Angular distributions, correlation and linear polarization in tracking arrays

- Status now
- Ang cor results with sources
- Ang cor formalism and results in-beam
- Lin pol sources with no source calibration
- Lin pol in-beam with no source calibration
- Angular distribution, new idea?
- Conclusions

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Amel Korichi, CSNSM

Status now, as we see it

method	source	in–beam	need source cal
ang dis	N/A	problem!	yes
ang cor	OK		no
lin–pol			yes

Good examples shown last time

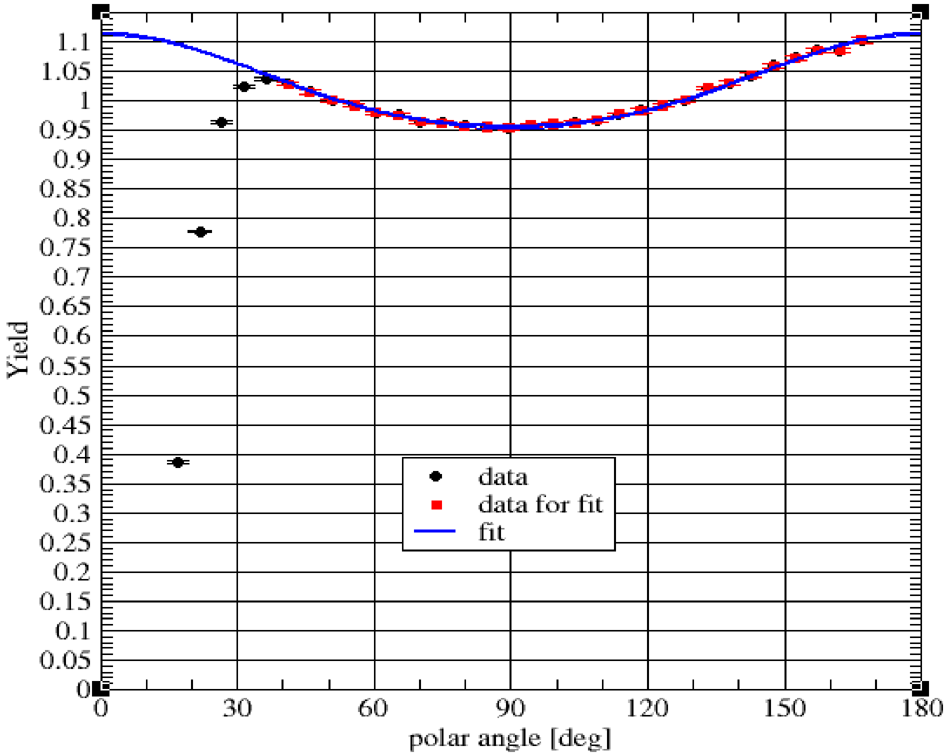
Yikes!

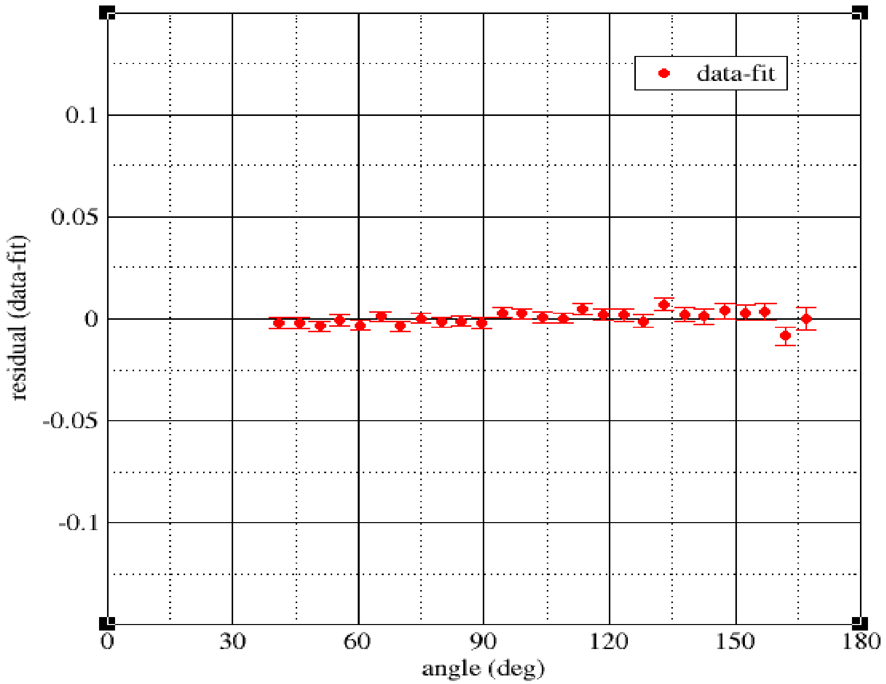
Lots of discussion...

Some source angcor results

(high statistics)

^{60}Co 1173/1333 (classic)



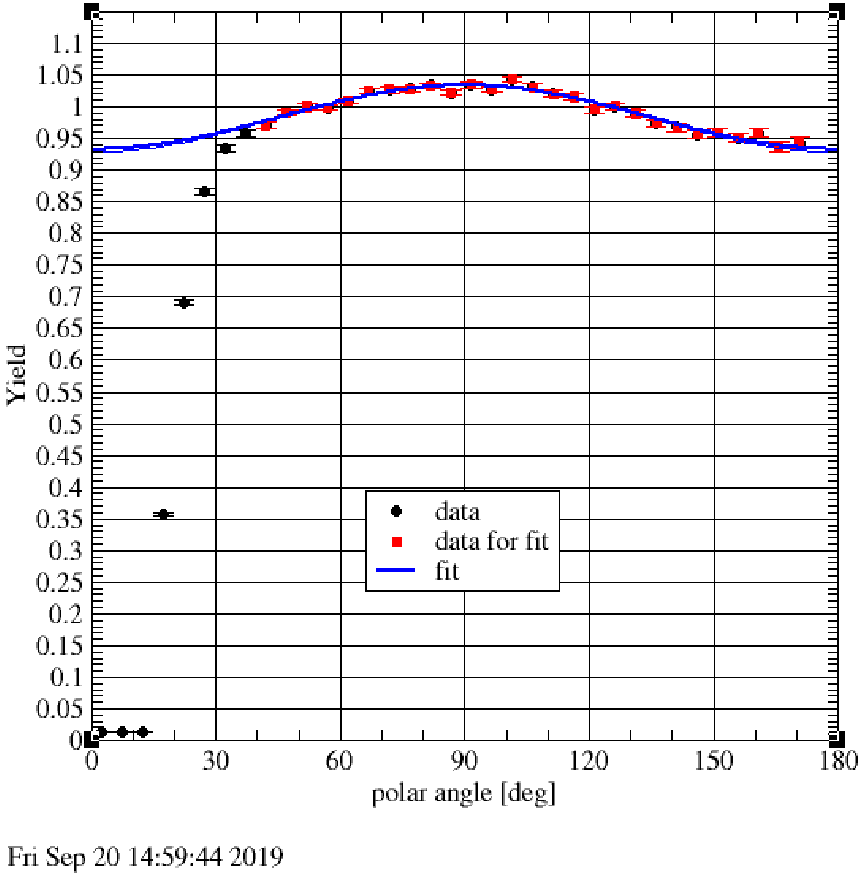


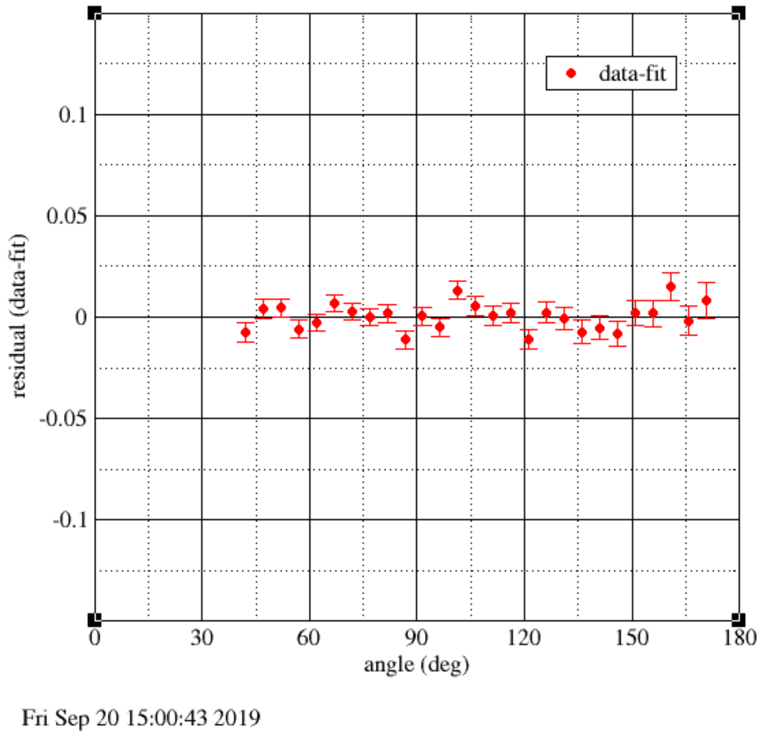
ordinary legfit a0,a2,a4 fit>>>

chi**2: 1.083
a0: 1.000 +/- 0.001
a2: 0.100 +/- 0.002
a4: 0.014 +/- 0.002

-------------------- Ii= 4.0
| L1= 2.0
| L1'= 3.0
| del= 0.000
-------------------- I= 2.0
| L2= 2.0
| L2'= 3.0
| del= 0.000
-------------------- If= 0.0
angular correlation coefficients:
A0 = +1.000000 A2 = +0.102041 A4 = +0.009070 A6 = +0.000000

^{88}Y 898/1836

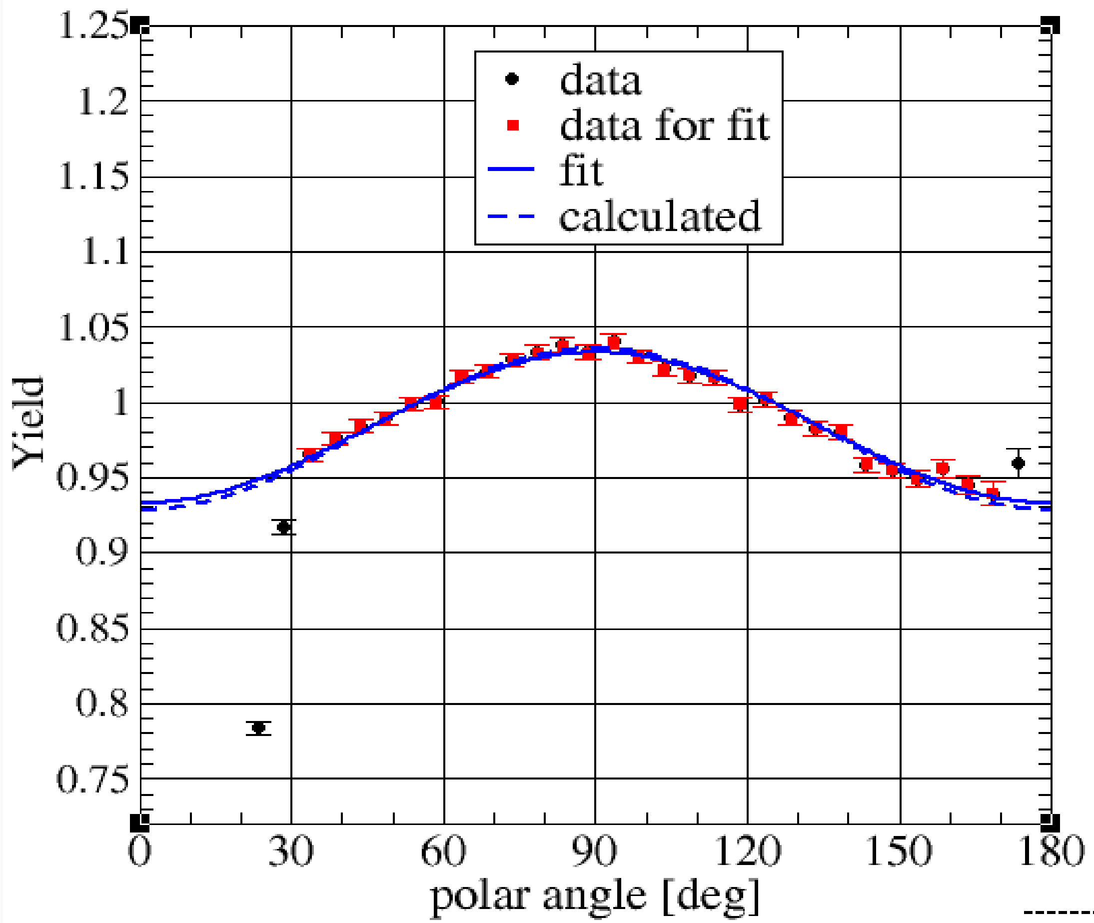


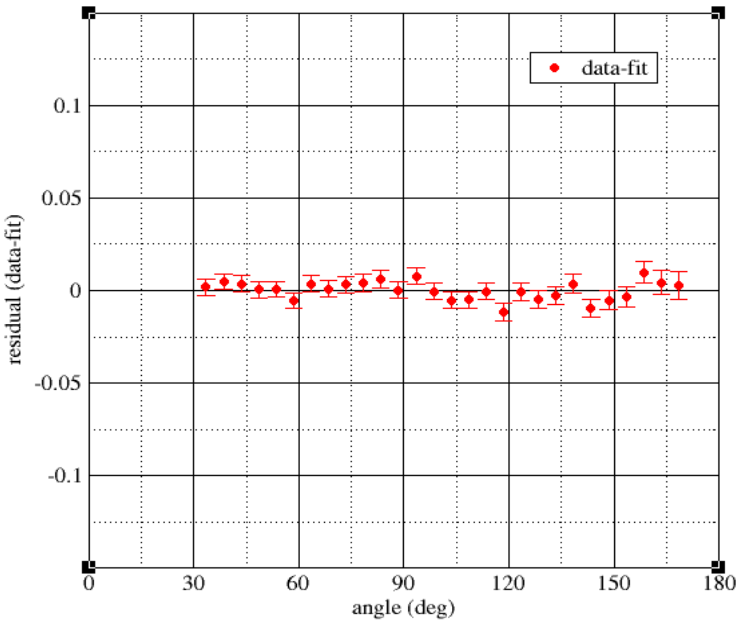


chi**2: 1.644
a0: 1.000 +/- 0.001
a2: -0.067 +/- 0.002
a4: 0.004 +/- 0.003

```
-------------------- Ii=   3.0
      | L1=    1.0
      | L1'=   2.0
      | del=  0.000
-------------------- I=   2.0
      | L2=    2.0
      | L2'=   3.0
      | del=  0.000
-------------------- If=   0.0
angular correlation coefficients:
A0 = +1.000000 A2 = -0.071429 A4 = -0.000000 A6 = -0.000000
```

^{152}Eu 344/778



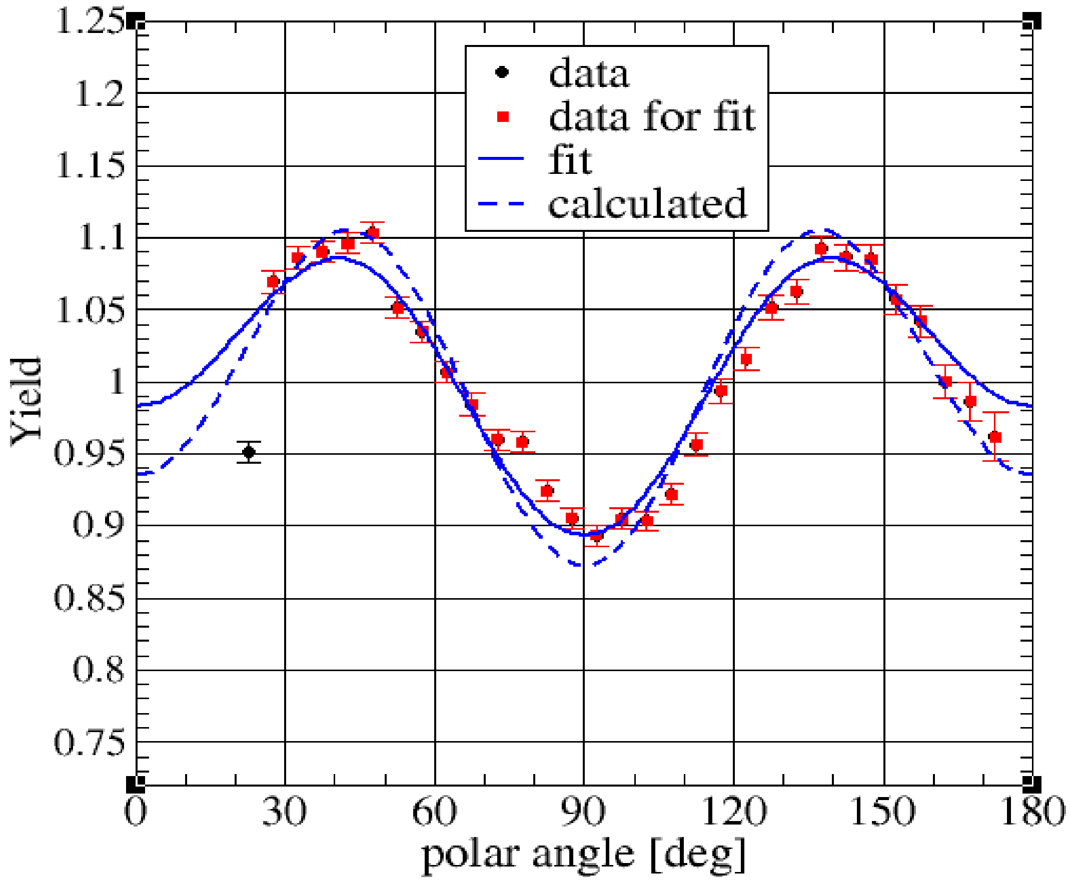


ordinary legfit a0,a2,a4 fit>>>

chi**2: 1.033
a0: 1.000 +/- 0.001
a2: -0.066 +/- 0.002
a4: 0.005 +/- 0.003

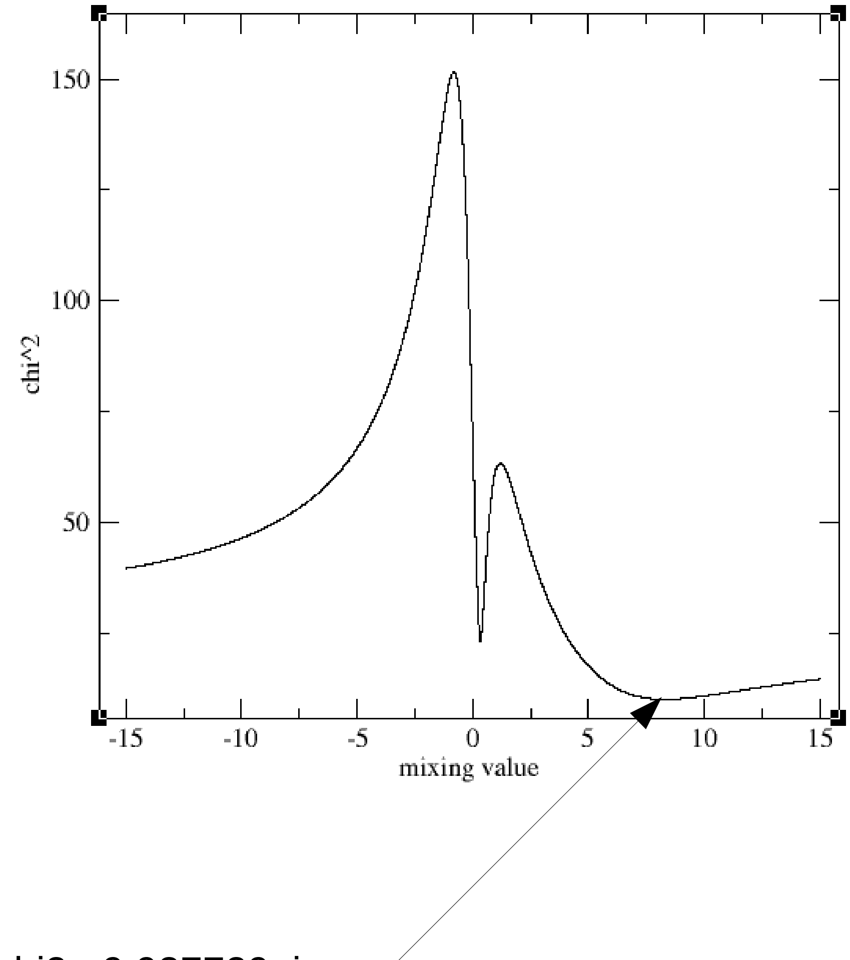
-------------------- Ii= 3.0
| L1= 1.0
| L1'= 2.0
| del= 0.000
-------------------- I= 2.0
| L2= 2.0
| L2'= 2.0
| del= 0.000
-------------------- If= 0.0
angular correlation coefficients:
A0 = +1.000000 A2 = -0.071429 A4 = -0.000000 A6 = -0.000000

^{152}Eu 245/867 Mixed! (interesting!)



chi**2: 3.890
a0: 1.000 +/- 0.001
a2: 0.114 +/- 0.004
a4: -0.131 +/- 0.005

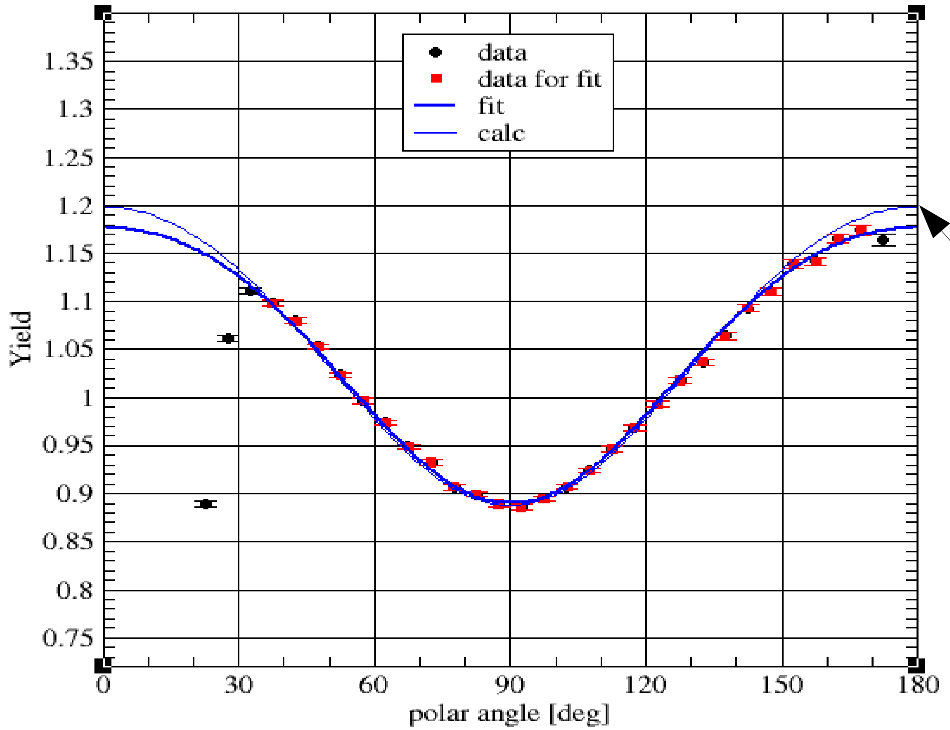
Mixing fit:



best fit, with chi2= 9.937729, is:
A0 = 1.000000 A2 = 0.117791 A4 = -0.182638 A6 = -0.000000
for delta2= 8.294 +/- 1.713 (== griffin -8.294 +/- 1.713)

ENSDF says -9.3 (no error)
(sign convensions...)
Assumed no attenuation

207Bi; 570/1064 (use for lin pol later)



Calculated curve

calc_a0a2a4 calc 6.5 2.5 0.5 4 5 0.02 2 3 0
-------------------- Ii=   6.5
1064 M4+E5 | L1=   4.0
| L1'=   5.0
| del= 0.020

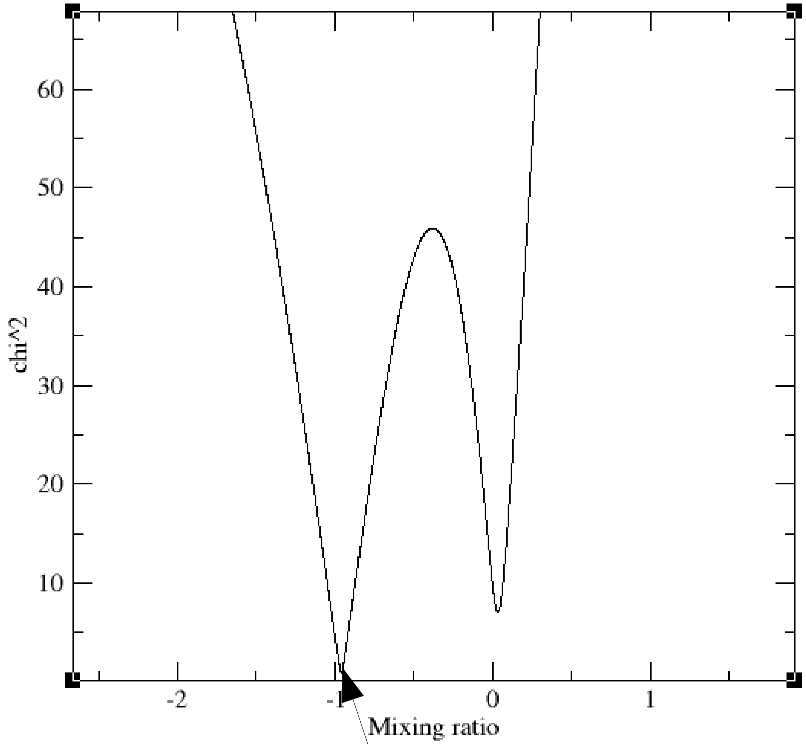
What ENSDF says

-------------------- I=   2.5
570 E2 | L2=   2.0
| L2'=   3.0
| del= 0.000
-------------------- If=   0.5

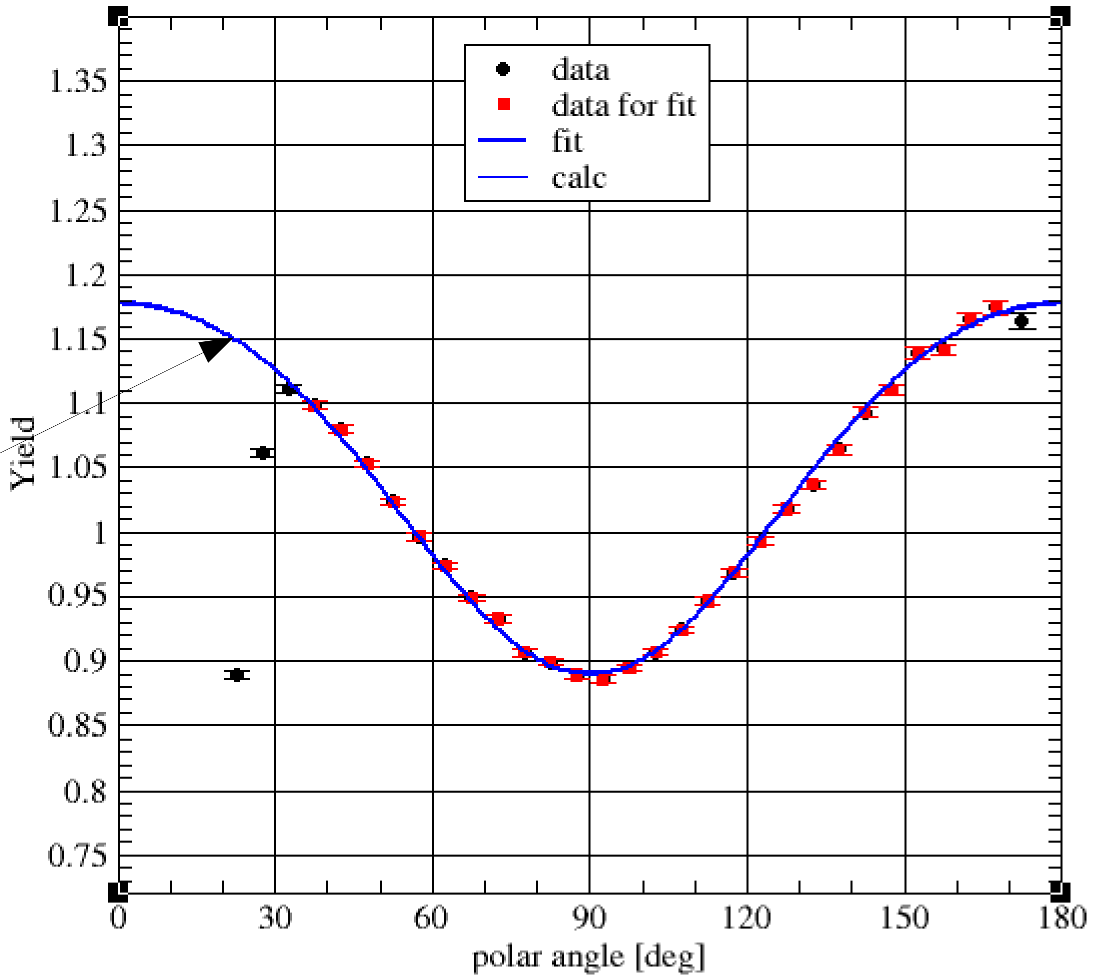
angular correlation coefficients:
A0 = +1.000000 A2 = +0.213305 A4 = -0.014544

chi**2:	2.281	
a0:	1.000 +/-	0.001
a2:	0.202 +/-	0.002
a4:	-0.025 +/-	0.002

Could ENSDF be wrong? Fit...



best fit, with chi2= 0.876589, is:
A0 = 1.000000 A2 = 0.202619 A4 = -0.023360 A6 = -0.000000
for delta1= -0.960 +/- 0.016 (== griffin 0.960 +/- 0.016)



Looks better

Perfect fit with mixing ratio of -0.96(2)

In-beam angular correlations:

DCO (Directional Correlation from Oriented nuclei)

Need to use a different angle

First state is no longer random in m-distribution

The formalism is quite complicated

NUCLEAR DATA TABLES, **11**, 351–406 (1973)

DIRECTIONAL CORRELATIONS OF GAMMA RADIATIONS EMITTED FROM NUCLEAR STATES ORIENTED BY NUCLEAR REACTIONS OR CRYOGENIC METHODS

K. S. KRANE
R. M. STEFFEN and R. M. WHEELER

Use this angle for the angular distribution rather than angle between the gamma rays as we do for sources

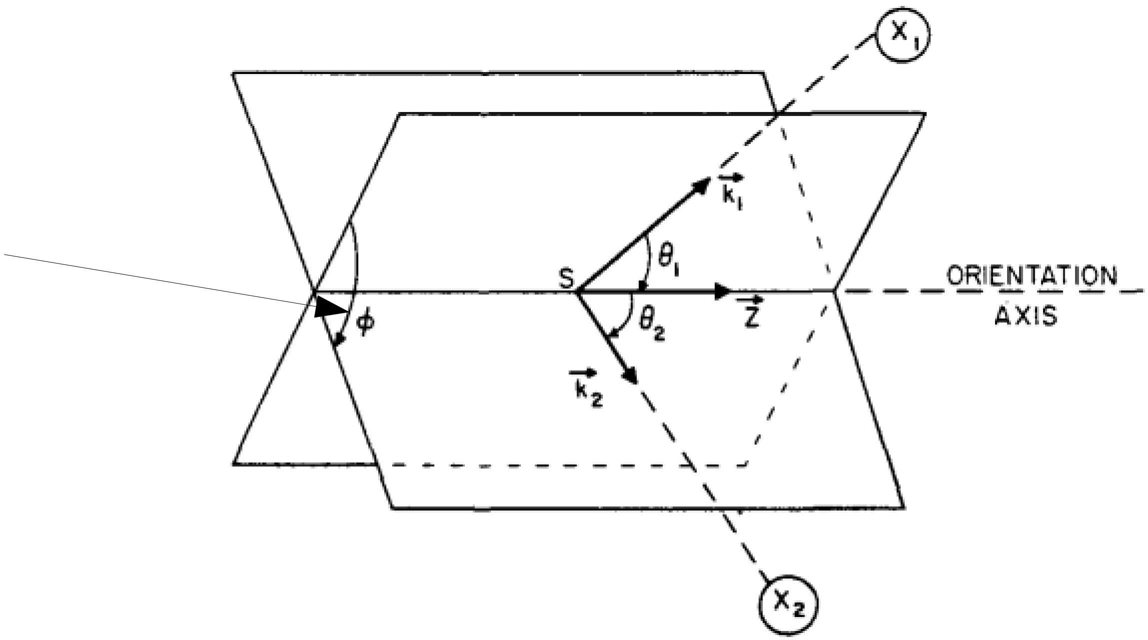


Fig. 2. The angles in a directional correlation of two successive radiations X_1 and X_2 emitted from an axial symmetric oriented source S (DCO)

Taste of the formulas (from Krane)

$$W(\theta_1,\theta_2,\Phi) = \sum_{\lambda_1\lambda\lambda_2} B_{\lambda_1}(I_1) A_{\lambda}^{\lambda_2\lambda_1}(X_1) A_{\lambda_2}(X_2) H_{\lambda_1\lambda\lambda_2}(\theta_1\theta_2\Phi).$$

$$H_{\lambda_1\lambda\lambda_2}(\theta_1,\theta_2,\Phi) = \sum_{q=-\lambda'}^{\lambda'} \frac{4\pi}{2\lambda_2+1} \langle \lambda_1 0 \lambda q | \lambda_2 q \rangle Y_{\lambda q}(\theta_1,0) Y^*_{\lambda_2 q}(\theta_2,\Phi).$$

Beam alignment related

Radiation distribution coefficients

Spherical harmonics
We don't observe K_1 and K_2 directions
i.e., Lambda==0
Breaks down to usual Legendre polynomials
and only even terms

For 'discrete' array

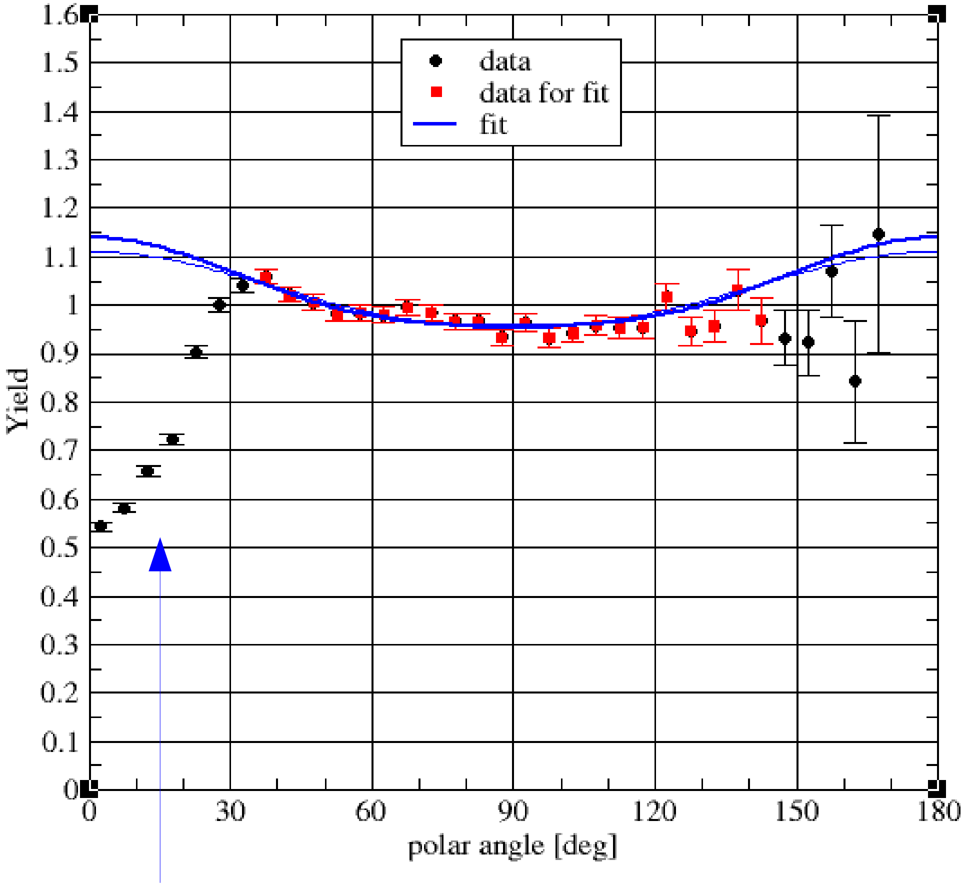
- Use full expression for each pair of gamma detectors
- Reduce number for identical pairs. For Eurogam-II about 83 pairs (E.S. Paul)
- Use full treatment for each of these pairs, where k_1 and k_2 specify the two detector directions

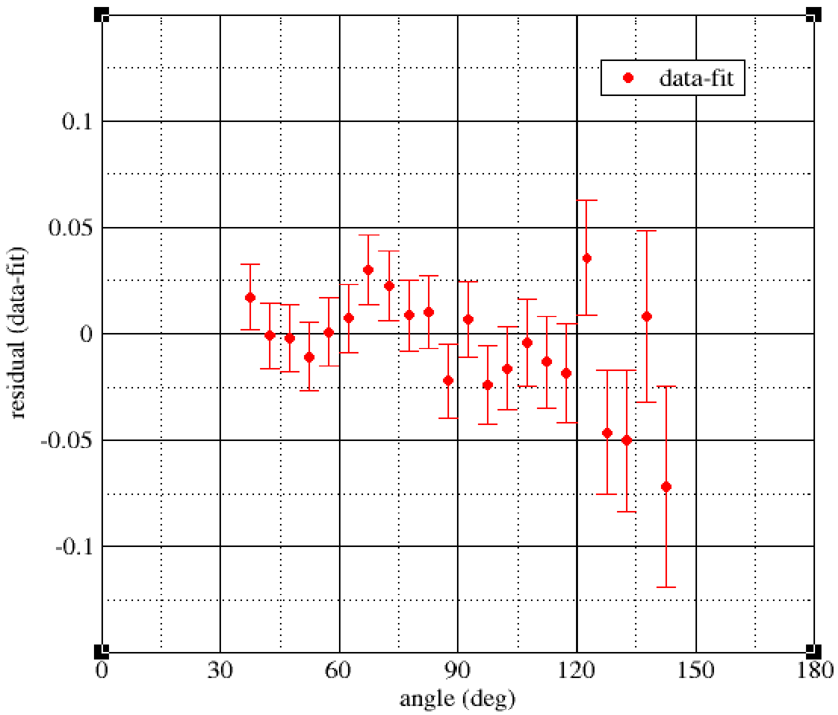
For 'continuous' arrays

- Since we don't observe the directions of the individual gamma rays, the standard formula works, we just have to **use the plane angles** rather than the angle between the gamma rays *(need rigorous proof...)*
- Calculating the coefficients might involve some weighted averages over the k_1 and k_2 directions that depends on the particular configuration
- We have: $$\omega(\theta) = a0 + \alpha_2 a_2 P_2(cos\Phi) + \alpha_4 a_4 P_4(cos\Phi) + ...$$

Plane angle
NOT
Angle bt gammas

^{158}Er in-beam; 8(2)6(2)4, <u>using plane angle</u>





Notice: 'cluster hole' is different

chi**2: 1.101
a0: 1.000 +/- 0.007
a2: 0.110 +/- 0.025
a4: 0.030 +/- 0.027

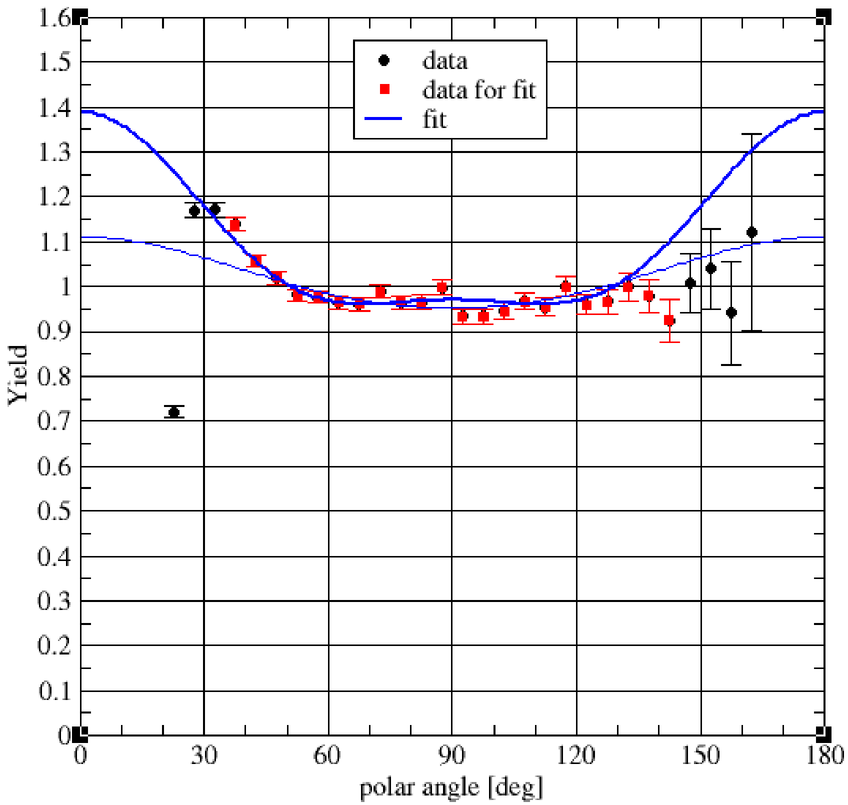
?

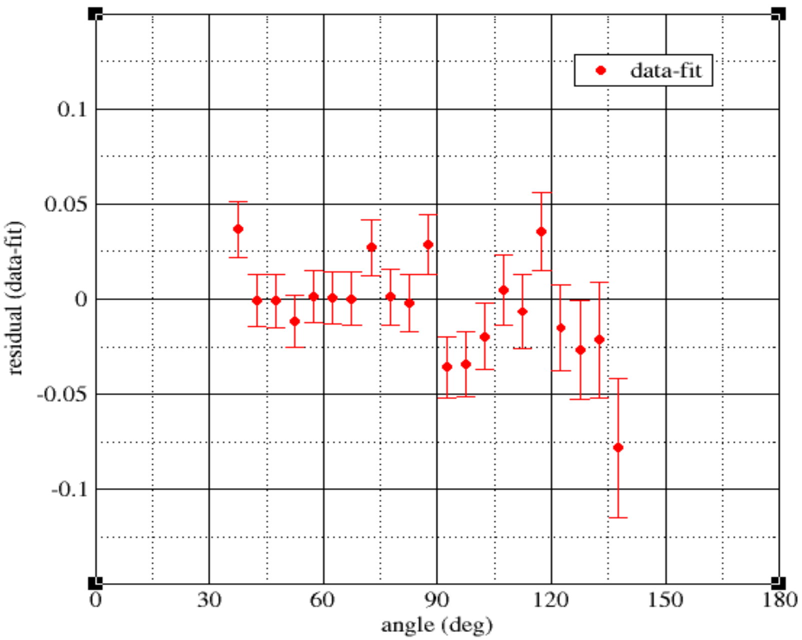
-------------------- Ii= 8.0
| L1= 2.0
| L1'= 3.0
| del= 0.000
-------------------- I= 6.0
| L2= 2.0
| L2'= 3.0
| del= 0.000
-------------------- If= 4.0

angular correlation coefficients:

A0 = +1.000000 A2 = +0.102041 A4 = +0.009070 A6 = +0.000000

^{158}Er in-beam; 8(2)6(2)4, using angle bt gammas wrong way!





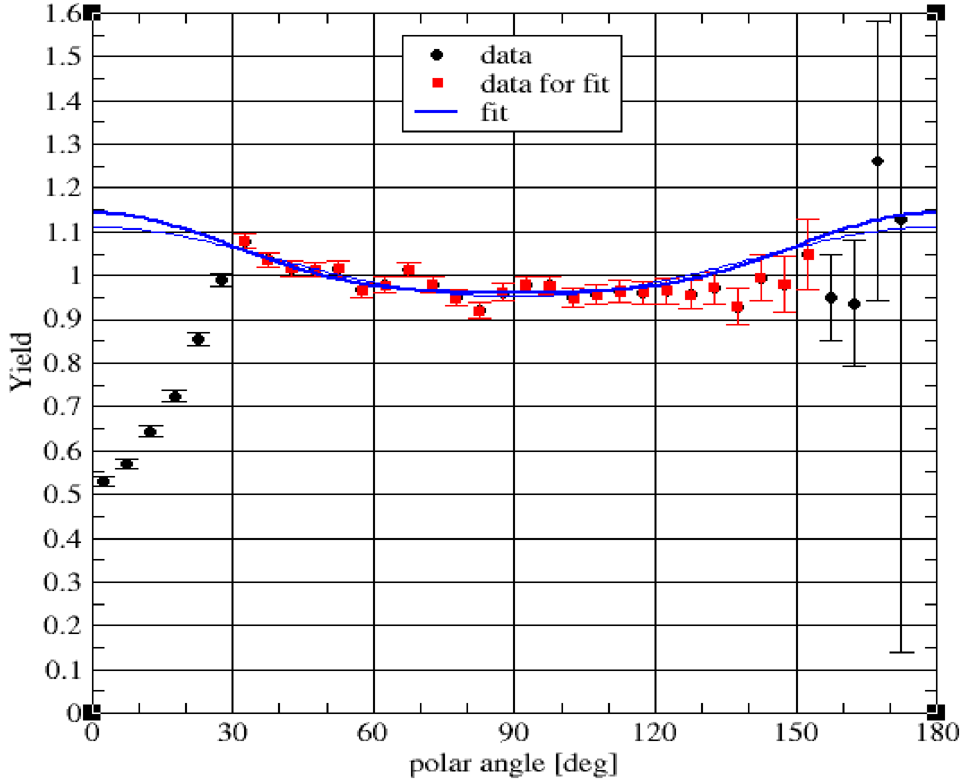
chi**2: 2.375
a0: 1.034 +/- 0.006
a2: 0.226 +/- 0.022
a4: 0.129 +/- 0.023

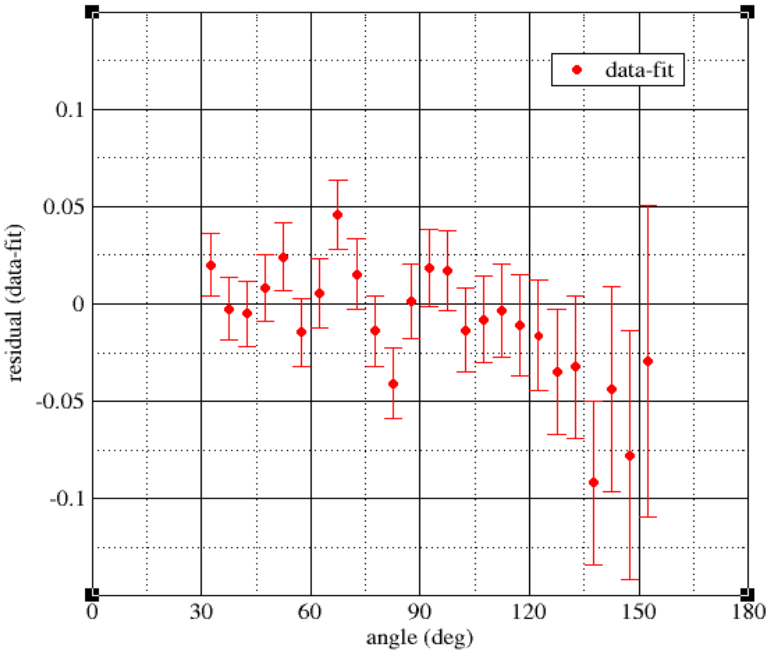
-------------------- Ii= 8.0
| L1= 2.0
| L1'= 3.0
| del= 0.000
-------------------- I= 6.0
| L2= 2.0
| L2'= 3.0
| del= 0.000
-------------------- If= 4.0

angular correlation coefficients:

A0 = +1.000000 A2 = +0.102041 A4 = +0.009070 A6 = +0.000000

^{158}Er in-beam; 10(2)8(2)6, using plane angle

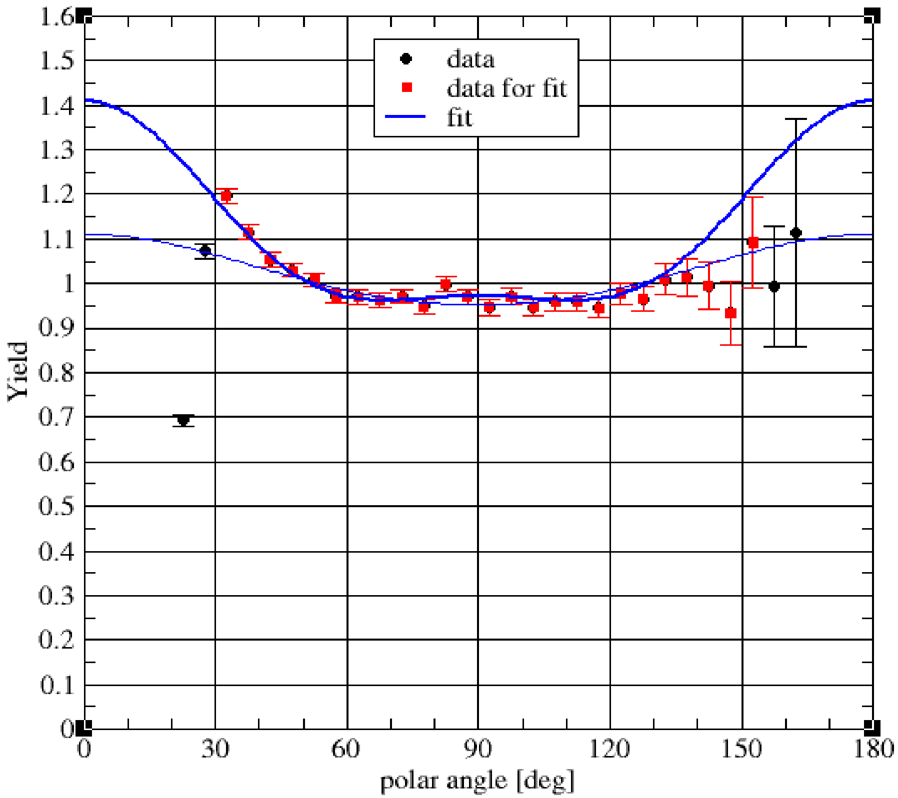


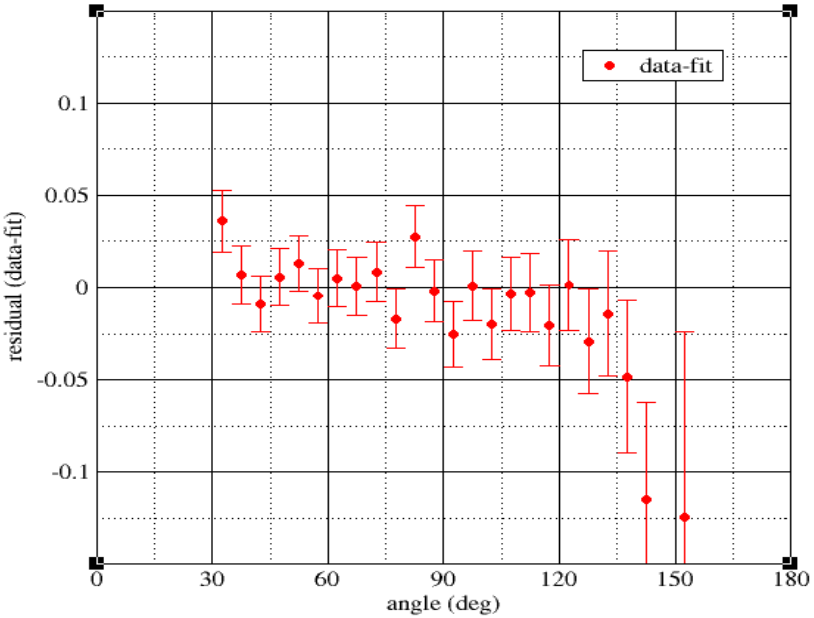


chi**2: 1.262
a0: 1.000 +/- 0.005
a2: 0.107 +/- 0.017
a4: 0.036 +/- 0.022

```
calc_a0a2a4 calc 10 8 6 2 3 0 2 3 0
-------------------- Ii=  10.0
      | L1=    2.0
      | L1'=   3.0
      | del=  0.000
-------------------- I=   8.0
      | L2=    2.0
      | L2'=   3.0
      | del=  0.000
-------------------- If=   6.0
angular correlation coefficients:
A0 = +1.000000 A2 = +0.102041 A4 = +0.009070 A6 = +0.000000
```

^{158}Er in-beam; 10(2)8(2)6, using angle bt gammas wrong way!



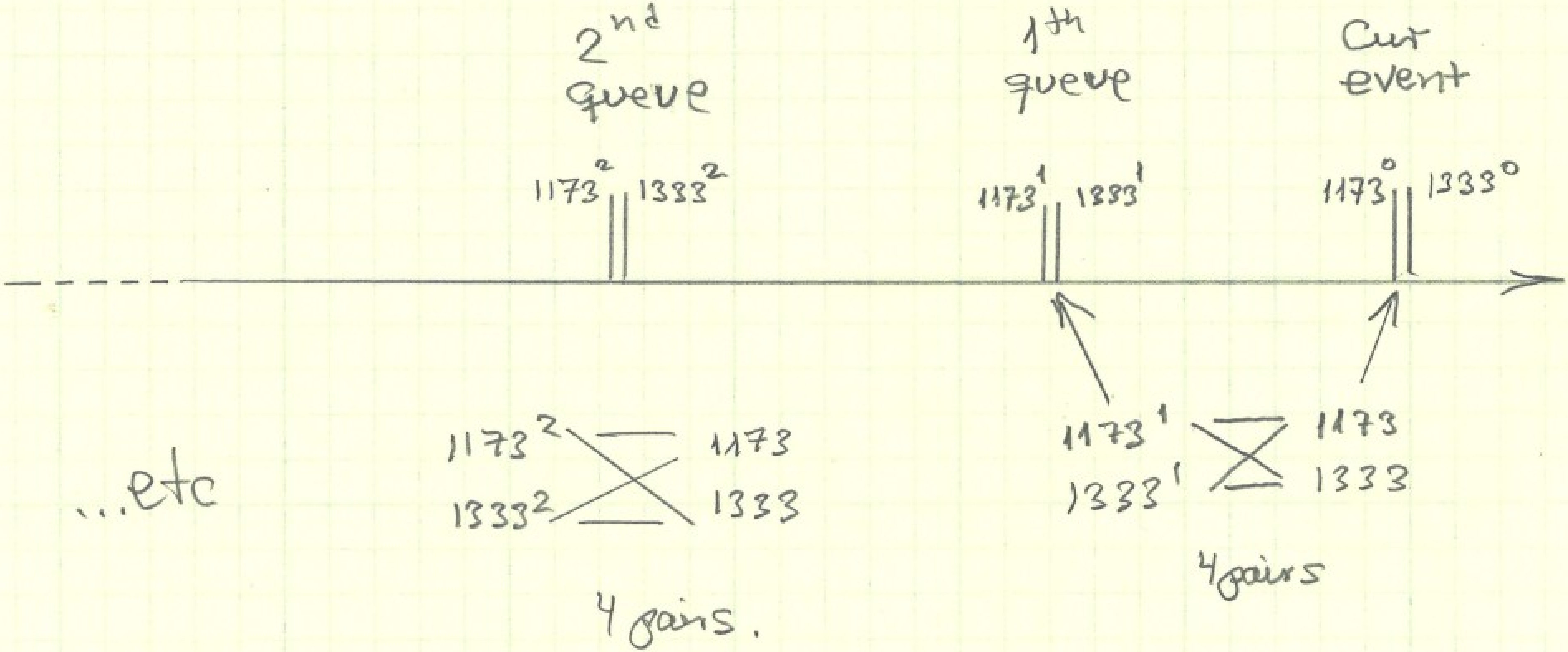


calc_a0a2a4 calc 10 8 6 2 3 0 2 3 0
-------------------- Ii= 10.0
| L1= 2.0
| L1'= 3.0
| del= 0.000
-------------------- I= 8.0
| L2= 2.0
| L2'= 3.0
| del= 0.000
-------------------- If= 6.0
angular correlation coefficients:
A0 = +1.000000 A2 = +0.102041 A4 = +0.009070 A6 = +0.000000

chi**2: 1.449
a0: 1.039 +/- 0.005
a2: 0.235 +/- 0.016
a4: 0.137 +/- 0.020

Normalization, response function

Create response function (reference angular correlation spectrum) mixing with old events in a queue. They are not in coincidence, so there is no angular distribution signal



After use, update the old event queue with the current at the 1'th place and forget the last one

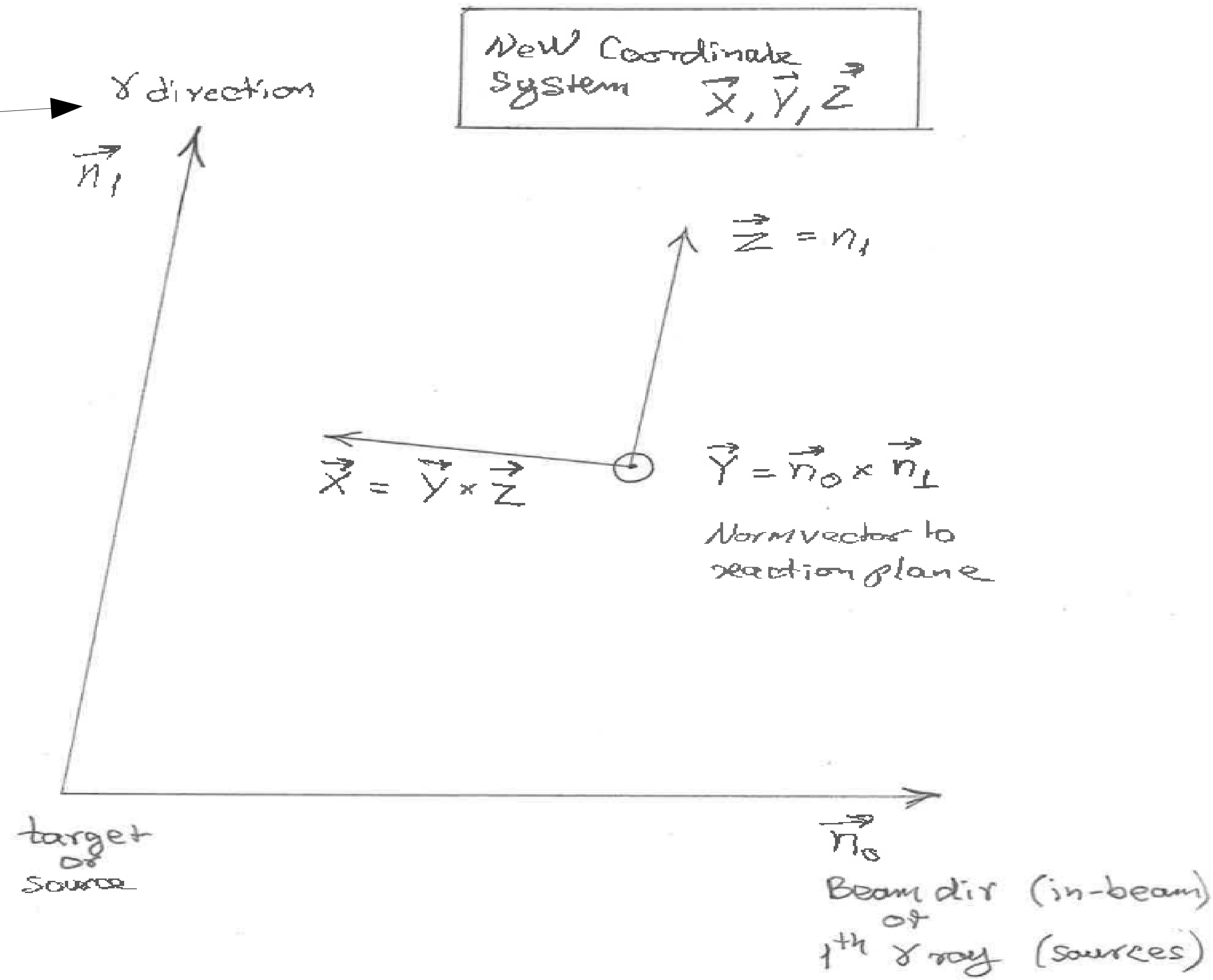
Linear polarization: sources

- For coincidences, we use one gamma ray to polarize the other.
- *We used to have to normalize with a source*
- **We will try to convince you that we can use the data itself for the normalization**

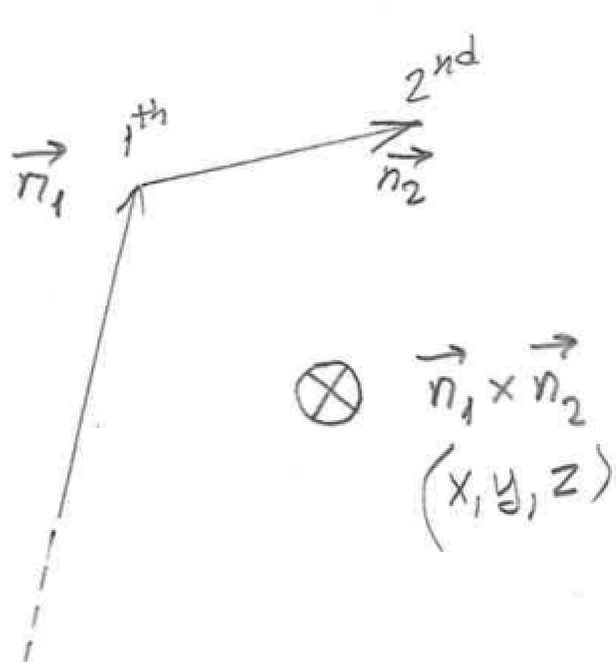
Our geometry for linear polarization

1: define a new coordinate system based on the reaction plane

Gamma ray to measure the polarization of



2: find normal vector for the scattering plane



3: find the x',y',z' coordinates of x,y,z in the new X,Y,Z coordinate system

4: the linear polarization AZIMUTH angle is now found as

atan2(y'/x')

Range: -180 … +180 degrees

Taste of formalism (sources, in-beam)

E: P=-1
M: P=+1

Angle we just defined

$$\omega(\theta,\gamma) = w(\theta) + Pcos(2\gamma) (A_2(L_1,L_1',I_i,I)\Re_2(L_2,L_2',I_f,I)P_2^2(cos\theta) + A_4(L_1,L_1',I_i,I)\Re_4(L_2,L_2',I_f,I)P_4^2(cos\theta))$$

'Usual' A_k coefficients
Use $alpha_k$*B_k for in-beam

Like A_k coefficients but has some extra 'K_k coefficients'

Associated Legendre polynomials

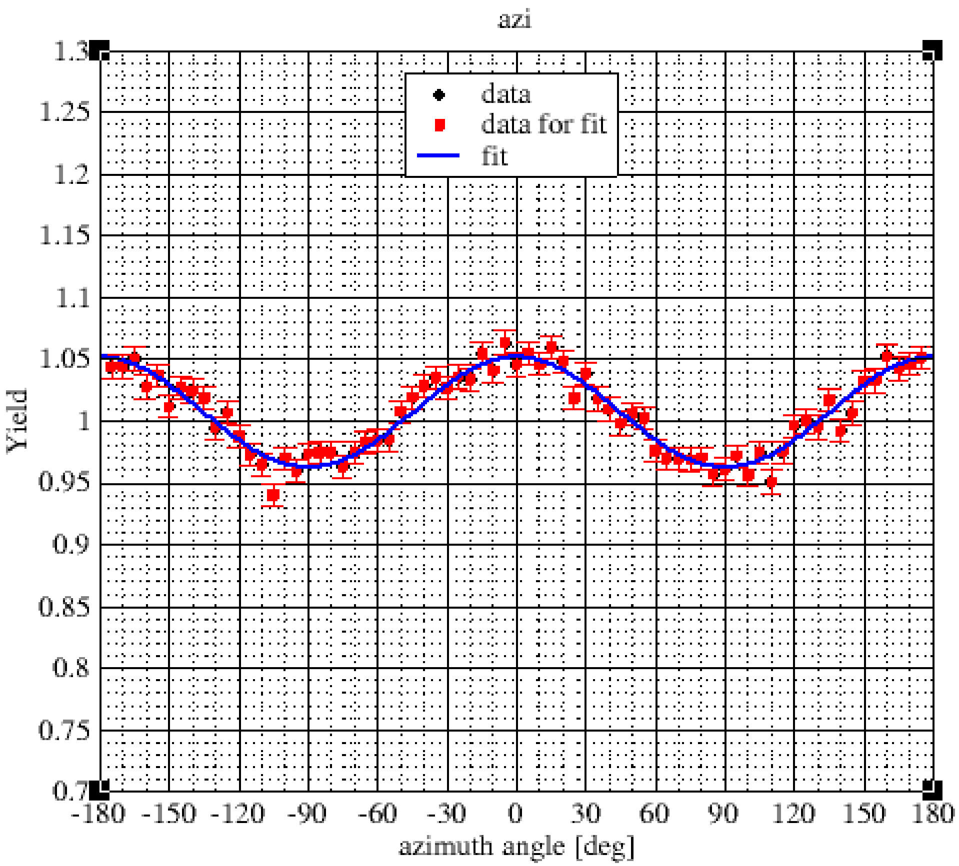
Angle between gamma rays for sources. Use plane angle for in-beam cases

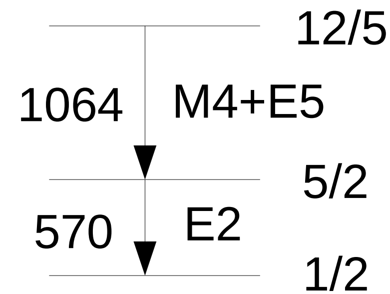
Sign of wiggle: P*(.....), not just P

(new) Response function

- For sources: replace n_0 vector with a number of old n_0 vectors from a queue of previous ones to produce a response function. The old queue is then updated for every event (FIFO).
-
- For in-beam, the beam axis is replaced with random directions in 3D to produce a response function.

^{207}Bi source; 570 E2 line





Polarization spectrum for the 570 keV E2 when polarized by the 1064 keV M4+E5

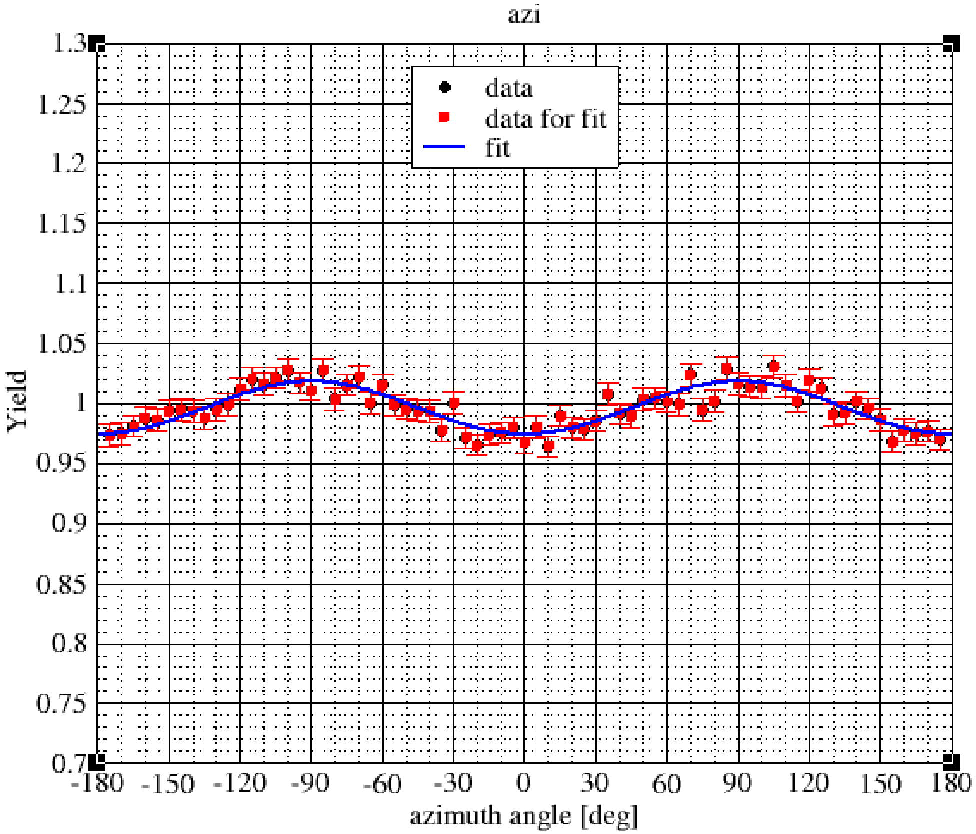
13/2(4)5/2(2)1/2

chi**2: 1.105
a0: 1.007 +/- 0.001
a2: 0.045 +/- 0.002

```
calc_a0a2a4 linpol 6.5 2.5 0.5  4 5 -0.96  2 3 0  E 70 110
-------------------- Ii=   6.5
      | L1=    4.0
      | L1'=   5.0
      | del=  -0.960
-------------------- I=   2.5
      | L2=    2.0
      | L2'=   3.0
      | del=  0.000
-------------------- If=   0.5
angular correlation coefficients:
A0 = +1.000000 A2 = +0.202619 A4 = -0.023360 A6 = -0.000000
w plot in "w.xy"; try xmgrace w.xy -par w.par
linear polarization coefficients:
C2 = +0.101309 C4 = +0.001947 C6 = -0.000000
linpol plot in "w_pol.xy"; try xmgrace w_pol.xy -par wlinpol.par
cos(2*azi) factor is +0.266040 (in 4pi)
```

No angle integration yet

^{207}Bi source; 1064 M4 line

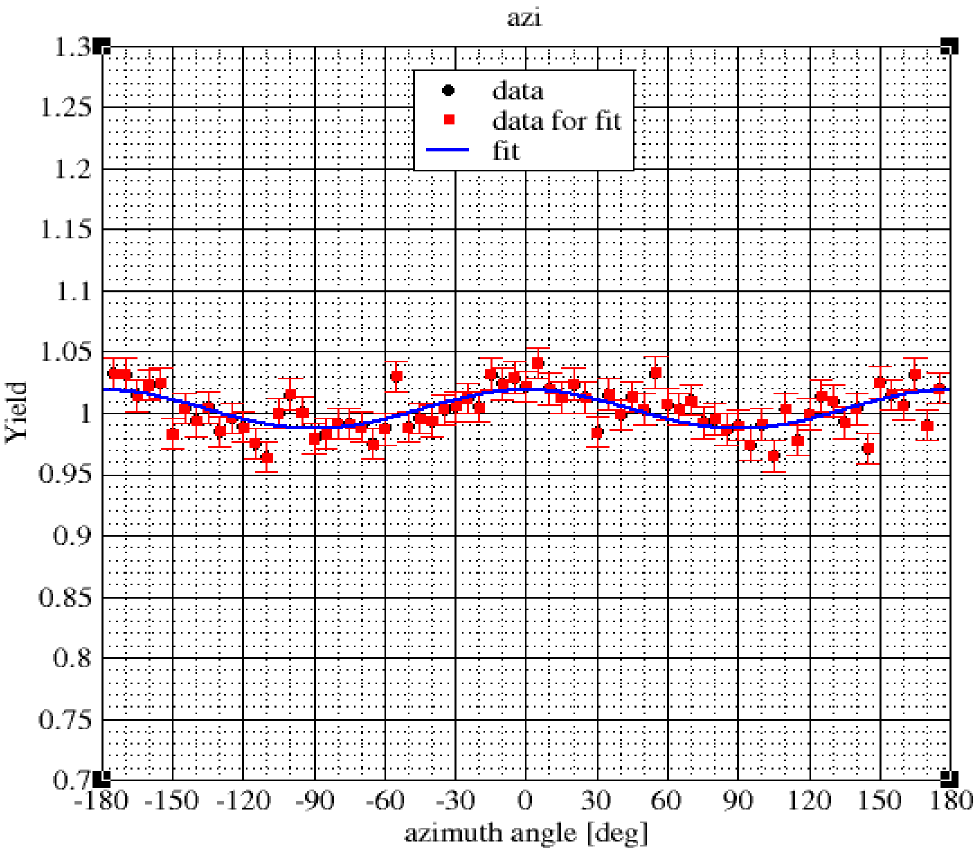


Polarization spectrum for the 1064 keV M4+E5 when polarized by the 570 keV E2

1/2(2)5/2(4)13/2
(backwards)

```
calc_a0a2a4 linpol 0.5 2.5 6.5   2 3 0  4 5 -0.96  M 70 110
-------------------- Ii=   0.5
      | L1=    2.0
      | L1'=   3.0
      | del=  0.000
-------------------- I=   2.5
      | L2=    4.0
      | L2'=   5.0
      | del=  -0.960
-------------------- If=   6.5
angular correlation coefficients:
A0 = +1.000000 A2 = +0.202619 A4 = -0.023360 A6 = -0.000000
w plot in "w.xy"; try xmgrace w.xy -par w.par
linear polarization coefficients:
C2 = -0.136224 C4 = +0.009237 C6 = +0.000000
linpol plot in "w_pol.xy"; try xmgrace w_pol.xy -par wlinpol.par
cos(2*azi) factor is -0.371947 (in 4pi)
```

chi**2: 0.845
a0: 0.996 +/- 0.001
a2: -0.022 +/- 0.002

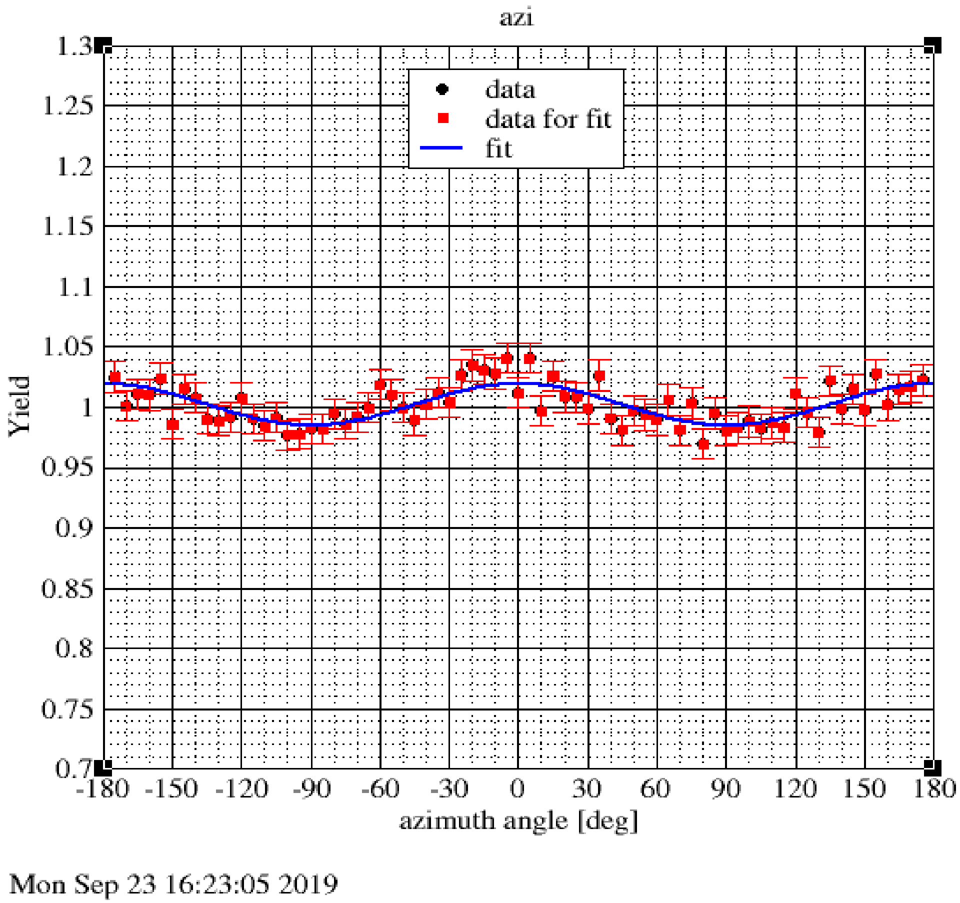


^{60}Co

1333 polarized by 1173
4(2)2(2)0

calc_a0a2a4 linpol 4 2 0 2 3 0 2 3 0 E 70 110
-------------------- Ii=   4.0
| L1=   2.0
| L1'=   3.0
| del= 0.000
-------------------- I=   2.0
| L2=   2.0
| L2'=   3.0
| del= 0.000
-------------------- If=   0.0
angular correlation coefficients:
A0 = +1.000000 A2 = +0.102041 A4 = +0.009070 A6 = +0.000000
w plot in "w.xy"; try xmgrace w.xy -par w.par
linear polarization coefficients:
C2 = +0.051020 C4 = -0.000756 C6 = +0.000000
linpol plot in "w_pol.xy"; try xmgrace w_pol.xy -par wlinpol.par
cos(2*azi) factor is +0.136063 (in 4pi)

chi**2:   0.852
a0:   1.002 +/-   0.001
a2:   0.017 +/-   0.002



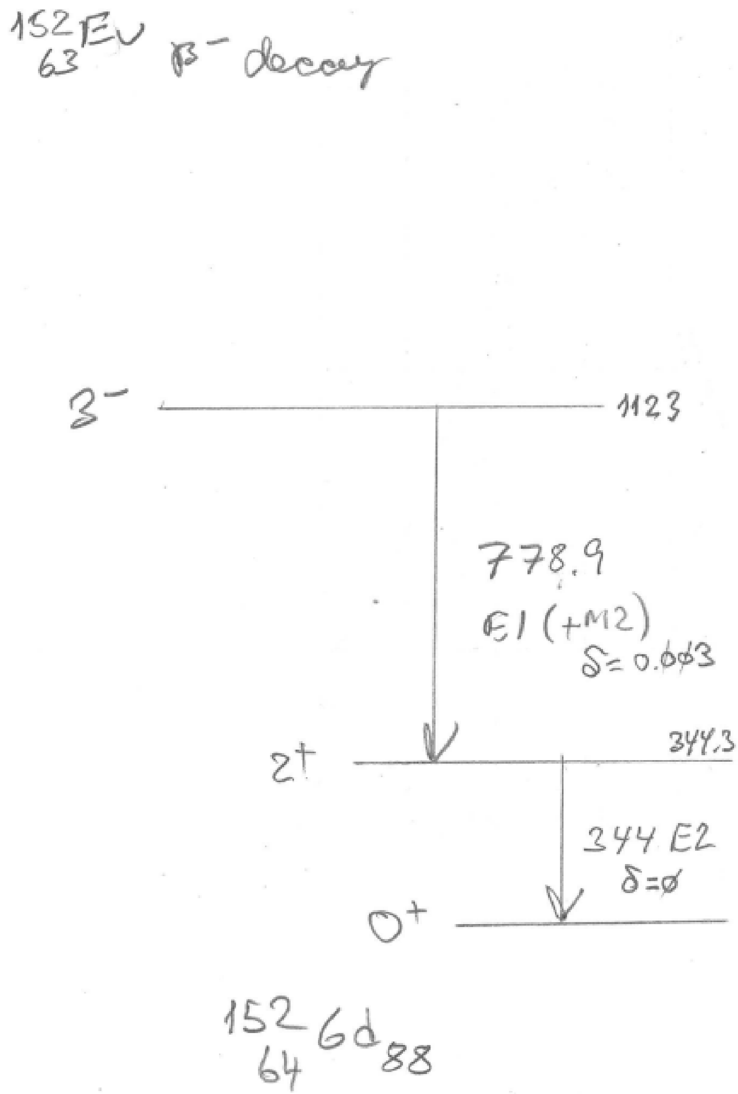
1173 polarized by 1333
0(2)2(2)4

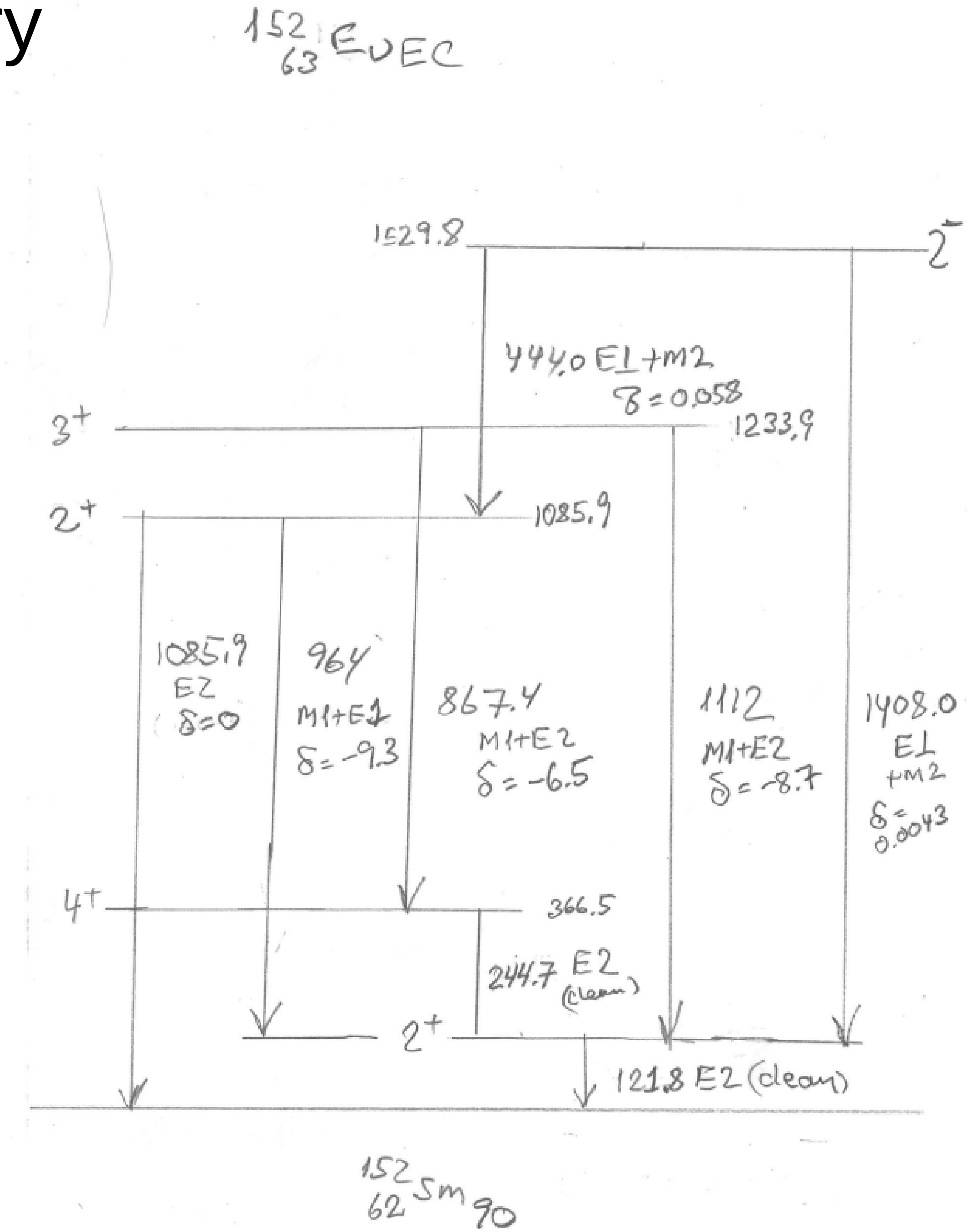
Backwards calculation...

calc_a0a2a4 linpol 0 2 4 2 3 0 2 3 0 E 70 110
-------------------- Ii=   0.0
      | L1=   2.0
      | L1'=   3.0
      | del= 0.000
-------------------- I=   2.0
      | L2=   2.0
      | L2'=   3.0
      | del= 0.000
-------------------- If=   4.0
angular correlation coefficients:
A0 = +1.000000 A2 = +0.102041 A4 = +0.009070 A6 = +0.000000
w plot in "w.xy"; try xmgrace w.xy -par w.par
linear polarization coefficients:
C2 = +0.051020 C4 = -0.000756 C6 = +0.000000
linpol plot in "w_pol.xy"; try xmgrace w_pol.xy -par wlinpol.par
cos(2*azi) factor is +0.136063 (in 4pi)

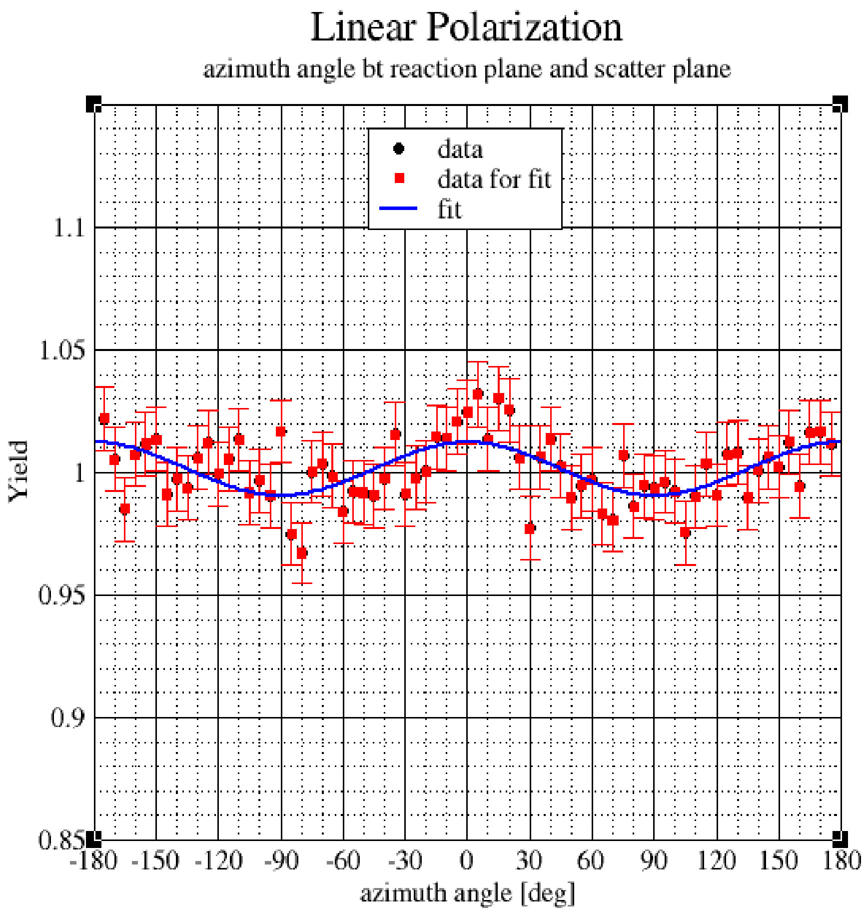
chi**2:   0.852
a0:   1.002 +/-   0.001
a2:   0.017 +/-   0.002

^{152}Eu: great laboratory





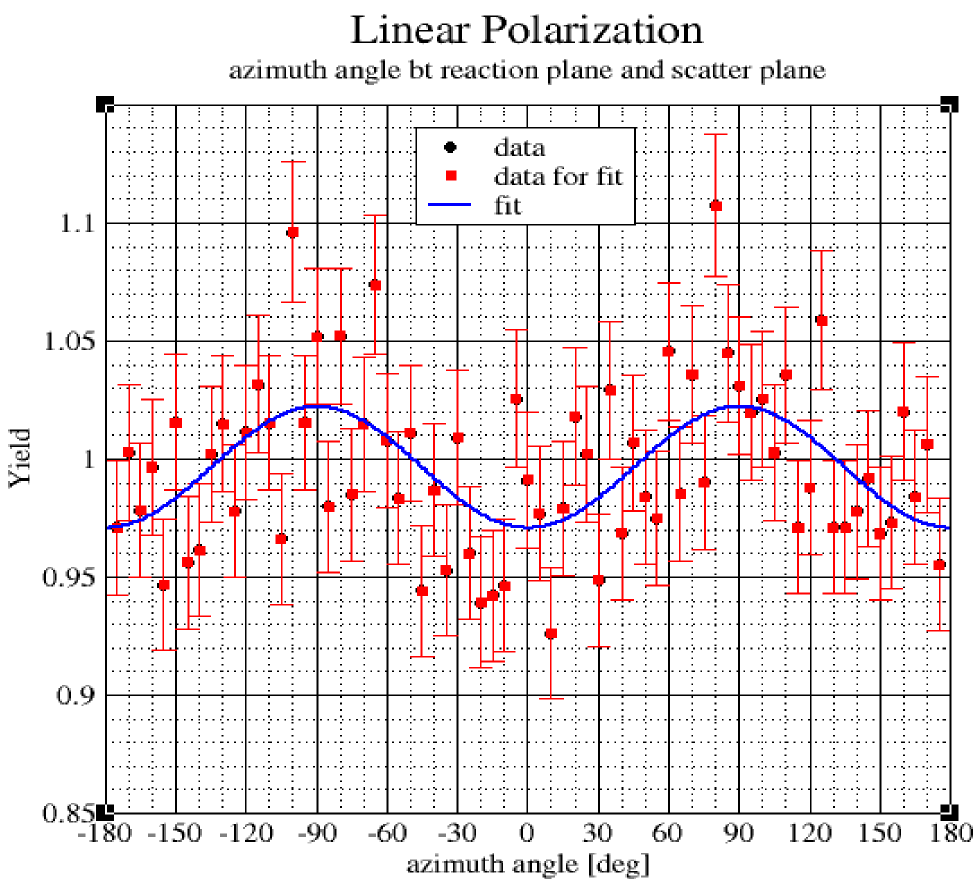
779 (E1) line polarized by 344 (E2) line



calc_a0a2a4 linpol 0 2 3 2 3 0 1 2 0 E 70 110
-------------------- Ii= 0.0
| L1= 2.0
| L1'= 3.0
| del= 0.000
-------------------- I= 2.0
| L2= 1.0
| L2'= 2.0
| del= 0.000
-------------------- If= 3.0
angular correlation coefficients:
A0 = +1.000000 A2 = -0.071429 A4 = -0.000000 A6 = -0.000000
w plot in "w.xy"; try xmgrace w.xy -par w.par
linear polarization coefficients:
C2 = +0.035714 C4 = -0.000000 C6 = -0.000000
linpol plot in "w_pol.xy"; try xmgrace w_pol.xy -par wlinpol.par
cos(2*azi) factor is +0.094610 (in 4pi)

chi**2: 0.736
a0: 1.001 +/- 0.002
a2: 0.011 +/- 0.002

1408 (E1) line polarized by 122 (E2) line.



Cautionary tale::

Naively: is E1, so should wiggle up!?

But NO!!

The other coefficients changed sign. We have to be careful for sources. (in-beam easier)

Always calculate!!

chi**2: 1.203
a0: 0.997 +/- 0.003
a2: -0.026 +/- 0.005

```
calc_a0a2a4 linpol  0 2 2  2 3 0  1 2 0 E 70 110
-------------------- Ii=   0.0
       |  L1=    2.0
       |  L1'=   3.0
       |  del=  0.000
-------------------- I=   2.0
       |  L2=    1.0
       |  L2'=   2.0
       |  del=  0.000
-------------------- If=   2.0
angular correlation coefficients:
A0 = +1.000000 A2 = +0.250000 A4 = +0.000000 A6 = +0.000000
w plot in "w.xy"; try xmgrace w.xy -par w.par
linear polarization coefficients:
C2 = -0.125000 C4 = +0.000000 C6 = +0.000000
linpol plot in "w_pol.xy"; try xmgrace w_pol.xy -par wlinpol.par
cos(2*azi) factor is -0.331133 (in 4pi)
```

~Incomplete survey of coincidence in ^{152}Eu

Don't expect much signal here

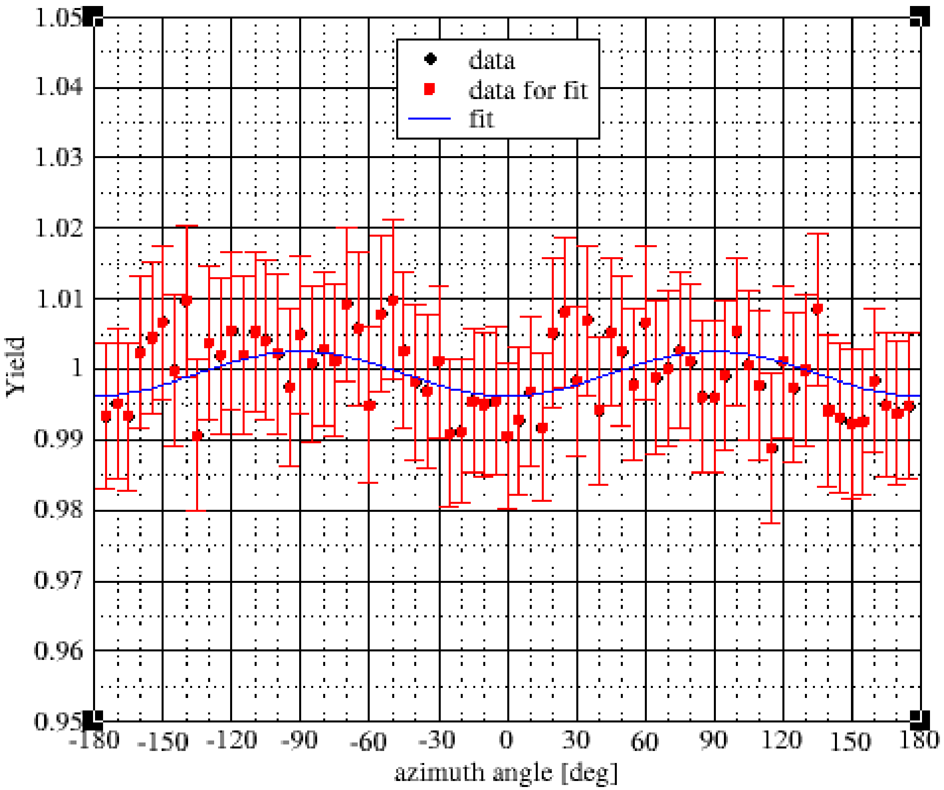
```
   +---   polarization of
   |           +--- polarize by
   |           |                  sign
[122 E2]     [1112 M1+E2]    obs=NEG   | calc=NEG
[122 E2]     [1408 E1]       (no signal)
[122 E2]     [245 E2]        obs=POS   | calc=POS  +0.013(6)
[122 E2]     [964 M1+E2]     obs=   | calc=
[245 E2]     [122 E2]        obs=POS   | calc=POS
[245 E2]     [867 M1+E2]     obs=POS   | calc=POS  +0.009(6)
[344 E2]     [779 E1]        obs=NEG   | calc=NEG  -0.059(8)
[444 E1]     [1086 E2]       obs=   | calc=
[444 E1]     [964 M1+E2]     obs=   | calc=
[779 E1]     [344 E2]        obs=POS   | calc=POS  +0.011(2)
[867 M1+E2]  [245 E2]        obs=NEG   | calc=NEG
[964 M1+E2]  [122 E2] weak   obs=NEG   | calc=NEG
[964 M1+E2]  [444 E1]        obs=   | calc=
[964 M1+E2]  [444 E1]        obs=   | calc=
[1086 E2]    [444 E1]        obs=POS   | calc=POS  +0.028(10)
[1112 M1+E2] [122 E2]        obs=   | calc=
[1408 E1]    [122 E2]        obs=NEG   | calc=NEG  -0.026(5)
```

In all cases I have looked at, the measured sign agrees with the calculated sign (amplitudes will come later)

In-Beam linear pol

- Goes a little like the source data processing; but n_0 is now the beam axis
- But we need to *change the uncorrelated first direction in the response spectrum to use random directions in 3D. The 'old' queue has random direction.*

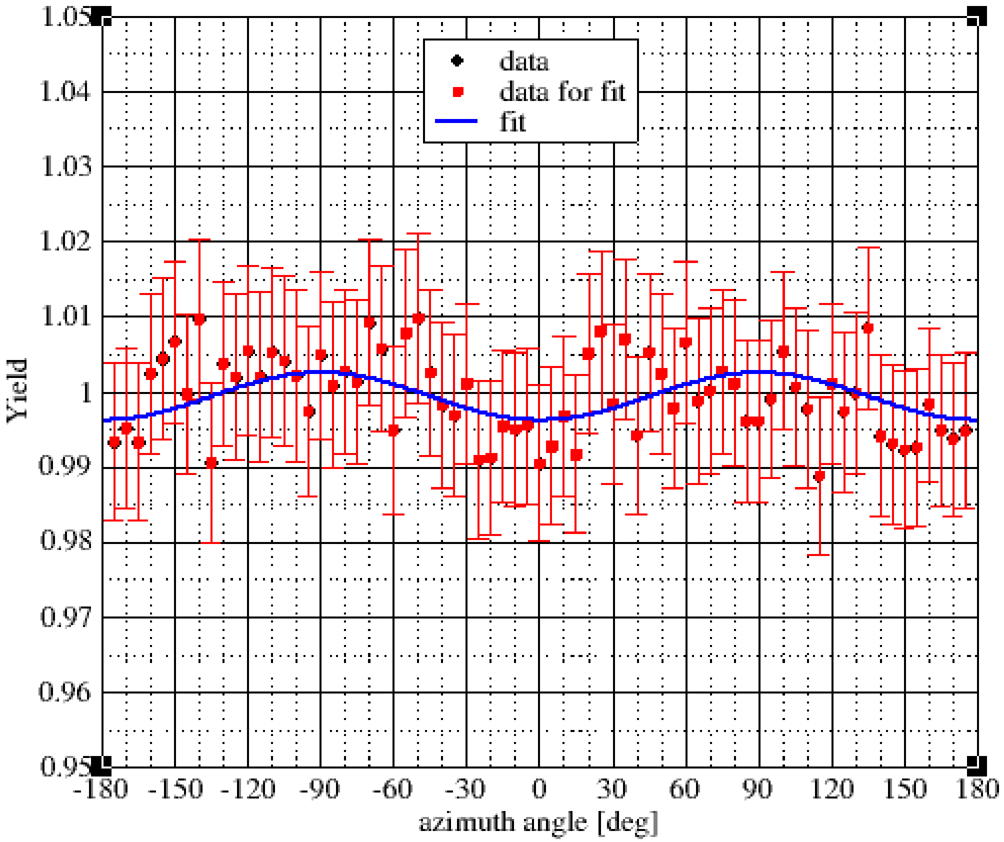
158 Er in-beam, 740 keV 22+->20+



calc_angdis linpol 22 20 2 3 0 4.0 E 70 110
alpha: _0 = +1.000000 _2 = +0.008672 _4 = +0.000000
-------------------- Ii= 22.0
| L1=   2.0
| L1'=   3.0
| del= 0.000
-------------------- If= 20.0
angular distribution coefficients:
A0 = +1.000000 A2 = +0.382060 A4 = -0.134187
[^^^^ unattenuated]
A0 = +1.000000 A2 = +0.003313 A4 = -0.000000
[^^^^ attenuated]
w plot in "w.xy"; try xmgrace w.xy -par w.par
linear polarization coefficients:
C2 = -0.001657 C4 = -0.000000
linpol plot in "w_pol.xy"; try xmgrace w_pol.xy -par wlinpol.par
cos(2*azi) factor is -0.004389 (in 4pi)

chi**2: 0.216
a0: 0.999 +/- 0.001
a2: -0.003 +/- 0.002

158Er 334 keV 4+->2+



calc_angdis linpol 4 2 2 3 0 4.0 E 70 110
alpha: _0 = +1.000000 _2 = +0.009995 _4 = +0.000000
-------------------- Ii=   4.0
| L1=   2.0
| L1'=   3.0
| del= 0.000
-------------------- If=   2.0
angular distribution coefficients:
A0 = +1.000000 A2 = +0.510204 A4 = -0.367347
[^^^^ unattenuated]
A0 = +1.000000 A2 = +0.005100 A4 = -0.000000
[^^^^ attenuated]
w plot in "w.xy"; try xmgrace w.xy -par w.par
linear polarization coefficients:
C2 = -0.002550 C4 = -0.000000
linpol plot in "w_pol.xy"; try xmgrace w_pol.xy -par wlinpol.par
cos(2*azi) factor is -0.006755 (in 4pi)

chi**2:   0.216
a0:   0.999 +/-   0.001
a2:   -0.003 +/-   0.002

Status now (as we see it)

method	source	in–beam	need source cal
ang dis	N/A	problem!	yes
ang cor	OK	OK[a]	no
lin–pol	OK[b]	OK[c]	no

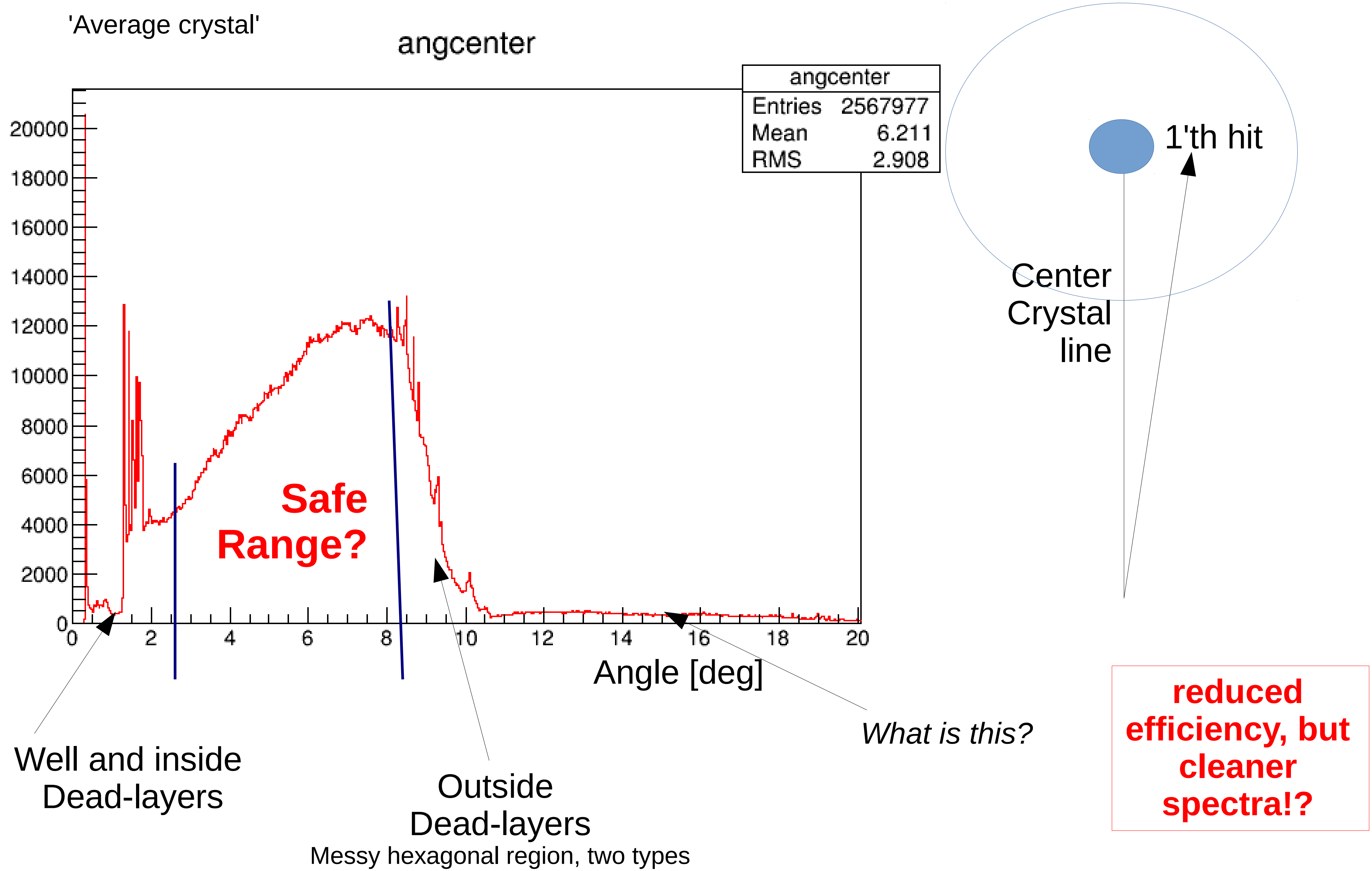
- [a] Using the new plane angle looks promising, but we need to verify.
- [b] Sign always seems right; but we need to work on calculating the amplitudes properly
- [c] Normalization seems to work: sign seems OK, but amplitudes are smaller than *expected* (why?)

Comment on in-beam ang dist

- As shown last time, the problem is that the interactions 'sees' the spaces between the crystals, the well in the crystals and the dead layers on the side
- The interaction in the dead layers and front&well *depends on the energies in a complicated way* making it difficult to produce a good response spectrum with a source.
- We suggest making masks in azimuth and polar angles that blocks out the dead layers (and other areas) might solve the problem.
- Simply find the angle of the first-hit direction to the center of the crystal it hit. Impose min angle to exclude the well and max angle to exclude the surface of the crystal

Already coded; but not yet tested

First hit angle-to-center analysis



Conclusions

- We still have problems with the in-beam angular distribution; but we have some ideas
- For the source and in-beam angular correlations, we have things under control
- For the source and in-beam linear polarizations, **we can now normalize with the data itself**. The signs are always understood, but understanding and calculating the amplitudes needs more work (always 'calculate' at least for sources)
- We need to work on AGATA data too
- **Need to understand background subtraction better**

This presentation was produced the old fashioned way without the use of AI or ML

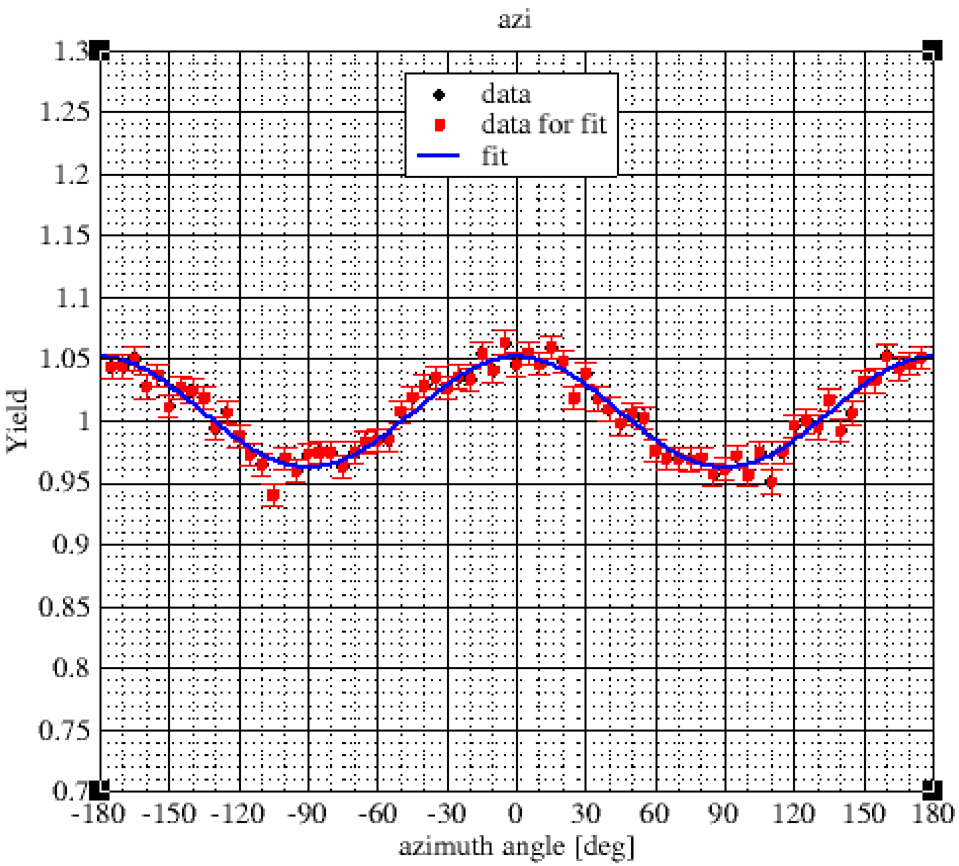
Thank you to **Shoufei** and **Dirk** for producing the high statistics GRETINA datasets we used

Note added after presentation

- Preliminary investigations show that the gating on the ‘pristine ge’, avoiding the dead-layers and the well, does not really help!
- **That fact** indicates that the dead-layers, and their possible energy dependence, cannot explain the problem with the angular distributions.
- That realization is progress in itself
- Further investigations are ongoing before the final conclusion

extras

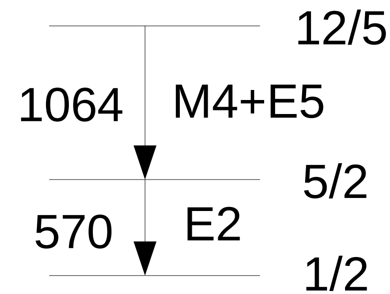
^{207}Bi source; 570 E2 line



chi**2: 1.105
a0: 1.007 +/- 0.001
a2: 0.045 +/- 0.002

Still same sign!

In case ENSDF is right and we are wrong about the delta2



Polarization spectrum for the 570 keV E2 when polarized by the 1064 keV M4+E5

13/2(4)5/2(2)1/2

```
calc_a0a2a4 linpol 6.5 2.5 0.5  4 5 0.02  2 3 0  E 70 110
-------------------- Ii=   6.5
      | L1=    4.0
      | L1'=   5.0
      | del=  0.020
-------------------- I=   2.5
      | L2=    2.0
      | L2'=   3.0
      | del=  0.000
-------------------- If=   0.5
angular correlation coefficients:
A0 = +1.000000 A2 = +0.213305 A4 = -0.014544 A6 = +0.000000
w plot in "w.xy"; try xmgrace w.xy -par w.par
linear polarization coefficients:
C2 = +0.106653 C4 = +0.001212 C6 = +0.000000
linpol plot in "w_pol.xy"; try xmgrace w_pol.xy -par wlinpol.par
cos(2*azi) factor is +0.281076 (in 4pi)
```