Nuclear Instruments and Methods in Physics Research A275 (1989) 333–339
North-Holland, Amsterdam

USE OF DCO RATIOS FOR SPIN DETERMINATION IN γ–γ COINCIDENCE MEASUREMENTS

A. KRÄMER-FLECKEN, T. MOREK *, R.M. LIEDER, W. GAST, G. HEBBINGHAUS, H.M. JÄGER and W. URBAN *

Institut für Kernphysik Kernforschungsanlage Jülich, D-5170 Jülich, FRG

Received 16 September 1988

The use of large detector arrays allows to measure γ–γ angular correlations and to determine spins and multipolarities, even of weak and unresolved transitions. The method utilizing directional correlations of γ-rays deexciting oriented states (DCO ratio method) has been described and applied to experimental data on ^{178}W taken with the γ–γ coincidence spectrometer OSIRIS. The spin of the 35 ns isomer in ^{178}W has been established to be 14.

1. Introduction

During the last few years large multidetector arrays for γ-ray spectroscopy, consisting of more than ten anti-Compton spectrometers, have been developed and applied to the study of nuclei with large angular momentum [1]. An anti-Compton spectrometer consists of a high-purity Ge-detector and a surrounding BGO scintillator. It allows to suppress electronically events for which the γ-radiation is Compton-scattered from the Ge detector into the BGO scintillator. In this way the Compton background can be reduced by a factor of ~ 10 [1]. The Compton suppression and the use of high-resolution Ge-detectors allows to identify weak γ-rays which previously disappeared in the background. For the spin determination of the nuclear levels established in multidetector experiments and the mixing ratios of the connecting transitions, γ-ray angular correlations have to be measured. The information about γ-ray angular correlations is obtained in experiments with multidetector arrays since the detectors are placed under different angles with respect to the beam direction.

The purpose of the present article is to describe a method which allows to deduce the angular correlation information from the γ–γ coincidence data. The method discussed in the article is based on the observation of Directional Correlations of γ-rays deexciting Oriented states (DCO ratio method). As an example it has been applied to determine spins and multipolarities in ^{178}W [2] utilizing the OSIRIS array [3] consisting of twelve anti-Compton spectrometers. For the interpretation of the experimental results the computer code DCOMAP was developed which allows to calculate the angular correlations of γ–γ cascades for any spin of the associated levels and as function of the dipole–quadrupole mixing ratios of the connecting transitions. The initial substate population distribution is taken into account. Calculations can be performed for arbitrary angular positions of the detectors.

* Permanent address: Institute of Experimental Physics, Warsaw University, ul. Hoza 69, PL-00681 Warsaw, Poland.

2. Calculation of DCO ratios

The theory of directional correlations of γ-radiation emitted from oriented states is well developed and was discussed by Steffen and Alder [4] and by Krane et al. [5]. Recently, simplifications of the formulas for γ–γ angular correlations involving high-spin states were proposed [6].

For most applications the theory of DCO ratios can be simplified with respect to the general directional correlation theory by taking into account the experimental conditions (i) that unpolarized beams are used and (ii) that the detectors are insensitive to the polarization of the γ-rays. Therefore, detectors placed at forward and backward angles with respect to the beam direction can be treated in the same way. The angular correlation of γ-rays emitted from oriented states depends on the spins of the involved levels, the multipolarities and mixing ratios of the γ-transitions and the m-substate population distribution of the initial state. A compound nucleus is produced by bombarding a target nucleus with a projectile. In the reaction a large angular momentum of $I \leqslant 80\hbar$ can be transferred to the nucleus. The angular momenta of the compound nuclei are aligned in a plane perpendicular to the beam direction. The neutrons and γ-rays emitted subsequently in random directions do not change the alignment very much.

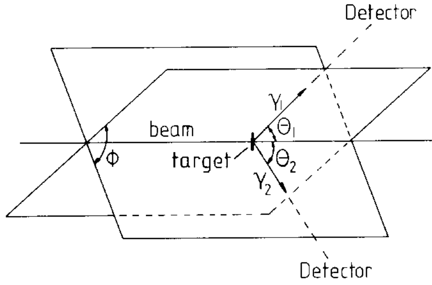

Fig. 1. Geometry of the detector arrangement with the beam as orientation axis.

Therefore a Gaussian distribution centered at $m = 0$ can be used to describe the m-substate population with a half width σ for a given spin. The quantity σ/I is approximately constant over a wide spin range. A deviation from this empirical fact occurs only in the low-spin region $I \leq 6$.

The γ-radiation from the decaying final nucleus is mostly of dipole or quadrupole nature or a mixture of both types. In an experiment the multipole order of the radiation and the dipole–quadrupole mixing ratio δ has to be determined. Two detectors 1 and 2, placed at different angles as shown in fig. 1, are necessary to determine the angular correlation of a cascade of two γ-rays. The angles between the detectors and the beam are denoted by θ_1 and θ_2. To describe the angular position of the detectors, a third angle ϕ is required, which is the angle between the two planes opened by each detector and the beam axis (cf. fig 1) The intensity of the transition γ_2, determined from a spectrum in detector 2 gated on the transition γ_1 in detector 1, is denoted by $W(\theta_1, \theta_2, \phi)$. The intensity of the transition γ_2, determined from a spectrum of detector 1 gated on the transition γ_1 in detector 2 (reversed case), is denoted by $W(\theta_2, \theta_1, \phi)$. The DCO ratio is

$$R_{\mathrm{DCO}} = \frac{W(\theta_2, \theta_1, \phi)}{W(\theta_1, \theta_2, \phi)}.$$

The corresponding experimental DCO ratio is

$$R_{\mathrm{DCO}} = \frac{I_{\theta_1}^{\gamma_2}(\mathrm{Gate}_{\theta_2}^{\gamma_1})}{I_{\theta_2}^{\gamma_2}(\mathrm{Gate}_{\theta_1}^{\gamma_1})}$$

It should be noted that an exchange of the angles or of the gating and observed transitions will invert the DCO ratio. The dependence of the DCO ratio on the angle θ_2 is shown in fig. 2 for fixed values $\theta_1 = 90°$ and $\phi = 0°$ for the 12–10–8 and 12–10–9 cascades. A DCO ratio $R_{\mathrm{DCO}} = 1.0$ is obtained independently of θ_2 if both

Table 1

DCO ratios for cascades of pure transitions. The calculations are carried out for the angles $\theta_1 = 90°$, $\theta_2 = 38°$ and $\phi = 18°$. The gating transition was the second one in each case. A width of $\sigma/I = 0.3$ was used for the substate population distribution

Spins of γ-ray cascade	Multipole orders of γ-rays	DCO ratio
10–8–6	2;2	1.00
10–8–7	2;1	0.56
10–8–7	2;2	0.66
10–8–8	2;1	1.07
10–8–8	2;2	0.57
9–8–6	1;2	1.81
9–8–7	1;2	0.92
9–8–7	1;1	1.00
9–8–8	1;1	1 79
9–8–8	1;2	1.12

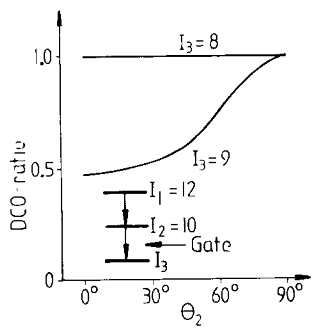

Fig. 2. Plot of the dependence of the DCO ratio on the angle θ_2. The DCO ratios have been calculated for $\theta_1 = 90°$ and $\phi = 0°$ assuming $\sigma/I = 0.3$ and pure multipole orders of $L = I_i - I_f$.

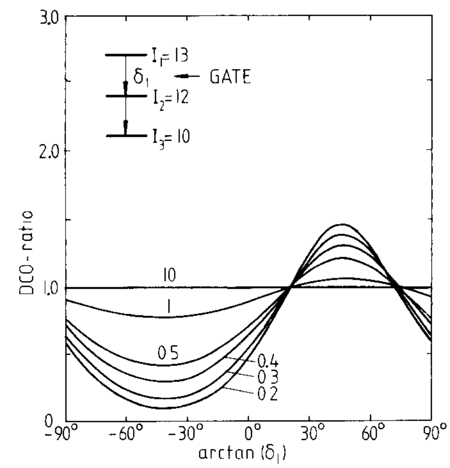

Fig. 3. Plot of the DCO ratio vs arctan (δ_1). The dependence of the DCO ratio on the width of the substate population distribution is shown for $\sigma/I = 0.2$–10. The angles were fixed to $\theta_1 = 90°$, $\theta_2 = 30°$ and $\phi = 0°$.

transitions are of the same multipole order. The largest difference in the DCO ratios of both cascades is observed if one detector is placed at 0° and the other one at 90° to the beam direction. One can see from fig. 2 that the DCO ratio changes only little if the detectors are placed at angles between 0° and 20° or between 70° and 90°. To obtain the largest effects in the DCO ratios the angle ϕ should be close to 0° or 180°. Therefore, an arrangement of the detectors in a plane parallel to the beam direction would give the best results with respect to DCO ratios. This arrangement is only possible for a small number of detectors. For large arrays one has to select detectors with values of the angles θ_1, θ_2 and ϕ for the analysis which give the largest effects for the DCO ratios. The experimental DCO ratios have to be corrected for the relative efficiencies of the detectors. A simple method to find the average correction factor is to study the DCO ratios for cascades of known multipolarities and spins. The best case is that of two transitions with the same multipolarities, for which the calculated DCO ratio is $R_{DCO} = 1$. The energies of the transitions for which the correction factor is determined should be similar to those under investigation, because of the energy dependence of the relative efficiencies of the detectors.

The dependence of the DCO ratio on the alignment of the initial state is demonstrated in fig. 3. in which the DCO ratio is plotted versus the mixing ratio δ_1 of the first transition for several values of σ/I. For large σ/I values the DCO ratio approaches 1. This is in agreement with DCO ratios obtained for γ-rays emitted from a radioacitve source, since in this case the alignment vanishes. The spin dependence of the DCO ratio on the multipolarities and the dipole–quadrupole mixing ratios of the γ-transitions and the spins of the levels are given in fig. 4 and in table 1. In table 1 transitions of pure

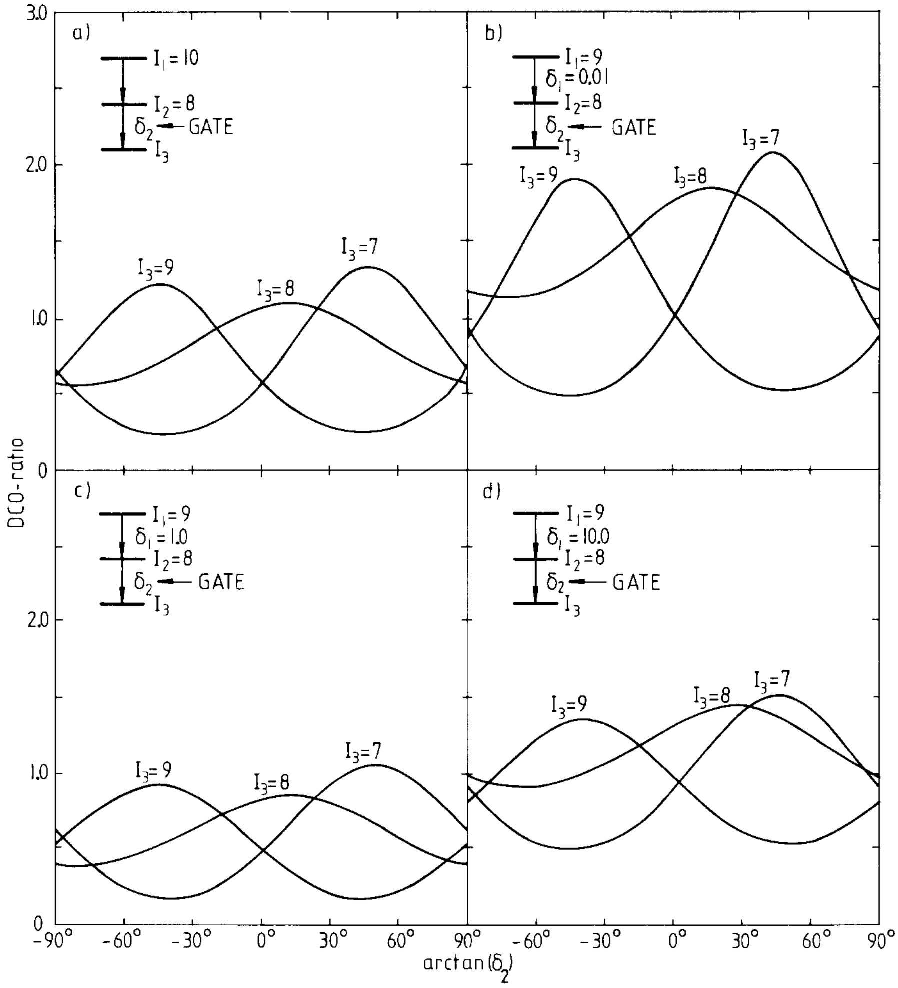

Fig. 4. The DCO ratio is plotted against arctan (δ_2) for a geometry of $\theta_1 = 90°$. $\theta_2 = 38°$ and $\phi = 18°$. A width of $\sigma/I = 0.3$ was used for the substate population distribution. The dependence of the DCO ratio on the spins of the involved levels and the mixing ratios of the γ-transitions is shown.

multipolarities are considered. The calculations have been carried out for the angles $\theta_1 = 90°$, $\theta_2 = 38°$ and $\phi = 18°$, corresponding to the angular positions of the detectors in the OSIRIS array (cf. sect. 3). The dependence on the mixing ratios of both transitions is shown in fig. 4, in which the DCO ratio is plotted against arctan δ_2). In fig. 4a the upper transition has a stretched quadrupole nature and several assumptions for I_3 have been made. The DCO ratios for the 10–8–7 and 10–8–8 cascades with arctan $(\delta_2) = 0°$ and arctan $(\delta_2) = \pm 90°$ correspond to the limiting cases given in table 1. In figs. 4b–d the upper transition is considered to have $\Delta I = 1$

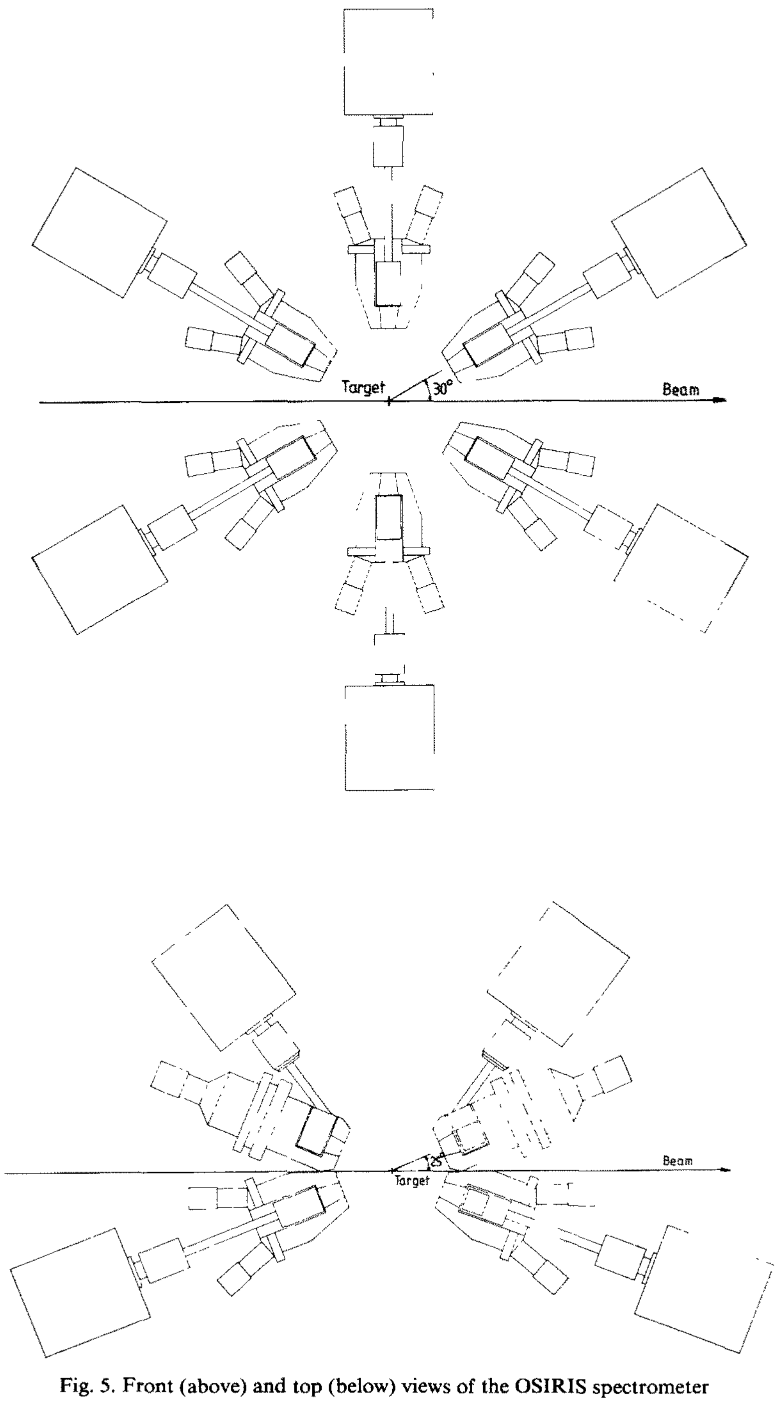

Fig. 5. Front (above) and top (below) views of the OSIRIS spectrometer

and a dipole–quadrupole mixture where δ_1 ranges from 0.01 to 10. The DCO ratios were calculated for three different spin values of I_3 in each case. It can be seen that several solutions exist for a given DCO ratio. Generally a spin change of $\Delta I = \pm 1$ cannot be distinguished. Therefore, unambiguous spin assignments cannot be carried out in all cases without additional information similarly to the measurement of angular distributions. Advantages of the DCO ratio method in comparison to the study of angular distributions are

(i) weak transitions can be studied,

(ii) members of multiplets can be analysed and

(iii) no normalisation to the beam charge is necessary.

By use of multidetector arrays the statistical accuracy of the DCO ratios can be increased by analyzing many detector combinations.

3. Detector arrangement of the OSIRIS array

The OSIRIS array consists of 12 Compton-suppressed Ge-detectors arranged in two rings. Front and top views of the arrangement are given in fig. 5. All detectors are tilted by 25° with respect to a vertical plane going through the beam direction. The angles between the detectors within one ring are all equal. For the ring shown in fig. 5 the angle between the beam direction and one detector, measured in the vertical plane, is indicated. The detector positions in the other ring are rotated against those in the previous one by 30°, measured in the vertical plane. For the analysis of DCO ratios the six detectors shown in the front view of fig. 5 are used because four of them have the same angle $\theta_2 = 38°$ or $180° - 38°$ and the other two have $\theta_1 = 90°$. The angle ϕ between the planes opened by the beam direction and the 38° and 90° detectors, respectively (cf. fig 1), is always $\phi = 18°$ or $180° - 18°$.

4. Determination of spins in ^{178}W

The use of the DCO ratio method for spin determinations was applied to the excited levels in ^{178}W. This nucleus was produced in an (^{18}O, 4n) reaction with an 80 MeV ^{18}O beam, delivered by the tandem Van de Graaff accelerator of the University of Cologne [7]. A partial level scheme of ^{178}W pertinent to the discussion in this article is displayed in fig. 6. It shows mainly the deexcitation of the isomer at 3527 keV, which has a half life of $T_{1/2} = 35$ ns, being established previoulsy by Dors et al. [2]. In our experiments using the OSIRIS array we identified three new delayed transitions related to this isomer, of 1571.4 as well as 991.9 and 1281.9 keV populating the 10^+ and 12^+ levels of the yrast band, respectively. In order to determine the spins of the isomer and of the 3055 and 3237 keV levels, we utilized DCO ratios. For the analysis it was assumed that the 35 ns isomer does not influence the σ/I value strongly.

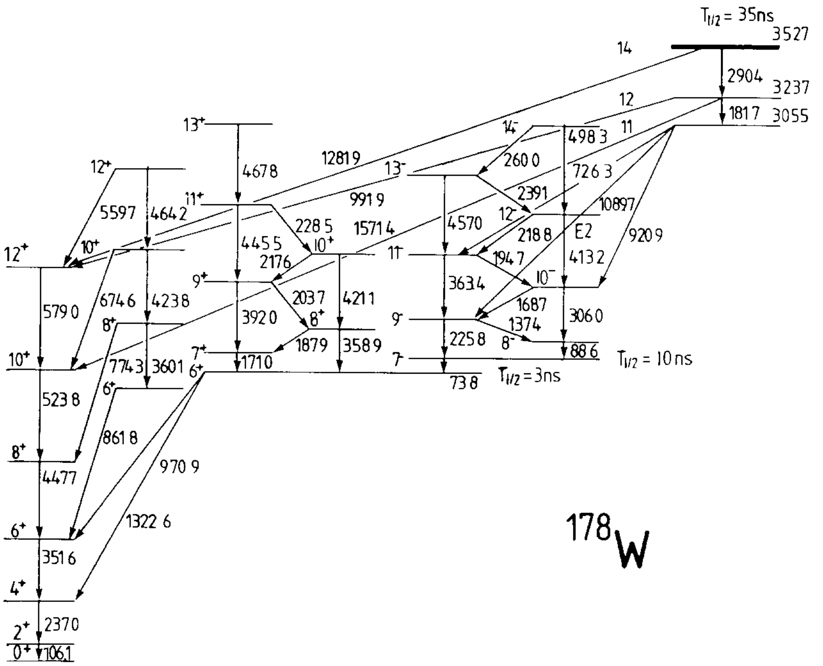

Fig. 6. Partial level scheme of ^{178}W.

To determine the spin of the 3055 keV level, cascades involving the 1090 and 921 keV transitions were investigated. For the 1090 (G)–226 keV and the 921 (G)–306 keV cascades (G indicates on which transition the gate was placed) DCO ratios $R_{DCO} = 1.0 \pm 0.2$ and $R_{DCO} = 0.66 \pm 0.10$ were obtained, respectively. The 1090–137 (G) keV and 921–169 (G) keV cascades were also analysed giving DCO ratios $R_{DCO} = 0.7 \pm 0.2$ and $R_{DCO} = 0.47 \pm 0.15$, respectively. In fig. 7 these experimental values are compared with calculated DCO ratios using the possible spin values of $I = 9$, 10 and 11 for the 3055 keV level. Spins of $I = 8$ and 12 can be excluded from the decay pattern. In these calculations we used an average M1/E2 mixing parameter of $\delta = -1.9$ for the 137 and 169 keV transitions as extracted from the angular distributions and branching ratios obtained by Dors et al. [3]. Considering figs. 7a and 7b commonly, the spins $I = 9$ and 10 can be excluded, since no solution for the same δ_1-value can be obtained. For $I = 11$ the 1090 keV transition has a pure quadrupole character and the calculated DCO ratios are $R_{DCO} = 1.0$ for the 1090–226 keV cascade and $R_{DCO} = 0.3 \pm 0.1$ for the 1090–137 keV cascade, taking into account the uncertainty of δ for the 137 keV transition. These DCO ratios are in reasonable agreement with the experimental values. Therefore, the spin $I = 11$ was assigned to the 3055 keV level. A comparision of the experimental and calculated DCO ratios for the 921–306 keV cascade (cf. fig. 7c) and the 921–169 keV cascade (cf. fig. 7d) allows to determine the mixing ratio δ of the 921 keV transition. A common solution for both cascades exists for $\delta_1 = 0.07 \pm 0.10$ and $\delta_1 > 85$, indicating almost pure dipole character or pure quadrupole character. The branching ratio of 1.2 ± 0.2 between the 1090 and 921

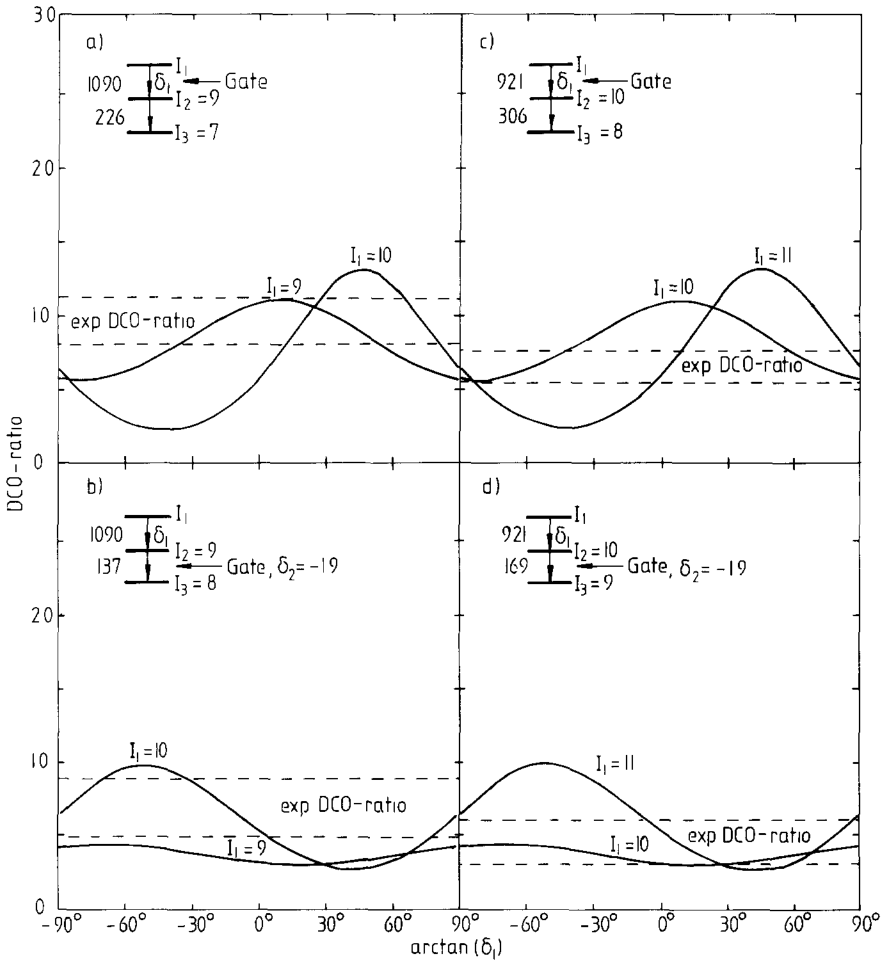

Fig. 7. Comparison of calculated and experimental DCO ratios to determine the spin of the 3055 keV level. The DCO ratios are plotted vs arctan (δ_1). The angles used in the experiment were $\theta_1 = 90°$, $\theta_2 = 38°$ and $\phi = 18°$. A width of $\sigma/I = 0.3$ was used for the substate population distribution.

keV transitions favours the first solution since $I_\gamma(1090)/I_\gamma(921) = 2.3$ is expected for pure quadrupole radiation.

To determine the spin of the 3237 keV state the experimental DCO ratios of the 182–921 (G) and 182–1090 (G) keV cascades were analysed. The experimental results $R_{DCO} = 0.72 \pm 0.10$ and $R_{DCO} = 1.5 \pm 0.2$, respectively, are compared with calculated values in fig. 8. Considering the deexcitation of the 3237 keV level, only spins of $I = 11$ or 12 are possible. The spin $I = 11$ cannot be excluded on the basis of DCO ratios but by consideration of transition intensities. For $I = 11$ an intensity ratio of $I_\gamma(1571)/I_\gamma(992) = 4.0$ is expected for the transitions deexciting into the 10^+ and 12^+ members of the yrast band whereas an experimental value of 0.77 ± 0.11 was found. For $I = 12$ one can deduce a mixing ratio of $\delta = 0.2 \pm 0.2$ or $\delta \geqslant 5$ for the 182 keV transition, as shown in fig. 8. The internal

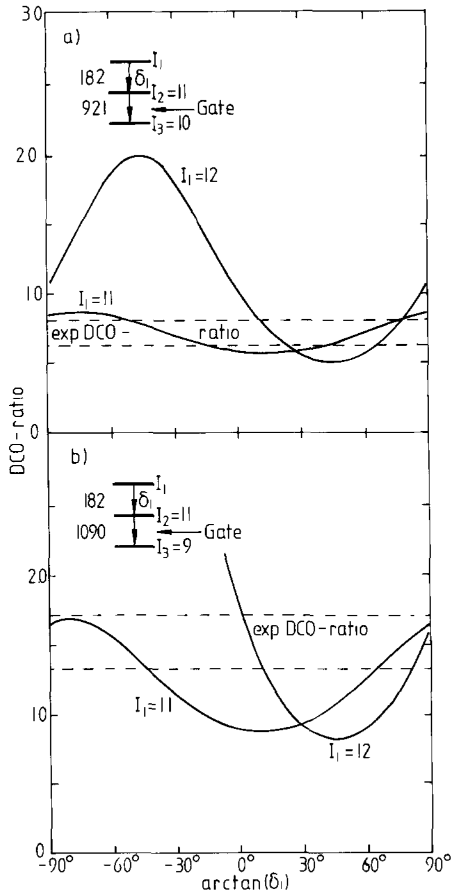

Fig. 8. Comparison of calculated and experimental DCO ratios to determine the spin of the 3237 keV level. The DCO ratios are plotted vs arctan (δ_1). For the 921 keV transition $\delta_2 = 0$ was assumed. For $\delta_2 > 85$ the calculated DCO ratios are similar. The same parameters as in fig. 7 were used.

conversion coefficient deduced from transition intensities supports the first solution considering an E1 multipolarity with a very small M2 admixture.

To determine the spin of the isomer at 3527 keV one can utilize the experimental DCO ratios for the 290–921 (G) keV sequence ($R_{DCO} = 0.53 \pm 0.12$), the 290–1090 (G) keV sequence ($R_{DCO} = 1.13 \pm 0.18$) and the 290 (G)–182 keV cascade ($R_{DCO} = 0.95 \pm 0.05$). For the former two sequences the intermediate 182 keV transition was not observed. However, the angular correlation is changed only very little in this case because the involved spins are large. A comparison of the experimental and calculated DCO ratios indicates that the spin of the isomer could be $I = 12$ or 14, but not 13. A spin assignment of $I = 12$ is unlikely, since no transitions to the 10^+ yrast state and the 3055 keV level were observed. For the adopted assignment of $I = 14$ for the isomer the calculated DCO ratios are $R_{DCO} = 0.6$ for the 290–921 keV sequence, $R_{DCO} = 1.0$ for the 290–1090 keV sequence and $R_{DCO} = 1.01$ for the 290–181 keV cascade, in agreement with the experimental results. An estimation of the DCO ratios for the weak transitions from the levels with spin 12 and 14 to the yrast band was not possible, since the statistical accuracy was not large enough.

It can be concluded that the investigation of DCO ratios allows to determine spins and dipole–quadrupole mixing ratios. DCO ratios of high precision can be obtained with the new multidetector arrays for γ-ray spectroscopy. As an example the spins of several levels in ^{178}W including the 35 ns isomer have been established. Furthermore the multipolarities of the related transitions and the mixing ratio δ of some of them were determined.

Acknowledgement

The authors would like to thank the accelerator crew of the University of Cologne for delivering the ^{18}O beam.

References

[1] R.M. Lieder et al., Nucl. Instr. and Meth. A220 (1984) 363.
[2] C.L. Dors et al., Nucl. Phys. A314 (1979) 61.
[3] W. Gast et al., to be published in Nucl. Instr. and Meth.
[4] R.M. Steffen and K. Alder, in: The Electromagnetic Interaction in Nuclear Spectroscopy, ed. W.D. Hamilton (North-Holland, Amsterdam, 1975), p. 505.
[5] K.S. Krane et al., Nucl. Data Tables 11 (1973) 351.
[6] C. Bargholtz and P.-E. Tegner, Nucl. Instr. and Meth. A256 (1987) 513.
[7] A. Krämer-Flecken et al., Jül. Spez. 403 (1987) 37.