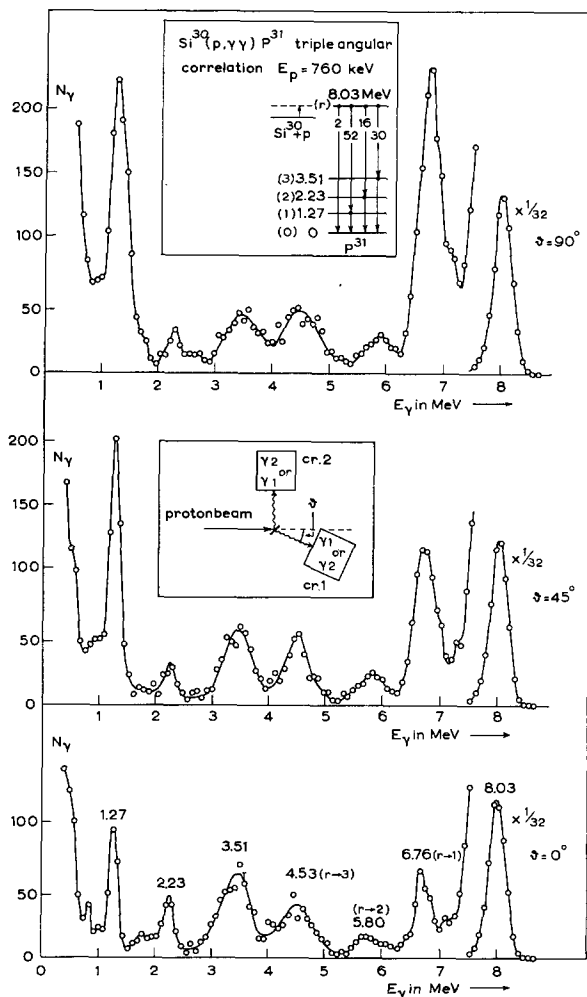


Fig. 10.  $\text{Si}^{30}(\text{p}, \gamma\gamma)\text{P}^{31}$  triple angular correlation at  $E_p = 760$  keV. The arrangement of the crystals with respect to the proton beam is given in the lower insert. The first and the second gamma ray of a cascade are denoted by  $\gamma_2$  and  $\gamma_1$  respectively. The spectra taken at angles of  $90^\circ$ ,  $45^\circ$ , and  $0^\circ$  show the angular correlations of six gamma rays with respect to the proton beam. The energies of the gamma rays are given in the spectrum at  $\phi = 0^\circ$ . The decay scheme is presented in the upper insert. Note the strong anisotropies of the gamma rays at 1.27 and 6.76 MeV. The sum peak represents (after subtraction of background and correction for summing effects in one crystal) the angular distribution of the ground-state transition with respect to the proton beam.

Another example is a radioactive isotope emitting beta and gamma radiation. Here a special sequence of one beta transition and two gamma transitions can be selected by using a beta detector insensitive to gamma rays. Then

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