

Spin alignment in deep-inelastic reactions – how high is it in experiments with thick target?

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Physics motivation

- 1. Spins of isomers produced in a **fusion-evaporation** reactions show **high degree of alignment** in the plane perpendicular to the beam direction, this is used in the measurements of magnetic moments.
- 2. Some nuclei (e.g. neutron-rich) cannot be reached in fusion reactions.
- 3. A way of getting to them are **deep-inelastic collisions**.
- 4. Do the products of deep-inelastic reactions show sufficient spin alignment for the measurements of magnetic moments? angular distributions as a way to check it.





GAMMASPHERE, Argonne National Laboratory, USA

- * ⁷⁶Ge (450MeV) beam on ²⁰⁸Pb (50mg/cm²) target ⇒ deep-inelastic collisions
- * Pulsed beam ⇒ prompt and delayed gamma-gamma coincidences

Spin transfer in deep-inelastic reactions

Entrance angular momentum l_i

 l_i

Angular momentum transfer from orbital into intrinsic rotation

$$l_{i} = J_{1} + J_{2} + l_{f}$$

$$\frac{J_{1}}{J_{2}} = \left(\frac{A_{1}}{A_{2}}\right)^{\frac{5}{3}}$$



Exit angular momentum l_f and intrinsic spins J_1 , J_2 of the fragments

Previous works in 70', 80'

- "The anisotropy of E2 transitions rises with increasing spin transfer"
 G. J. Wozniak et. al., Phys. Rev. Lett. 45, 1081 (1980)
- "The anisotropies of stretched E2 transitions (…) imply rather strong alignment"
 G. Mouchaty et. al., Z. Phys. A 316, 285 (1984)
- "The angular momentum gained by the reactants should be oriented perpendicular to the reaction plane. In reality, however, they have sizable dispersion in their orientation" *K. Krishan et. al., J. Phys. G* 14, 1423 (1988)

Angular distributions – Yamazaki formalism

The angular-distribution function for a transition $J_i \rightarrow J_f$, where J represents the spin of the nuclear state is usually expressed as:

$$W(\Theta) = 1 + \alpha_2 A_2^{\max} P_2(\cos\Theta) + \alpha_4 A_4^{\max} P_4(\cos\Theta)$$

 Θ – the angle between the beam direction and the direction of γ ray emission

 $P_n(\cos\Theta)$ – Legendre polynomials

 α_n – attenuation coefficient



| - | 206Po 8.8 D | 207Po 5.80 H | 208Po 2.898 Y | 209Po 102 Y | 210Po 138.376 D | 211Po 0.516 S | 212Po 0.299 μS | 213Po 3.72 μS | 214Po 164.3 μS |
|----|-----------------------|--------------------------|--------------------------|-----------------------|--------------------|---------------------------|---------------------------|-----------------------------|------------------------|
| ۷ | €: 94.55% α: 5.45% | €: 99.98% d: 0.02% | α: 100.00% ε: 4.0E-3% | ಚ: 99.52% ∉: 0.48% | ຜ: 100.00% | a: 100.00% | a: 100.00% | a: 100.00% | a: 100.00% |
| | 205Bi 15.31 D | 206Bi 6.243 D | 207Bi 31.55 Y | 200- | 209Bi STABLE | 210Bi 5.012 D | 211Bi 2.14 M | 212Bi 60.55 M | 213Bi 45.59 M |
| 83 | €: 100.00% | e: 100.00% | €: 100.00% | ²⁰⁰ Βι | 100% | β-: 100.00% α: 1.3E-4% | α: 99.72% β-: 0.28% | β-: 64.06% α: 35.94% | β-: 97.80% α: 2.20% |
| | 204Pb ≥1.4E+17 Y | 205Рb 1.73E+7 Ү | 206Pb STABLE | 207Pb STABLE | 20251 | 209Pb 3.253 H | 210Pb 22.20 Y | 211Pb 36.1 M | 212Pb 10.64 H |
| 82 | 1.42% cl | e: 100.00% | 24.1% | 22.1% | ²⁰⁰ PD | β-: 100.00% | β-: 100.00% α: 1.9E-6% | β-: 100.00% | β-: 100.00% |
| | 203TI STABLE | 204 TI 3.783 Y | 205TI STABLE | 206TI 4.202 M | 207TI 4.77 M | 208TI 3.053 M | 209 TI 2.161 M | 210Tl 1.30 M | 211TI >300 NS |
| 81 | 29.324% | β−: 97.08% ∉: 2.92% | 70.40% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% β-n: 7.0E-3% | β- |
| | 202Hg STABLE | 203Hg 46.594 D | 204Hg STABLE | 205Hg 5.14 M | 206Hg 8.32 M | 207Hg 2.9 M | 208Hg 41 M | 209Hg 35 S | 210Hg >300 NS |
| 80 | 27.00% | β-: 100.00% | 0.07% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β- |
| | 122 | 123 | 124 | 125 | 126 | 127 | 128 | 129 | N |





80

100



Angle [deg]

1630 keV

| z | 206Po 8.8 D €: 94.55% α: 5.45% | 207Po 5.80 H ε: 99.98% α: 0.02% | 208Po 2.898 Υ α: 100.00% ε: 4.0E-3% | 209Po 102 Υ α: 99.52% ε: 0.48% | 210Po 138.376 D α: 100.00% | 211Po 0.516 S α: 100.00% | 212Po 0.299 μS α: 100.00% | 213Po 3.72 μS α: 100.00% | 214Po 164.3 μS α: 100.00% |
|----|-----------------------------------------|--------------------------------------------|----------------------------------------------|-----------------------------------------|----------------------------------|-----------------------------------------------|-----------------------------------------------|------------------------------------------------|--------------------------------------------|
| 83 | 205Bi 15.31 D ε: 100.00% | 206Bi 6.243 D €: 100.00% | 207Bi 31.55 ¥ €: 100.00% | 208Bi 3.68E+5 Y €: 100.00% | ²⁰⁹ Bi | 210Bi 5.012 D β-: 100.00% α: 1.3E-4% | 211Bi 2.14 M α: 99.72% β-: 0.28% | 212Bi 60.55 M β-: 64.06% α: 35.94% | 213Bi 45.59 M β-: 97.80% α: 2.20% |
| 82 | 204Pb ≿1.4E+17 Y 1.4% α | 205Pb 1.73E+7 Y 6: 100.00% | 206Pb STABLE 24.1% | 207Pb STABLE 22.1% | ²⁰⁸ Pb | 209Pb 3.253 H β-: 100.00% | 210Pb 22.20 Υ β-: 100.00% α: 1.9E-6% | 211Pb 36.1 M β-: 100.00% | 212Pb 10.64 H β-: 100.00% |
| 81 | 203TI STABLE 29.524% | 204TI 3.783 Υ β-: 97.08% ε: 2.92% | 205TI STABLE 70.48% | 206TI 4.202 Μ β-: 100.00% | 207TI 4.77 M β-: 100.00% | 208TI 3.053 M β-: 100.00% | 209Tl 2.161 M β-: 100.00% | 210Tl 1.30 M β-: 100.00% β-n: 7.0E-3% | 211TI >300 NS β- |
| 80 | 202Hg STABLE 29.86% | 203Hg 46.594 D β-: 100.00% | 204Hg STABLE 6.87% | 205Hg 5.14 M β-: 100.00% | 206Hg 8.32 M β-: 100.00% | 207Hg 2.9 M β-: 100.00% | 208Hg 41 M β-: 100.00% | 209Hg 35 S β-: 100.00% | 210Hg >300 NS β- |
| | 122 | 123 | 124 | 125 | 126 | 127 | 128 | 129 | N |



2741 keV





| | 206Po 8.8 D | 207Po 5.80 H | 208Po 2.898 Y | 209Po 102 Y | 210Po 138.376 D | 211Po 0.516 S | 212Po 0.299 μS | 213Po 3.72 μS | 214Po 164.3 μS |
|----|-----------------------|------------------------|--------------------------|-----------------------|--------------------|------------------|---------------------------|-----------------------------|------------------------|
| Z | €: 94.55% α: 5.45% | €: 99.98% a: 0.02% | α: 100.00% ε: 4.0E-3% | α: 99.52% ε: 0.48% | a: 100.00% | a: 100.00% | a: 100.00% | a: 100.00% | a: 100.00% |
| | 205Bi 15.31 D | 206Bi 6.243 D | 207Bi 31.55 Y | 208Bi 3.68E+5 Y | 209Bi STABLE | 2100: | 211Bi 2.14 M | 212Bi 60.55 M | 213Bi 45.59 M |
| 83 | e: 100.00% | e: 100.00% | e: 100.00% | e: 100.00% | 100% | 210 BI | α: 99.72% β+: 0.28% | β-: 64.06% α: 35.94% | β-: 97.80% α: 2.20% |
| | 204Pb ≥1.4E+17 Y | 205Рb 1.73E+7 Ү | 206Pb STABLE | 207Pb STABLE | 200-1 | 209Pb 3.253 H | 210РЬ 22.20 У | 211Pb 36.1 M | 212Pb 10.64 H |
| 82 | 1.4% d | €: 100.00% | 24.1% | 22.1% | ²⁰⁸ Pb | β-: 100.00% | β-: 100.00% α: 1.9E-6% | β-: 100.00% | β-: 100.00% |
| | 203TI STABLE | 204TI 3.783 Y | 205TI STABLE | 206TI 4.202 M | 20711 4.77 M | 208TI 3.053 M | 209 TI 2.161 M | 210Tl 1.30 M | 211Tl >300 NS |
| | 29.524% | β-: 97.08% ε: 2.92% | 70.48% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% β-n: 7.0E-3% | β- |
| | 202Hg STABLE | 203Hg 46.594 D | 204Hg STABLE | 205Hg 5.14 M | 206Hg 8.32 M | 207Hg 2.9 M | 208Hg 41 M | 209Hg 35 S | 210Hg >300 NS |
| 80 | 29.86% | β-: 100.00% | 6.87% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β- |
| | 122 | 123 | 124 | 125 | 126 | 127 | 128 | 129 | N |

 $\begin{array}{c}
14- & 2726 \\
 & 1403 (E3) \\
11+ & 1323 \\
 & 653 (E1) \\
10- & 210 Bi \\
\end{array}$

1403 keV



| | 206Po 8.8 D | 207Po 5.80 H | 208Po 2.898 Y | 209Po 102 Y | 210Po 138.376 D | 211Po 0.516 S | 212Po 0.299 μS | 213Po 3.72 μS | 214Po 164.3 μS |
|----|-----------------------|--------------------------|--------------------------|-----------------------|--------------------|---------------------------|---------------------------|-----------------------------|------------------------|
| Z | €: 94.55% α: 5.45% | €: 99.98% d: 0.02% | α: 100.00% ε: 4.0E-3% | α: 99.52% ε: 0.48% | α: 100.00% | a: 100.00% | a: 100.00% | a: 100.00% | a: 100.00% |
| | 205Bi 15.31 D | 206Bi 6.243 D | 207Bi 31.55 Y | 208Bi 3.68E+5 Y | 209Bi STABLE | 210Bi 5.012 D | 211Bi 2.14 M | 212Bi 60.55 M | 213Bi 45.59 M |
| 83 | €: 100.00% | ε: 100.00% | €: 100.00% | €: 100.00% | 100% | β-: 100.00% α: 1.3E-4% | α: 99.72% β-: 0.28% | β-: 64.06% α: 35.94% | β-: 97.80% α: 2.20% |
| | 204Pb ≥1.4E+17 Y | 205РЬ 1.73Е+7 Ү | 206Pb STABLE | 207Pb STABLE | 200-1 | 200-1 | 210Pb 22.20 Y | 211Pb 36.1 M | 212Pb 10.64 H |
| 82 | 1.4% d | €: 100.00% | 24.1% | 22.1% | ²⁰⁸ Pb | ²⁰⁹ Pb | β-: 100.00% α: 1.9E-6% | β-: 100.00% | β-: 100.00% |
| | 203TI STABLE | 204 TI 3.783 Y | 205TI STABLE | 206TI 4.202 M | 20711 4.77 M | 208TI 3.053 M | 209 TI 2.161 M | 210Tl 1.30 M | 211Tl >300 NS |
| 81 | 29.524% | β−: 97.08% ε: 2.92% | 70.48% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% β-n: 7.0E-3% | β- |
| | 202Hg STABLE | 203Hg 46.594 D | 204Hg STABLE | 205Hg 5.14 M | 206Hg 8.32 M | 207Hg 2.9 M | 208Hg 41 M | 209Hg 35 S | 210Hg >300 NS |
| 80 | 29.86% | β-: 100.00% | 6.87% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β- |
| | 122 | 123 | 124 | 125 | 126 | 127 | 128 | 129 | N |





1.40

1.20

1.00

0.80

0

Relative intensity



| _ | 206Po 8.8 D | 207Po 5.80 H | 208Po 2.898 Y | 209Po 102 Y | 210Po 138.376 D | 211Po 0.516 S | 212Po 0.299 μS | 213Po 3.72 μS | 214Po 164.3 μS |
|----|-----------------------|--------------------------|--------------------------|-----------------------|--------------------|---------------------------|---------------------------|-----------------------------|------------------------|
| Z | €: 94.55% a: 5.45% | €: 99.98% a: 0.02% | α: 100.00% €: 4.0E−3% | α: 99.52% ε: 0.48% | a: 100.00% | a: 100.00% | a: 100.00% | a: 100.00% | a: 100.00% |
| | 205Bi 15.31 D | 206Bi 6.243 D | 207Bi 31.55 Y | 208Bi 3.68E+5 Y | 209Bi STABLE | 210Bi 5.012 D | 211Bi 2.14 M | 212Bi 60.55 M | 213Bi 45.59 M |
| 83 | e: 100.00% | e: 100.00% | €: 100.00% | €: 100.00% | 100% | β-: 100.00% α: 1.3E-4% | α: 99.72% β-: 0.28% | β-: 64.06% α: 35.94% | β-: 97.80% α: 2.20% |
| | 204Pb ≥1.4E+17 Y | 205Рb 1.73Е+7 Ү | 206Pb STABLE | | | 209Рb 3.253 Н | 210Pb 22.20 Y | 211Pb 36.1 M | 212Pb 10.64 H |
| 82 | 1.4% d | €: 100.00% | 24.1% | ²⁰⁷ Pb | ²⁰⁸ Pb | β-: 100.00% | β-: 100.00% α: 1.9E-6% | β-: 100.00% | β-: 100.00% |
| | 203TI STABLE | 204 TI 3.783 Y | 205TI STABLE | 20611 4.202 M | 20711 4.77 M | 208 TI 3.053 M | 209 TI 2.161 M | 210Tl 1.30 M | 211TI >300 NS |
| 81 | 29.524% | β-: 97.08% ε: 2.92% | 70.40% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% β-n: 7.0E-3% | β- |
| | 202Hg STABLE | 203Hg 46.594 D | 204Hg STABLE | 205Hg 5.14 M | 206Hg 8.32 M | 207Hg 2.9 M | 208Hg 41 M | 209Hg 35 S | 210Hg >300 NS |
| 80 | 29.00% | β-: 100.00% | 0.07% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β- |
| | 122 | 123 | 124 | 125 | 126 | 127 | 128 | 129 | N |





Relative intensity



²⁰⁶Bi: 1 proton 3 neutron holes

²⁰⁶Bi 205Rn 206Rn 207R 210Rn 211Rn 212Rn 213Rn 214Rn 215Rn 216Rn 217Rn 218Rn 219Rn 220Rn 204Rn 208Rn 209Rn Ζ 203At 204At 205At 206At 207At 208At 209At 210At 211At 212At 213At 214At 215At 216At 217At 218At 219At 203Po 204Po 205Po 206Po PO7Po 208Po 209Po 210Po 211Po 212Po 213Po 214Po 215Po 216Po 217Po 218Po 202Po 84 201Bi 202Bi 203Bi 204Bi 205Bi 206Bi 207Bi 208Bi 209Bi 210Bi 211Bi 212Bi 213Bi 214Bi 215Bi 216Bi 217Bi 201Fb 202Fb 203Pb 204Pb 205Pb 206Pb 207Pb 208Pb 210Pb 211Pb 212Pb 213Pb 215Pb 216Pb 209Pb 214Pb 200Pb 207TI 08TI 209TI 210TI 211TI 212TI 213TI 201TI 202TI 203TI 204TI 205TI 206TI 199TI 200TI 214TI 215TI 198Hg 199Hg 200Hg 201Hg 202Hg 203Hg 204Hg 205Hg 206Hg 207Hg 208Hg 209Hg 210Hg 211Hg 212Hg 213Hg 214Hg 80 197Au 198Au 199Au 200Au 201Au 202Au 203Au 204Au 205Au 206Au 207Au 208Au 209Au 210Au 196Pt 197Pt 198Pt 199Pt 200Pt 201Pt 202Pt 203Pt 204Pt 205Pt ²⁰⁸Pb 78 118 120 122 124 126 128 130 132 N









Cross coincidences

Vectorial sum of J_z component is equal to zero

Cross coincidences



| z | 206Po 8.8 D ε: 94.55% α: 5.45% | 207Po 5.80 H ε: 99.98% α: 0.02% | 208Po 2.898 Υ α: 100.00% ε: 4.0E-3% | 209Po 102 Y a: 99.52% e: 0.48% | ²¹⁰ Pc | 211Po 0.516 S :: 100.00% | 212Po 0.299 μS α: 100.00% | 213Po 3.72 μS α: 100.00% | 214 164. a: 10 |
|----|-----------------------------------------|--------------------------------------------|----------------------------------------------|-----------------------------------------|--------------------------------|-----------------------------------------------|-----------------------------------------------|------------------------------------------------|----------------------------|
| 83 | 205Bi 15.31 D € 100.00% | 206Bi 6.243 D € 100.00% | 207Bi 31.55 Y 6: 100.00% | 208Bi 3.68E+5 Y €: 100.00% | STABLE 100% | 210Bi 5.012 D β-: 100.00% α: 1.3E-4% | 211Bi 2.14 M α: 99.72% β-: 0.28% | 212Bi 60.55 M β-: 64.06% α: 35.94% | 213 45.5 β-:9 α:2 |
| 82 | 204Pb ≿1.4E+17 Υ 1.4% α | 205Pb 1.73E+7 Y 4: 100.00% | 206Pb STABLE 24.1% | 207Pb STABLE 22.1% | ²⁰⁸ Pt | 209Pb 3.253 H -: 100.00% | 210Pb 22.20 Υ β-: 100.00% α: 1.9E-6% | 211Pb 36.1 M β-: 100.00% | 212 10.6 β-: 10 |
| 81 | 203TI STABLE 29.524% | 204Tl 3.783 Υ β-: 97.08% ε: 2.92% | 205TI STABLE 70.48% | 206TI 4.202 M β-: 100.00% | 4.77 M β-: 100.00% | 208TI 3.053 M β-: 100.00% | 209Tl 2.161 M β-: 100.00% | 210Tl 1.30 M β-: 100.00% β-n: 7.0E-3% | 21 >30 |
| 80 | 202Hg STABLE 29.86% | 203Hg 46.594 D β-: 100.00% | 204Hg STABLE 6.87% | 205Hg 5.14 M β-: 100.00% | 206Hg 8.32 M β-: 100.00% | 207Hg 2.9 M β-: 100.00% | 208Hg 41 M β-: 100.00% | 209Hg 35 S β-: 100.00% | 210 >30 |
| | 122 | 123 | 124 | 125 | 126 | 127 | 128 | 129 | ١ |





| z | 74Se STABLE 0.89% | 75Se 119.79 D | 76Se STABLE 9.37% | 77Se STABLE 7.63% | 78Se STABLE 23.77% | 79Se 2.95E+5 Y | 80Se STABLE 49.61% | 81Se 18.45 M | 82Se STABLE 8.73% |
|-----|-------------------------|-------------------------|-------------------------|-------------------------|--------------------------|-------------------|--------------------------|------------------|---------------------------|
| | | e: 100.00% | | | | β-: 100.00% | 2β- | β-: 100.00% | |
| | 73As 80.30 D | 74As 17.77 D | 75As STABLE 100% | 76As 1.0942 D | 77As 38.83 H | 78As 90.7 M | 79As 9.01 M | 80As 15.2 S | 81As 33.3 S |
| 33 | e: 100.00% | €: 66.00% β−: 34.00% | 100% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% |
| | 72Ge STABLE | 73Ge STABLE | 74Ge STABLE | 75Ge 82.78 M | 760- | 77Ge 11.30 H | 78Ge 88.0 M | 79 Ge 18.98 S | 80Ge 29.5 S |
| 32 | 27.43% | 1.15% | 30.30% | β-: 100.0 | ^v Ge | 3-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% |
| | 71Ga STABLE | 72Ga 14.10 H | 73Ga 4.86 H | 74Ga 8.12 M | 126 S | 76Ga 32.6 S | 77Ga 13.2 S | 78Ga 5.09 S | 79Ga 2.847 S |
| 31 | 59.092% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% β-n: 0.09% |
| 70- | | 71Zn 2.45 M | 72Zn 46.5 H | 73Zn 23.5 S | 74Zn 95.6 S | 75Zn 10.2 S | 76Zn 5.7 S | 77Zn 2.08 S | 78Zn 1.47 S |
| I | ⁄°Zn | 8-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% | β-: 100.00% |
| L | 70 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | N |



- * Products of deep-inelactic collisions show high degree of spin alignment
- * The statistic in coincidence measurements is not high highly efficient gamma arrays needed (Gammasphere, AGATA)
- The magnet must be small enough to put it in the center of the system of the detectors





Thank you for your attention