Nature of the Pygmy Dipole Resonance

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- Introduction
- The PDR in stable nuclei
  - (γ,γ') experiments
  - (α,α'γ) experiments
- The PDR in unstable nuclei
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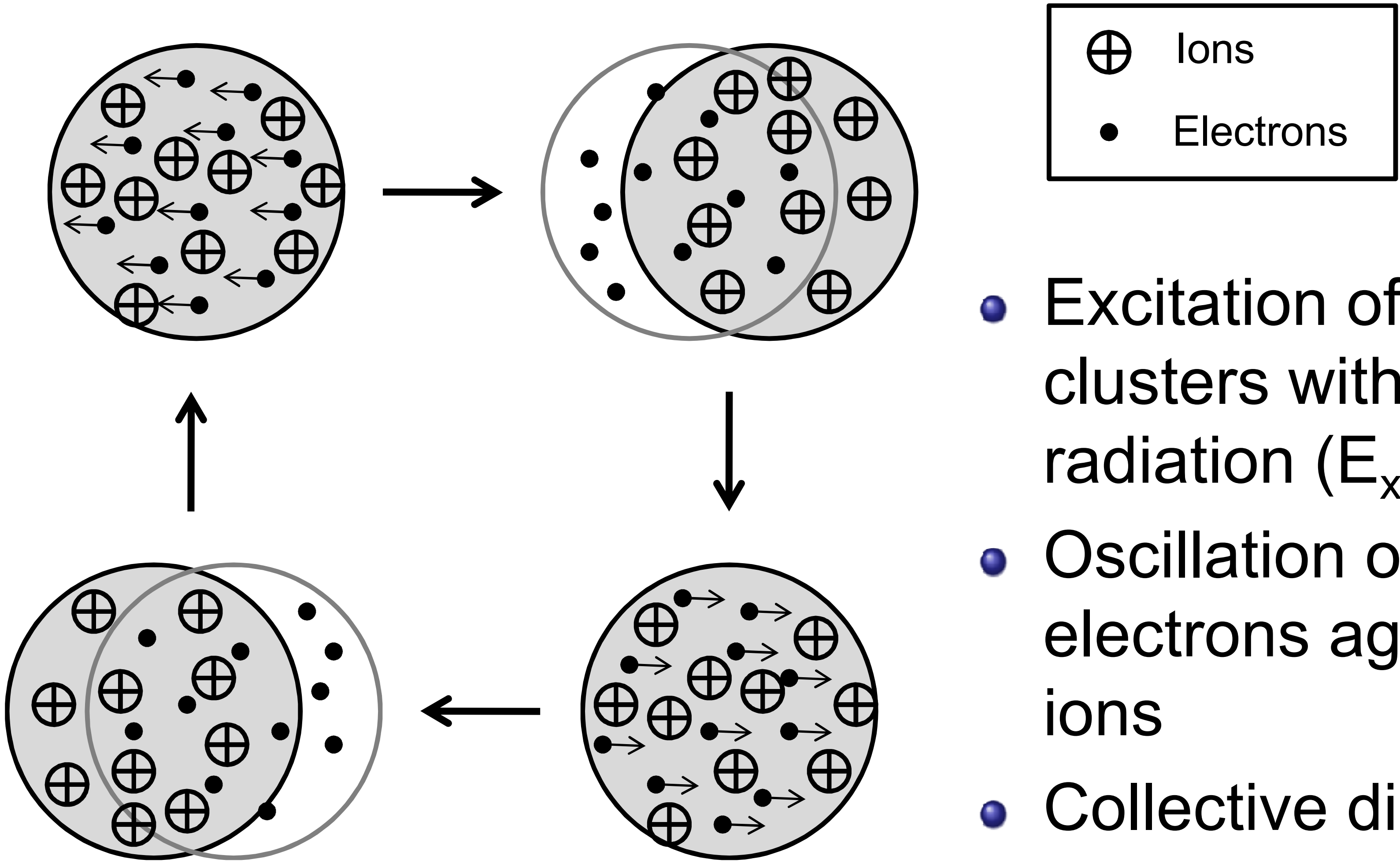
Collective dipole oscillations in small sodium clusters

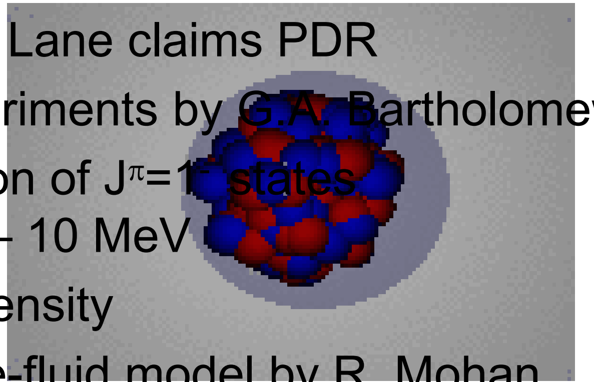


- Excitation of metal clusters with radiation (E_x~1 eV)
- Oscillation of electrons against ions
- Collective dipole resonance

W. A. de Heer *et al.*, Phys. Rev. Lett. **59** (1987) 1805

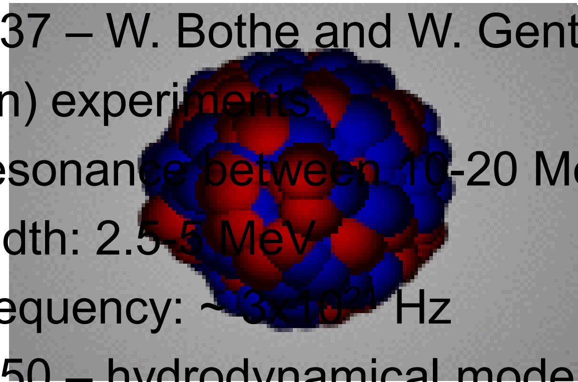
Electric dipole strength in an atomic nucleus

Pygmy Dipole Resonance

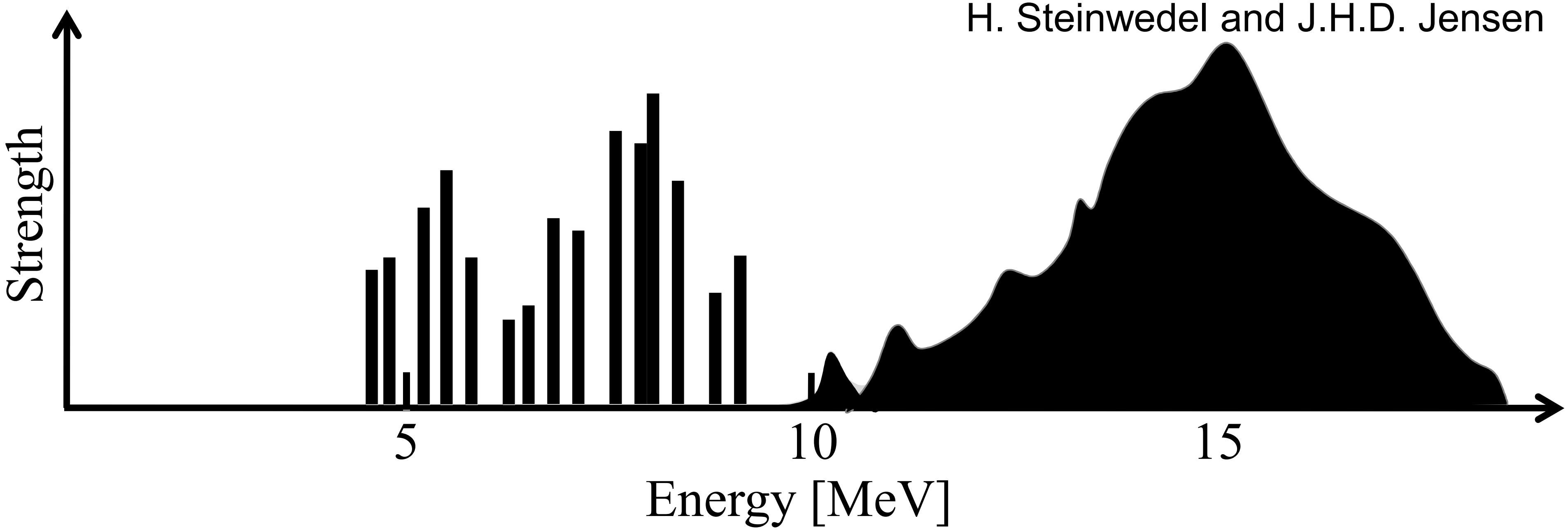


- 1971 – A.M. Lane claims PDR
- 1973 – experiments by G.A. Bartholomew
- Concentration of $J^{\pi}=1^{-}$ states between 5 – 10 MeV
- High level density
- 1971 – three-fluid model by R. Mohan

Giant Dipole Resonance



- 1937 – W. Bothe and W. Gentner
- (γ,n) experiments
- Resonance between 10-20 MeV
- Width: 2.5-5 MeV
- Frequency: ~ 3×10^{21} Hz
- 1950 – hydrodynamical model by H. Steinwedel and J.H.D. Jensen

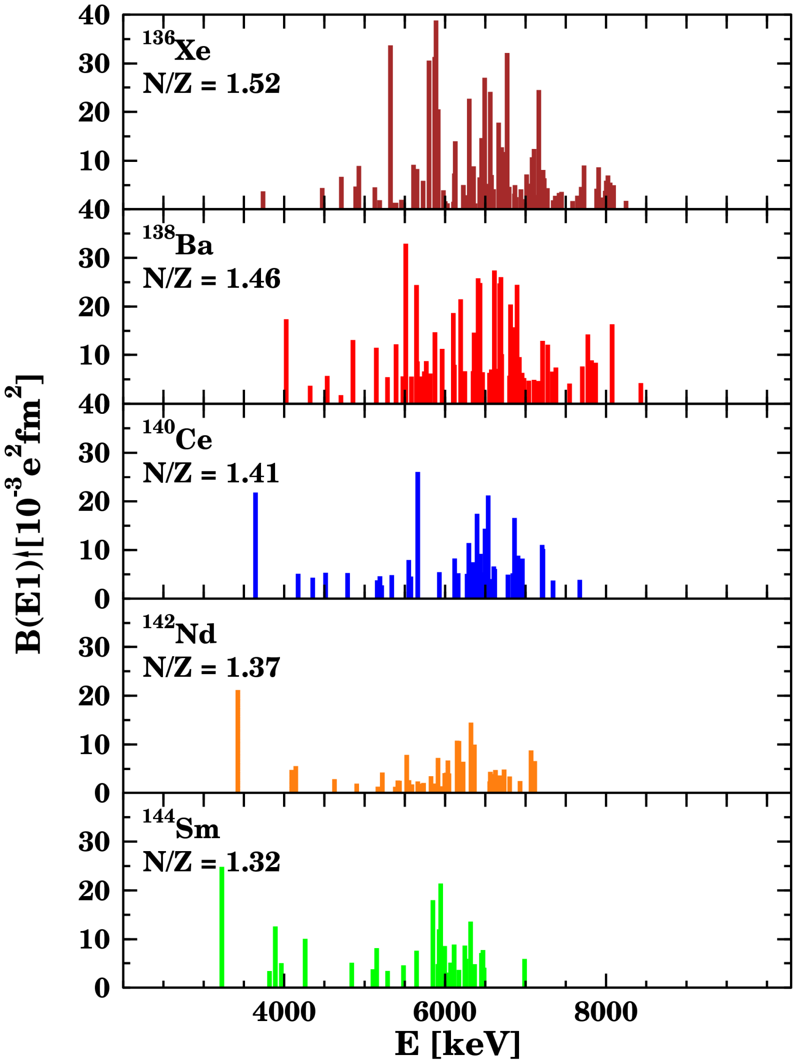


Relevance of the Pygmy Dipole Resonance

- γ-ray strength function around the particle threshold
  H. K. Toft *et al.*, Phys. Rev. C **83** (2011) 044320
- Determination of neutron skin thickness (r_n-r_p)
  A. Klimkiewicz *et al.*, Phys. Rev. C **76** (2007) 051603(R)
- Equation of state of neutron rich matter
  J. Piekarewicz, Phys. Rev. C **73** (2006) 044325
- Information on neutron star properties from (r_n-r_p)
  C. J. Horowitz and J. Piekarewicz, Phys. Rev. Lett. **86** (2001) 5647
- Influence on nucleosynthesis processes
  S. Goriely, Phys. Lett. B **436** (1998) 10
- Supernova explosion mechanism
  J. Piekarewicz, Phys. Rev. C **73** (2006) 044325

PDR strength in stable N=82 isotones

(γ,γ') @ S-DALINAC



- Real photon scattering
- Using HPGe detectors
- Strong fragmentation
- Concentration around 5.5 - 7.0 MeV
- 1% of EWSR
- Scaling with N/Z

A. Zilges *et al*., Phys. Lett. B **542** (2002) 43
S. Volz *et al*., Nucl. Phys. **A779** (2006) 1
D. Savran *et al*., Phys. Rev. Lett. **100** (2008) 232501

Experiments on the PDR using the (γ,γ') method

S-DALINAC
(TU Darmstadt)

ELBE
(Helmholtz Zentrum
Dresden-Rossendorf)

HIγS
(Duke University, USA)

Former bremsstrahlung facility in Gent

- A<60:
  ^{26}Mg, ^{40,44,48}Ca, ^{48}Ti, ^{52}Cr, ^{56}Fe, ^{58}Ni
- A<100:
  ^{70,72,74,76}Ge, ^{88}Sr, ^{89}Y, ^{90}Zr, ^{92,94,96,98,100}Mo
- A>100:
  ^{112,116,120,124}Sn, ^{136}Xe, ^{138}Ba, ^{140}Ce, ^{142}Nd, ^{144}Sm, ^{204,206,207,208}Pb

α scattering versus real photon scattering

	(α,α')*	(γ,γ')
Interaction	Strong	Electromagnetic
Location of interaction	Surface	Whole nucleus
Isospin	Isoscalar	Isovectorial E1 excitation
Multipolarity	E0, E1, E2, E3, …	E1, M1, (E2)
Energy resolution (at E_x = 8 MeV)	30-100 keV (straggling)	7-10 keV

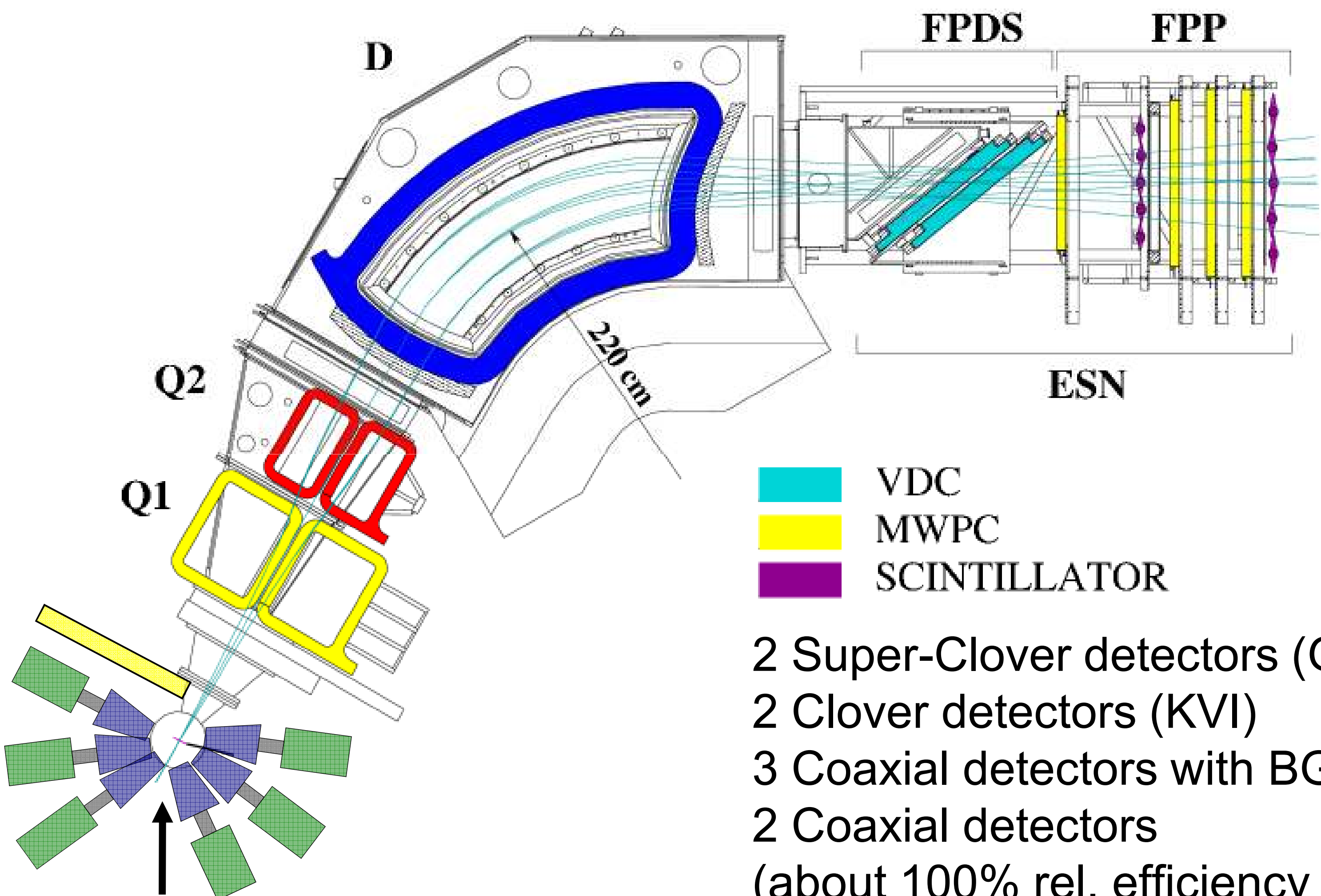
* 130 MeV (intermediate energies) and scattering at forward angles

⇒ New structure information

⇒ Essential for spectroscopy of the PDR

⇒ $(\alpha,\alpha'\gamma)$ coincidence experiments!

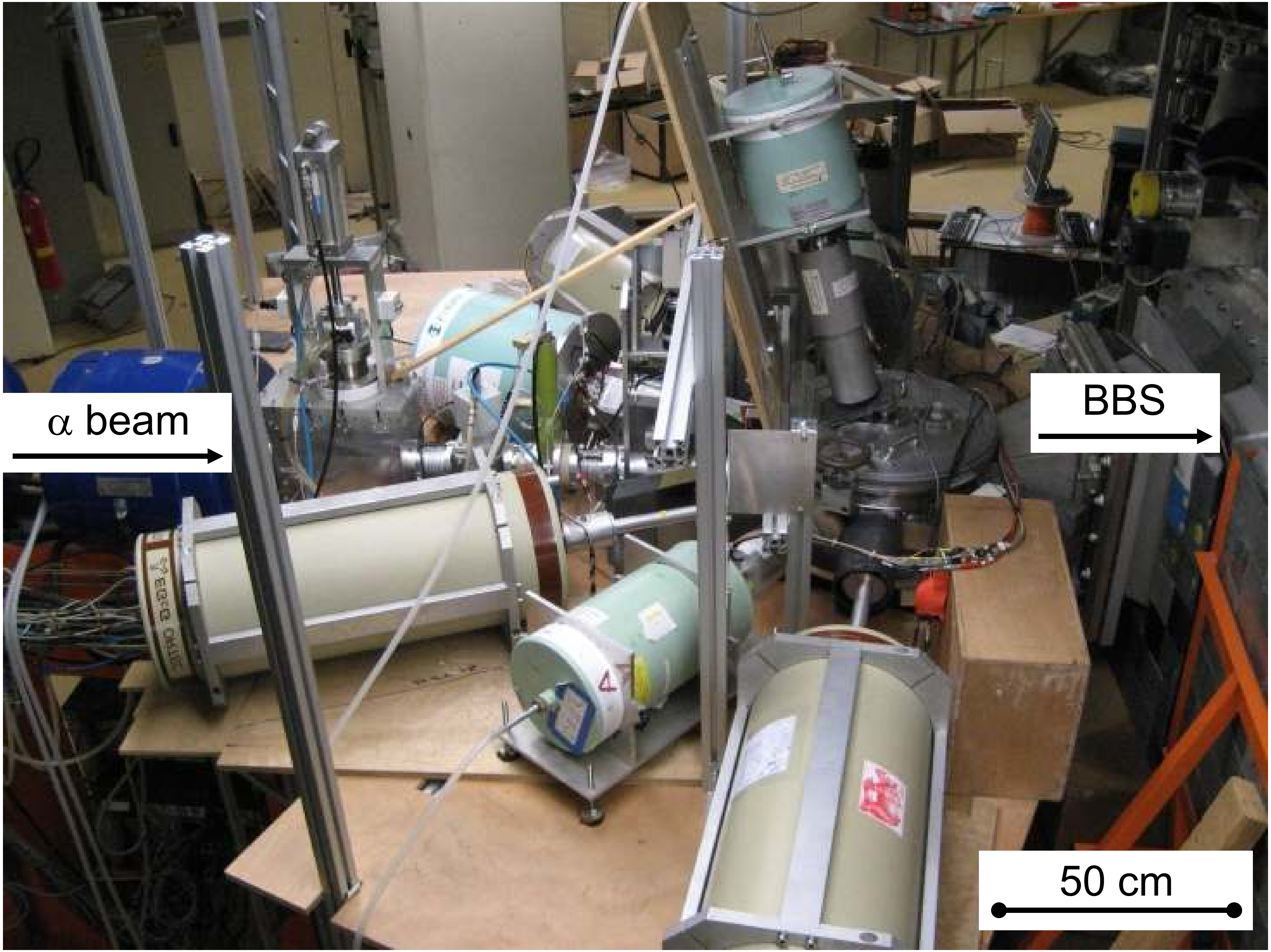
Setup at KVI



2 Super-Clover detectors (GSI)
2 Clover detectors (KVI)
3 Coaxial detectors with BGO
2 Coaxial detectors
(about 100% rel. efficiency each)
→ 0.5% absolute photo-peak efficiency

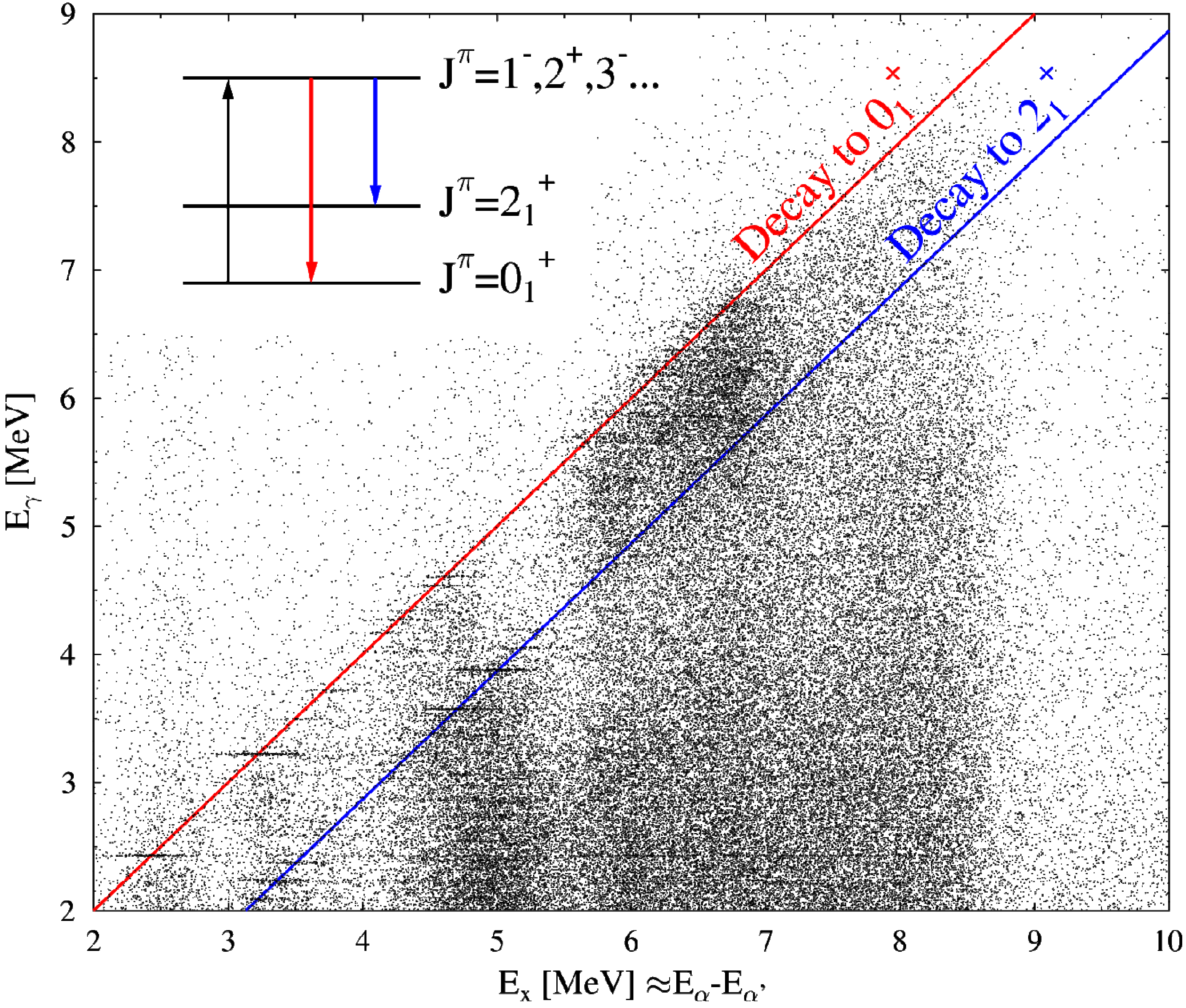
α beam
E_α=136 MeV, θ_α=3.5°

D. Savran *et al.*, Nucl. Inst. and Meth. Phys. Res. A **564** (2006) 267

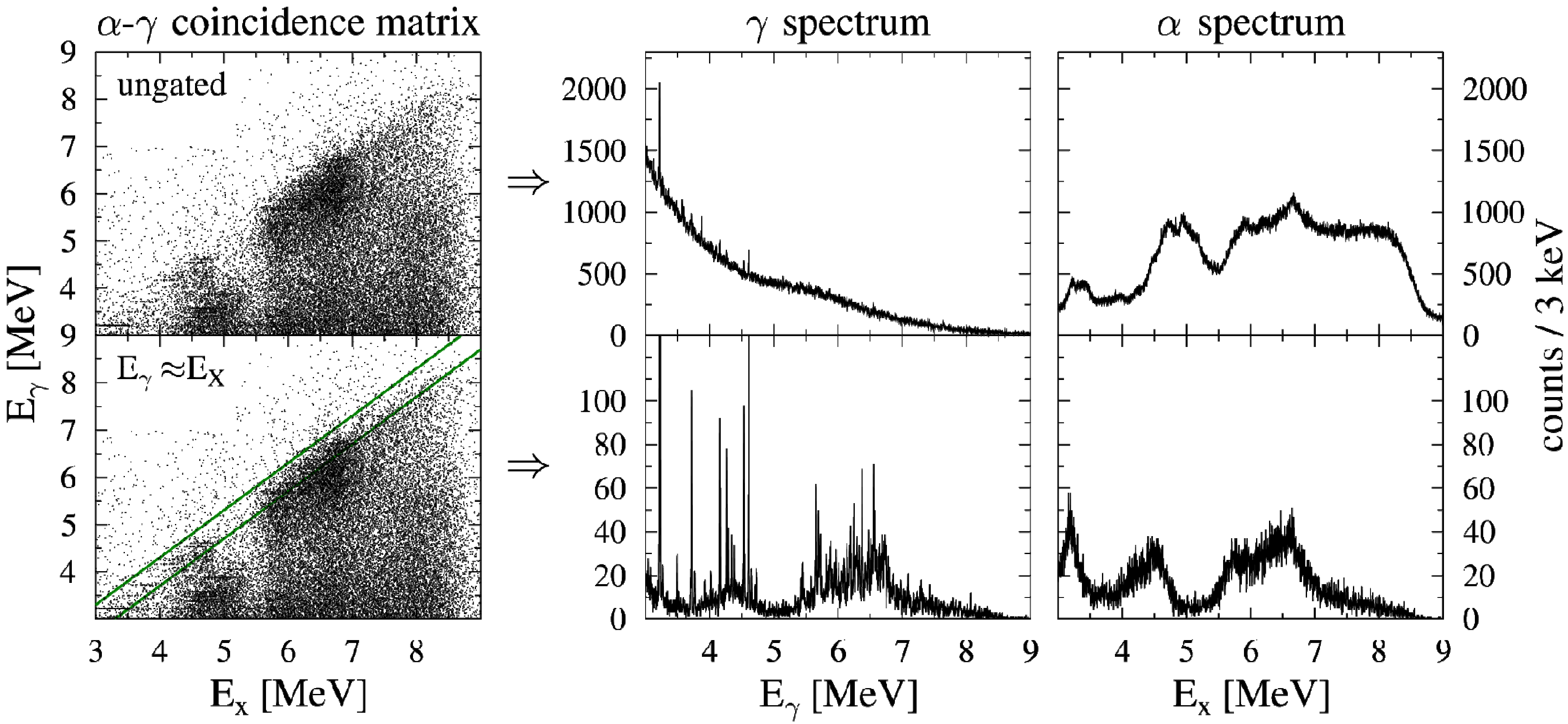

α beam
BBS
50 cm

Big-Bite Spektrometer

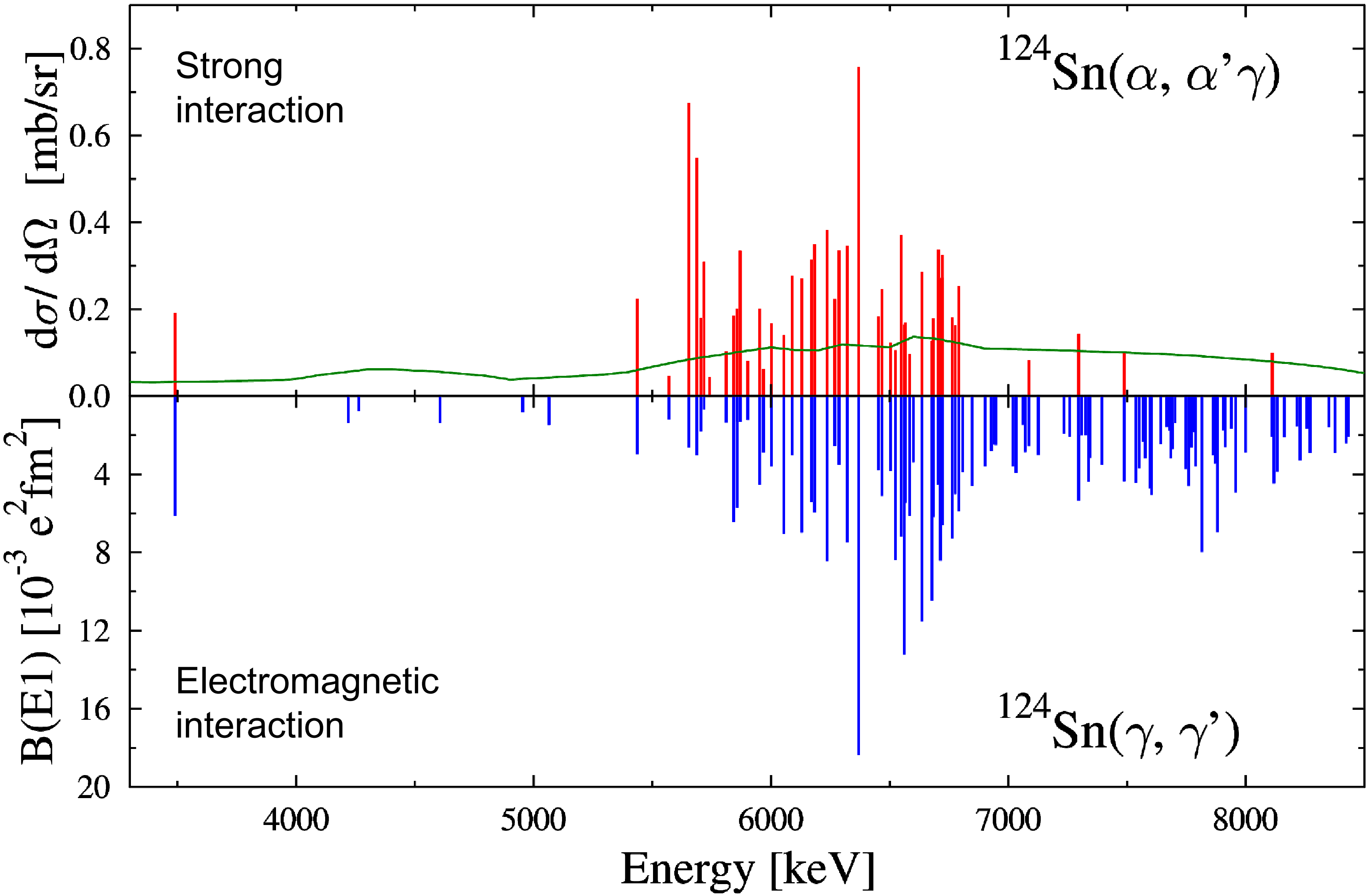
^{124}Sn: 2d coincidence matrix



$^{124}Sn(\alpha,\alpha'\gamma)$ - selectivity

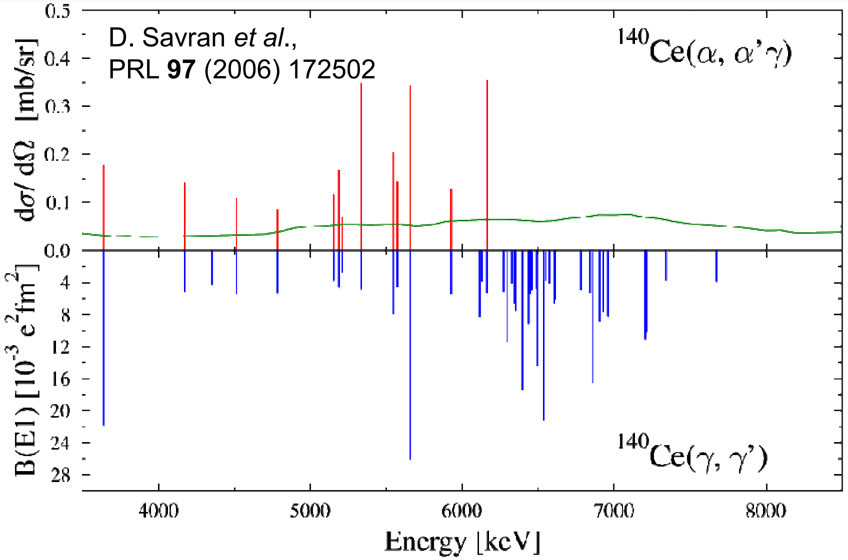


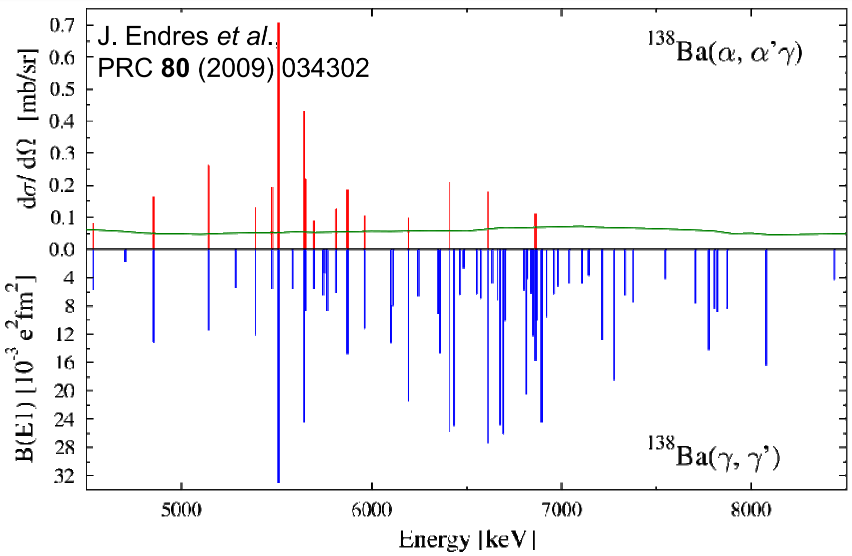
Comparison of $(\alpha,\alpha'\gamma)$ with (γ,γ') for ^{124}Sn

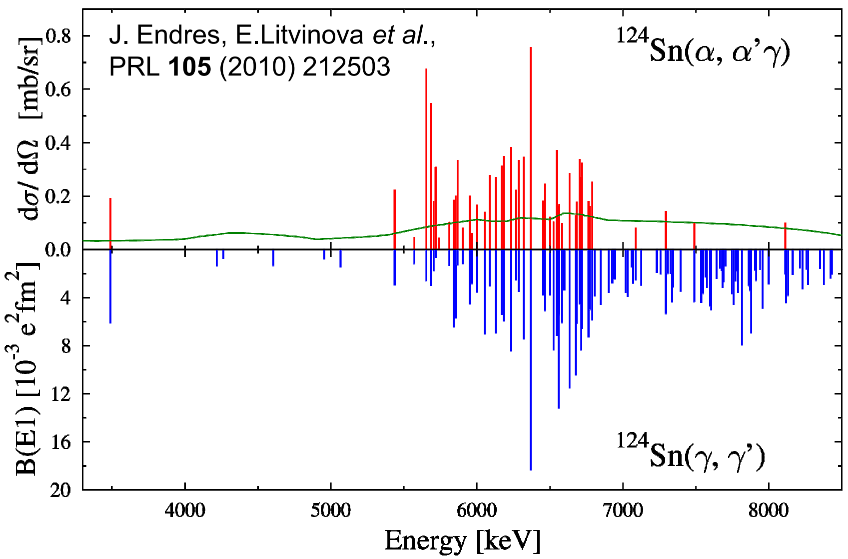


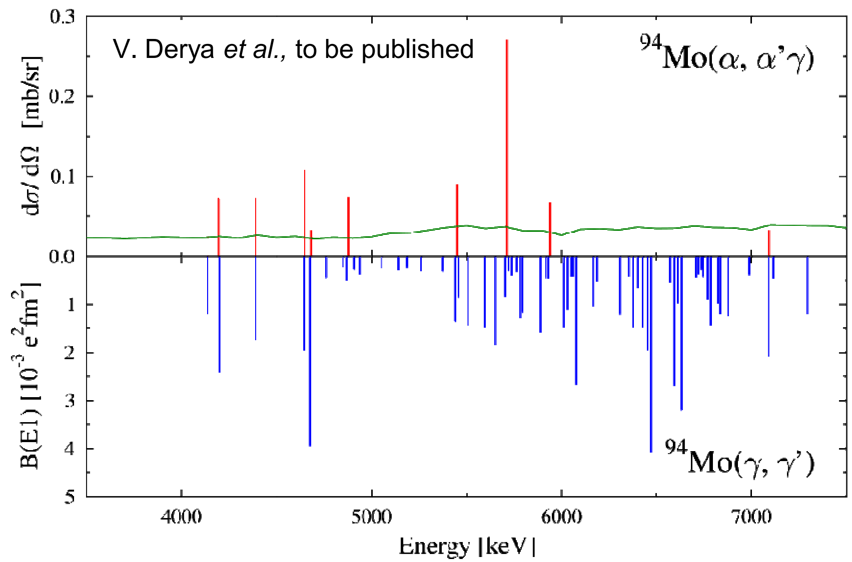
J. Endres, E.Litvinova *et al.*, Phys. Rev. Lett. **105** (2010) 212503

E1 strength distribution in ^{140}Ce, ^{138}Ba, ^{124}Sn, and ^{94}Mo







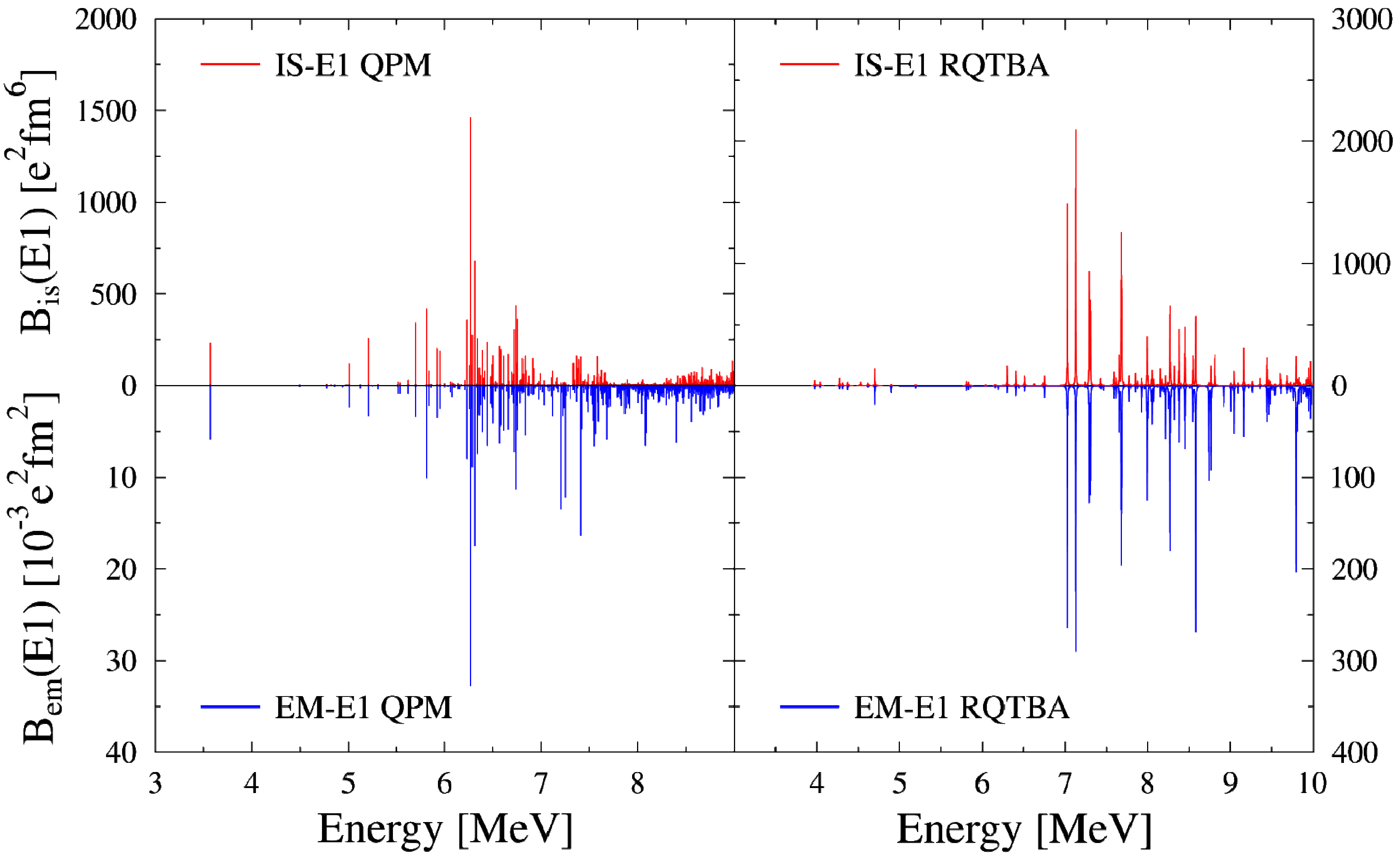


Theoretical approaches

- QPM (Quasiparticle-Phonon Model)
  N. Tsoneva and H. Lenske, Phys. Rev. **C** 77 (2008) 024321
- RQRPA (Relativistic Quasiparticle Random Phase Appr.)
  N. Paar *et al.,* Rep. Prog. Phys. **70** (2007) 691
- RQTBA (Relativistic Quasiparticle Time Blocking Appr.)
  E. Litvinova, P. Ring, and V. Tselyaev, Phys. Rev. C **78** (2008) 014312

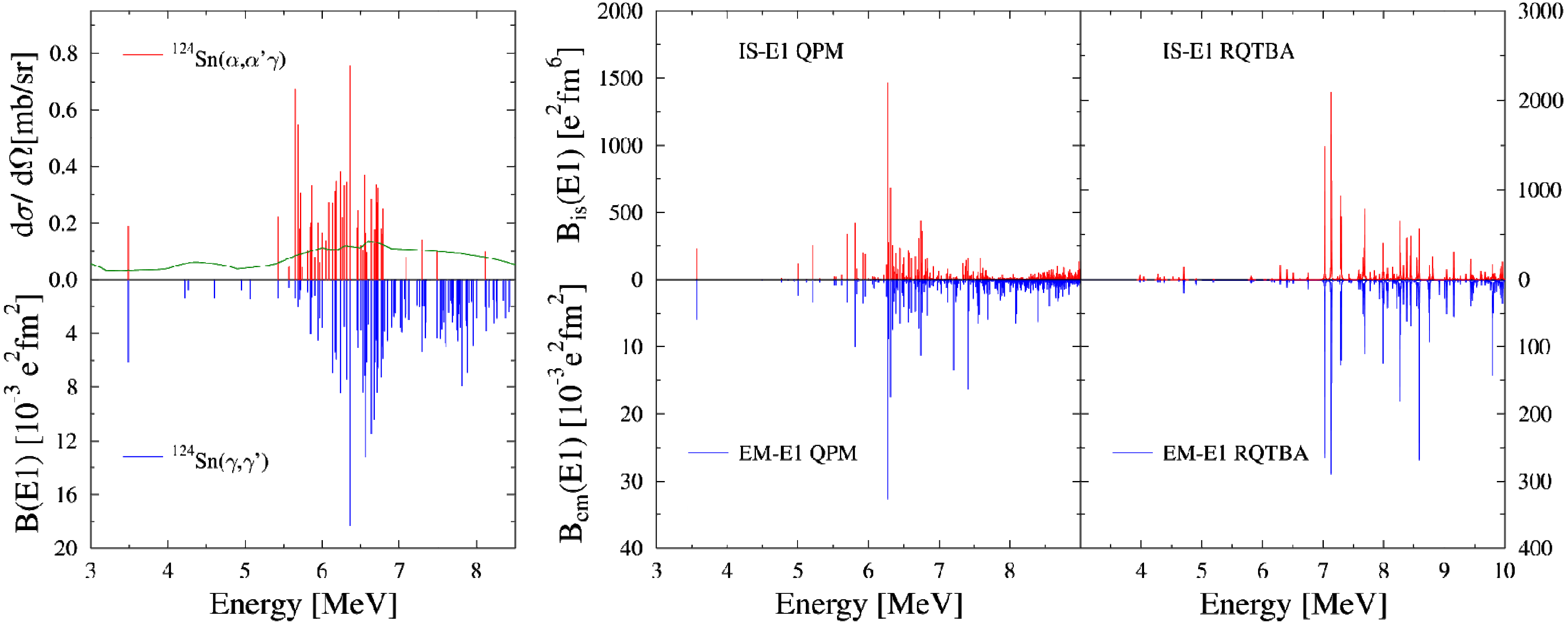
- QPM allows quantitative description of PDR
  → Summed strength, location, fragmentation
  D. Savran *et al*., Phys. Rev. Lett. **100** (2008) 232501
- RQTBA allows interpretation of the PDR splitting
  J. Endres, E. Litvinova *et al*., Phys. Rev. Lett. **105** (2010) 212503

QPM and RQTBA calculations for ^{124}Sn

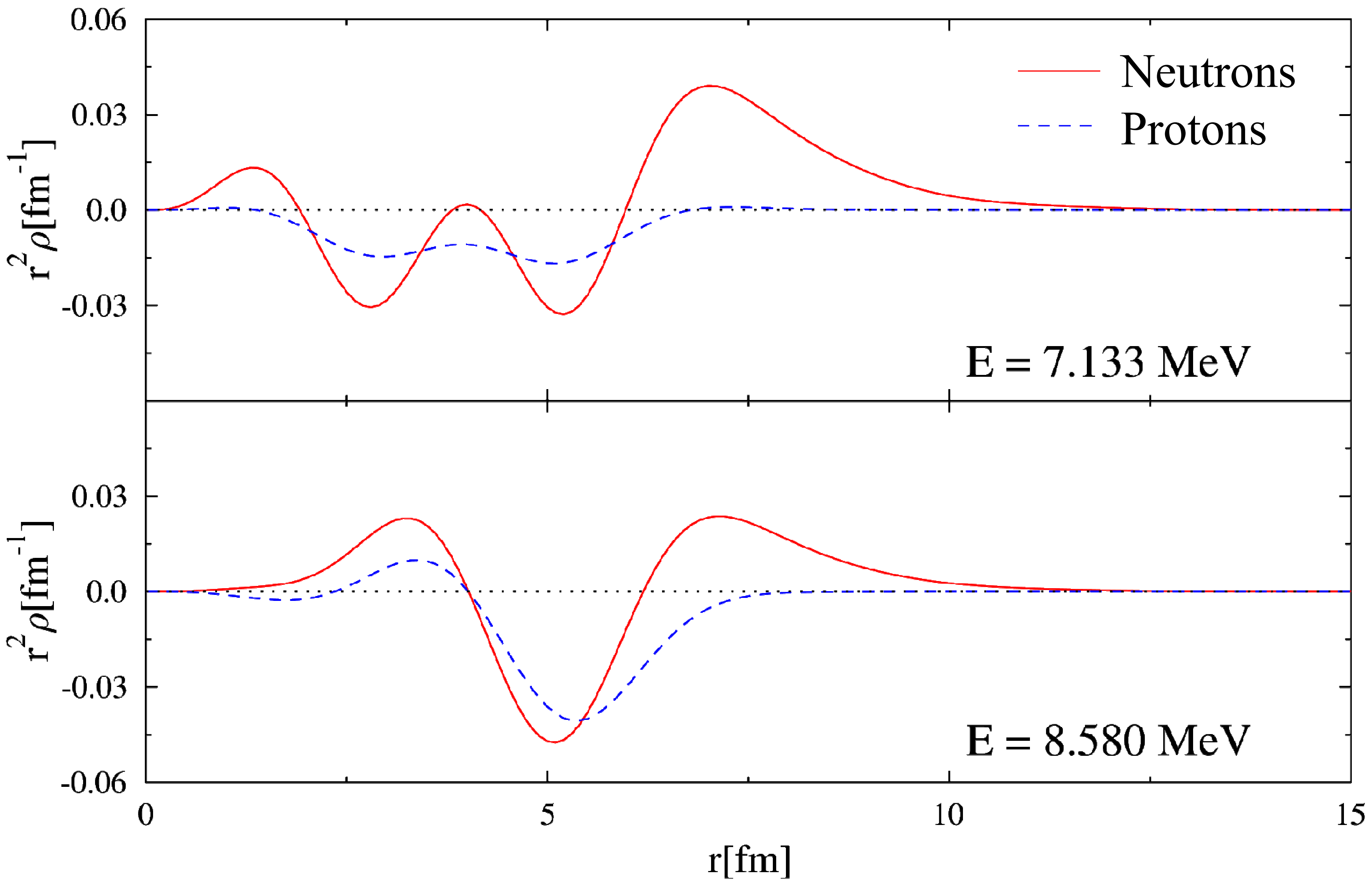


J. Endres, E.Litvinova *et al.*, Phys. Rev. Lett. **105** (2010) 212503

Comparison of experiment and theory

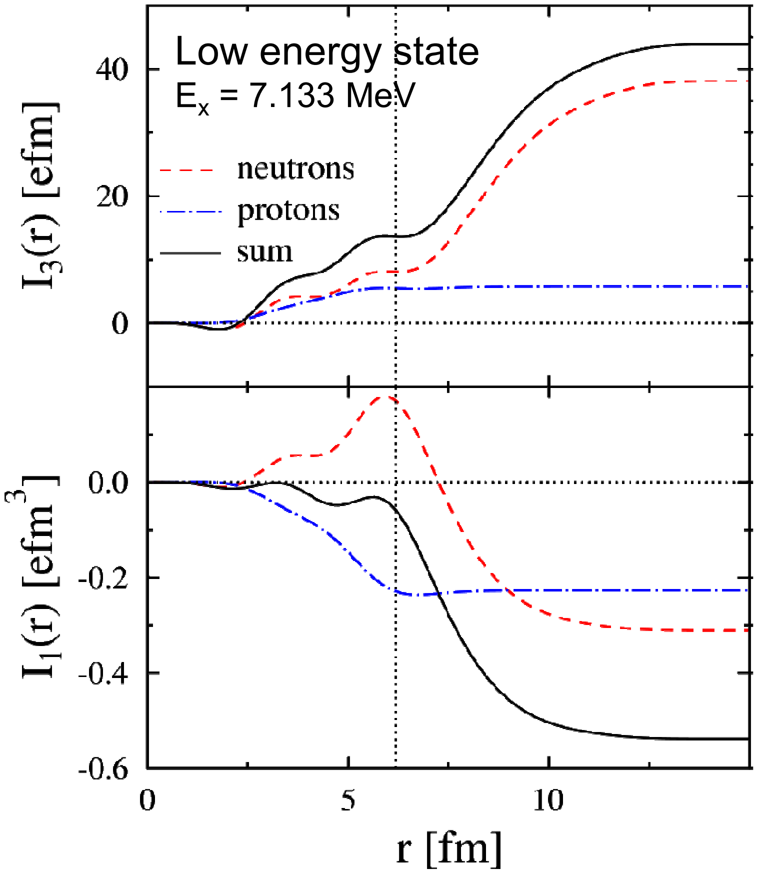


Transition densities in RQTBA



Radial integrals of transition densities for RQTBA states

- $$I_\eta(r) = \int_0^r \rho_{em\,(is)}(R)\,R^{\eta+2}\,dR \quad \left| \begin{array}{l} em : \eta = 1 \\ is : \eta = 3 \end{array} \right.$$



- α particles → sensitive to surface neutron oscillation mode
→ less sensitive to transitions of the IVGDR

J. Endres, E.Litvinova *et al.*, Phys. Rev. Lett. **105** (2010) 212503

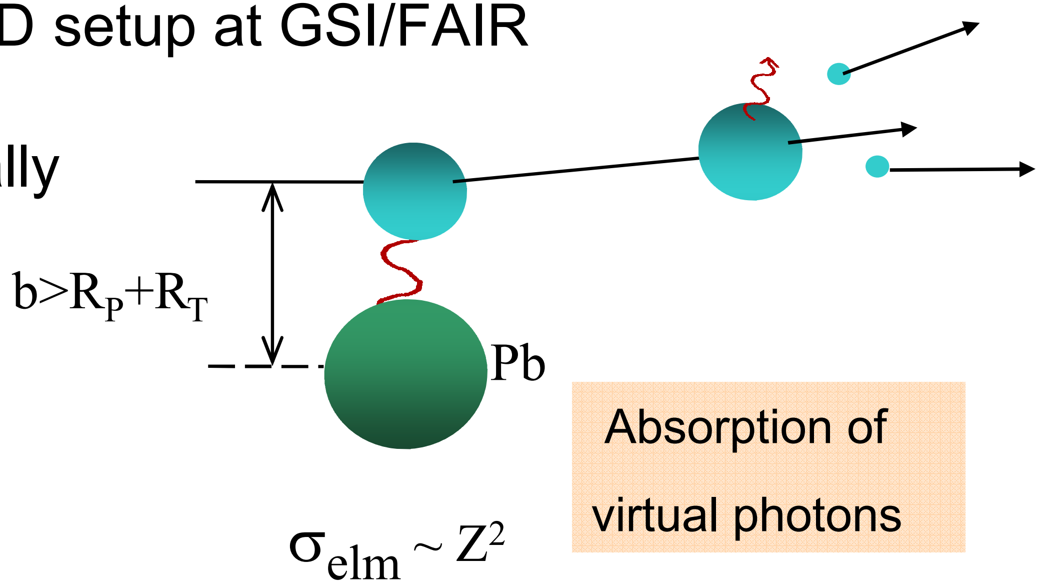
PDR in stable nuclei using (γ,γ') and $(\alpha,\alpha'\gamma)$

- Advantages of (γ,γ') and $(\alpha,\alpha'\gamma)$ experiments:
  - High energy resolution
  - High selectivity to E1 transitions
  - Analysis of single states feasible
  - Structure of the PDR is accessible

- Limitations:
  - Only stable isotopes
  - E1 strength *below* the particle threshold

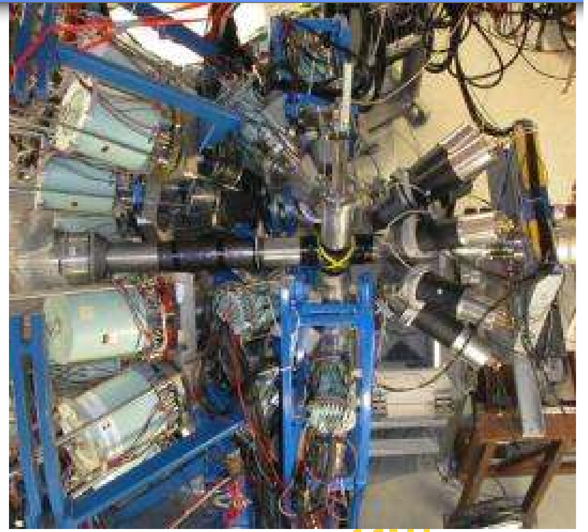
PDR in unstable nuclei using exotic-beam facilities

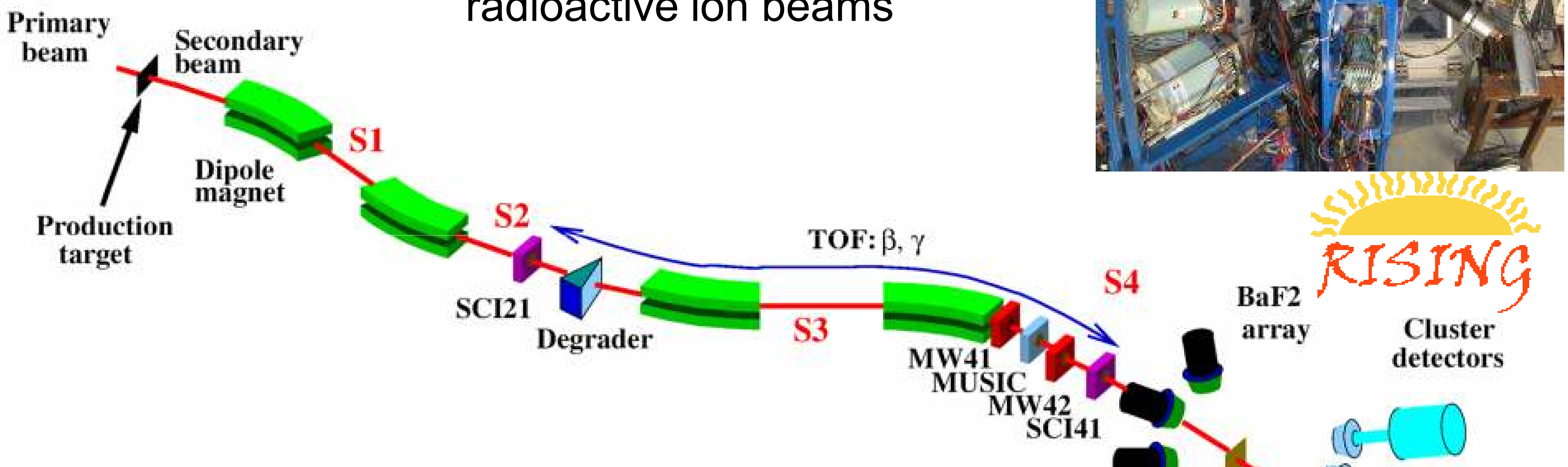
- Production of radioactive beam
  e.g. in-flight fission of heavy primary beam
- Selection of nuclei with fragment separator
- Coulomb excitation of selected nuclei
  e.g. using a ^{208}Pb target
- Detection system
  e.g. (Super)FRS-(Neu)LAND setup at GSI/FAIR
  → Excitation energy determined by a kinematically complete measurement



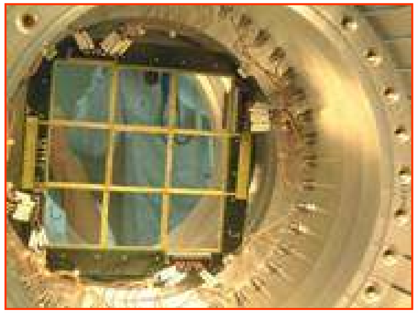
High resolution γ-spectroscopy at the FRS at GSI

- ^{68}Ni beam by fragmentation of ^{86}Kr @ 900 MeV/u on Be target (4g/cm^2)
- FRS provides secondary radioactive ion beams





Calorimeter Telescope for beam identification CATE Position sensitive

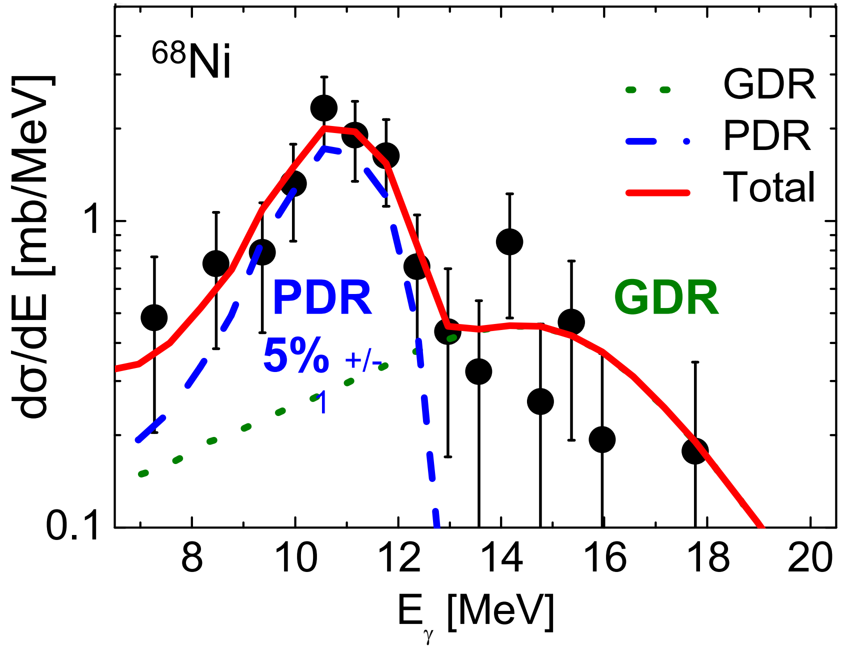


H.J. Wollersheim *et al.*, Nucl. Inst. and Meth. Phys. Res. A **537** (2005) 637

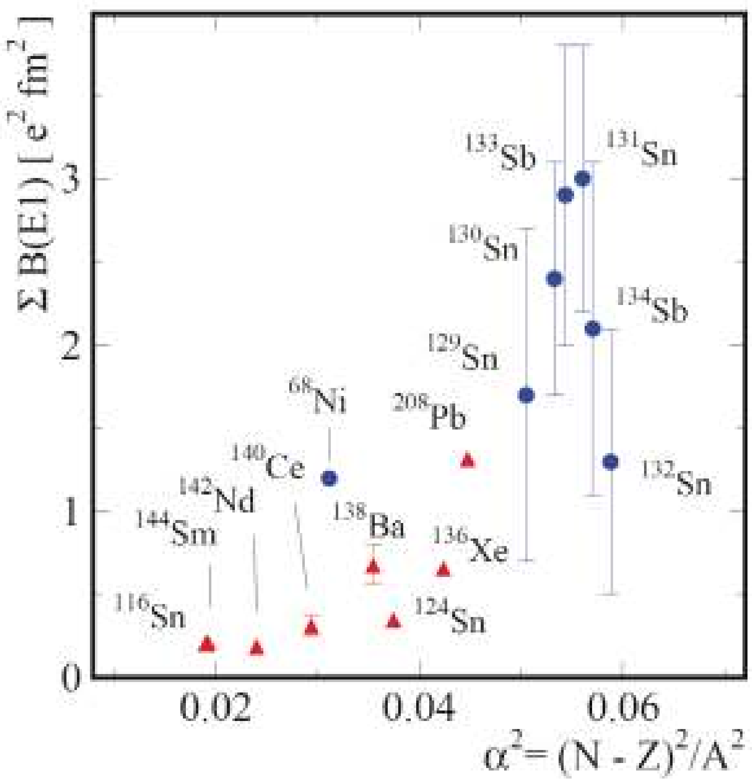
^{68}Ni analysis of experiment at GSI (RISING-Setup)

- PDR in ^{68}Ni around 11 MeV
- Exhausts ~5% of EWSR
- Neutron skin thickness: 0.200(15) fm

O. Wieland and A. Bracco, Prog. Part. Nucl. Phys. 66 (2011) 374



O.Wieland *et al.*, Phys. Rev. Lett. **102** (2009) 092502



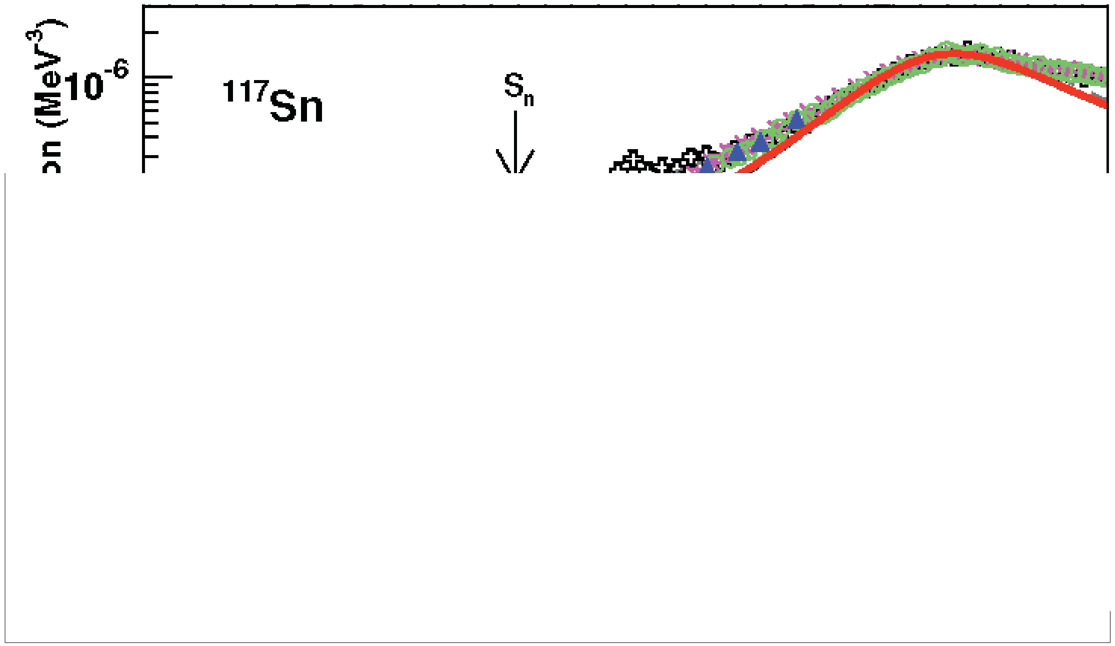
- Asymmetry dependence is still an open question
- Further investigations in the near future

NuPECC Long Range Plan 2010

Conclusion and outlook

- PDR is an important topic in nuclear structure and nuclear astrophysics
- (γ,γ') and ($\alpha,\alpha'\gamma$) experiments:
  - High selectivity to single transitions
  - Details of the structure of the PDR below S_n
  - Splitting of the PDR
  - Next step: investigation of light nuclei
- Radioactive beams:
  - PDR in Sn isotopes and ^{68}Ni above S_n
  - Next step: Systematic studies

- PDR influences the γ-ray strength function around the particle threshold



H. K. Toft *et al.*, Phys. Rev. C **83** (2011) 044320

Collaboration

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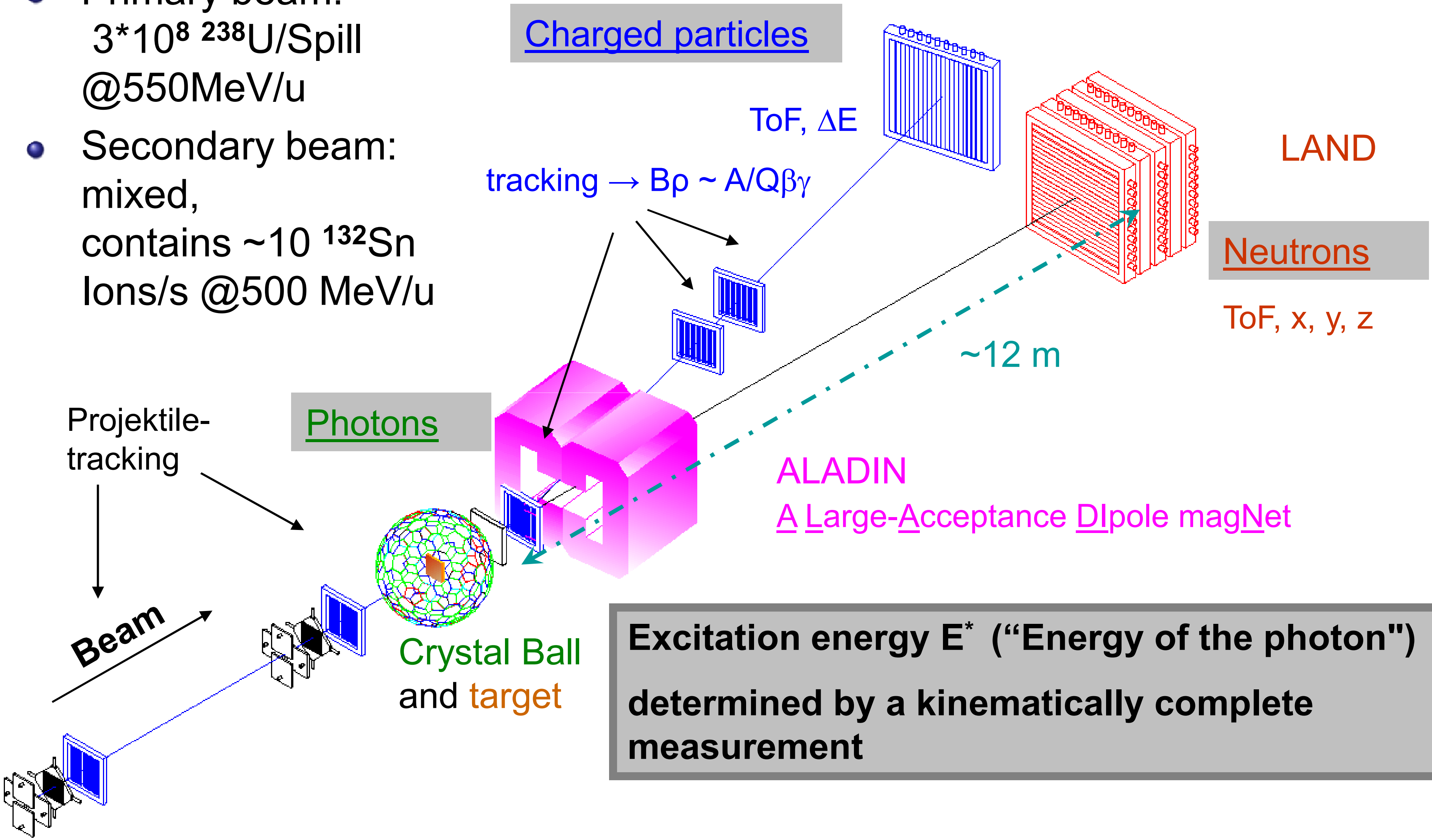
Technical University Darmstadt

L. Popescu
SCK-CEN, Mol

K. Sonnabend
Goethe-University Frankfurt

Experimental method: LAND setup @GSI

- Primary beam: $3 \cdot 10^8$ ^{238}U/Spill @550MeV/u
- Secondary beam: mixed, contains ~10 ^{132}Sn Ions/s @500 MeV/u



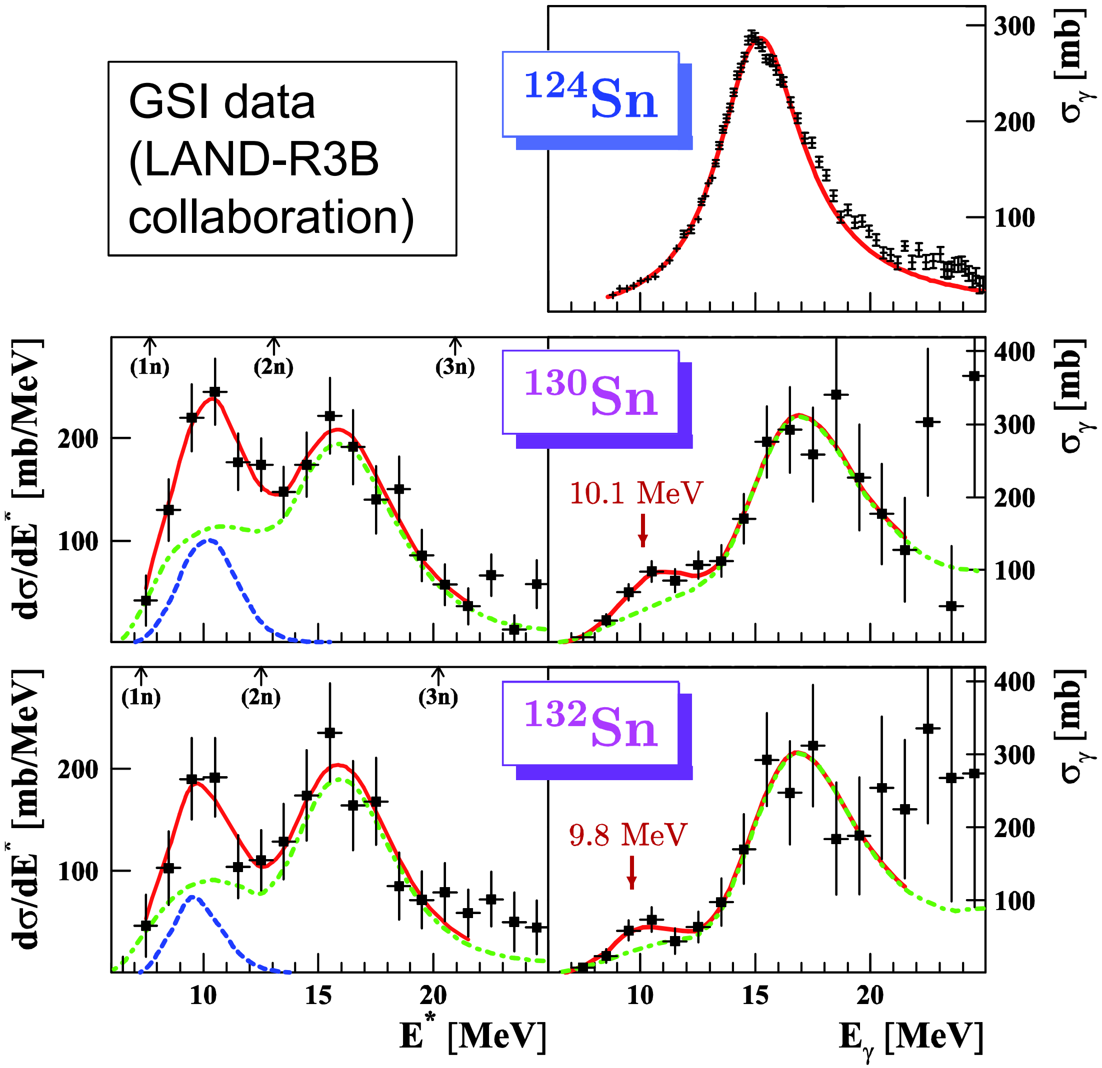
Excitation energy E* ("Energy of the photon")

determined by a kinematically complete measurement

T. Blaich *et al.*, Nucl. Inst. and Meth. Phys. Res. A **314** (1992) 136

Results: even neutron rich Sn isotopes

GSI data (LAND-R3B collaboration)

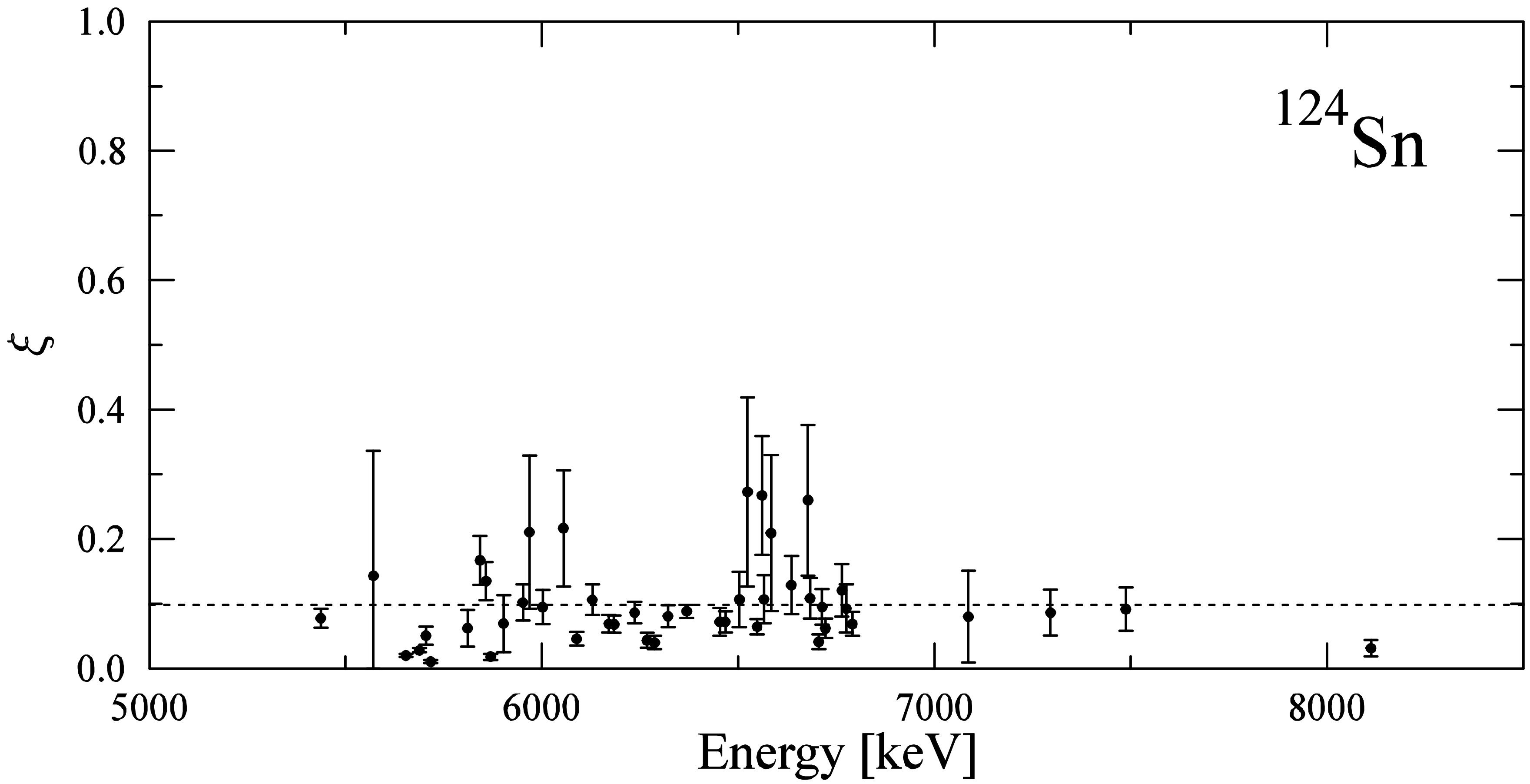


- PDR around 10 MeV
- PDR exhausts 7(3)% for ^{130}Sn and 4(3)% for ^{132}Sn of the TRK EWSR *above* the one-neutron separation energy
- Neutron skin thickness: 0.23(4) fm for ^{130}Sn, 0.24(4) fm for ^{132}Sn

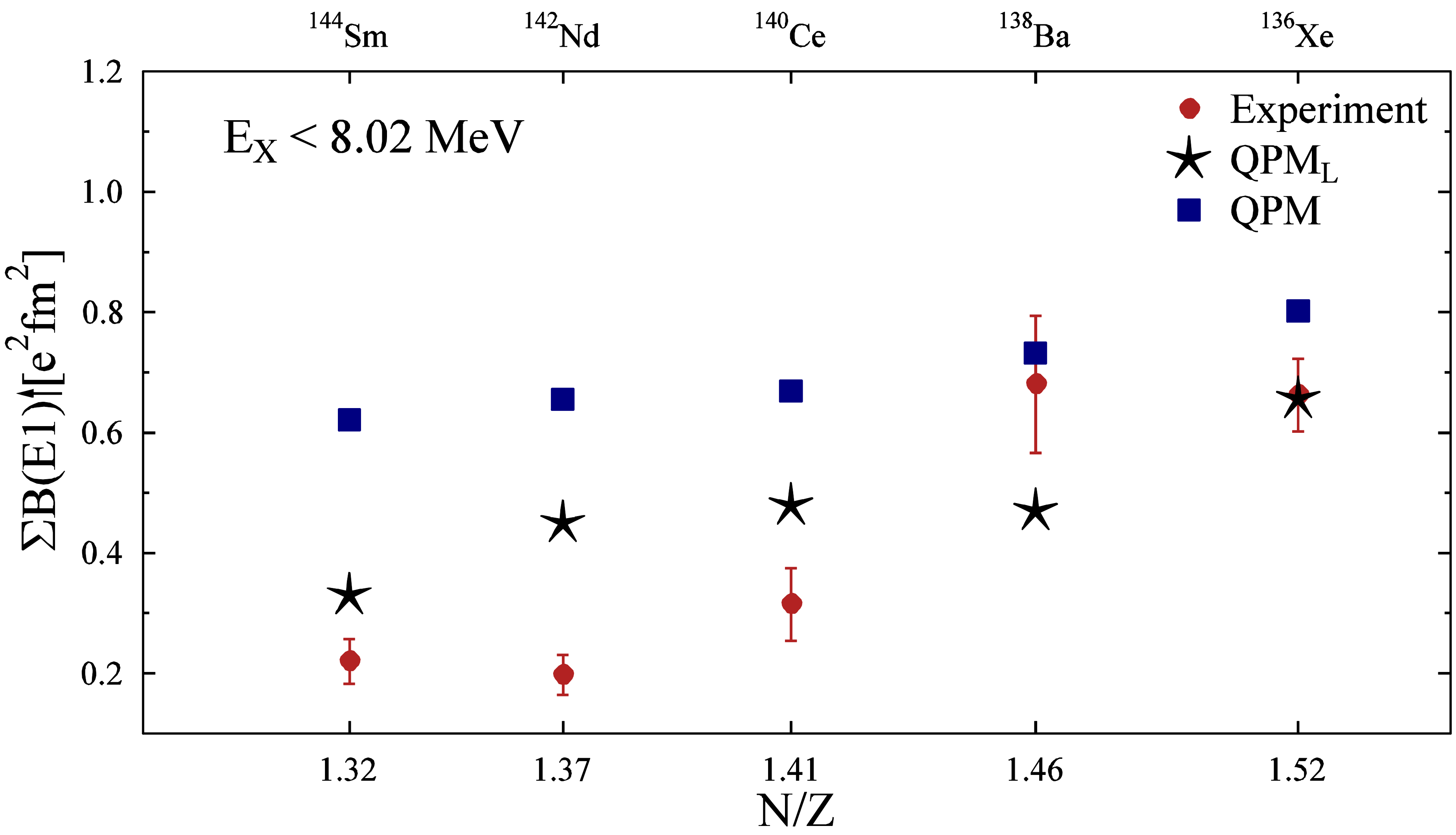
A. Klimkiewicz *et al.*, Phys. Rev. C **76** (2007) 051603(R)

P. Adrich *et al.*, Phys. Rev. Lett. **95** (2005) 132501

Ratio of Coulomb excitation

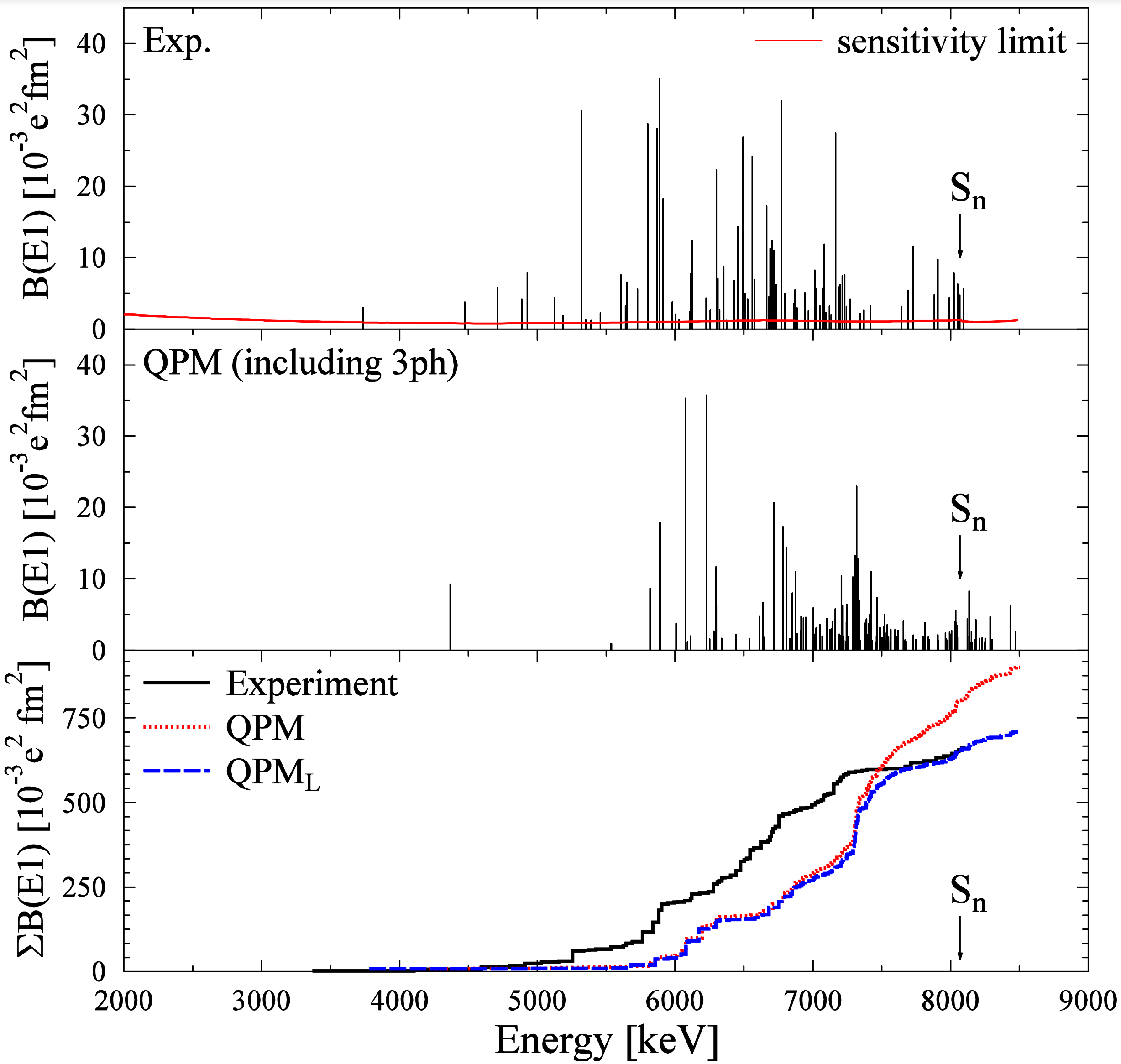


Integrated B(E1) strength



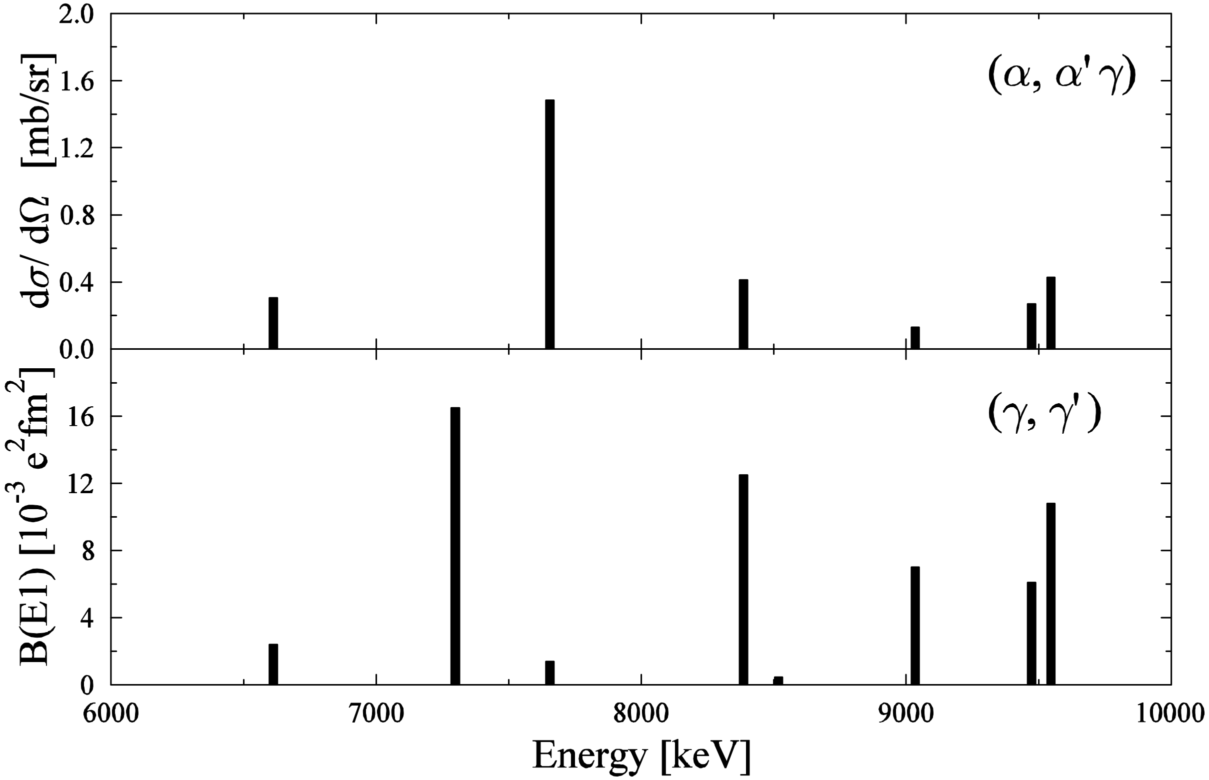
D. Savran et al., PRL **100** (2008) 232501

B(E1) strength distribution in ^{136}Xe



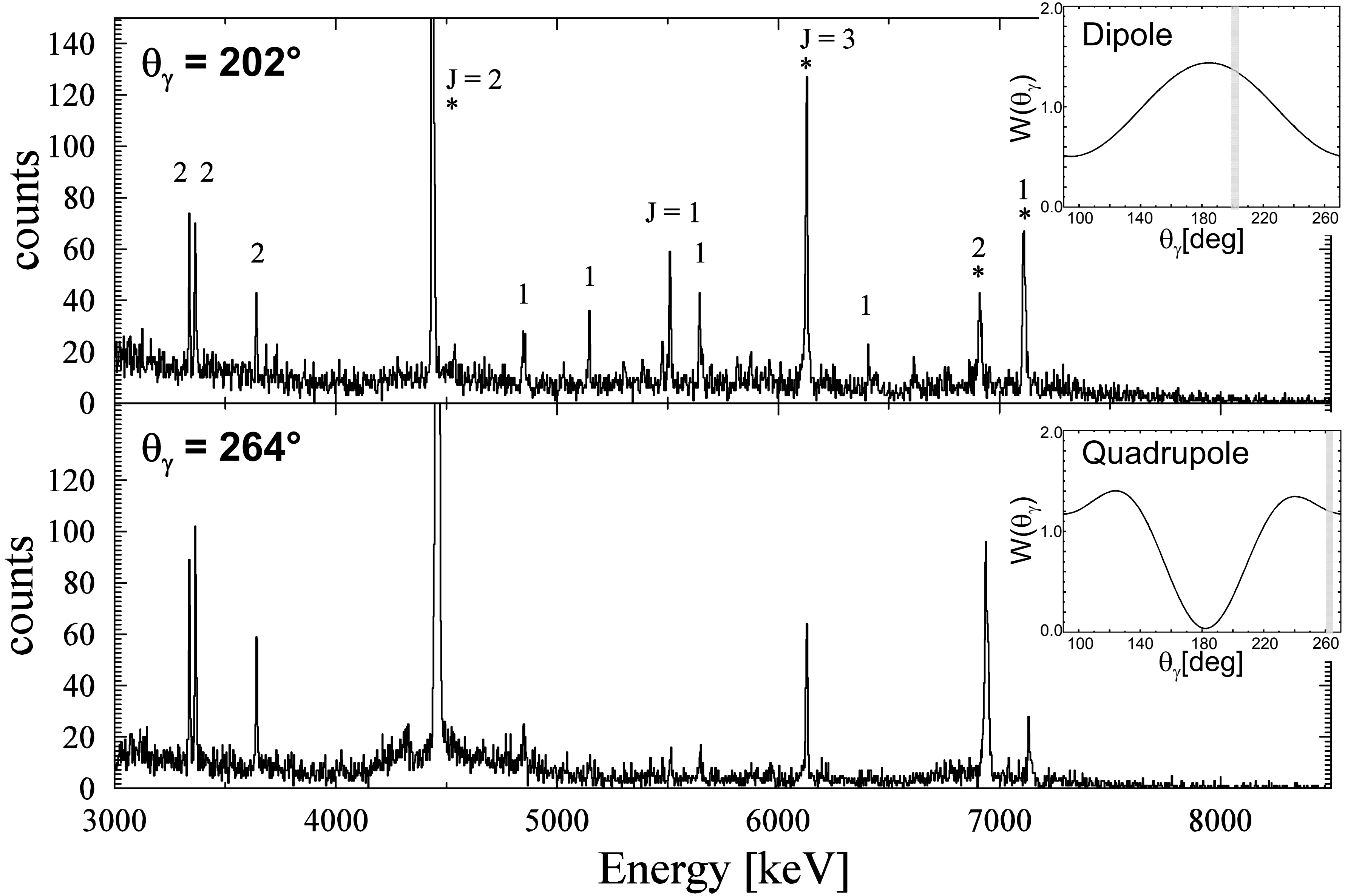
D. Savran et al., PRL **100** (2008) 232501

E1 strength distribution in ^{48}Ca



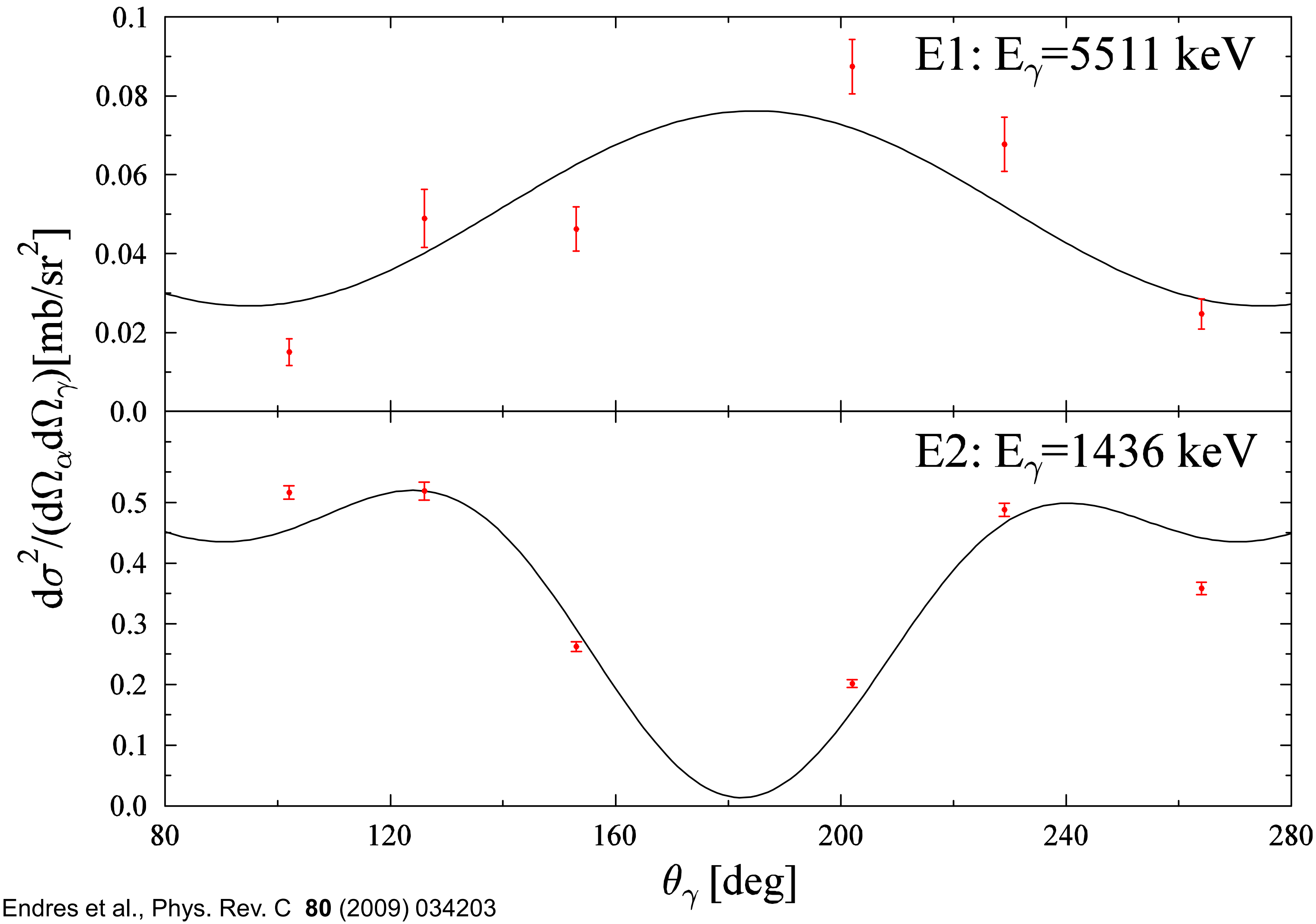
- Low level density
- Sensitivity up to 9.5 MeV
- Different pattern

Multipole assignment with α–γ angular correlation



J. Endres et al., Phys. Rev. C **80** (2009) 034203

Multipole assignment with α–γ angular correlation



J. Endres et al., Phys. Rev. C **80** (2009) 034203

Photoabsorption cross section of sodium clusters