Relativistic *M1* Coulomb excitation of ^{85}Br

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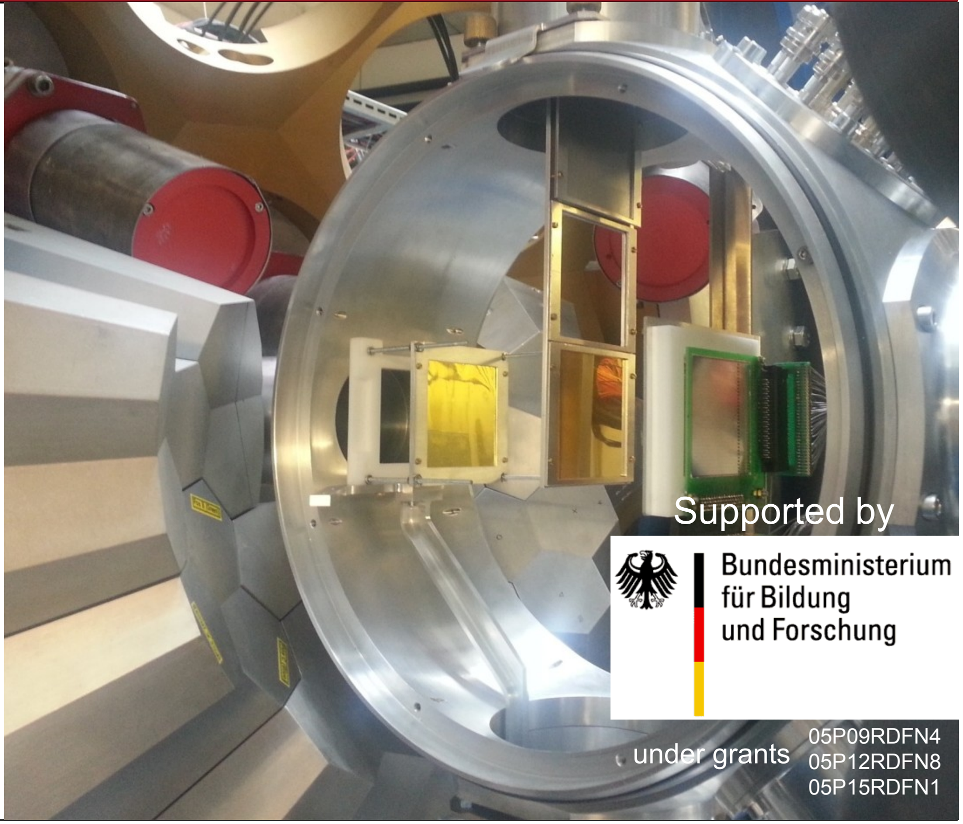
C. Stahl, M. Lettmann, M. Reese, G. Rainovski, N. Pietralla
for the PreSPEC and AGATA collaborations

- *M1* excitations of the atomic nucleus
- Towards a technique for *M1* studies of exotic nuclei
- The *Coulex Multipolarimetry* technique
- PreSPEC-AGATA experiment S426:
  The $\pi p_{3/2} \rightarrow \pi p_{1/2}$ spin-flip transition of ^{85}Br



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M1 excitations of the atomic nucleus

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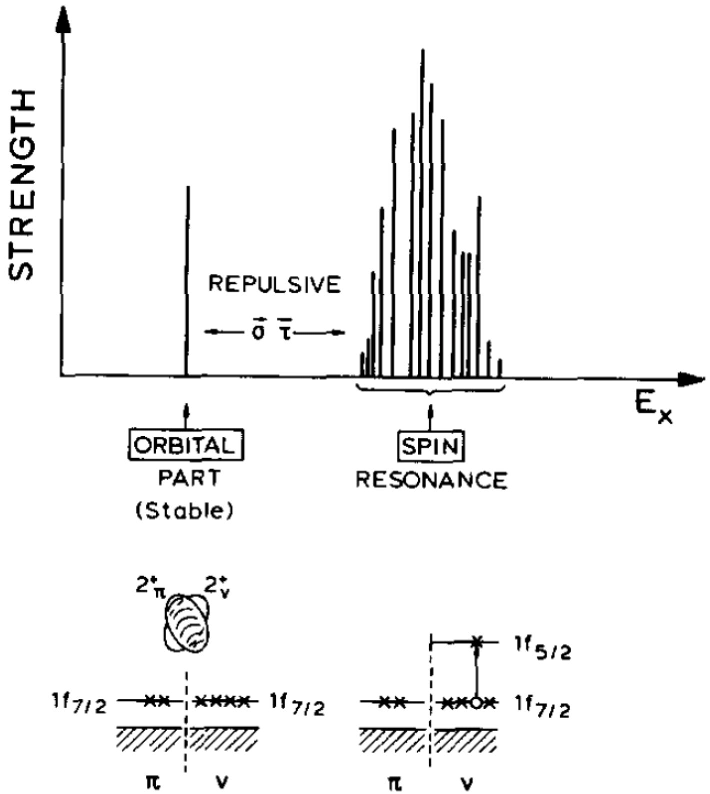
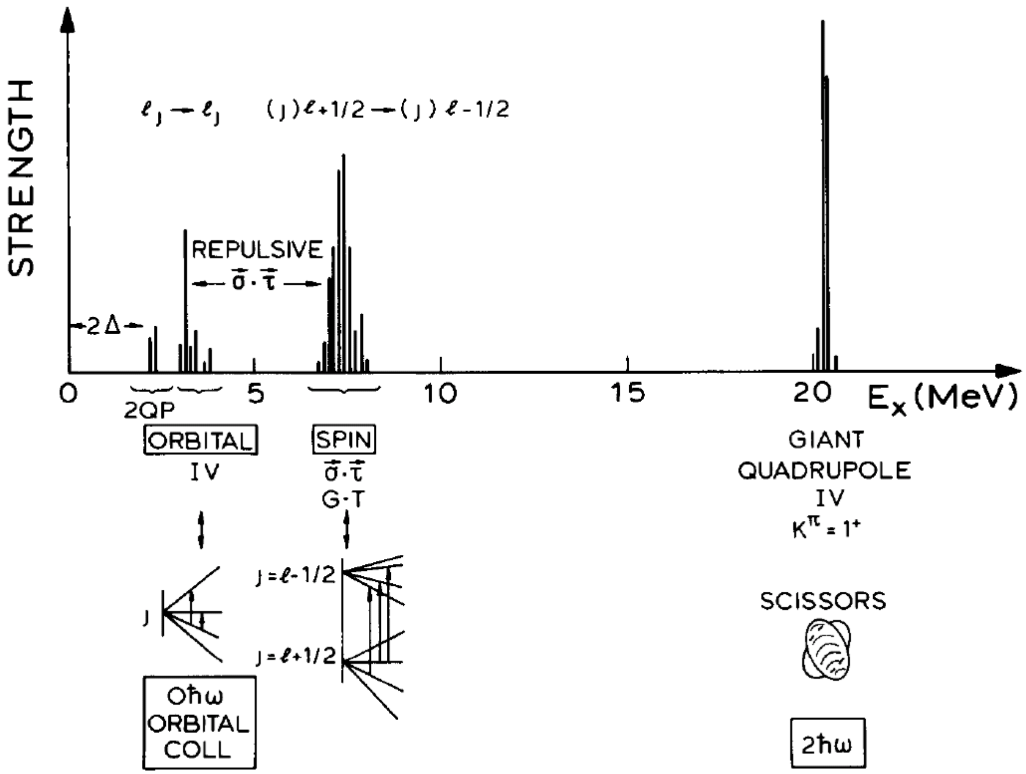
M1 strength distribution in..

.. light nuclei



.. heavy deformed nuclei



Figures: A. Richter, Nucl. Phys. A 507, 99c (1990)

M1 excitations of the atomic nucleus

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The *M1* operator: Not so simple..

$$B(M1) = \frac{1}{2J_i+1}\frac{3}{4\pi}\left|\langle J_f T_f T_{zf} \| \boldsymbol{\mu} \| J_i T_i T_{zi}\rangle\right|^2 \quad \text{with} \quad \boldsymbol{\mu} = \left[\sum_{j=1}^{A} g_\ell \boldsymbol{\ell}_j + g_s \mathbf{s}_j\right]\mu_N$$

Introduce isoscalar and isovector g-factors:

$$g_\ell^{\mathrm{IS}} = \tfrac{1}{2}(g_\ell^\pi + g_\ell^\nu) \qquad g_\ell^{\mathrm{IV}} = \tfrac{1}{2}(g_\ell^\pi - g_\ell^\nu)$$
$$g_s^{\mathrm{IS}} = \tfrac{1}{2}(g_s^\pi + g_s^\nu) \qquad g_s^{\mathrm{IV}} = \tfrac{1}{2}(g_s^\pi - g_s^\nu)$$

$$B(M1) = \frac{1}{2J_i+1}\frac{3}{4\pi}\mu_N^2\left|\langle J_f T_f T_{zf} \| \sum_{j=1}^{A}\left(g_\ell^{\mathrm{IS}}\boldsymbol{\ell}_j + g_s^{\mathrm{IS}}\frac{1}{2}\boldsymbol{\sigma}_j\right) - \sum_{j=1}^{A}\left(g_\ell^{\mathrm{IV}}\boldsymbol{\ell}_j + g_s^{\mathrm{IV}}\frac{1}{2}\boldsymbol{\sigma}_j\right)\tau_j^0 \| J_i T_i T_{zi}\rangle\right|^2$$

Apply Wigner-Eckart theorem on isospin space:

$$B(M1) = \frac{1}{2J_i+1}\frac{3}{4\pi}\mu_N^2\left[\left(g_\ell^{\mathrm{IS}} M_{M1}(\ell) + g_s^{\mathrm{IS}}\frac{1}{2}M_{M1}(\sigma)\right) - \frac{C_{M1}}{\sqrt{2T_f+1}}\left(g_\ell^{\mathrm{IV}} M_{M1}(\ell\tau) + g_s^{\mathrm{IV}}\frac{1}{2}M_{M1}(\sigma\tau)\right)\right]^2$$

Only this Gamow-Teller part is dominantly excited by hadronic probes!

Equations: Y. Fujita *et al.*, Prog. Part. Nuc. Phys. 66, 549–606 (2011)

M1 excitations of the atomic nucleus

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How to excite *M1* states by different probes..

.. for different isospins

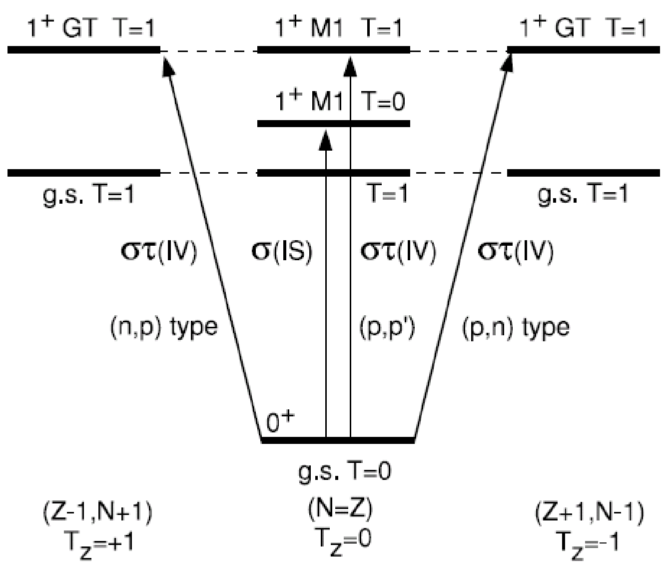

Figure: Y. Fujita *et al*., Prog. Part. Nuc. Phys. 66, 549–606 (2011)

.. for orbital- and spin-excitations

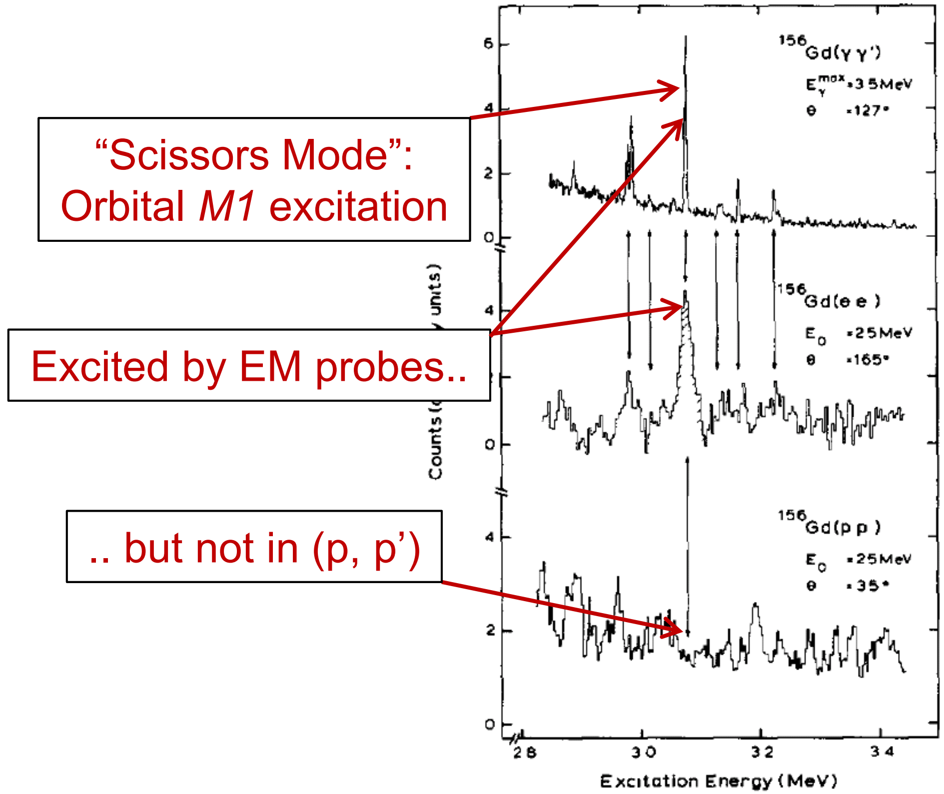

Figure: A. Richter, Nucl. Phys. A 507, 99c (1990)

Towards a technique for *M1* studies of exotic nuclei

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Study *M1* strengths in exotic nuclei by..

- **Proton scattering**: Well possible in inverse kinematics (e.g. MINOS@RIKEN)
  → missing some classes of excitation modes like Scissors Mode
  (not studied in radioactive nuclei so far!)

- **Electron scattering:** No setups for RIBs available yet (ELISe, SCRIT?)

- **Coulomb excitation:** Doesn't work for Coulomb barrier beam energies, but..

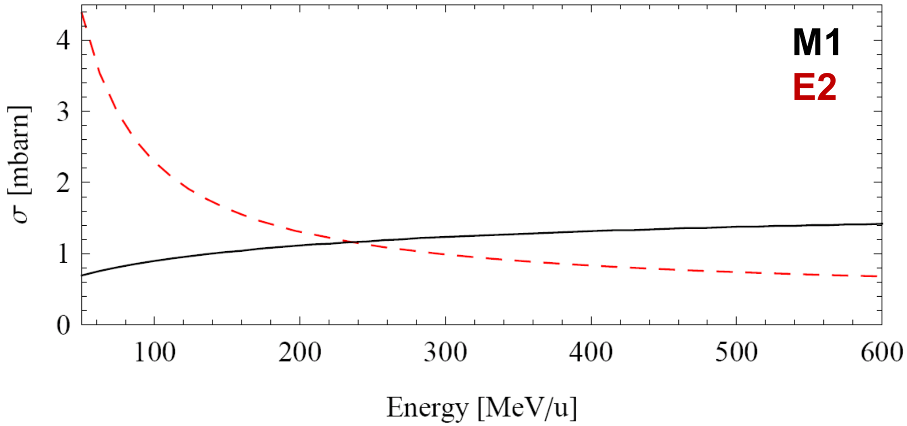

Fig.: Coulomb-excitation cross section for the 1191-keV level of ^{85}Br. Assuming 1 W.u. for the *E2*, $1\mu_N^2$ for the *M1* transition strength. Target material: Gold.

Towards a technique for *M1* studies of exotic nuclei

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M1 states can be populated by relativistic Coulomb excitation – but how to proof M1 character of a transition?

- **Standard method**: Analysis of γ-ray angular distributions, depends on δ

  → strongly hindered at relativistic beam energies:
  γ-intensity forward-boosted, need much statistics, ..
  → need pronounced γ-ray angular distribution (= strong alignment)
  → not applicable in some cases, e.g. if *J=0, ½*

- **Infer δ from ‚inverse' of the γ-decay**, the Coulomb excitation!

Towards a technique for *M1* studies of exotic nuclei

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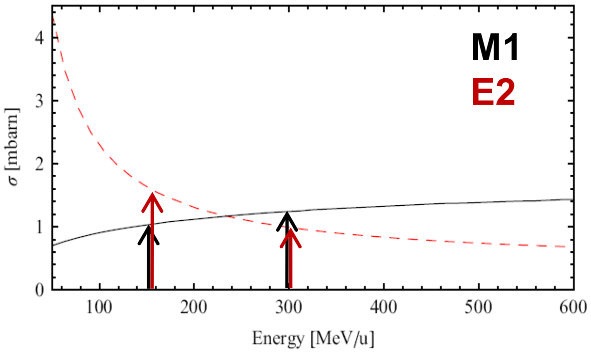
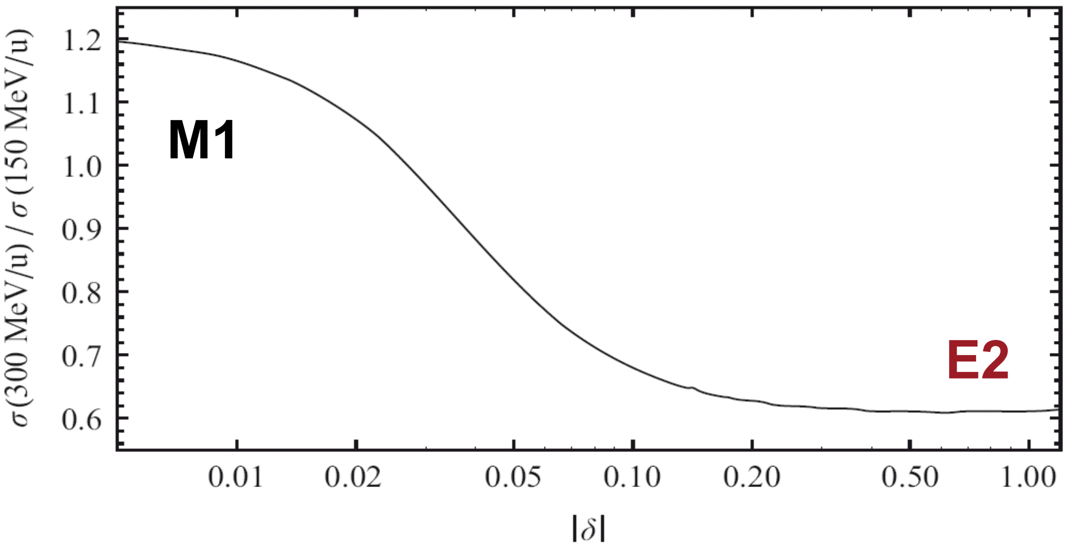
M1 states can be populated by relativistic Coulomb excitation – but how to proof M1 character of a transition?





- Comparison of Coulomb excitation cross sections at two different beam energies yields δ
- **Drawback:** Need much beam time for two measurements

The *Coulex Multipolarimetry* technique

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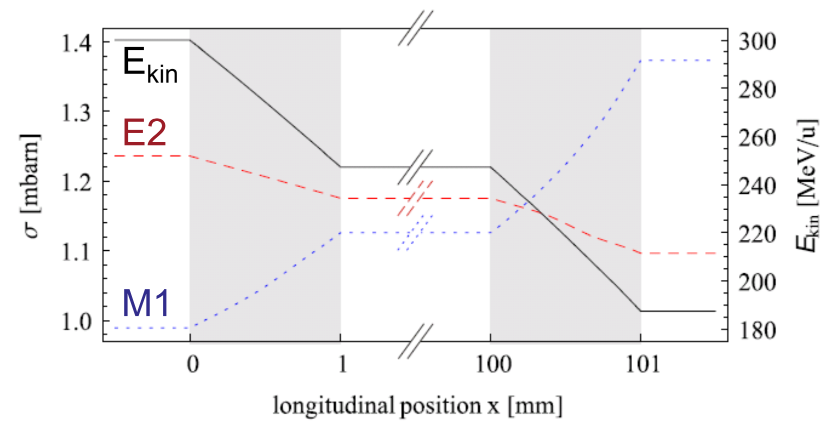
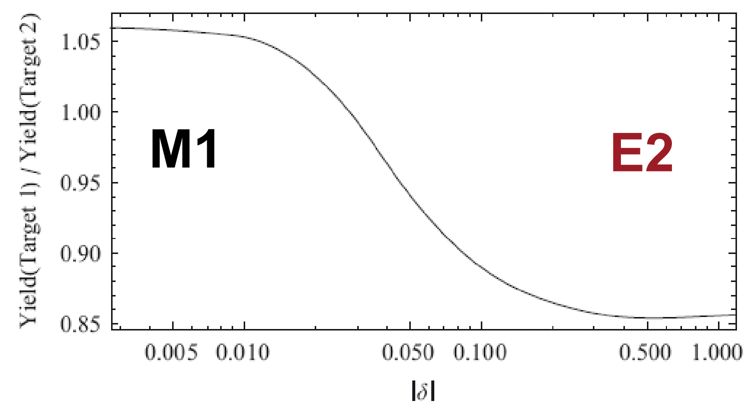
Measure δ via Coulomb excitation cross sections:

Either perform two experiments at two different beam energies.. Or:

- Use two thick targets
- Beam enters second target with reduced velocity



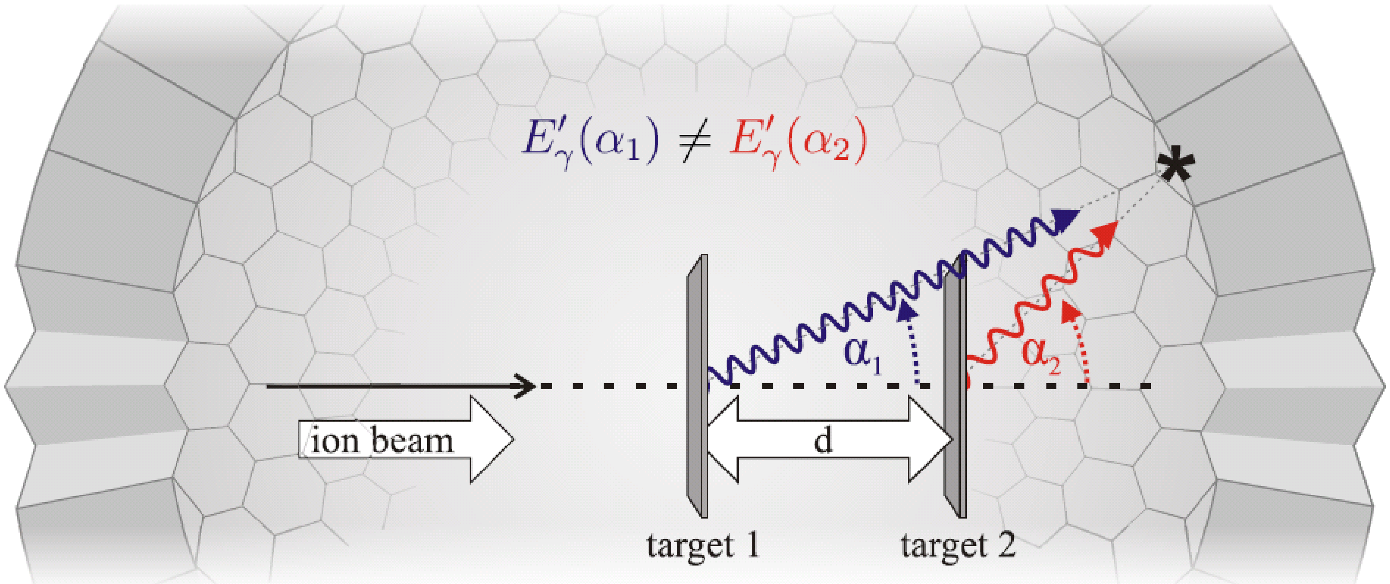
- Compare Yields from both targets



C. Stahl *et al.*, NIM A 770, 123 (2015)

The *Coulex Multipolarimetry* technique

How to separate excitations in the first and second target?

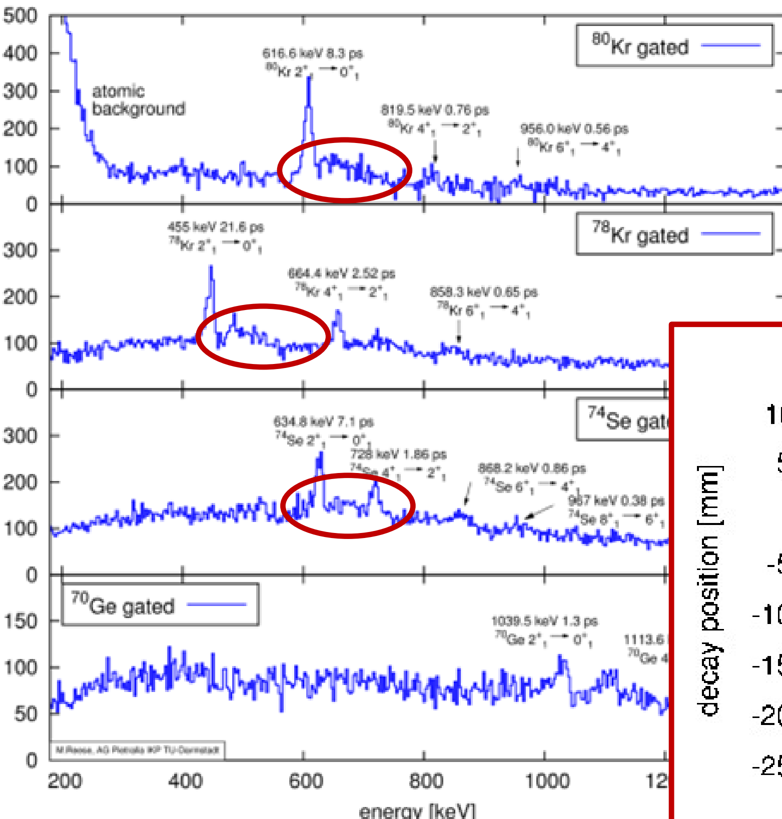


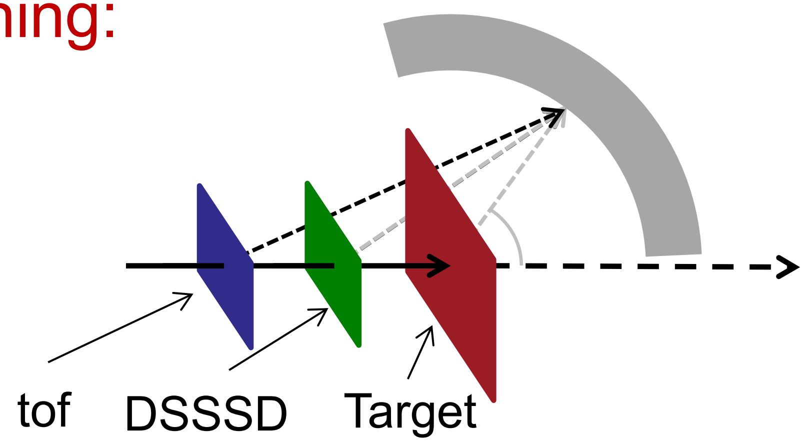
- Place two targets in ~10 cm distance
- Longitudinal γ-ray vertex affects observed Doppler shift

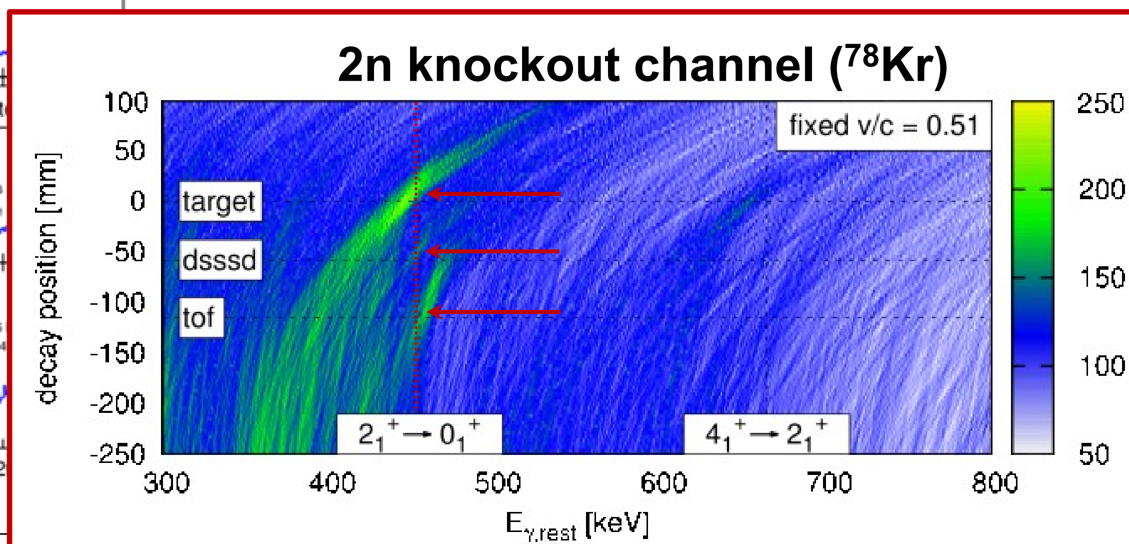
C. Stahl *et al.*, NIM A 770, 123 (2015)

The *Coulex Multipolarimetry* technique

Observed in PreSPEC commissioning:

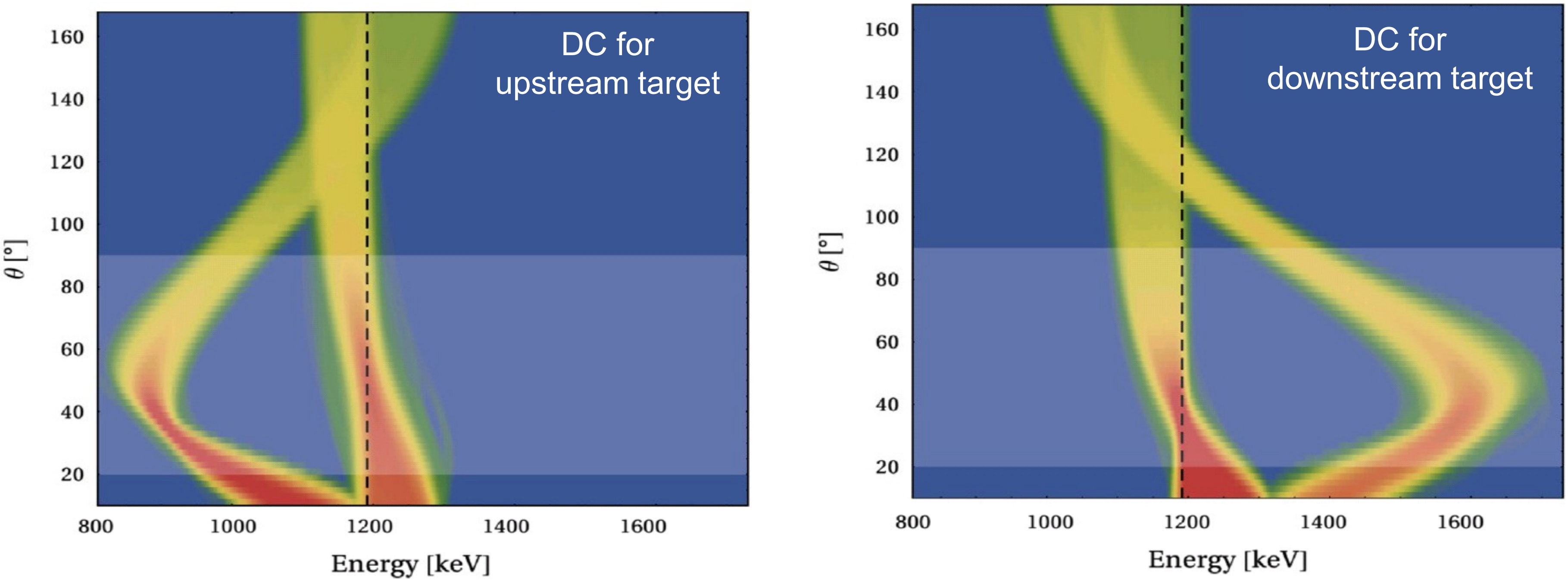






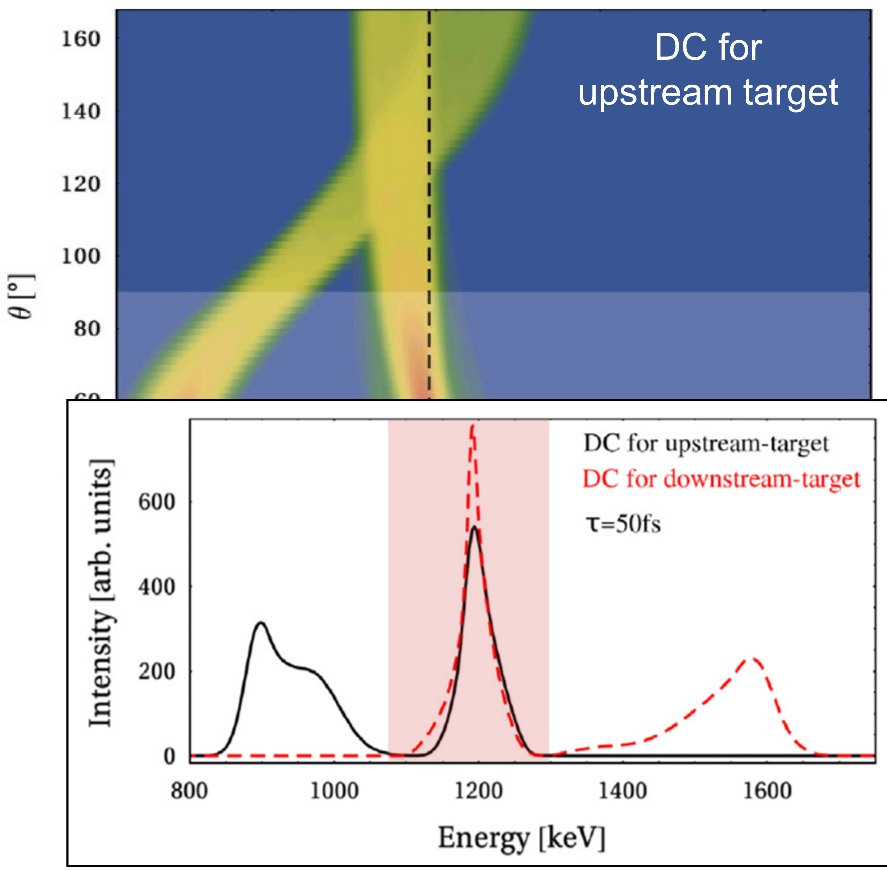
The *Coulex Multipolarimetry* technique

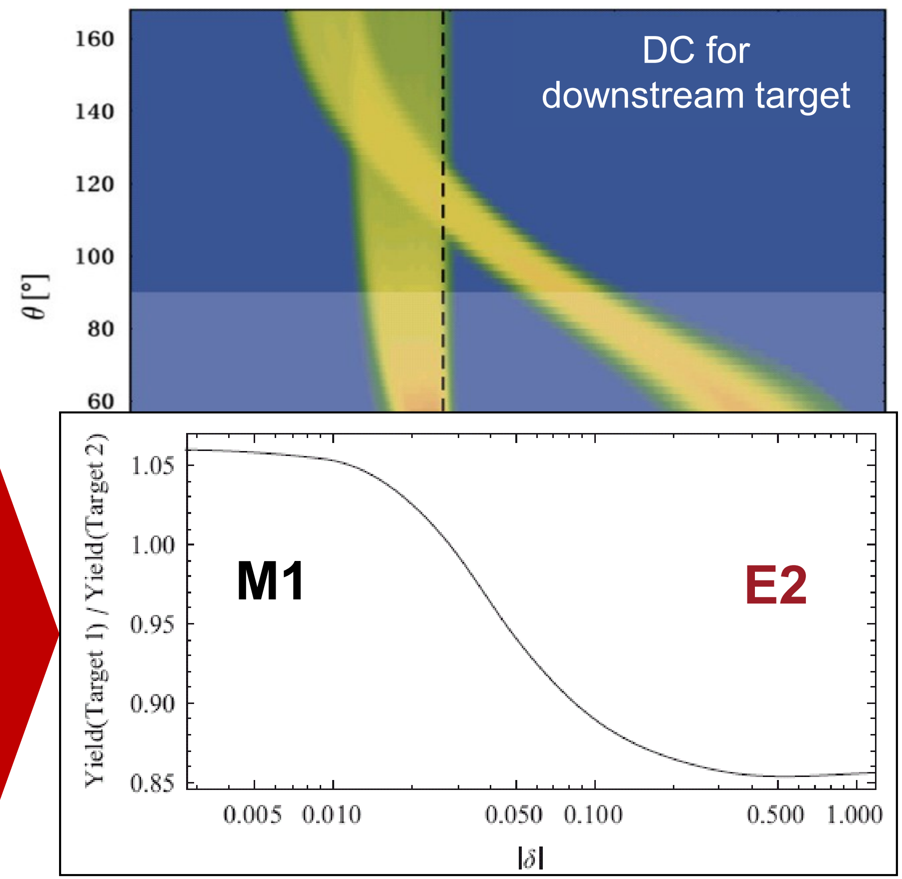
Good separation possible due to AGATA's position resolution



The *Coulex Multipolarimetry* technique

Good separation possible due to AGATA's position resolution





PreSPEC-AGATA experiment S426:
The $\pi p_{3/2} \rightarrow \pi p_{1/2}$ spin-flip transition of ^{85}Br

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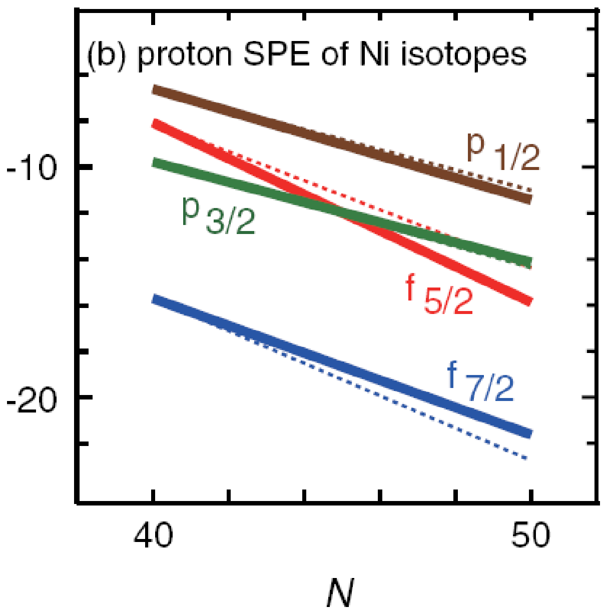
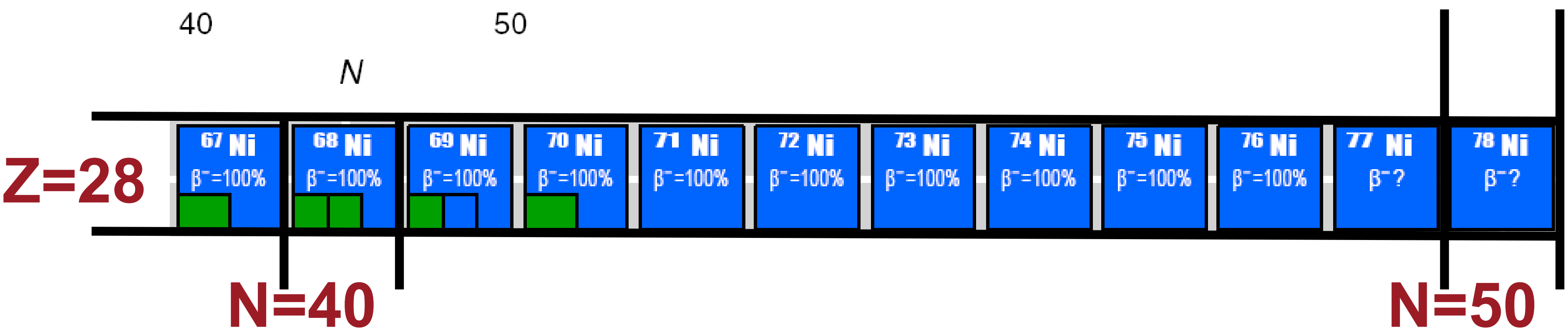
Evolution of the proton SPEs towards ^{78}Ni



Proton single-particle energies change as function of the **Neutron** number

→ Effect of the Tensor Force

T. Otsuka et al., PRL 104, 012501 (2010)
K.T. Flanagan et al., PRL 103, 142501 (2009)



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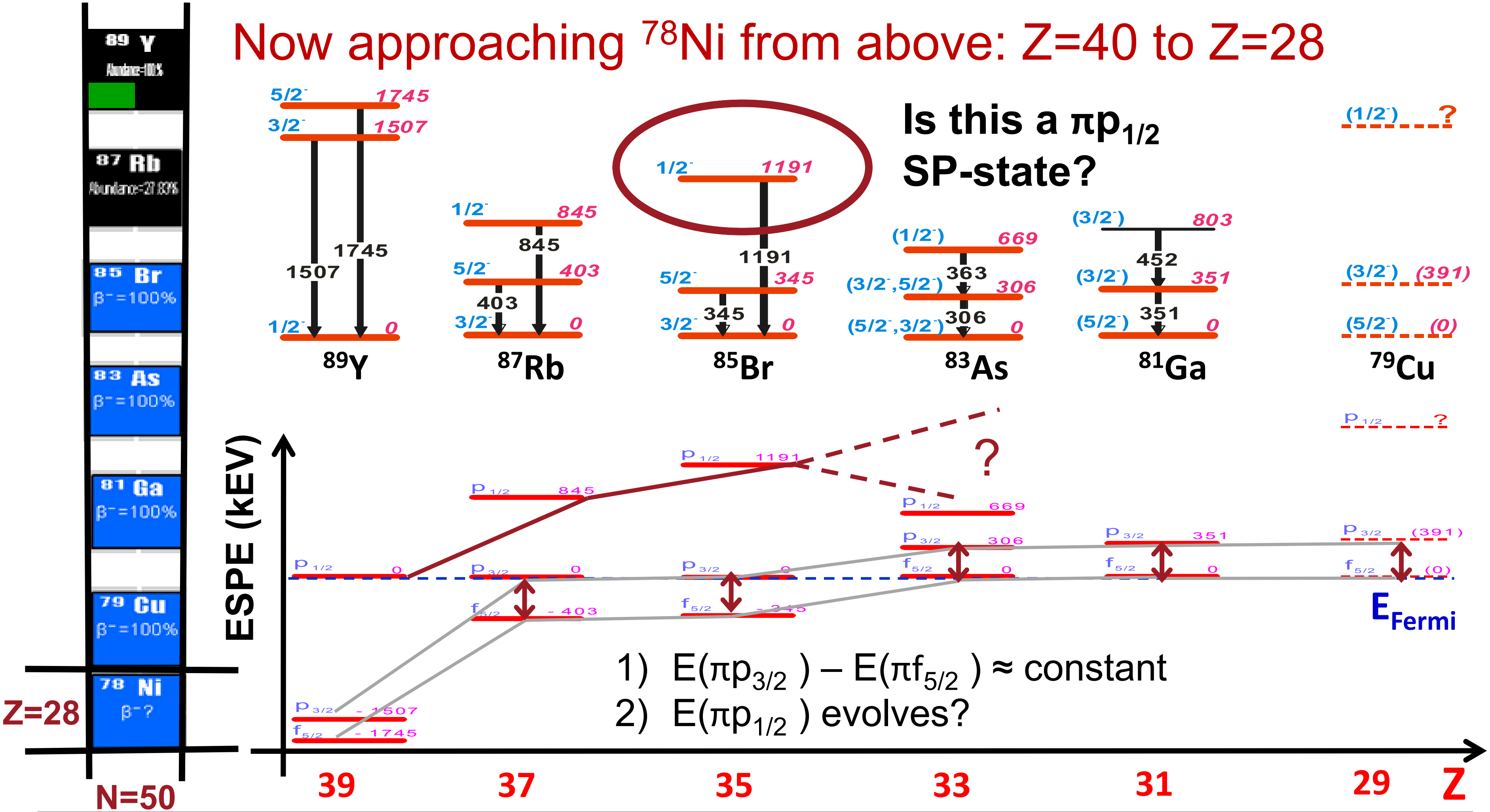
Now approaching ^{78}Ni from above: Z=40 to Z=28

Is this a $\pi p_{1/2}$ SP-state?



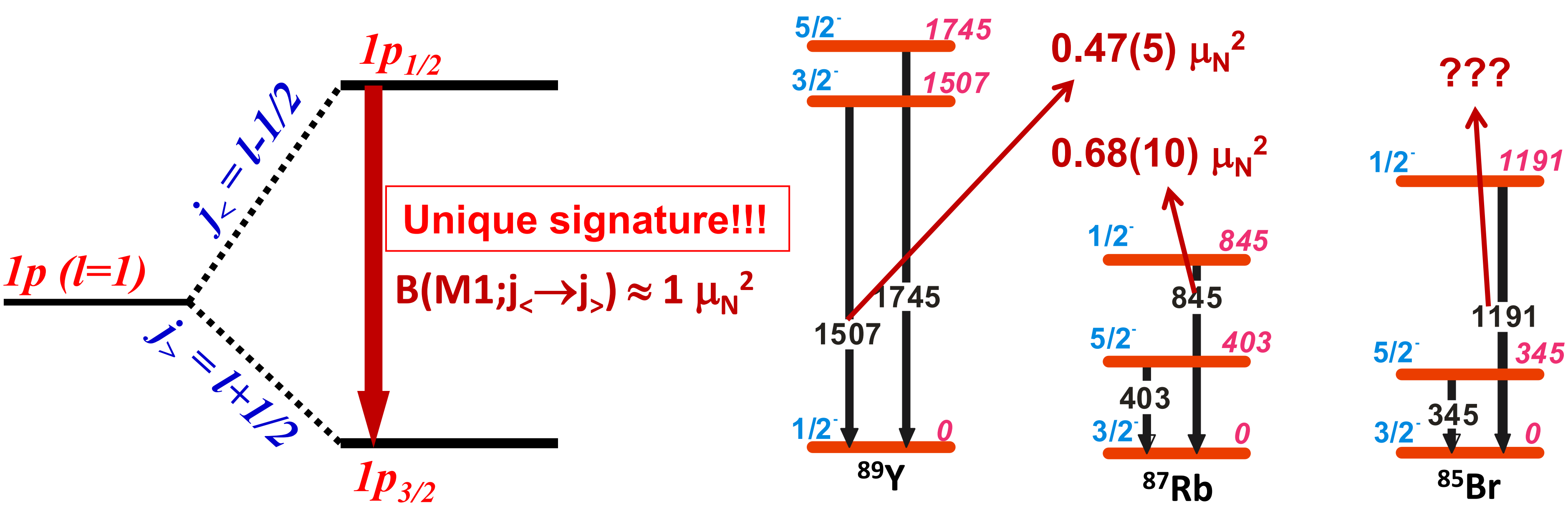
1) $E(\pi p_{3/2}) - E(\pi f_{5/2}) \approx$ constant

2) $E(\pi p_{1/2})$ evolves?

PreSPEC-AGATA experiment S426:
The $\pi p_{3/2} \rightarrow \pi p_{1/2}$ spin-flip transition of ^{85}Br

How to prove that the $1/2^-$ state of ^{85}Br at 1191 keV is the $\pi p_{1/2}$ state?

If it is, we can directly observe
the spin-orbit splitting via a Spin-Flip M1-transition!



PreSPEC-AGATA experiment S426:
The $\pi p_{3/2} \rightarrow \pi p_{1/2}$ spin-flip transition of ^{85}Br

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PreSPEC-AGATA setup at GSI's Fragment Separator (FRS)

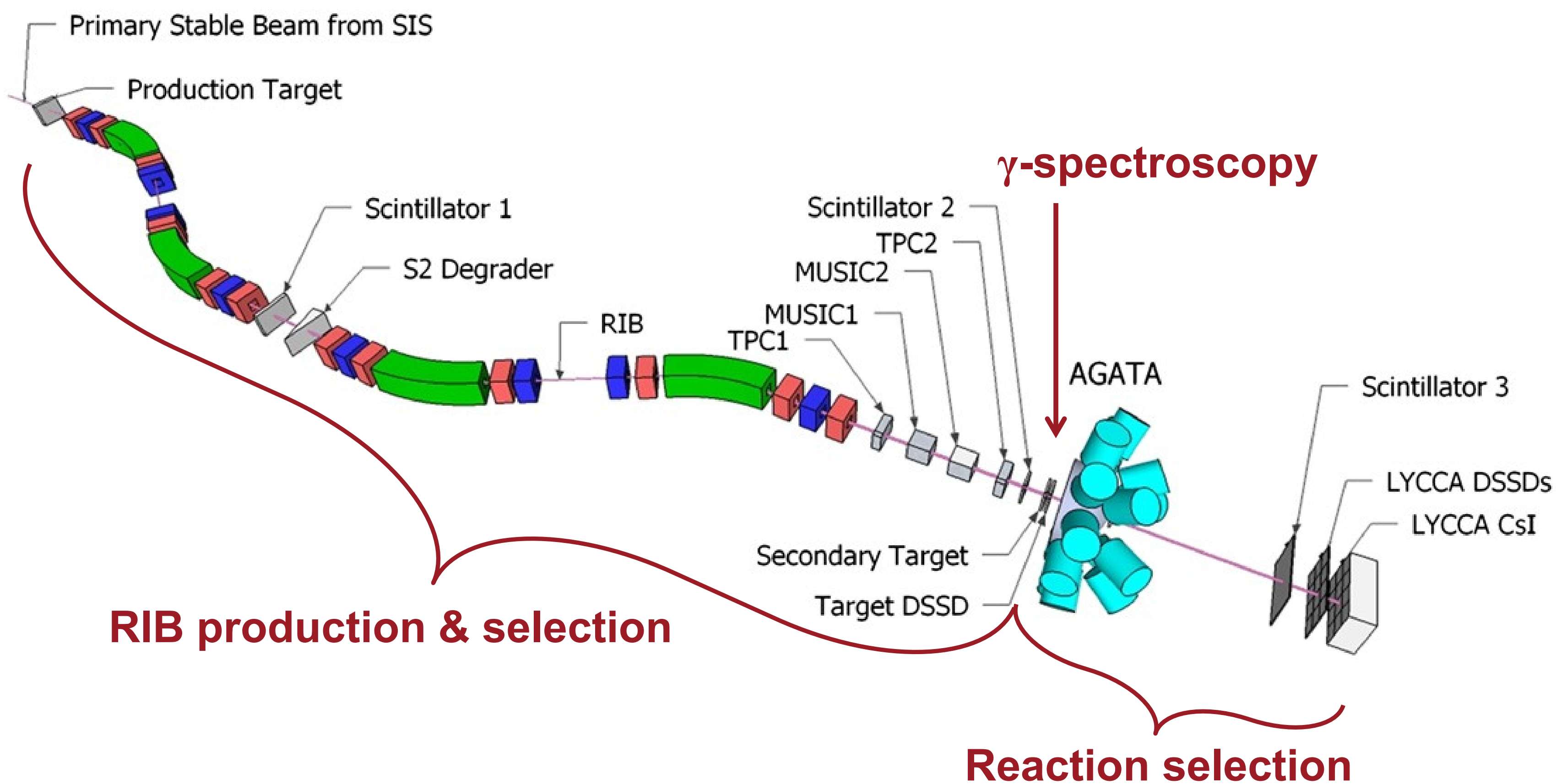
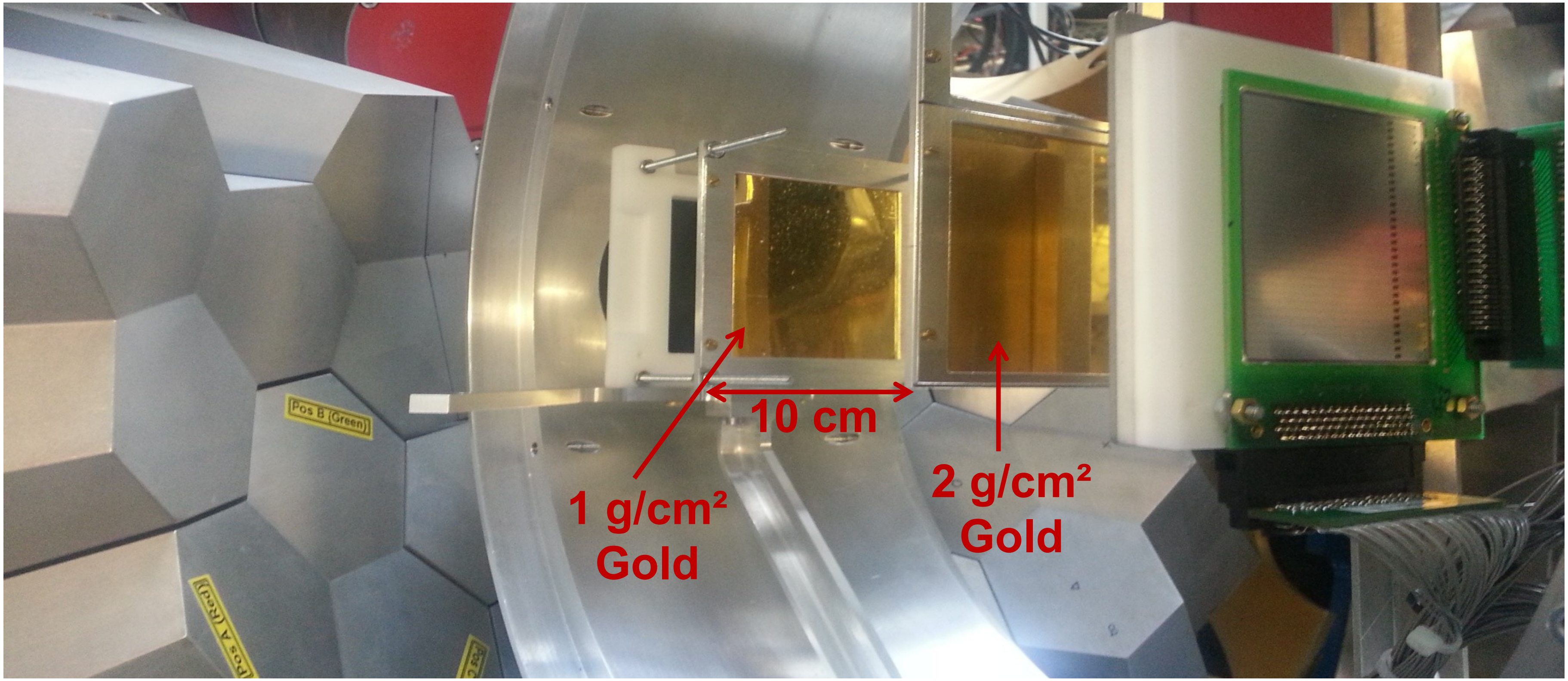


Figure: C. Domingo-Pardo *et al.*, NIM A 694, 297 (2012)

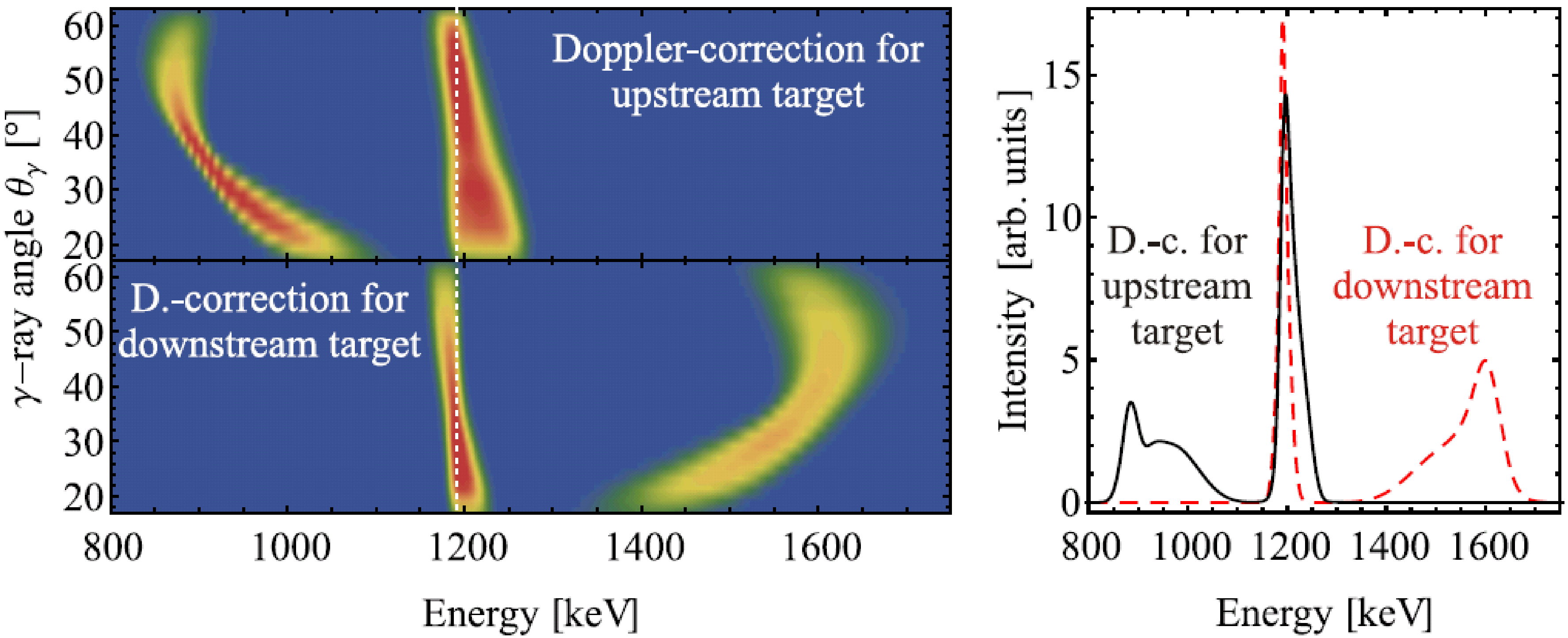
PreSPEC-AGATA experiment S426:
The $\pi p_{3/2} \rightarrow \pi p_{1/2}$ spin-flip transition of ^{85}Br

Setup for experiment S426



PreSPEC-AGATA experiment S426:
The $\pi p_{3/2} \rightarrow \pi p_{1/2}$ spin-flip transition of ^{85}Br

Expected lineshapes



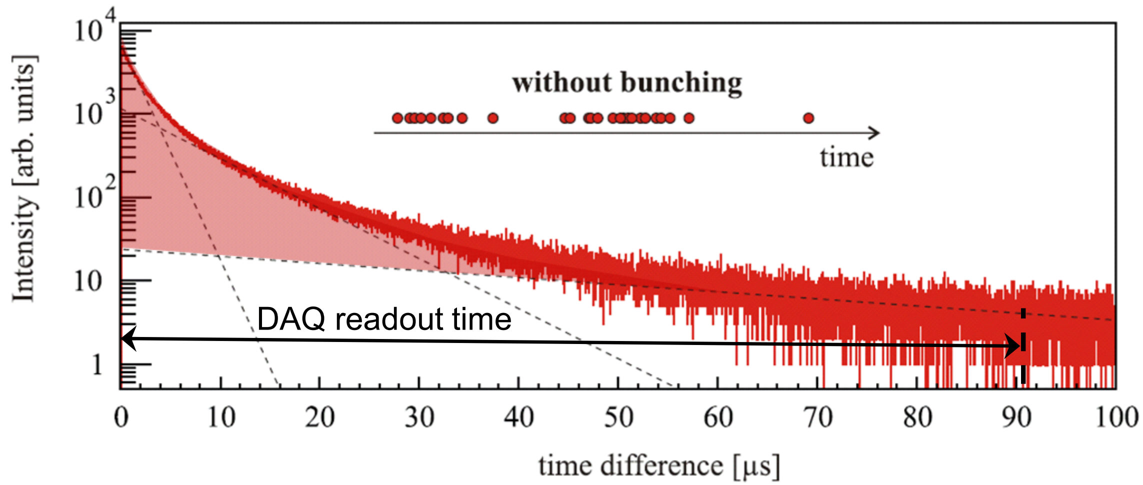
- 24 shifts budgeted by the PAC, but could take only 9
- Triggered development of “Two-Target”-method, but we had to do more..

PreSPEC-AGATA experiment S426:

The $\pi p_{3/2} \rightarrow \pi p_{1/2}$ spin-flip transition of ^{85}Br

Changing the time structure of the SIS beam

- "Random" time structure (Poisson): Expect exponential distribution
- Observe excess of small time differences: Ions "cluster"
- Loosing excessively many events in dead-time at high rates



Time differences between subsequent ions in the beam

Measured by S2 scintillator and using a VULOM with modified firmware (Thanks to **Nick Kurz**!)

PreSPEC-AGATA experiment S426:
The $\pi p_{3/2} \rightarrow \pi p_{1/2}$ spin-flip transition of ^{85}Br

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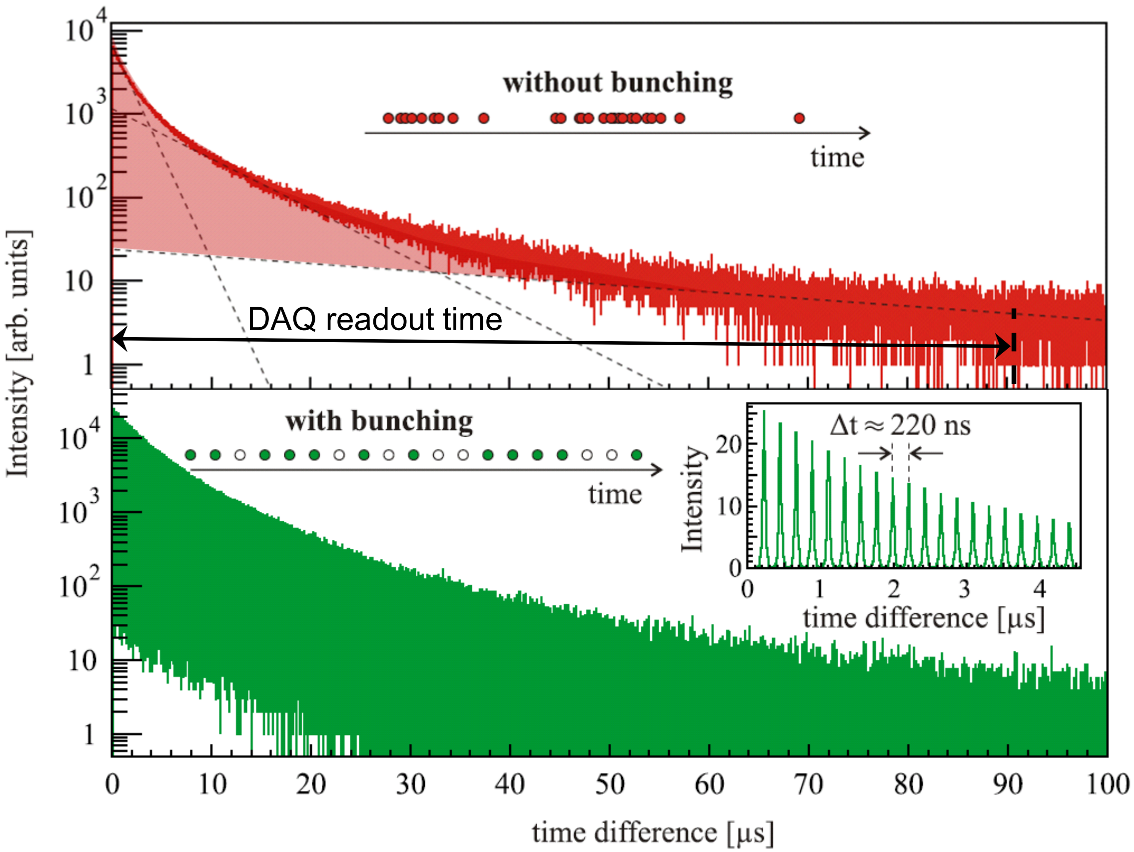
Changing the time structure of the SIS beam

- "Random" time structure (Poisson): Expect exponential distribution
- Observe excess of small time differences: Ions "cluster"
- Loosing excessively many events in dead-time at high rates
- It's a known problem with a known (but forgotten?) solution: Micro-Bunching

P. Forck *et al.*: *"Measurements and improvements of the time structure of a slowly extracted beam from a synchrotron"*, Proceedings of EPAC 2000, Vienna, Austria, p. 2237 ***(2000)***

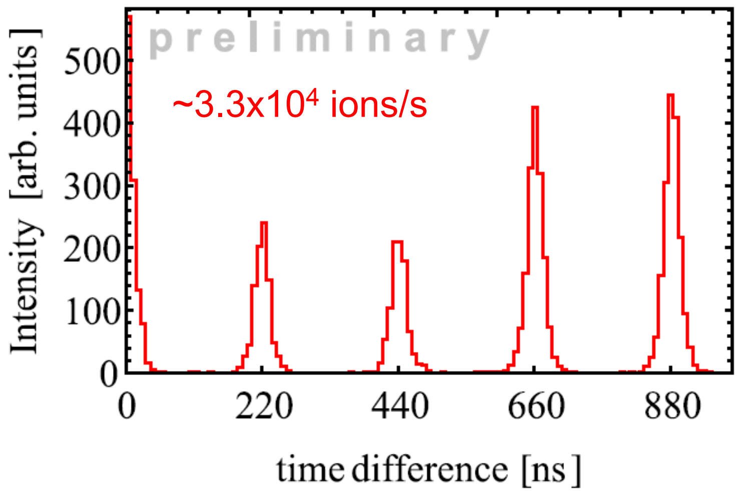
P. Forck *et al.*: "*Beam Diagnostics Developments for Current Operation of SIS18 and HEBT*", GSI scientific report 2005, p. 129 ***(2006)***

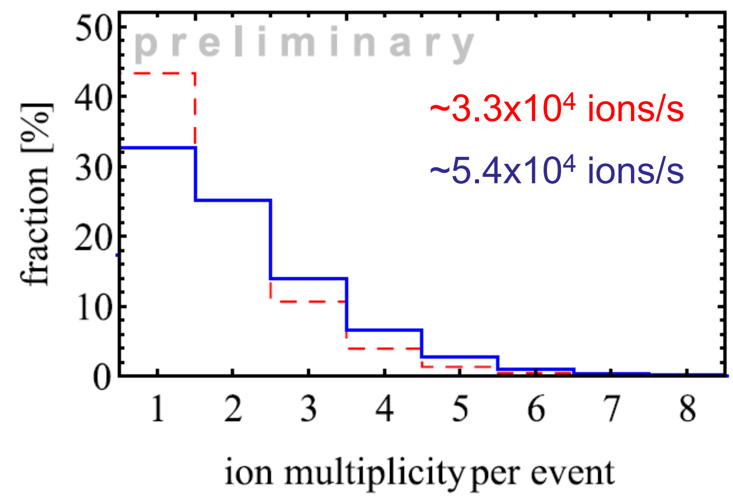


PreSPEC-AGATA experiment S426:
The $\pi p_{3/2} \rightarrow \pi p_{1/2}$ spin-flip transition of ^{85}Br

Properties of the events recorded with “micro-bunched” SIS beam

Time differences and multiplicities measured by highly segmented LYCCA-wall CsI detectors



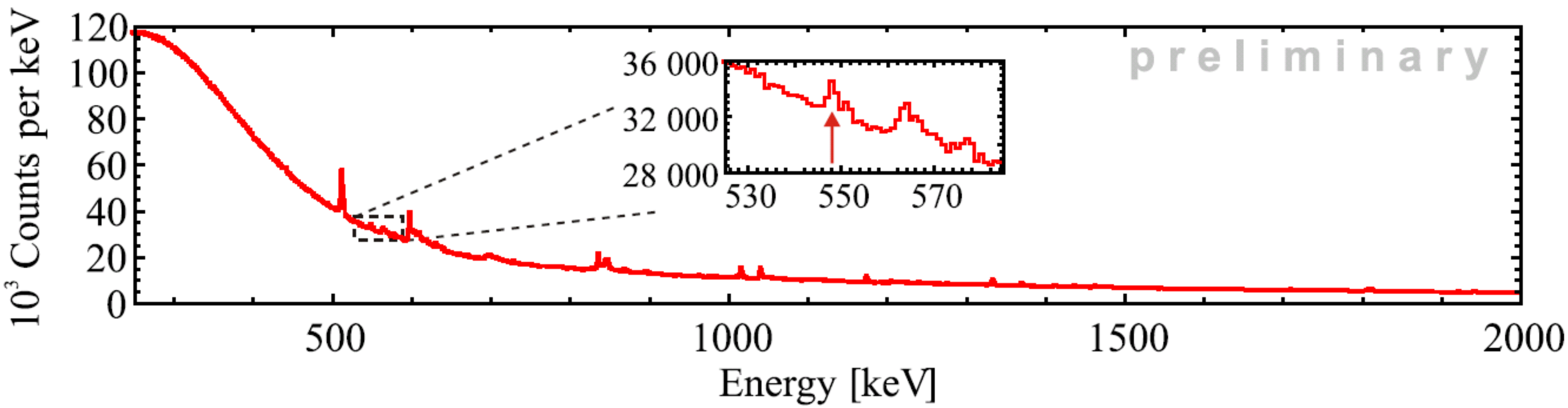


Time difference “0”: ~5% of the data, cannot distinguish ions	Time difference ≥ 220 ns: Resolvable by all detectors (including AGATA)

66% of the events contain >1 ion:
Can be split, gain in statistics:
~ Factor 4.6

PreSPEC-AGATA experiment S426:
The $\pi p_{3/2} \rightarrow \pi p_{1/2}$ spin-flip transition of ^{85}Br

Observed target-excitation



Conditions:

- Bromine identified in LYCCA
- Only one ion/event
- AGATA in "calorimetric" mode
  → no tracking applied

Observations:

- ~8500 events observed
- With all ion multiplicities: expect ~38,000 counts
- From calculation: expect ~96,000 counts
- Miss a factor of 2.5 – seen in all PRESPEC - exp.

PreSPEC-AGATA experiment S426:
The $\pi p_{3/2} \rightarrow \pi p_{1/2}$ spin-flip transition of ^{85}Br

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Expected ^{85}Br events

- Scaling to observed target excitations: B(*M1*) = $0.58\mu_N^2$, B(*E2*) = 2 W.u.
- Use factor 4.6 for splitting events
- Expect 1370 events from decay of the ^{85}Br 1191-keV $½^-$ state.

Challenge: Background

- Have to reduce background in order to observe the 1191-keV transition

Reduce background by:

- Cleaner gating in LYCCA
- AGATA as Compton-Camera: Reject BG from upstream/downstream target
- Optimized FRS slit settings (done in advance of measurement)
- Improved time resolution, γ-neutron discrimination

PreSPEC-AGATA experiment S426:
The $\pi p_{3/2} \rightarrow \pi p_{1/2}$ spin-flip transition of ^{85}Br

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Expected ^{85}Br events

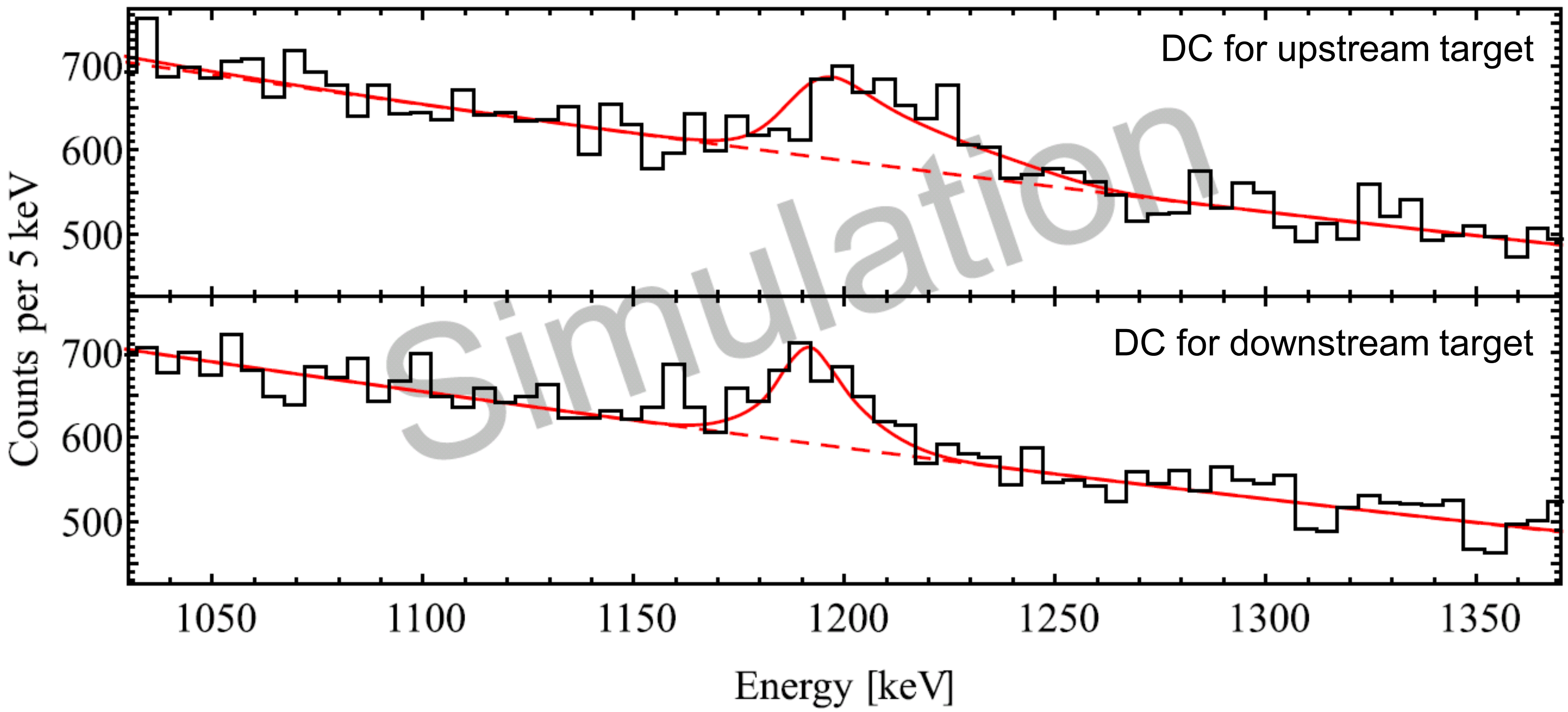

Fig.: Simulated spectra for in total 1370 events from the decay of the ^{85}Br 1191-keV ½$^-$ state.
Assumption: Background reduced by a factor 10 compared to level observed in a 2012 test-run.

Summary

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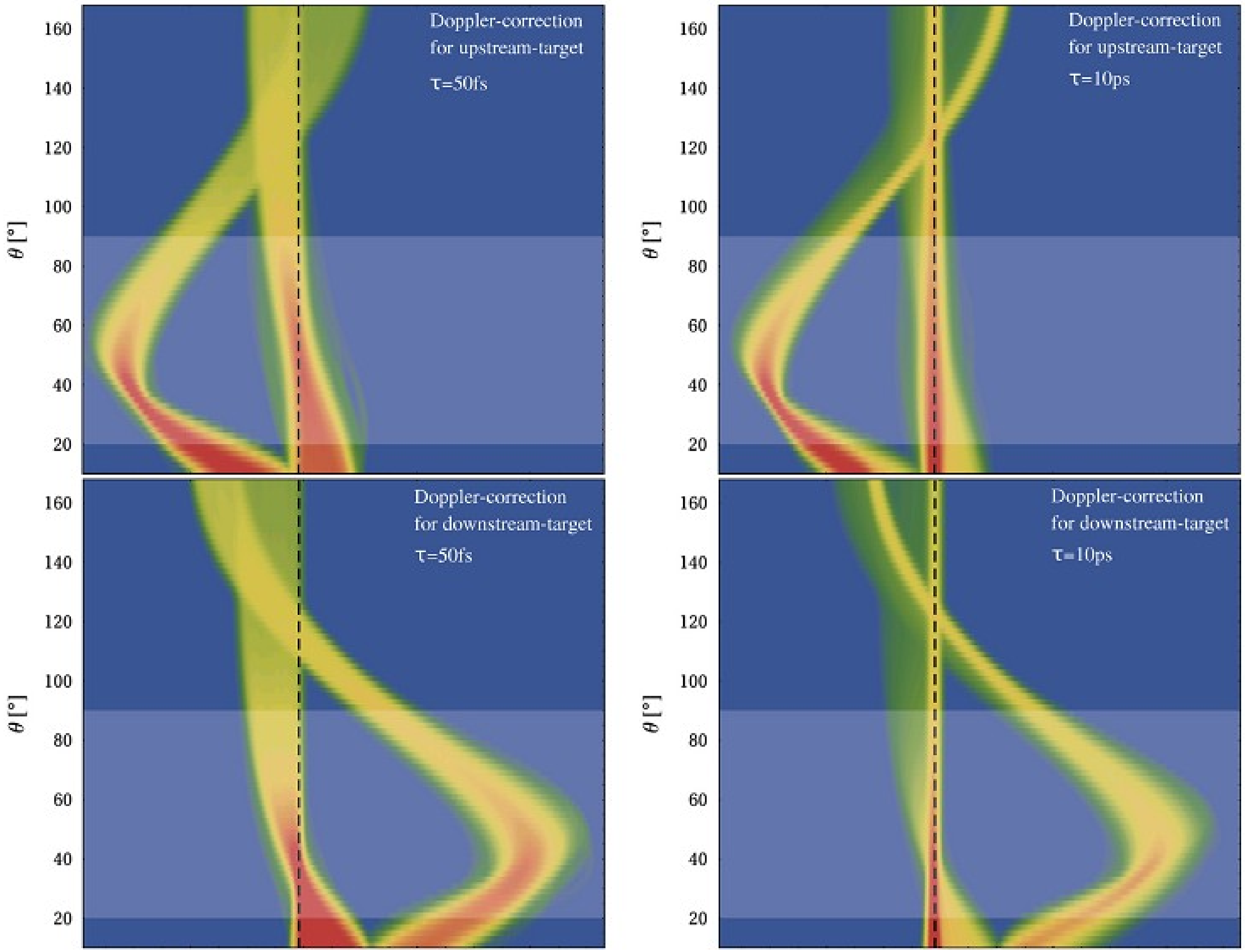
- **Access to *M1* excitations of exotic nuclei** by relativistic Coulomb excitation
- **Identification of *M1* decays** by the *Coulex Multipolarimetry Method:*

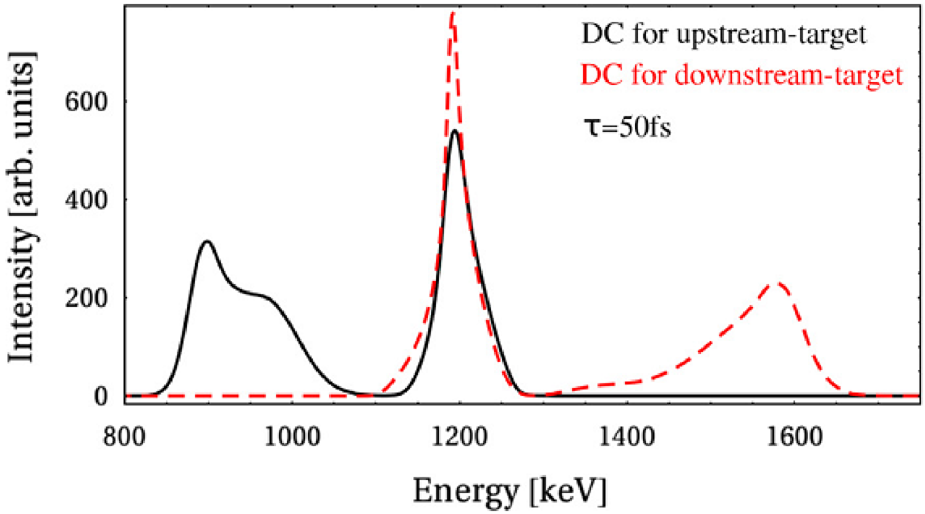
  [C. Stahl et al., NIM A 770, 123 (2015)]

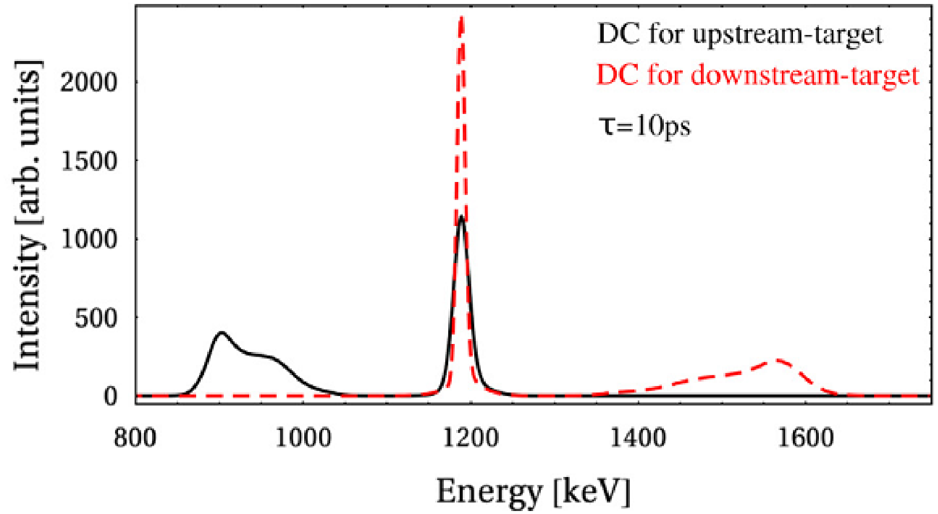
  → Compare yields from excitations in two spatially separated targets
  → Identify excitation in either target via Doppler shift
  → Ideal tool: Position-sensitive AGATA detectors
- **First application:** Identification of the $\pi p_{3/2} \rightarrow \pi p_{1/2}$ spin-flip transition of ^{85}Br
- **PreSPEC-AGATA experiment S426:**

  → Running at high rates: >50,000 ions/s (in spill)
  → Improved time structure of the beam: Micro-bunching
  → Can split events containing multiple ions: $\Delta t_{ion} \approx n \cdot 220$ ns
  → Have to exploit AGATA's capabilities for background reduction

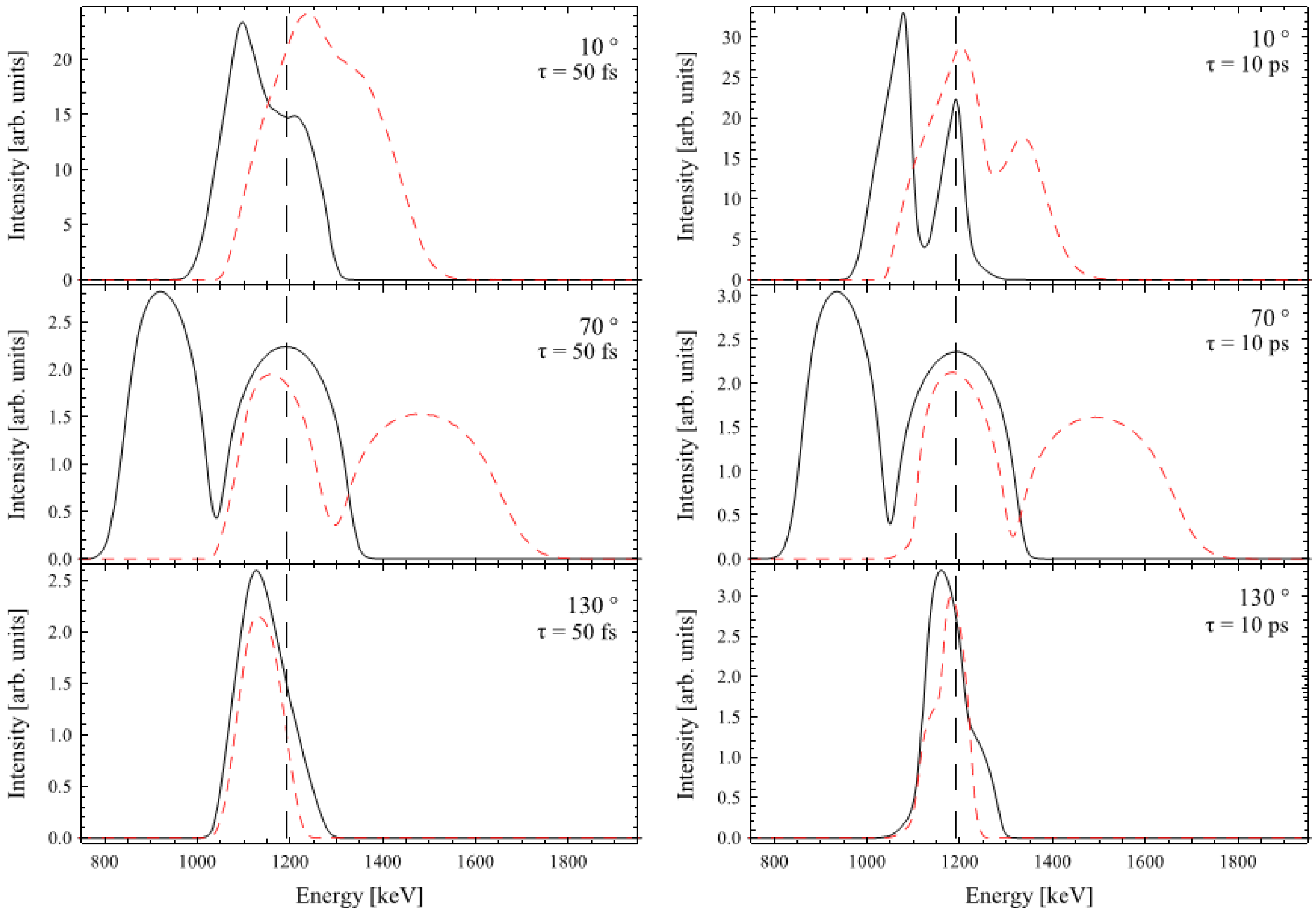

Doppler-correction
for upstream-target
τ=50fs
Doppler-correction
for upstream-target
τ=10ps
Doppler-correction
for downstream-target
τ=50fs
Doppler-correction
for downstream-target
τ=10ps
θ [°]
160
140
120
100
80
60
40
20

Lifetime effects





Application with “regular” detectors



Cylindrical Detectors

D=8cm
at 23.5cm around upstream target

“Geometric” DSAM

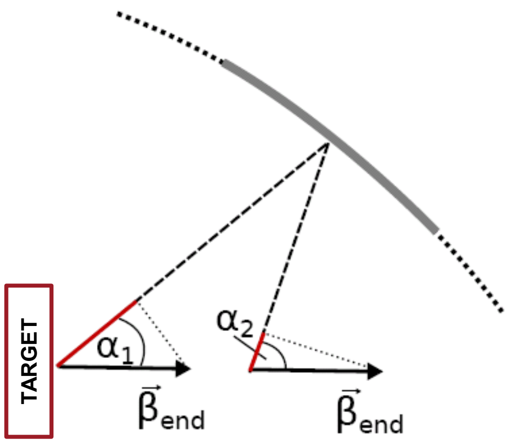
Application of the DSA Method with relativistic, radioactive ion beams

- **Another sensitivity region with “geometric DSAM” in the order of 100ps:**

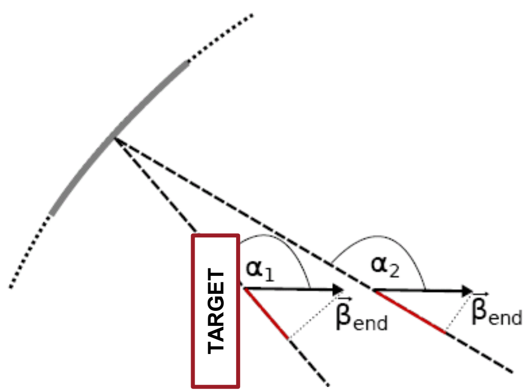
  Doppler-correction on exit velocity “fails”, if decay occurs far behind the target (assumed angle between direction of ion motion and gamma detection is wrong)

  P. Doornenbal et al., NIM A 613 (2010) 218–225; C. Domingo-Pardo et al., NIM A 694 (2012) 297–312

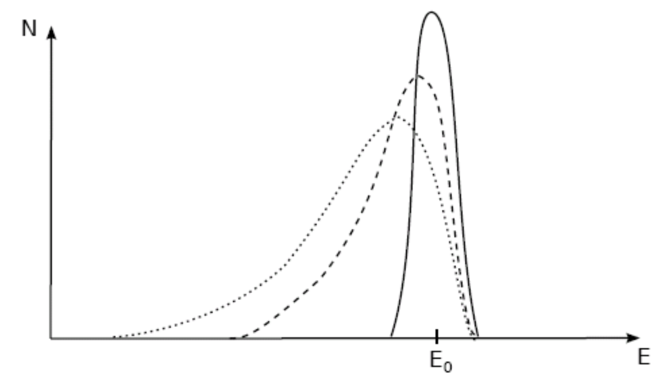
  → **A “continuous Plunger”:**



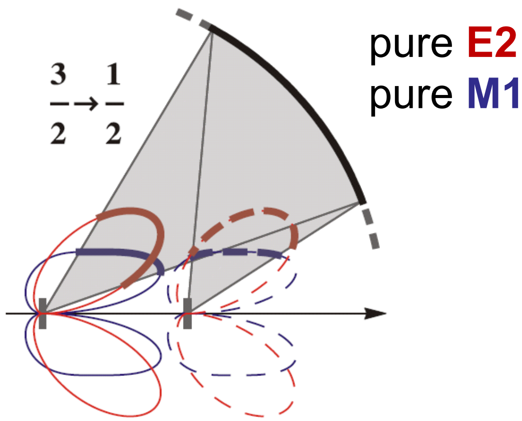
Detector under forward-angle:
Over-estimation of Doppler-shift

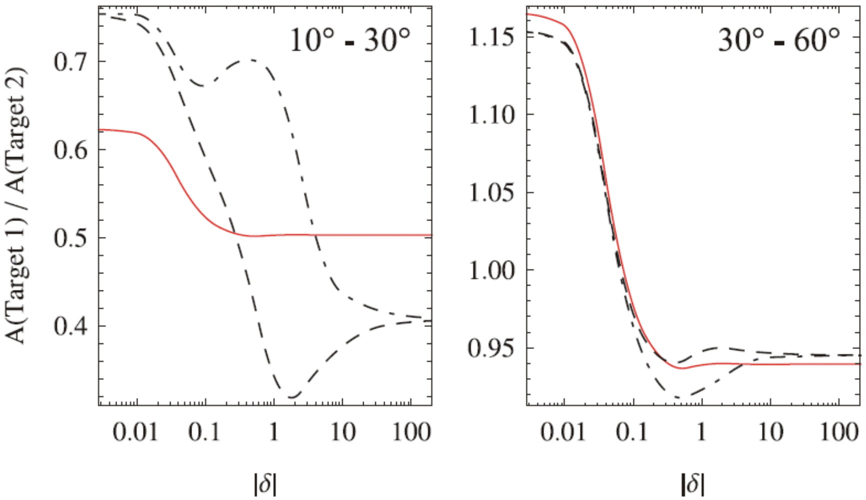


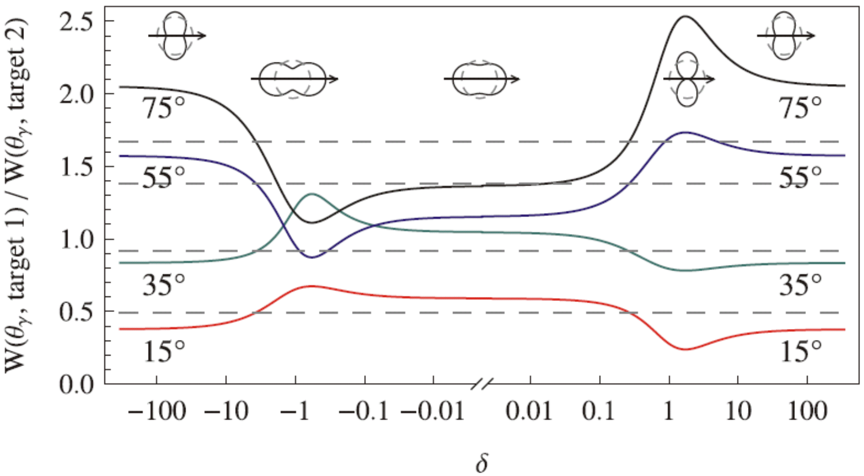
Detector under backward-angle:
Under-estimation of Doppler-shift

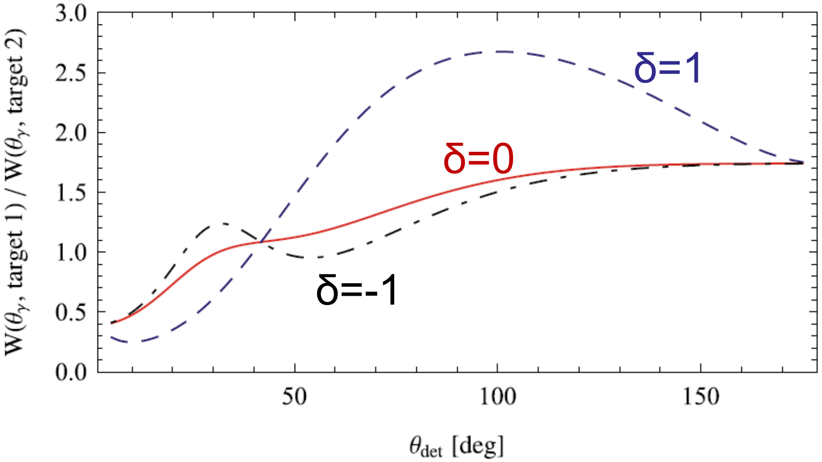


Non-isotropic γ-ray emission









Choosing the target distance