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The program GCORR and procedures for the analysis of gamma-gamma correlation data from detector arrays

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The program *GCORR* and procedures for the analysis of gamma-gamma correlation data from detector arrays

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December 30, 1991

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Abstract

A procedure for measuring $\gamma - \gamma$ correlations with an array of Ge detectors is described. In particular, the program *GCORR* used for the analysis, is documented. In conjunction with the program *COMBIN* used for the calculation of equivalent detector combinations and the program *CORR_EFF* used for the calculation of efficiencies, *GCORR* is a general tool for planning correlation experiments and analysing and interpreting the data.

1 Introduction

Gamma-ray angular correlation measurements are one of the classical γ-spectroscopic tools for determining the spins and parities (J^π) of states and multipole mixing ratios (δ) of transitions. Complete $\gamma - \gamma$ correlations from nuclear reactions (triple correlations) have been measured with NaI detectors [1,2] and limited correlations (*e.g.* DCO ratios [3,4]) with high-resolution Ge detectors.

The use of heavy-ion-induced fusion-evaporation reactions to study high-spin states introduces two problems with singles angular distribution measurements, which are normally used to deduce spins and mixing ratios. Firstly, these reactions produce very complicated spectra since many bands in several nuclei are usually populated. Secondly, due to the large recoil velocity, the peaks are Doppler shifted by different amounts for different lifetimes, which makes singles spectra difficult to analyse. The second problem can, to some extent, be solved by using very thin (possibly stacked) targets.

The use of coincidence data introduces two obvious advantages. Firstly, the peaks are better separated and the background is lower in two dimensions [5]. Secondly, even if a peak is contaminated in singles, there is usually a coincidence gate in which it is not.

One problem, however, with coincidence data is to obtain enough statistics to make correlation data useful. For this one needs of the order of 10^9 $\gamma - \gamma$ events, which is only obtainable with multi-detector arrays.

The present report mainly describes the program *GCORR*. For a description of the NORDBALL set-up, examples of data and other experimental procedures, the reader is referred to reference [6].

Alignment parameterization and the angular correlation function are introduced in section 2. Section 3 deals with the program *GCORR*, *i.e.* the analysis of data in terms of physical parameters (J^π and δ). Section 4 outlines another program, *COMBIN*, which is an aid to determine equivalent detector combinations for an arbitrary array of detectors. The program *CORR_EFF*, for the calculation of detection efficiencies for any combination of detector pairs, is documented in section 5. Section 6 summarizes the procedure for analysis of correlation data.

2 Calculation of angular correlations

2.1 Alignment

A high-spin nuclear state produced by a heavy-ion fusion-evaporation reaction is aligned perpendicular to the beam axis, *i.e.* choosing the beam axis as the z-axis the population of the magnetic substates $p(m)$ is symmetric and peaks around $m = 0$. It is convenient in the calculations to represent the alignment in terms of spin-alignment attenuation factors α_λ instead of the population parameters $p(m)$. Yamazaki [7] defines the spin-alignment attenuation factors α_λ in terms

of the statistical tensors for complete alignment ($p(0) = 1$ for integer spins and $p(\pm 1/2) = 1/2$ for half-integer spin) as

$$\alpha_{\lambda_1}(I_1) = \rho_{\lambda_1}(I_1)/\rho_{\lambda_1}(I_1, \text{complete alignment}) \quad (1)$$

where I_1 is the spin of the initial state, the statistical tensor $\rho_{\lambda_1}(I_1)$ is given by equation 1 in reference [7] and λ_1 is an integer. If the population is symmetric with respect to the z-axis ($p(-m) = p(m)$), terms with odd λ_1 will vanish.

Since the different substates in a fusion-evaporation reaction are populated in a 'random walk' process, the assumption that the $p(m)$ follow a gaussian distribution with one parameter σ is often made [7]:

$$p(m) = \exp(-(m/\sigma)^2)/n \quad (2)$$

where n is a factor which normalizes $\Sigma p(m)$ to 1.

This assumption has been tested [8,9] and found to be not universally valid. These tests, however, involved states of fairly low spin, and experience with higher spins (> 10) shows that the gaussian assumption is quite adequate.

For lower spins one can improve the situation by using a modified gaussian substate population [9], with the exponent 2 in the above expression replaced by a parameter k, which then yields two parameters, σ and k, which define the alignment.

2.2 The correlation function

The angular correlation of two γ rays emitted in cascade has been extensively discussed in the literature. In the present application the formalism of Directional Correlation from Oriented nuclei (DCO) by Krane *et al.* [10] is the most convenient.

Consider a cascade of two γ rays depopulating an oriented state. The γ rays X_1 and X_2 are observed at angles θ_1 and θ_2 with respect to the z-axis with the angle $\phi = \Delta\phi = \phi_1 - \phi_2$ between the planes defined by the z-axis and the outgoing γ rays. The intensity $W(\theta_1, \theta_2, \phi)$ in these directions is given by equation 11 in reference [10]

$$W = N \sum_{\lambda\lambda_1\lambda_2} B_{\lambda_1}(I_1) Q_\lambda A_\lambda^{\lambda_2\lambda_1}(X_1) U_{\lambda_2} Q_{\lambda_2} A_{\lambda_2}(X_2) H_{\lambda_1\lambda\lambda_2}(\theta_1, \theta_2, \phi) \quad (3)$$

where N is a normalization factor. The factor B_{λ_1} describes the alignment. (B_{λ_1} is equivalent to Yamazaki's ρ_{λ_1} [7].)

The finite detector solid angles have been taken into account by including the solid-angle attenuation coefficients Q_λ and Q_{λ_2} [11] for γ_1 and γ_2, respectively. The Q coefficients are calculated by the program of Krane [12]. Since this correction is small for typical detector arrays, the same values can be used for all detectors and all γ-ray energies.

The effect of unobserved (skip-over) transitions has been taken into account by inserting the appropriate de-orientation factors (U_{λ_2}) [7].

The physical parameters, spins of the states involved and multipolarities and mixing ratios of the transitions, are contained in the A coefficients. The indices λ, λ_2 and λ_1 are even integers limited by the spins and multipolarities. The A coefficients are given in terms of $9j$ and $3j$ symbols and mixing ratios by equations 60 and 46 in reference [10].

For directional correlations of aligned states ($p(m) = p(-m)$) all λ's are even and the angular function H becomes [10]

$$H_{\lambda_1\lambda\lambda_2}(\theta_1,\theta_2,\phi) = \sum_{q\geq 0} \xi \cdot P_\lambda^q(\cos\theta_1) \cdot P_{\lambda_2}^q(\cos\theta_2) \cdot \cos(q\phi) \tag{4}$$

where

$$\xi = (2-\delta_{q0}) < \lambda_1 0 \lambda q \mid \lambda_2 q > \left(\frac{2\lambda+1}{2\lambda_2+1}\right)^{1/2} \left[\frac{(\lambda-q)!(\lambda_2-q)!}{(\lambda+q)!(\lambda_2+q)!}\right]^{1/2}$$

P_λ^q are associated Legendre functions and $< \lambda_1 0 \lambda q \mid \lambda_2 q >$ is a Clebsch-Gordan coefficient.

The following symmetries can be deduced:

$$W(\theta_1,\theta_2,\phi) = W(180^\circ-\theta_1, 180^\circ-\theta_2, \phi) \tag{5.1}$$

$$W(\theta_1,\theta_2,\phi) = W(\theta_1, 180^\circ-\theta_2, \phi+180^\circ) = W(180^\circ-\theta_1, \theta_2, \phi+180^\circ) \tag{5.2}$$

$$W(\theta_1,\theta_2,\phi) = W(\theta_1, 180^\circ-\theta_2, 180^\circ-\phi) = W(180^\circ-\theta_1, \theta_2, 180^\circ-\phi) \tag{5.3}$$

The first symmetry follows from the fact that the initial state is aligned, which implies equivalence of "beam up" and "beam down" directions. The second and third symmetries follow from the relations

$$\cos(q\phi) = (-1)^q \cos q(\phi+180^\circ) = (-1)^q \cos q(180^\circ-\phi)$$

and

$$P_\lambda^q(\cos\theta) = (-1)^q P_\lambda^q(\cos(180^\circ-\theta))$$

These symmetries can be used to reduce the number of different detector combinations, see section 4.

3 The program *GCORR*

3.1 Program design

Assuming a combination of spins and parities of the states involved as well as the multipolarities/mixing ratios of the transitions and treating the alignment as one or two free parameters (see below), the program calculates the observables

(*e.g.* intensities at certain angles), and fits these to the data. The contribution to the sum of the squared residuals Q^2 from each observable is given by

$$Q_i^2 = ((e_i - t_i)/\Delta_i)^2 \tag{6}$$

where e and t are the experimental and theoretical values, respectively, and Δ is the experimental uncertainty.

Possible values of and uncertainties in the physical parameters are determined in the traditional way by χ^2 analysis. The 99.9% confidence limit is used for the rejection of spin combinations. The method of James *et al.* [13] is used to determine the uncertainties in mixing ratios.

Three logical variables (BER_H, BER_F, BER_A) are used to speed up the calculation of the correlations. Equation 4 shows that H only depends on the angles and (through the λ coefficients) on spins and multipolarities. The function H needs consequently only to be calculated once for each set of angles for the analysis of one spin combination. The same is true for the function F, since it depends only on spins and multipolarities (equation 46 in reference [10]). The function A (equation 60 in reference [10]) depends, in addition, on the mixing ratio, and has to be calculated each time a mixing ratio is changed.

The following parameters (most of which define sizes of arrays) are defined in the program.

Parameter	Value	Meaning
MAXSKIP	10	Maximum number of unobserved transitions
MAXCORR	18	Maximum number correlation data points
MAXSPIN	40	Maximum level spin
MAXK,MAXL1	4,6	Maximum value of indices in equation 1

With some limitations these parameters can be easily changed. Increasing $MAXCORR$ would however involve some changes in the printout routine, and $MAXSPIN$ should not be increased above 40 unless other routines for calculating vector coupling coefficients are used.

The parameter $MAXK$ refers to the indices λ and λ_2, and should be increased if multipolarities higher than quadrupole are considered. $MAXL1$ refers to the index λ_1. For most cases $MAXL1 = 6$ is sufficient, but $MAXL1$ should never be smaller than $MAXK$.

Finally, the user is encouraged not to treat the program as a black box, but to try to understand at least superficially how the program works. There are many checks on data and parameters in the program, but it is obviously not protected against any eventuality, so *inspect your output carefully to ensure that the program has behaved as expected.*

3.1.1 Parameters

Except for spins/parities of levels involved (from which multipolarities are calculated) and alignment (see subsection 3.1.2) there are three continuous parameters that can be either varied or fixed: multipole mixing ratio of the first and

second γ ray (δ_1 and δ_2) and the correlation normalization (N in equation 3). Since varying two mixing ratios simultaneously would take a very long time, the program is restricted to varying either δ_1 or δ_2.

3.1.2 Alignment parameterization

The alignment is parameterized in terms of population parameters according to a slightly modified version of equation 2:

$$p(m) = \exp(-(m/\sigma)^k)/n \tag{7}$$

where k can either be fixed (normally = 2) or varied, and σ is normally varied.

The spin-alignment attenuation coefficients α_{λ_1} are calculated from the population parameters by equation 1.

3.1.3 Data types

The program can analyse three different types of data: correlation data, conversion coefficient data and mixing ratio data. The latter two complement the correlation data very well in that inherent ambiguities in spin assignments (see [6]) are sometimes resolved.

Theoretical correlation data are calculated according to equation 3. The sign convention for the multipole mixing ratio is that of Krane *et al.* [10]. *DCO* ratio data can also be analysed, with the *DCO* ratio R defined by

$$R = W(\theta_1, \theta_2, \phi)/W(\theta_2, \theta_1, \phi) = W(1,2)/W(2,1). \tag{8}$$

Internal conversion coefficient data $\alpha_{L,L+1}$ for any shell for a transition with multipolarities L and $L+1$ and mixing ratio δ are calculated from the expression

$$\alpha_{L,L+1} = \frac{\alpha_L + \delta^2 \alpha_{L+1}}{1 + \delta^2} \tag{9}$$

where α_L and α_{L+1} are the theoretical conversion coefficients for the two multipolarities. Alternatively, conversion coefficient data can be given as ratios between two different shells.

If the mixing ratio of a γ ray for a particular spin combination has been determined from other data, *e.g.* another correlation, it can be included as data. Care must, however, be taken when using δ data, since the procedure is only correct when the $\chi^2(\delta)$ dip that determines the value and uncertainty of δ is at least approximately parabolic.

If one can establish a relation between the alignment α_2 and the spin of the initial state I_1 (*e.g.* by analysing stretched E2 cascades, see reference [6]), this relation can be entered as data to be included in the analysis.

3.2 Input/output

A description of the input of *GCORR* is given in appendix 1 and a sample input (with simulated and realistic data) in appendix 2. Data records start in column one. Records with a space in column one are ignored by the program (used for comments).

Part of the program output with the input of appendix 2 is shown in appendix 3. First, all input data and parameters are printed (not shown). The first page shown displays the analysis for the first spin combination with $\arctan(\delta_2)$ varying from 30 to 60 degrees. The first column gives the goodness of fit Q^2. The theoretical values for the best fit to the data are given for the normalization N, conversion coefficients, alignment, and the first seven correlations (the number is limited by the space on one line). Varied parameters are marked with a number greater than zero. The column labelled 'calls' gives the number of times the function for calculating Q^2 has been called.

Page two of the output gives the best theoretical values of all observables for the best δ_2. In addition, the experimental data with uncertainties of all observables are given. The line marked "2 sigma dev." is used to identify data where the theoretical value deviates by more than two standard deviations from the experimental value. The last two lines give the best value and uncertainty of the varied mixing ratio. The parameter *SIGMA* is the value of Q^2 at one standard deviation, determined according to the prescription of James *et al.* [13]. The uncertainty determined from this is the larger of the internal error (determined from the uncertainty in the data) and the external error (determined from the spread in the data).

Page three of the output displays a graph of the normalized χ^2 (Q^2 divided by the number of degrees of freedom) *versus* $\arctan(\delta)$ with the 95% and 99.9% confidence limits.

4 The program *COMBIN*

This program determines equivalent detector pairs (a set of equivalent pairs is here called a geometry) for any detector array using the symmetries of equation 5. This is obviously trivial for an array with only a few detectors, but even for NORDBALL with 20 detectors (190 pairs) it is quite a considerable task.

Before running the program one must check that the parameters defined in the Fortran code are large enough since they determine array dimensions: *MAXDET* is the maximum number of detectors and *MAXGEO* is the maximum number of detector pairs in one geometry. The program does, however, check that these parameters are large enough.

The program input for the NORDBALL array is shown in appendix 4. The first line is the angle tolerance in degrees. The following lines give detector number, θ and ϕ for each of the 20 detectors. All input is in free format.

The angle tolerance parameter given in the input is the maximum difference (in degrees) in θ and ϕ for two detector pairs to be considered equivalent. The value of this parameter has to be estimated on the grounds of the estimated correlations and accuracies, but a couple of degrees should be acceptable for most cases.

The program first determines the sets of angles θ_1, θ_2 and ϕ for all detector pairs, and then "renormalizes" these angles with the symmetries 5.1 and 5.2 so that $\theta_1 \leq 90°$ and $\theta_2 \leq 90°$. The resulting sets of angles are then compared, and those that agree within the tolerance are grouped together into a geometry.

Part of the output is shown in appendix 5. The first page is a print-out of the input data. The second page shows the nine sets of equivalent detector pairs for the NORDBALL array. The geometries here labelled 1 to 9 are identical to the geometries A, B, C, D, E, J, N, O and R in reference [6].

There are two different classes of geometries: geometries 3, 4 and 5 are non-symmetrical, while the others are symmetrical. For the symmetrical geometries $W(\theta_1, \theta_2, \phi)$ does not change with the interchange of γ_1 and γ_2 since both γ rays are detected at the same (or equivalent) angle. The resulting $\gamma - \gamma$ efficiency-corrected matrices are symmetrical except for statistical variations. The non-symmetrical geometries do, however, change with the interchange of γ_1 and γ_2, and hence there is physical information in the DCO ratio (equation 8).

For symmetrical geometries the order of the γ rays (or detector numbers) is irrelevant, so all pairs of the symmetrical geometries are given in numerical order. For the non-symmetrical geometries, however, the order is relevant, and hence some of the detector pairs for geometries 3, 4 and 5 are in reverse numerical order.

Finally, it should be noted that a setup with less symmetry than NORDBALL would yield a greater number of different geometries, which would require more work in sorting and analysing and result in fewer counts in the peaks.

5 The program *CORR_EFF*

The program *CORR_EFF* calculates correlation intensities from peak volumes (see subsection 6.5, equation 11) using the expression of equation 12 for the efficiency of a set of detector pairs.

A sample input for *CORR_EFF* is given in appendix 6, which is a command file for running the program. The first input line (second line) is the name of the file where the detector efficiencies are defined (see appendix 7). The second input line is the name of the file defining the detector combinations (see appendix 8).

Next follows the name of the output file, whether or not the efficiencies and detector combinations should be printed, and the estimated relative uncertainty in the efficiency data. After these records the program will accept two types of data records: γ ray energies or peak volume data.

The record with γ ray energies is recognized by a space in the first column.

The energies of the γ rays in the cascade considered should be given in *time order*, meaning that the first γ ray is higher up in the level scheme than the second γ ray.

The peak volume data are recognized by a valid geometry label (in the example the geometries A, B, C, D, E, J, N, O and R are defined). The rest of the record contains (in free format) the peak volumes and uncertainties. The first volume corresponds to the order defined by the previous γ record, and the second corresponds to that where the order of the γ rays is reversed. Note that this applies to both symmetrical and non-symmetrical geometries, since even for the symmetrical geometries the efficiency need not be the same.

Appendix 7 shows the detector efficiency input. The first record contains the number of detectors, and the rest of the file gives the coefficients a, b, c, d, e and f (see equation 10) for each detector. All input is in free format. The efficiency of all detectors should be defined in this file. For detectors not involved in the analysis, the efficiency should be entered with $a = -50$ and b, c, d, e and $f = 0$.

The detector combination input is shown in appendix 8. The first record defines the name of the geometry (one character), and the second gives the number of detector pairs. There then follows a list of detector pairs in free format. Notice the similarity of this part of the input with the output of *COMBIN* in appendix 5.

Part of the output from the program is shown in appendix 9. The table gives the γ-ray energies, geometry, volume (from input) and the calculated efficiencies and the correlation intensities, W. The last column gives the average of the values of W (useful if the geometry is symmetric) and the DCO ratio. The DCO ratio can, for symmetric geometries, be used as a check of the efficiency data since it should be equal to 1 (the first data entry in the example has a DCO ratio for the N geometry of 0.896, indicating that the efficiency at the lowest energies is incorrect).

6 Procedures for correlation measurements

In this section the procedure for the analysis of $\gamma - \gamma$ correlation data is summarized.

6.1 The experiment

A run useful for extracting correlation data should contain at least of the order of 10^9 $\gamma - \gamma$ events. It is important to obtain good detector efficiency data (accuracy better than a few percent) from singles runs with radioactive sources at the target position. The self-absorption in the sources should be similar to that in the target.

6.2 Determination of geometries

The equivalent detector pairs for the array are determined, *e.g.* with the program *COMBIN*.

If any detector was found to be defect or exhibited bad energy resolution for part of the run, it must be removed completely from the analysis, since it will be part of some geometries but not all. The time spectra should be checked for excessive tailing. Tailing would indicate poor timing characteristics of a detector, which might make the efficiency for low γ-ray energies suspect. Detectors with poor timing should also be removed from the analysis.

If the number of geometries is large, a limited number must be chosen based on the number of detector pairs (statistics) of the geometry and its estimated sensitivity to physical parameters. This latter can be determined by running *GCORR* with the *CA* option (see input description in appendix 1). For NORDBALL data the geometries 1, 2, 3, 4, 5, 7 and 8 (see appendix 5) are normally sorted.

6.3 Sorting

The data are sorted into matrices, one matrix for each geometry. The time gates should be wide open, so the detector efficiencies determined in singles will be applicable.

The matrices are then background subtracted according to the method given by Palameta and Waddington [14] in order to remove ridges parallel to the energy axes due to Compton scattering in the detector and γ rays from the continuum. The background subtraction method has been modified to take into account the fact that the $\gamma - \gamma$ matrices are not symmetrical due to statistics, correlation effects and the variation in efficiency from detector to detector.

6.4 Detector efficiency

The detector efficiencies are determined from the efficiency runs. One detector is assigned the efficiency $\epsilon = 1$ for $E_\gamma = 300$ keV, and all other detector efficiencies are normalized to this, so that an absolute efficiency for all detectors (except for the arbitrary normalization) is obtained. The efficiency of each detector is fitted (*e.g.* with the PC program *SigmaPlot* [15]) to the function

$$\epsilon_i(E_\gamma) = \exp(a + bx + cx^2 + dx^3 + ex^4 + fx^5) \qquad (10)$$

where ϵ_i is the efficiency of detector i and

$$x = \log(E_\gamma/1000)$$

This function was found to be quite adequate for the energy range 100-1500 keV (see reference [6]).

If a detector has been removed from the analysis, the corresponding efficiency must be entered as zero.

6.5 Extracting correlations

Each pair of coincident γ rays, $(E_{\gamma_1}, E_{\gamma_2})$, is represented in the matrix corresponding to geometry X by two peaks with volumes $V_X(1,2) = V_X(E_{\gamma_1}, E_{\gamma_2})$ and $V_X(2,1) = V_X(E_{\gamma_2}, E_{\gamma_1})$. These volumes should be determined and converted into correlation intensities with the expressions

$$W_X(1,2) = V_X(1,2)/\epsilon_X(E_{\gamma_1}, E_{\gamma_2}) \tag{11.1}$$

$$W_X(2,1) = V_X(2,1)/\epsilon_X(E_{\gamma_2}, E_{\gamma_1}) \tag{11.2}$$

with the efficiencies of geometry X given by

$$\epsilon_X(E_{\gamma_1}, E_{\gamma_2}) = \sum_{i,j \in X} \epsilon_i(E_{\gamma_1}) \cdot \epsilon_j(E_{\gamma_2}) \tag{12.1}$$

$$\epsilon_X(E_{\gamma_2}, E_{\gamma_1}) = \sum_{i,j \in X} \epsilon_i(E_{\gamma_2}) \cdot \epsilon_j(E_{\gamma_1}) \tag{12.2}$$

These efficiencies can be easily calculated (program *CORR_EFF*, see section 5) from the above parameterization for any geometry.

Since the *DCO* ratio (equation 8) is 1 for stretched E2 cascades, this ratio can be used to check the correctness of the efficiencies. The stretched E2 cascades can also be used to establish a connection between the alignment (α_2) and the spin of the initial state, see reference [6].

6.6 Analysis in terms of physical parameters

The correlation data and other available data are analysed in terms of physical parameters (spins of levels, multipolarities and mixing ratios of transitions) with the program *GCORR*.

7 Ordering the programs

The programs can be obtained (preferably distributed by means of computer mail) on request to

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Fax: +46-46-104709
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The programs are, with few exceptions (DO...ENDDO construct, TIME and DATE functions), written in standard FORTRAN 77.

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[15] Program *SigmaPlot*, Jandel Scientific GmbH, Schimmelbuschstrasse 25, 4006 Erkrath, Germany

Appendix 1
GCORR input description

Level scheme:

```
-----O----- I_1
     I
     I GAMMA1
     V
----------- I_2
-----O----- I_3
     I
     I GAMMA2
     V
----------- I_4
```

Parameters:
1 NORM. of correlation
5 DELTA1 (degrees)
6 DELTA2 (degrees)

11 Ln(SIG/I_1) (I_1 is initial spin)
12 POWER

Up to MAXSKIP (=10) unobserved gammas between I_2 and I_3. Without unobserved gammas I_2=I_3.

* INPUT *

The basic data card has the FORMAT (A2, 2A4, free format integer or real). Cards are recognized by the A2 string. The 2A4 is for your benefit. Parameters skipped over have to be entered as 0.

ST STOP (end job)

G1 GAMMA1 start, stepsize ,lower limit, upper limit (in DELTA1, defaults: 0.0, 0.0, -90.0, 90.0)
G2 GAMMA2 start, stepsize ,lower limit, upper limit (in DELTA2, defaults: 0.0, 0.0, -90.0, 90.0)

CO C X W(theta1,theta2,phi), error, theta1, theta2, phi (Experimental correlation intensity)
RA R X R(theta1,theta2,phi), error, theta1, theta2, phi (Experimental DCO ratio)

Up to MAXCORR (=18) correlations (with a common normalization) and DCO ratios are allowed. R is the DCO ratio R=W(theta1,theta2,phi)/W(theta2,theta1,phi).

QK Q(K):s Q(2), Q(4) (Solid angle attenuation factors for the detectors. If MAXK>4, correspondingly higher Q(K):s must be given.)

UK U(K):s U(2), U(4) (Deorientation factors for unobserved transitions. Calculated from spins and mixing ratios if not given. If MAXK>4, correspondingly higher U(K):s must be given.)

AL ALIGN alpha(2), error alpha(2); value, error, lower limit, upper limit (for power); (defaults: 0.0, 0.0, 2.0, 0.0, 1.0, 2.0)

D1 DELTA1 DELTA1, error in DELTA1 (degrees)
D2 DELTA2 DELTA2, error in DELTA2 (degrees)

C1 CC1 CC1, error in CC1, TH(low), TH(high)
CC1 is experimental conversion coefficient for gamma1. TH are theoretical conversion coefficients for the two possible multipolarities.
For CC ratios also: TH(low), TH(high) for shell 2

C2 CC2 CC2, error in CC2, TH(low), TH(high)
As C1, but for gamma2.

```
UD Udeltas UD1,<UD2,...>  Unobserved deltas (degrees)
             Default=0.0

CA CALC    CALC (>=0 Fix correlation norm. to 1000.
                 <0 Release correlation norm.)
           (Used to calc. correlations for planning experiments)

CH CHECK   CHECK (>=0 check input on, no analysis, <0 normal analysis
           (default))

HI HIST    HIST (>=0 histogram on (default), <0 hist. off)

DU DUMP    RDUMP (=0. dump all on, >0 dump rdump on, <0 dump off,
           (default))

TI TITLE   Analysis header (character string, col. 11-80)

CL CLEAR   (Clears all parameters and data and resets defaults)

SP SPINS   J1, J2,...Jn  Spin sequence of correlation. Observed
              transitions are J1->J2 and Jn-1->Jn.
              Spins are entered as reals (5/2+=2.5, 2-=-2.0)

*!         A space, a * or a ! in the first column makes the
             command dummy (for comments and removed data)

*Experimental data*

  Up to 18 correlation points W(theta1,theta2,phi) with one
  common normalization or ratios
  R(theta1,theta2,phi)=W(theta1,theta2,phi)/W(theta2,theta1,phi)

Conversion coefficient data
  One conversion coefficient or ratio per gamma.

Delta data
  Value and uncertainy of any gamma. This should be used when
  a mixing ratio has been determined from a separate set of data.
  If one for instance has a cascade E2--M1/E2--E2, and determines
  delta2 from the first two transitions, one can use this value
  as delta1 data for the last two transitions.

Alignment data
  It may be possible to establish a relation alpha2 of a state
  from E2-E2 correlations. This value may then be used (with
  its error) in other correlations with the same initial state.
  Alternatively, one may be able to establish a relation between
  alpha2 and J. The use of alignment data greatly improves
  the sensitivity of correlation data.
```

Appendix 2
Sample input for *GCORR*

```
  Sample input of GCORR (artificial data)
  Analysis title:
TI TITLE  TEST OF GCORR angular correlation DELTA1=-45 DELTA2=+45

  Fix ATAN(delta1) to -45 degrees (delta1=-1.0):
G1 515 keV    -45 0 0 0

  Vary ATAN(delta2) from 30 to 60 degrees in steps of 1 degree:
G2 411 keV    45 1  30 60

  Q(K) coefficients:
QK            1.00 1.00

  Correlation data:
   name       val err  angles
CO C1         165  10  37 79 0
CO C2         1259 10  79 37 0
CO D1         590  10  37 79 72
CO D2         2181 10  79 37 72
CO E1         353  10  37 79 144
CO E2         1814 10  79 37 144
CO N          1756 10  79 79 72

  DCO ratio data:
RA RatC       0.131 0.010 37 79 0

  Mixing ratio data (NOTE: ATAN(delta) should be entered):
D1 Delta1     -45 10
D2 Delta2     45 10

  Conversion ratio data for gamma1:
C1 CC1        0.429 0.050 1 2 3 4

  Conversion coefficient data for gamma2:
C2 CC2        3.00 0.10 2 4

  Alignment data:
AL ALIGN      0.8 0.03  2 0  0 2

  Spin sequence:
SP SPINS      14 13 12

  STOP:
ST STOP

****************************************

  Typical real data:

TI        164Yb E1-E2 crossovers  326-915
G1 326 keV    0 0 0 0
G2 915 keV    0 5 -90 90
QK            0.99 0.96
CO A           25 2       37 37 72
CO B           26 2       37 37 144
co C1          27 3       37 79 0
CO C2          16 3       79 37 0
CO D1          35 2       37 79 72
CO D2          23 2       79 37 72
co E1          35 2      37 79 144
co E2          18 2      79 37 144
co N           24 2      79 79 72
co O           17 2      79 79 144
SP SPINS      -9 -7 6
ST
```

Appendix 3
Sample output from *GCORR*

TEST OF GCORR angular correlation DELTA1=-45 DELTA2=+45

gamma1: 515 keV, 14+ -----> 13+
gamma2: 411 keV, 13+ -----> 12+

GCORR, VAX/VMS version October 1991, LPE
Modified gaussian approximation used for magnetic substate populations
Krane and Steffen sign convention for mixing ratios (=-Delta(Rose and Brink))
* PARAMETER 6 FIXED *

	Corr.	Conv.coeff.		Mixing ratios		Alignment parameters					Correlations (Ratios renormalized to 1000)							
	N	CC1	CC2	D1	D2	Alpha2	Alpha4	Sigma	Power	Calls								
Parameters	2			0	0			1	0									
Data	Yes	Yes	Yes	Yes	Yes	Yes					C1	C2	D1	D2	E1	E2	N	
SQ.RES.																		
379.6	1017.	0.429	2.500	-45.0	30.0	0.83	0.55	4.83	2.00	95	202.	1416.	554.	2103.	384.	1793.	1744.	+
314.7	1015.	0.429	2.531	-45.0	31.0	0.83	0.54	4.90	2.00	103	196.	1403.	558.	2111.	383.	1795.	1745.	+
258.4	1014.	0.429	2.562	-45.0	32.0	0.82	0.53	4.97	2.00	95	189.	1390.	561.	2119.	383.	1796.	1746.	+
210.0	1012.	0.429	2.593	-45.0	33.0	0.82	0.52	5.03	2.00	106	183.	1377.	564.	2126.	382.	1797.	1746.	+
168.7	1011.	0.429	2.625	-45.0	34.0	0.82	0.51	5.09	2.00	94	178.	1365.	568.	2134.	382.	1798.	1747.	+
133.9	1009.	0.429	2.658	-45.0	35.0	0.81	0.51	5.13	2.00	116	173.	1353.	570.	2140.	381.	1799.	1748.	+
104.8	1008.	0.429	2.691	-45.0	36.0	0.81	0.50	5.18	2.00	110	169.	1342.	573.	2147.	381.	1799.	1749.	+
80.9	1007.	0.429	2.724	-45.0	37.0	0.81	0.50	5.22	2.00	102	165.	1331.	575.	2153.	380.	1800.	1750.	+
61.5	1006.	0.429	2.758	-45.0	38.0	0.80	0.49	5.26	2.00	98	161.	1321.	577.	2158.	380.	1800.	1750.	+
46.0	1005.	0.429	2.792	-45.0	39.0	0.80	0.49	5.29	2.00	92	159.	1311.	579.	2164.	379.	1800.	1751.	+
34.1	1005.	0.429	2.826	-45.0	40.0	0.80	0.48	5.31	2.00	88	156.	1301.	581.	2169.	379.	1800.	1752.	+
25.1	1004.	0.429	2.861	-45.0	41.0	0.80	0.48	5.33	2.00	107	155.	1292.	582.	2174.	378.	1800.	1753.	+
18.7	1003.	0.429	2.895	-45.0	42.0	0.80	0.48	5.35	2.00	128	153.	1284.	583.	2179.	377.	1799.	1754.	+
14.5	1003.	0.429	2.930	-45.0	43.0	0.79	0.48	5.37	2.00	116	153.	1276.	584.	2183.	377.	1799.	1755.	+
12.3	1003.	0.429	2.965	-45.0	44.0	0.79	0.47	5.38	2.00	112	153.	1268.	585.	2187.	376.	1798.	1755.	+
11.6	1003.	0.429	3.000	-45.0	45.0	0.79	0.47	5.38	2.00	130	153.	1261.	586.	2191.	376.	1797.	1756.	+
12.4	1003.	0.429	3.035	-45.0	46.0	0.79	0.47	5.39	2.00	119	154.	1254.	586.	2195.	375.	1796.	1757.	+
14.6	1003.	0.429	3.070	-45.0	47.0	0.79	0.47	5.38	2.00	118	156.	1248.	586.	2199.	375.	1795.	1758.	+
17.9	1004.	0.429	3.105	-45.0	48.0	0.79	0.47	5.38	2.00	123	158.	1243.	587.	2202.	374.	1794.	1759.	+
22.4	1005.	0.429	3.139	-45.0	49.0	0.79	0.48	5.37	2.00	121	161.	1237.	586.	2205.	374.	1792.	1760.	+
28.1	1005.	0.429	3.174	-45.0	50.0	0.80	0.48	5.36	2.00	122	164.	1233.	586.	2209.	373.	1790.	1761.	+
35.1	1006.	0.429	3.208	-45.0	51.0	0.80	0.48	5.34	2.00	88	169.	1228.	586.	2211.	373.	1788.	1762.	+
43.5	1008.	0.429	3.242	-45.0	52.0	0.80	0.48	5.32	2.00	115	173.	1224.	585.	2214.	373.	1786.	1763.	+
53.5	1009.	0.429	3.276	-45.0	53.0	0.80	0.49	5.29	2.00	91	178.	1221.	584.	2217.	372.	1784.	1764.	+
65.4	1010.	0.429	3.309	-45.0	54.0	0.80	0.49	5.27	2.00	101	184.	1218.	583.	2219.	372.	1781.	1766.	+
79.5	1012.	0.429	3.342	-45.0	55.0	0.80	0.49	5.23	2.00	104	190.	1215.	582.	2222.	372.	1779.	1767.	+
96.1	1014.	0.429	3.375	-45.0	56.0	0.81	0.50	5.20	2.00	99	197.	1213.	580.	2224.	372.	1776.	1768.	+
115.7	1016.	0.429	3.407	-45.0	57.0	0.81	0.51	5.15	2.00	114	205.	1210.	578.	2226.	372.	1773.	1769.	+
139.0	1016.	0.429	3.438	-45.0	58.0	0.82	0.52	5.08	2.00	76	212.	1208.	574.	2227.	370.	1767.	1769.	+
165.7	1020.	0.429	3.469	-45.0	59.0	0.82	0.52	5.05	2.00	128	221.	1207.	575.	2230.	372.	1765.	1772.	+
197.2	1023.	0.429	3.500	-45.0	60.0	0.82	0.53	4.99	2.00	132	230.	1206.	572.	2231.	372.	1761.	1774.	+

* PARAMETER 6 RESTORED *

Best fit

	Corr. N	Conv.coeff. CC1	CC2	Mixing ratios D1	D2	Alignment parameters Alpha2	Alpha4	Sigma	Power	Calls	Correlations (Ratios renormalized to 1000) C1	C2	D1	D2	E1	E2	N	
Parameters	2			0	4			1	0									
Data	Yes	Yes	Yes	Yes	Yes	Yes												
SQ.RES.																		
11.6	1003.	0.429	2.997	-45.0	44.9	0.79	0.47	5.38	2.00	20	153.	1262.	586.	2191.	376.	1797.	1756.	+
Data		0.429	3.000	-45.0	45.0	0.80					165.	1259.	590.	2181.	353.	1814.	1756.	
Errors		0.050	0.100	10.0	10.0	0.03					10.	10.	10.	10.	10.	10.	10.	
2 sigma dev.															****			

Additional data:

	Corr. N	Mixing ratios D1	D2	Correlations (Ratios renormalized to 1000) RatC
Parameters	2	0	4	
Data	Yes	Yes	Yes	
SQ.RES.				
11.6	1003.	-45.0	44.9	121.
Data		-45.0	45.0	131.
Errors		10.0	10.0	10.
2 sigma dev.				

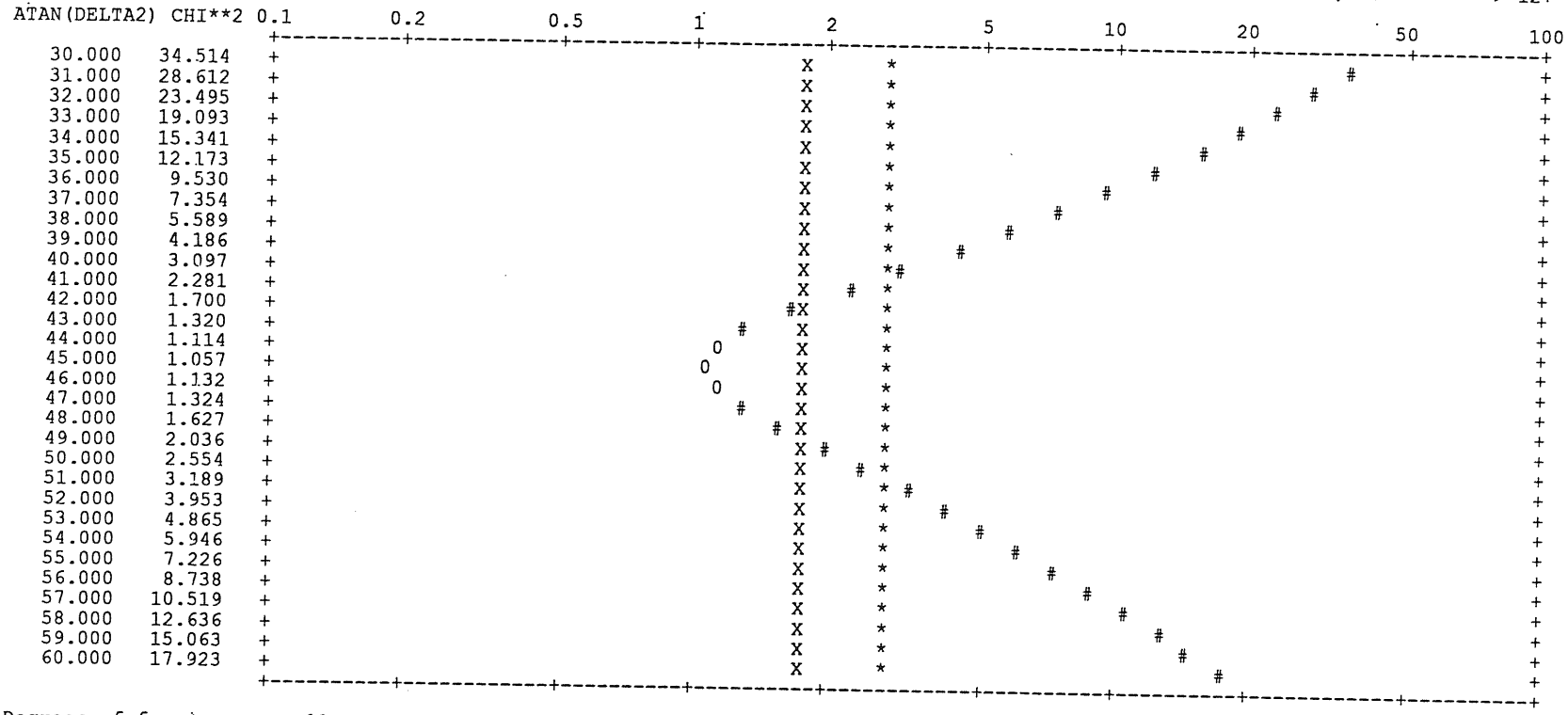
** Check theoretical conversion coefficients:
Delta1: 1.0000 for the lower multipole and 2.0000 for the higher multipole
3.0000 for the lower multipole and 4.0000 for the higher multipole for shell 2

** Check theoretical conversion coefficients:
Delta2: 2.0000 for the lower multipole and 4.0000 for the higher multipole

Best mixing ratio for gamma2: 0.997 + 0.042 - 0.039. Sigma= 12.62
** Note that uncertainty may be suspect if sq.res. dip is very narrow! **

TEST OF GCORR angular correlation DELTA1=-45 DELTA2=+45

gamma1: 515 keV, 14+ -----> 13+
gamma2: 411 keV, 13+ -----> 12+



Degrees of freedom = 11
X = 95% conf. limit = 1.7890
* = 99.9% conf. limit= 2.8422
# Data
0 Data within one st.dev. of best value

++++++++++ THAT'S ALL FOLKS!

Appendix 4
Input for *COMBIN*

```
 0.1
 1     143    216.0
 2     143.   144.
 3     143.   72.
 4     143.   0.
 5     143.   288.
 6     101.   216.
 7     101.   144.
 8     101.   72.
 9     101.   0.
10     101.   288.
11     79.    252.
12     79.    180.
13     79.    108.
14     79.    36.
15     79.    324.
16     37.    252.
17     37.    180.
18     37.    108.
19     37.    36.
20     37.    324.
```

Appendix 5
Part of output from *COMBIN*

```
*++++++++++++++++++++++*
* COMBIN               *
*++++++++++++++++++++++*

 October 1991/LPE

 +++ Correlation combinations for detector arrays +++

DATE: 10-NOV-91
TIME: 12:25:10


 Max. number of detectors, MAXDET=                20
 Max. combinations, MAXCOM=                      190
 Max. combinations per geometry, MAXGEO=          80


 Number of detectors=          20
 Angle tolerance=  0.1000000     degrees

  No      Theta        Phi
   1      143.0      216.0
   2      143.0      144.0
   3      143.0       72.0
   4      143.0        0.0
   5      143.0      288.0
   6      101.0      216.0
   7      101.0      144.0
   8      101.0       72.0
   9      101.0        0.0
  10      101.0      288.0
  11       79.0      252.0
  12       79.0      180.0
  13       79.0      108.0
  14       79.0       36.0
  15       79.0      324.0
  16       37.0      252.0
  17       37.0      180.0
  18       37.0      108.0
  19       37.0       36.0
  20       37.0      324.0
```

Detector combinations by geometry

Geometry 1. Number of combinations: 20 Angles: 37.0 37.0 72.0
Detectors:

1	2	1	5	1	18	1	20	2	3
2	16	2	19	3	4	3	17	3	20
4	5	4	16	4	18	5	17	5	19
16	17	16	20	17	18	18	19	19	20

Geometry 2. Number of combinations: 20 Angles: 37.0 37.0 144.0
Detectors:

1	3	1	4	1	16	1	17	2	4
2	5	2	17	2	18	3	5	3	18
3	19	4	19	4	20	5	16	5	20
16	18	16	19	17	19	17	20	18	20

Geometry 3. Number of combinations: 20 Angles: 37.0 79.0 0.0
Detectors:

1	6	1	14	2	7	2	15	3	8
3	11	4	9	4	12	5	10	5	13
19	6	20	7	16	8	17	9	18	10
16	11	17	12	18	13	19	14	20	15

Geometry 4. Number of combinations: 40 Angles: 37.0 79.0 72.0
Detectors:

1	7	1	10	1	13	1	15	2	6
2	8	2	11	2	14	3	7	3	9
3	12	3	15	4	8	4	10	4	11
4	13	5	6	5	9	5	12	5	14
18	6	20	6	16	7	19	7	17	8
20	8	16	9	18	9	17	10	19	10
17	11	20	11	16	12	18	12	17	13
19	13	18	14	20	14	16	15	19	15

Geometry 5. Number of combinations: 40 Angles: 37.0 79.0 144.0
Detectors:

1	8	1	9	1	11	1	12	2	9
2	10	2	12	2	13	3	6	3	10
3	13	3	14	4	6	4	7	4	14
4	15	5	7	5	8	5	11	5	15
16	6	17	6	17	7	18	7	18	8
19	8	19	9	20	9	16	10	20	10
18	11	19	11	19	12	20	12	16	13
20	13	16	14	17	14	17	15	18	15

Geometry 6. Number of combinations: 5 Angles: 37.0 37.0 0.0
Detectors:

1	19	2	20	3	16	4	17	5	18

Geometry 7. Number of combinations: 20 Angles: 79.0 79.0 72.0
Detectors:

6	7	6	10	6	13	6	15	7	8
7	11	7	14	8	9	8	12	8	15
9	10	9	11	9	13	10	12	10	14
11	12	11	15	12	13	13	14	14	15

Geometry 8. Number of combinations: 20 Angles: 79.0 79.0 144.0
Detectors:

6	8	6	9	6	11	6	12	7	9
7	10	7	12	7	13	8	10	8	13
8	14	9	14	9	15	10	11	10	15
11	13	11	14	12	14	12	15	13	15

Geometry 9. Number of combinations: 5 Angles: 79.0 79.0 0.0
Detectors:

6	14	7	15	8	11	9	12	10	13

Appendix 6
Input for *CORR_EFF*

```
$ RUN CORR_EFF
YB164_L.EFF
CORR_EFF.DAT
CORR_EFF.OUT
YES
0.02
 262 124
N  40198 201 34032 185
 375 262
E 391761 629 358760 601
N 137179 371 122574 352
 200 300
A 10000 12000
B
C
D
R
```

Appendix 7
Detector efficiency input for *CORR_EFF*

```
20
    -0.27053    -0.475322    -0.125147    -0.432873    -0.591019    -0.149843
   -0.326493    -0.346037   -0.0253792    0.0160717    -0.257256   -0.0790279
   -0.341936    -0.498224   -0.0269054     -0.39639    -0.403752   -0.0767667
   -0.264559    -0.434109     0.100864    -0.269356    -0.478446    -0.119111
   -0.409585    -0.508384    -0.104385     -0.27515    -0.429377    -0.111326
   -0.391717    -0.435438    0.0224832    0.0086558    -0.315224   -0.0985052
   -0.361561    -0.550899    0.0548265     -0.23958    -0.366017   -0.0788916
   -0.523338    -0.501152     -0.16028    -0.275475    -0.611614    -0.186858
   -0.434119    -0.566078    0.0769845     -0.12338     -0.33096   -0.0784332
   -0.477118       -0.506     0.138649     -0.19928    -0.389321   -0.0938317
    -0.50215    -0.621364     0.149538     0.242025    0.0302855    0.0160332
   -0.532126    -0.645042     0.107622     0.137407    0.0416496    0.0268327
   -0.616925    -0.667069   -0.0576175    -0.142092    -0.135306   -0.0110605
   -0.475287    -0.512753    -0.193199    -0.400657    -0.481184     -0.10834
    -0.66057    -0.753728     0.158885     0.299834     0.209589    0.0738645
   -0.516215    -0.604739    0.0335535   -0.0756567    -0.111489   0.00612409
   -0.506187    -0.558767    0.0876446    -0.338708    -0.537577    -0.130846
   -0.456693    -0.577429    0.0621573    0.0819393    0.0398644     0.047855
   -0.691582    -0.670617     0.121849     0.156006    0.0779367    0.0414437
   -0.762838    -0.649098   -0.0318577    0.0370159   -0.0204663    0.0212306
```

Appendix 8
Detector combination input for *CORR_EFF*

```
A
20
      1  2       1  5       1 18       1 20       2  3
      2 16       2 19       3  4       3 17       3 20
      4  5       4 16       4 18       5 17       5 19
     16 17      16 20      17 18      18 19      19 20
B
20
      1  3       1  4       1 16       1 17       2  4
      2  5       2 17       2 18       3  5       3 18
      3 19       4 19       4 20       5 16       5 20
     16 18      16 19      17 19      17 20      18 20
C
20
      1  6       1 14       2  7       2 15       3  8
      3 11       4  9       4 12       5 10       5 13
     19  6      20  7      16  8      17  9      18 10
     16 11      17 12      18 13      19 14      20 15
D
40
      1  7       1 10       1 13       1 15       2  6
      2  8       2 11       2 14       3  7       3  9
      3 12       3 15       4  8       4 10       4 11
      4 13       5  6       5  9       5 12       5 14
     18  6      20  6      16  7      19  7      17  8
     20  8      16  9      18  9      17 10      19 10
     17 11      20 11      16 12      18 12      17 13
     19 13      18 14      20 14      16 15      19 15
E
40
      1  8       1  9       1 11       1 12       2  9
      2 10       2 12       2 13       3  6       3 10
      3 13       3 14       4  6       4  7       4 14
      4 15       5  7       5  8       5 11       5 15
     16  6      17  6      17  7      18  7      18  8
     19  8      19  9      20  9      16 10      20 10
     18 11      19 11      19 12      20 12      16 13
     20 13      16 14      17 14      17 15      18 15
J
5
      1 19       2 20       3 16       4 17       5 18
N
20
      6  7       6 10       6 13       6 15       7  8
      7 11       7 14       8  9       8 12       8 15
      9 10       9 11       9 13      10 12      10 14
     11 12      11 15      12 13      13 14      14 15
O
20
      6  8       6  9       6 11       6 12       7  9
      7 10       7 12       7 13       8 10       8 13
      8 14       9 14       9 15      10 11      10 15
     11 13      11 14      12 14      12 15      13 15
R
5
      6 14       7 15       8 11       9 12      10 13
```

Appendix 9
Part of output from *CORR_EFF*

```
PROGRAM CORR_EFF
 Calculates efficiencies for correlation geometries
Version 2.0
 Number of detectors:          20
 Number of geometries:          9

Input:
 Filename for file contaning efficency coefficients
 Filename for file contaning detector combinations
 Output filename
 Print detector combinations and efficiencies (Y/N)
 Fractional uncertainty in efficiency
 <Space> Egamma1 Egamma2 (in time order)
 Geometry name (one character) V1 dV1 V2 dV2

Output:
 Egamma1, Egamma2, Geometry, V, dV, Eff, dEff, W, dW, Average/DCO Ratio
 dW includes uncertainty in efficiency, DCO ratio does not


 logE parametrization, file= YB164_L.EFF
 Detector combinations, file=CORR_EFF.DAT
 Fractional unc. in efficiency:  2.0000000E-02
```

E1	E2	Geometry	V	dV	Eff	dEff	W	dW	Average/DCO ratio	
262.0	124.0	N(1,2)	40198.	201.	10.526	0.211	3818.79	78.73	4014.14	58.76
262.0	124.0	N(2,1)	34032.	185.	7.989	0.160	4259.82	88.29	0.896	0.007
375.0	262.0	E(1,2)	391761.	629.	41.019	0.820	9550.67	191.63	9161.94	130.10
375.0	262.0	E(2,1)	358760.	601.	40.632	0.813	8829.51	177.21	1.082	0.003
375.0	262.0	N(1,2)	137179.	371.	21.005	0.420	6530.76	131.80	6551.18	93.54
375.0	262.0	N(2,1)	122574.	352.	18.651	0.373	6571.90	132.79	0.994	0.004
200.0	300.0	A(1,2)	10000.	12000.	17.214	0.344	580.91	697.19	0.00	0.00
200.0	300.0	B(1,2)	0.	0.	16.863	0.337	0.00	0.00	0.00	0.00
200.0	300.0	C(1,2)	0.	0.	17.400	0.348	0.00	0.00	0.00	0.00
200.0	300.0	D(1,2)	0.	0.	36.546	0.731	0.00	0.00	0.00	0.00
200.0	300.0	R(1,2)	0.	0.	4.103	0.082	0.00	0.00	0.00	0.00

```
 Normal program end
```