

# The photoresponse of heavy nuclei – some implications on nucleosynthesis

- Nuclear physics and the p-process
- Photoresponse of atomic nuclei
- Structure of the Pygmy Dipole Resonance
- Outlook



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# The p-process of nucleosynthesis

The diagram shows a periodic table with several isotopes highlighted and labeled with process names:

- p- or  $\gamma$ -process:** Labeled with a red box and red arrows pointing to isotopes like Hg-186, Au-185, Pt-184, Ir-183, Os-182, Re-181, and W-180.
- s-process:** Labeled with a green box and green arrows pointing to isotopes like Hg-187, Hg-188, Hg-190, Hg-192, Hg-194, Hg-195, Hg-196, Hg-197, Au-186, Au-187, Au-188, Au-189, Au-190, Au-191, Au-192, Au-193, Au-194, Au-195, Au-196, Au-197, Au-198, Au-199, Au-200, and Au-201.
- r-process:** Labeled with a blue box and blue arrows pointing to isotopes like Pb-188, Pb-189, Pb-190, Pb-191, Pb-192, Pb-193, Pb-194, Pb-195, Pb-196, Pb-197, Pb-198, Pb-199, Pb-200, Pb-201, Pb-202, Pb-203, Pb-204, Pt-185, Pt-187, Pt-188, Pt-189, Pt-190, Pt-191, Pt-192, Pt-193, Pt-194, Pt-195, Pt-196, Pt-197, Pt-198, Pt-199, Pt-200, Ir-184, Ir-185, Ir-186, Ir-187, Ir-188, Ir-189, Ir-190, Ir-191, Ir-192, Ir-193, Ir-194, Ir-195, Ir-196, Ir-197, Ir-198, Os-183, Os-184, Os-185, Os-186, Os-187, Os-188, Os-189, Os-190, Os-191, Os-192, Os-193, Os-194, Os-195, Os-196, Os-197, Re-182, Re-183, Re-184, Re-185, Re-186, Re-187, Re-188, Re-189, Re-190, Re-192, and W-181.

# Nuclear reactions and decays during p-process

Pb 188 25, 5 s	Pb 189 51 s	Pb 190 1.2 m	Pb 191 2,2 m	Pb 192 3,5 m	Pb 193 5,8 m	Pb 194 12,0 m	Pb 195 16,0 m	Pb 196 16 m	Pb 197 43 m	Pb 198 2,40 h	Pb 199 12,2 h	Pb 200 21,5 h	Pb 201 81 s	Pb 202 8,8 h	Pb 203 52-104 s	Pb 204 8,2 m	Pb 204 31,3 h	
$\gamma$ , p <sup>+</sup> $\alpha$ , 5,900 $\gamma$ , 165; 158; $\nu$ , 107	$\gamma$ , 5,72 $\nu$ , 271; 107	$\gamma$ , 5,577 $\nu$ , 142; 142; $\nu$ , 151...; 8	$\gamma$ , 3 <sup>+</sup> $\nu$ , 287; 8	$\gamma$ , 5,23 $\nu$ , 194; 908;	$\gamma$ , 5,112 $\nu$ , 195; 908;	$\gamma$ , 4,04 $\nu$ , 196; 1619;	$\gamma$ , 3 <sup>+</sup> $\nu$ , 282; 502	$\gamma$ , 4,04 $\nu$ , 196; 1619;	$\gamma$ , 282; 502	$\gamma$ , 200; 385;	$\gamma$ , 125; 153	$\gamma$ , 148; 257	$\gamma$ , 56; 125	$\gamma$ , 28; 125;	$\gamma$ , 29; 95;	$\gamma$ , 27; 125;		
Tl 187 45 s	Tl 188 1,2 m	Tl 189 1,4 m	Tl 190 2,3 m?	Tl 190 3,7 m	Tl 191 2,6 m?	Tl 191 10,8 m	Tl 192 9,6 m	Tl 193 33 m	Tl 195 3,6 s	Tl 196 1,18 h	Tl 197 1,4 h	Tl 198 2,84 h	Tl 199 1,87 h	Tl 199 1,5 h	Tl 200 26,1 h	Tl 201 73,1 h	Tl 202 12,23 d	Tl 203 29,524
Hg 186 1,4 m	Hg 187 2,4 m	Hg 188 3,2 m	Hg 189 8,7 m	Hg 190 7,7 m	Hg 191 20,0 m	Hg 192 60,8 m	Hg 193 ~50 m	Hg 194 4,9 h	Hg 195 520 a	Hg 195 40 h	Hg 196 0,15	Hg 197 2,3 h	Hg 198 0,15	Hg 199 42,6 m	Hg 200 16,87	Hg 201 23,10	Hg 202 29,86	
Au 18 4,2 m	Au 187 3,4 m	Au 188 3,4 m	Au 189 4,6 m	Au 190 28,3 m	Au 191 1,9	Au 192 3,18 h	Au 193 5,0 h	Au 194 3,9 h	Au 195 17,65 h	Au 196 38,0 h	Au 197 39,3 s	Au 198 101,1 d	Au 199 6,7 h	Au 200 8,2 s	Au 201 8,2 d	Au 202 26,4 m		
Pt 184 17,3 m	Pt 185 33 m	Pt 186 1,2 h	Pt 187 2,3	Pt 188 11 h	Pt 189 0,01	Pt 190 6,5	Pt 191 2,8 d	Pt 192 0,79	Pt 193 4,33 d	Pt 194 ~30 s	Pt 195 32,9	Pt 196 4,02 d	Pt 197 38,8	Pt 198 25,3	Pt 199 94,4 m	Pt 200 18,7 h	Pt 201 48,4 m	
Ir 183 55 m	Ir 184 3,0 h	Ir 185 11,1	Ir 186 16,64 h	Ir 187 10,5 h	Ir 188 41,5 h	Ir 189 13,3 d	Ir 190 3,5 h	Ir 191 1,2 h	Ir 192 11,0 h	Ir 193 4,94 s	Ir 194 37,3	Ir 195 10,63 d	Ir 196 62,7	Ir 197 171 d	Ir 198 18,3 h	Ir 199 3,139 d	Ir 200 26,4 m	
Os 182 22,1 h	Os 183 0,9 h	Os 183 13,0 h	Os 185 0,02	Os 185 94 d	Os 186 0,58	Os 186 2,0-10 <sup>10</sup> a	Os 187 1,6	Os 188 13,3	Os 189 8 h	Os 190 14,1	Os 191 8,9 m	Os 192 13,10 h	Os 193 15,4 d	Os 194 6,1 s	Os 195 30,11 h	Os 196 6,0 a	Os 197 34,9 m	
Re 181 20 h	Re 182 15 h	Re 183 71 d	Re 184 169 d	Re 184 38,0 d	Re 185 2,10 <sup>3</sup> a	Re 186 37,40	Re 186 5-10 <sup>10</sup> a	Re 187 62,60	Re 188 14,8 m	Re 188 16,98 h	Re 189 1,0 h	Re 190 217; 218;	Re 191 9,8 m	Re 192 1,4	Re 193 140 h	Re 194 52 s	Re 195 49 s	
W 180 0,13	W 181 121,2 d	W 182 26,3	W 183 53,6	W 184 14,1	W 185 30,67	W 186 1,67 m	W 186 76,1 d	W 187 28,6	W 187 23,72 h	W 188 0,6; 1,3...	W 189 69 d	W 189 11 m	W 190 30,0 m	W 190 9	W 191 2	W 192 9	W 193 9	

( $\gamma$ ,n)

( $\gamma$ ,p)

( $\gamma$ , $\alpha$ )

$\beta^+$

In addition ( $n,\gamma$ ) and ( $p,\gamma$ ) reactions and the  $\nu p$ -process may become important.

122

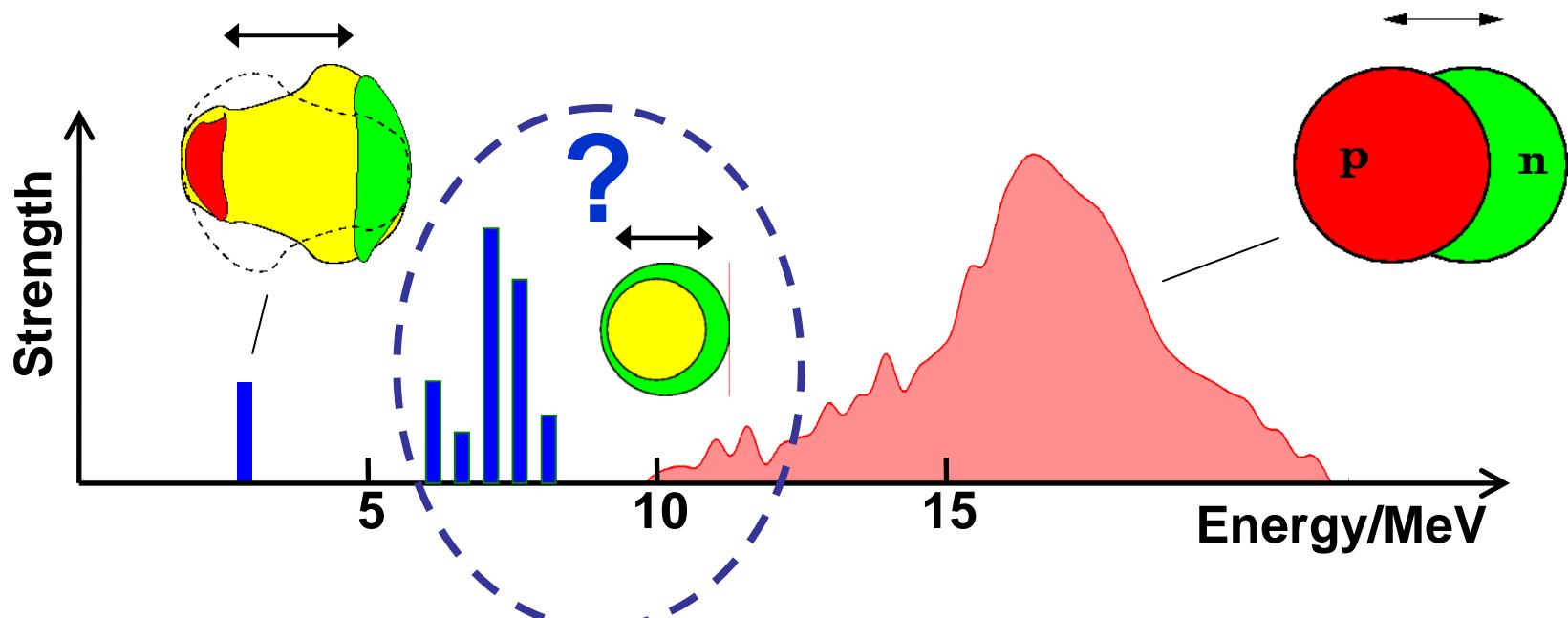
118

120

# Nuclear physics in the p-process network

- Ground state masses
- Properties of excited states
- Nuclear level densities
- Photoresponse ( $\gamma, \gamma'$ ), ( $\gamma, n$ ), ( $\gamma, \alpha$ ), ( $\gamma, p$ )
- Optical potentials

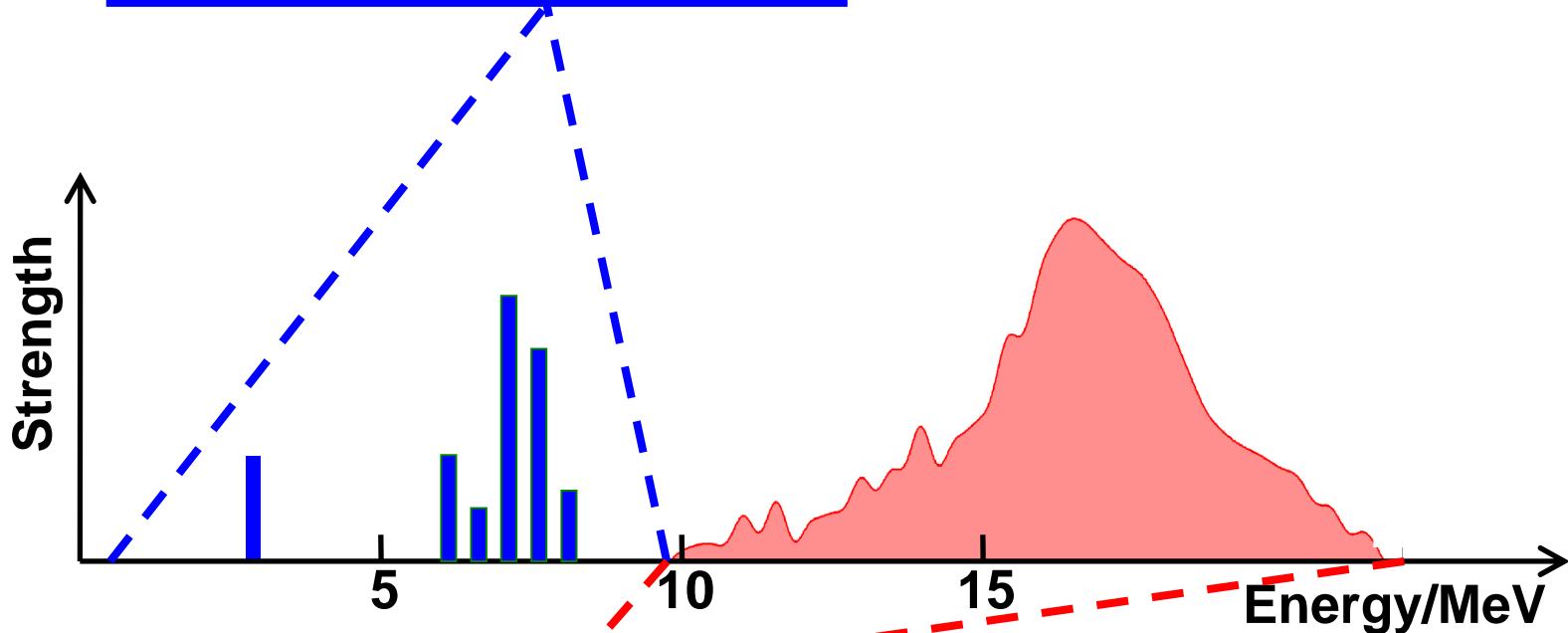
# The photoresponse of atomic nuclei – E1 strength



- Two Phonon Excitation:  $E_x \sim 3$  MeV,  $B(E1) \sim 10^{-2}$  W.u.
- Giant Dipole Resonance:  $E_x \sim 18$  MeV,  $B(E1) \sim 10$  W.u.
- Pygmy Dipole Resonance ?
  - F. Iachello, PLB 160 (1985) 1
  - G. Colò et al., PLB 485 (2000) 362
  - D. Vretenar et al., PLB 487 (2000) 334

# Experimental tools

## Photon scattering ( $\gamma, \gamma'$ )



## Photodissociation ( $\gamma, n$ ), ( $\gamma, p$ ), ...

Talks by A. Junghans  
and K. Sonnabend

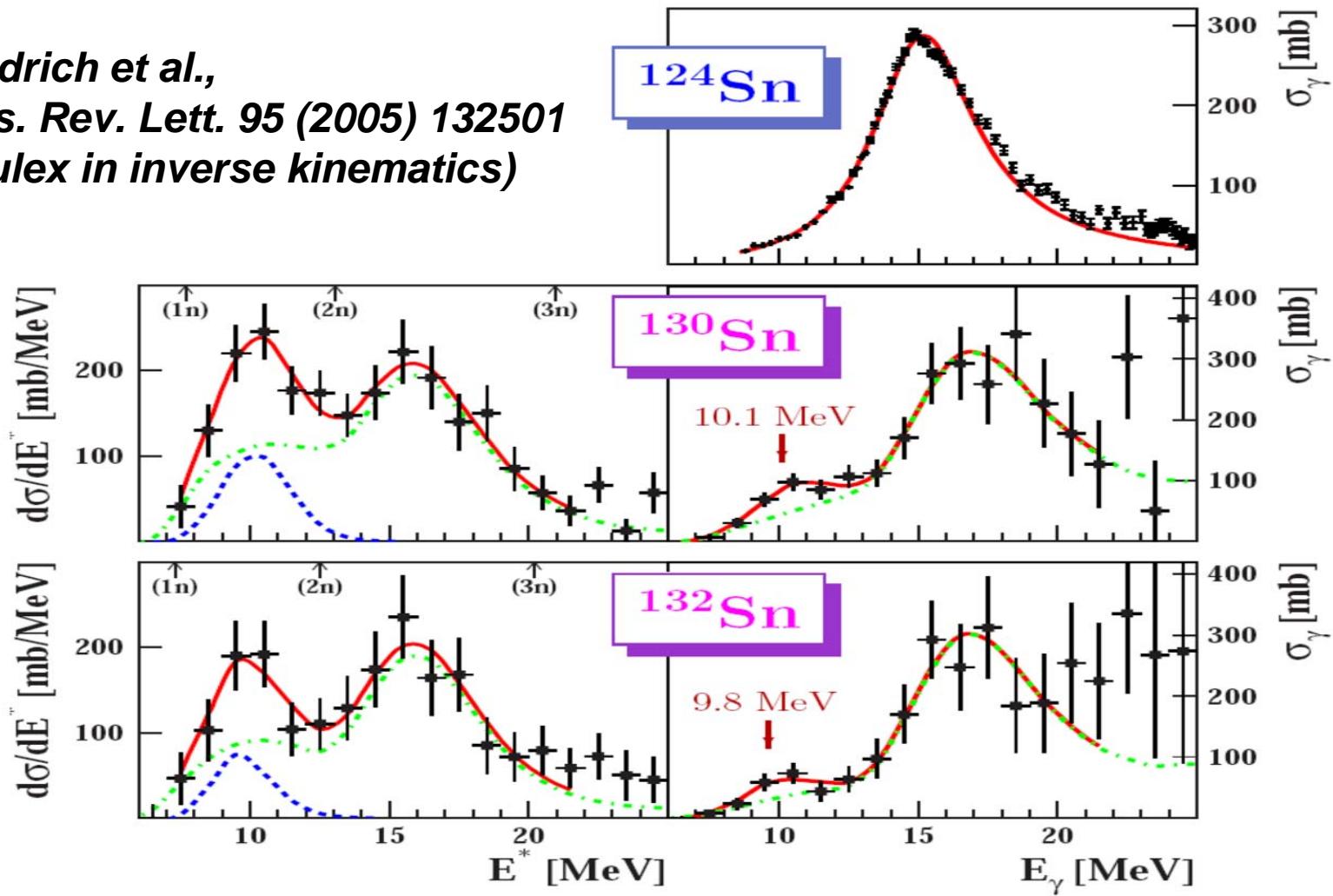
Real and virtual photons can be used for excitation!

# E1 strength above threshold in exotic nuclei

P. Adrich et al.,

Phys. Rev. Lett. 95 (2005) 132501

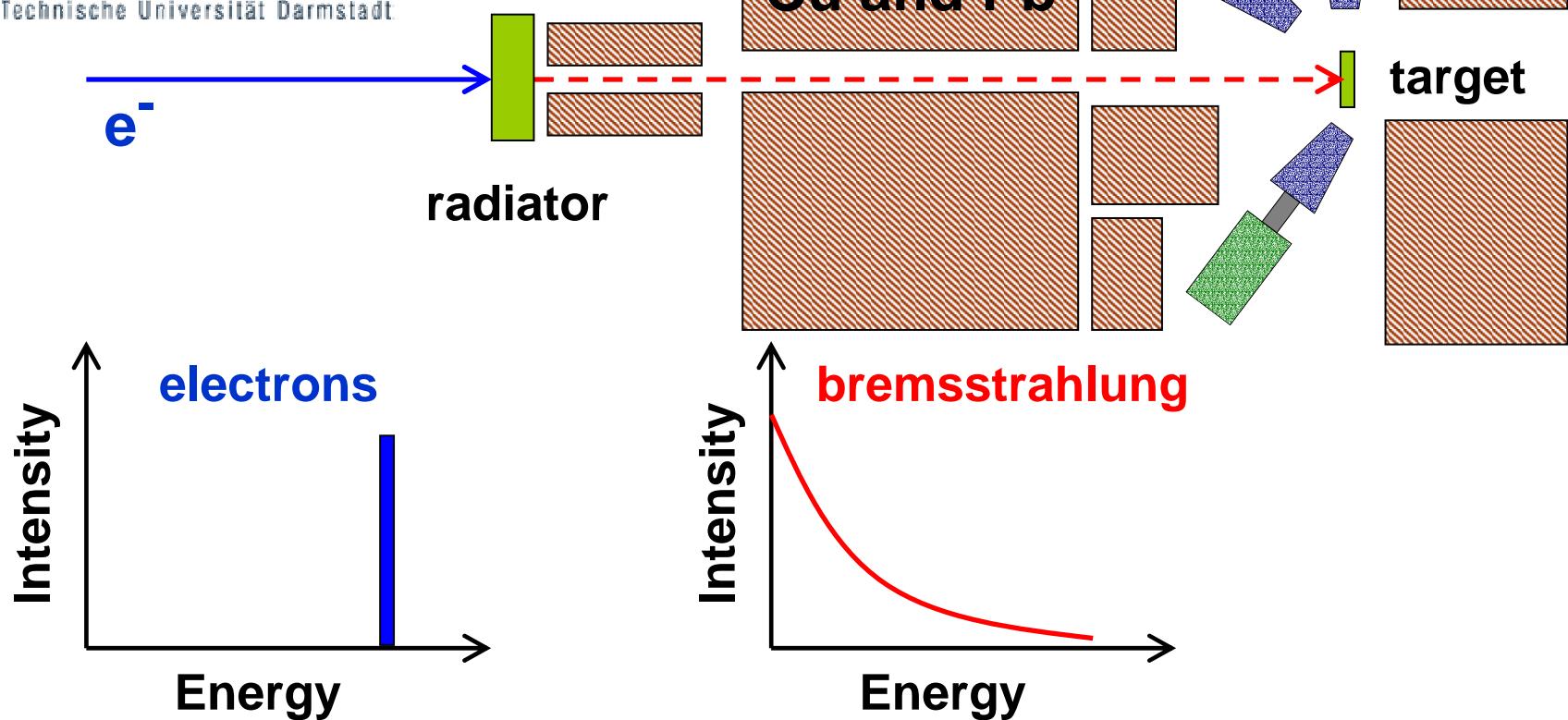
(Coulex in inverse kinematics)



(Results on  $^{18,20}\text{O}$ : E. Tryggestad et al., PRC 67 (2003) 064309)

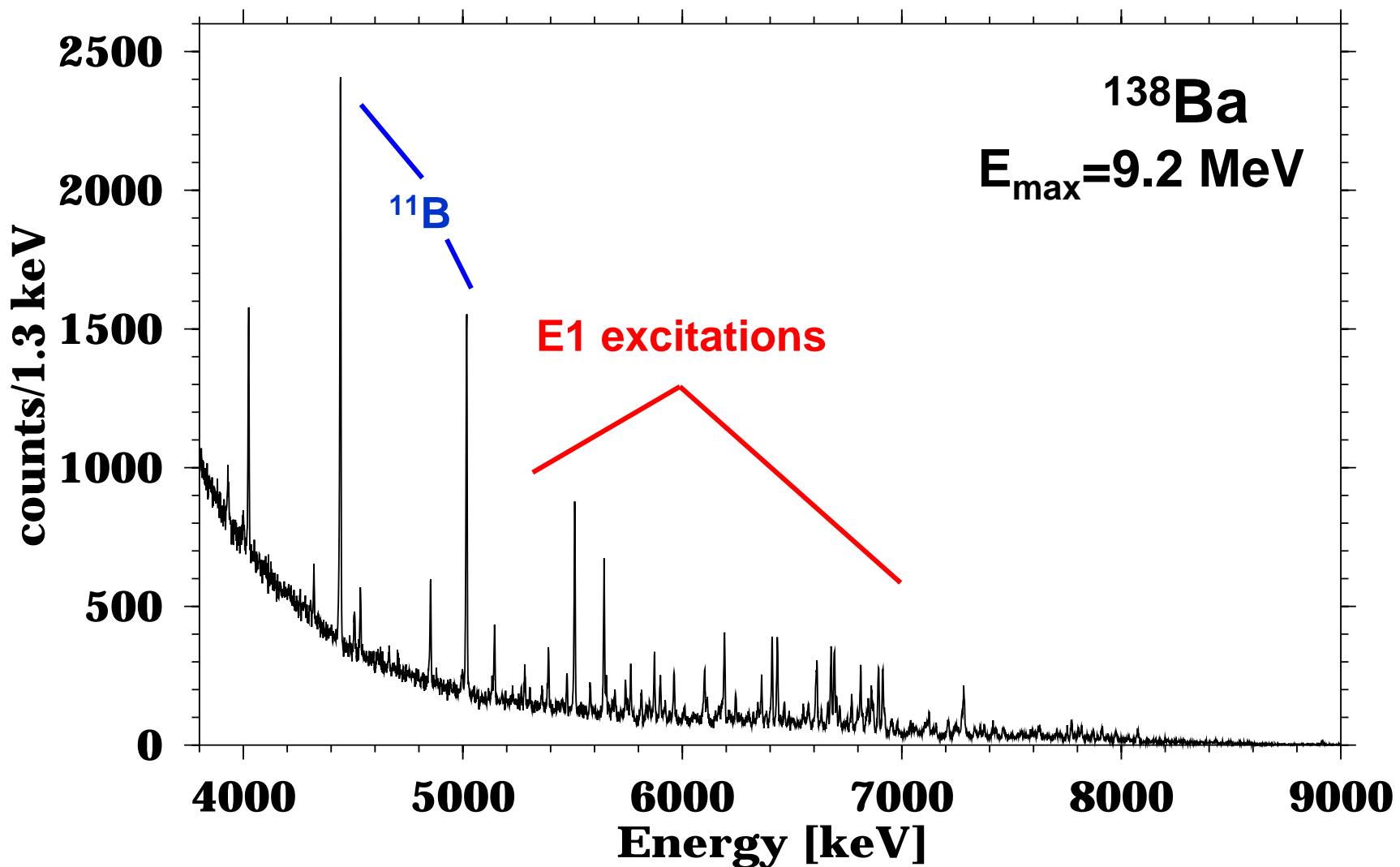
# Photoresponse below threshold of stable nuclei: Real photon scattering - NRF

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Review: U. Kneissl, H.H. Pitz, and A.Z., Prog. Part. Nucl. Phys. 37 (1996) 349

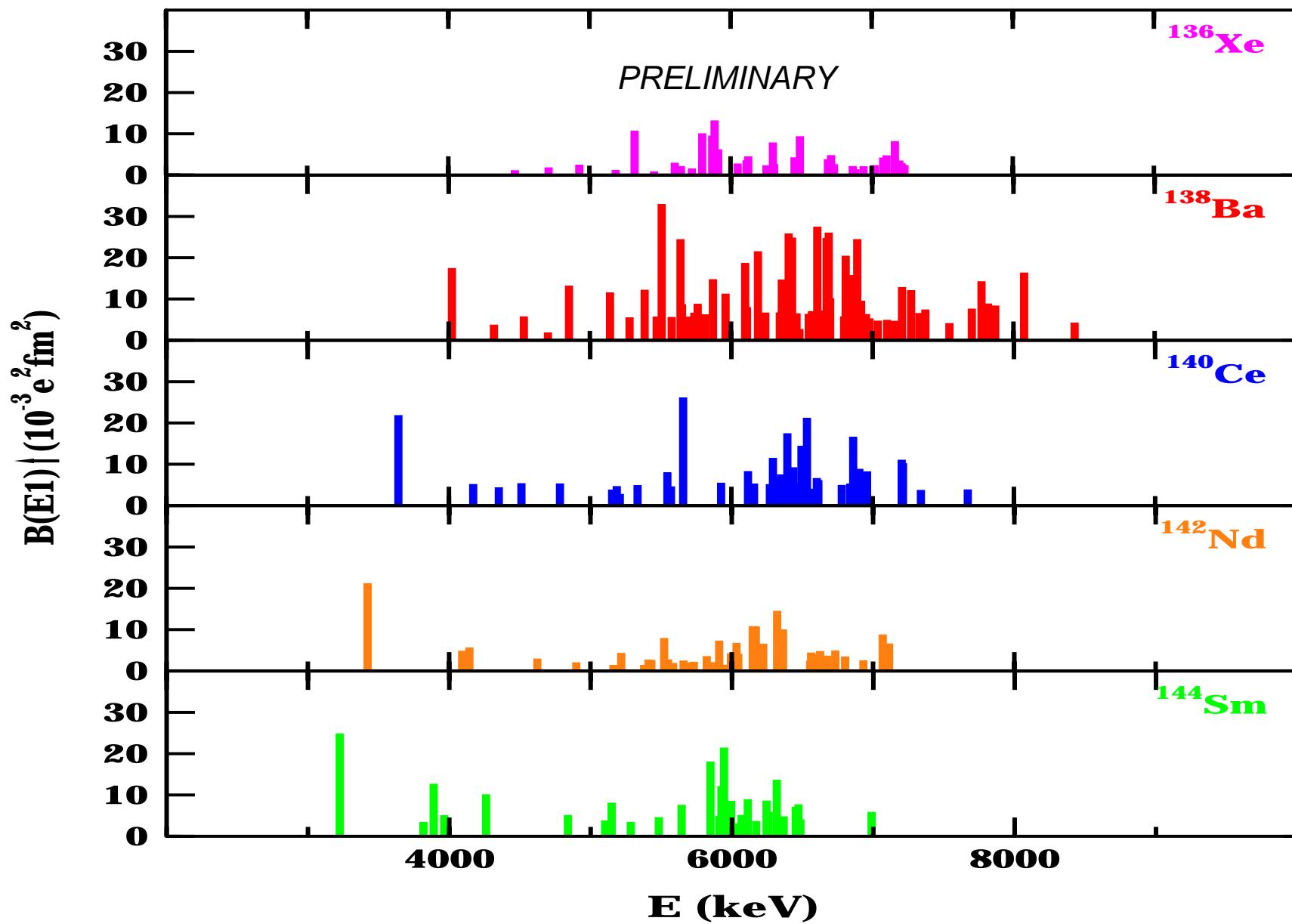
# Photon scattering off $^{138}\text{Ba}$



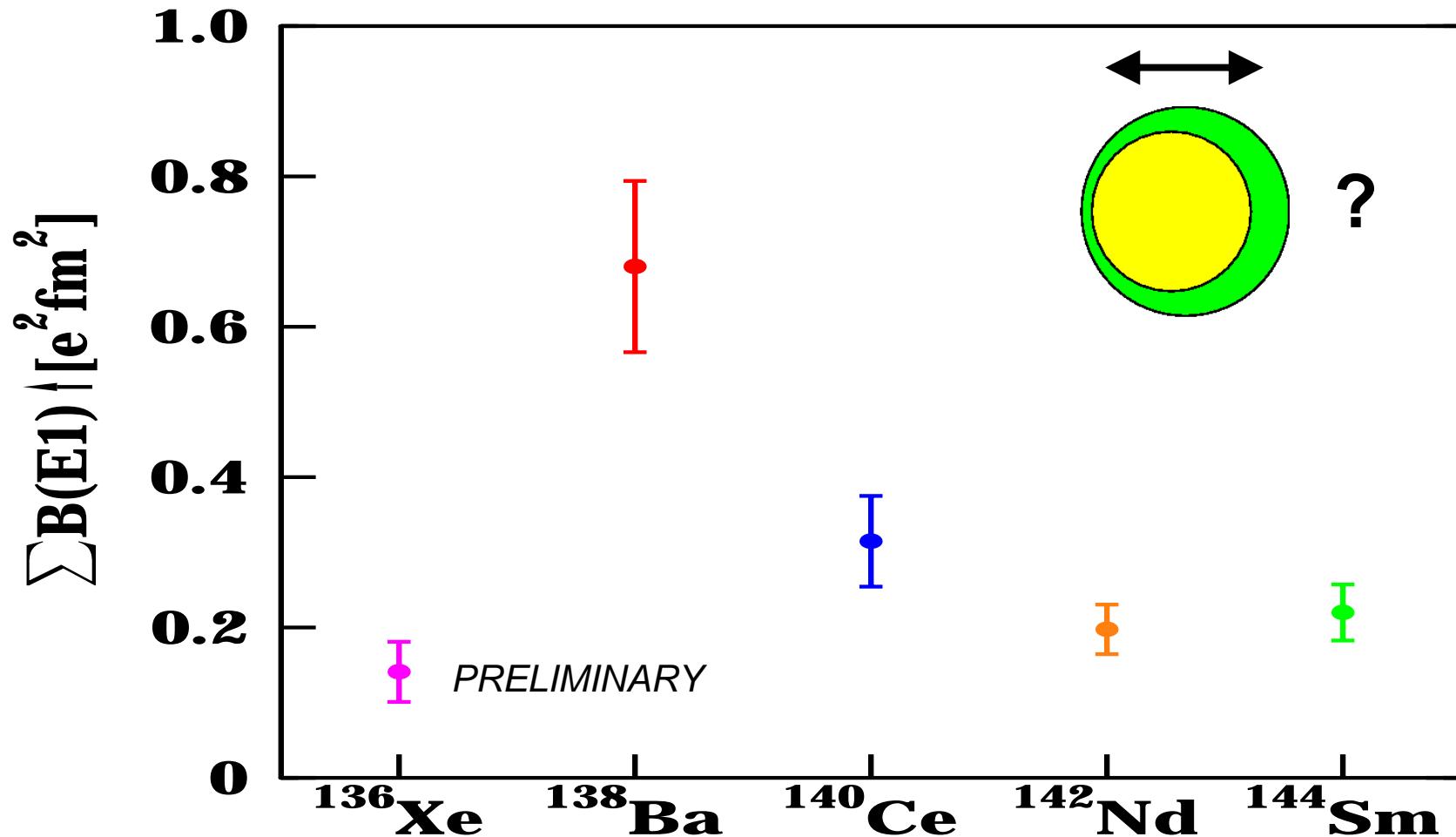
# Photon scattering using bremsstrahlung

- Excitation with „white“ photon spectrum
  - $\gamma$  decay from bound states measured with very high energy resolution
- Complete photoresponse below the particle threshold, i.e. B(E1), B(M1), B(E2) strength
- + Model independent
  - + One experiment covers wide energy range
  - Increasing background at small energies
  - Studies of radioactive nuclei impossible
  - Limited information about nuclear structure

# E1 strength below threshold in N=82 nuclei

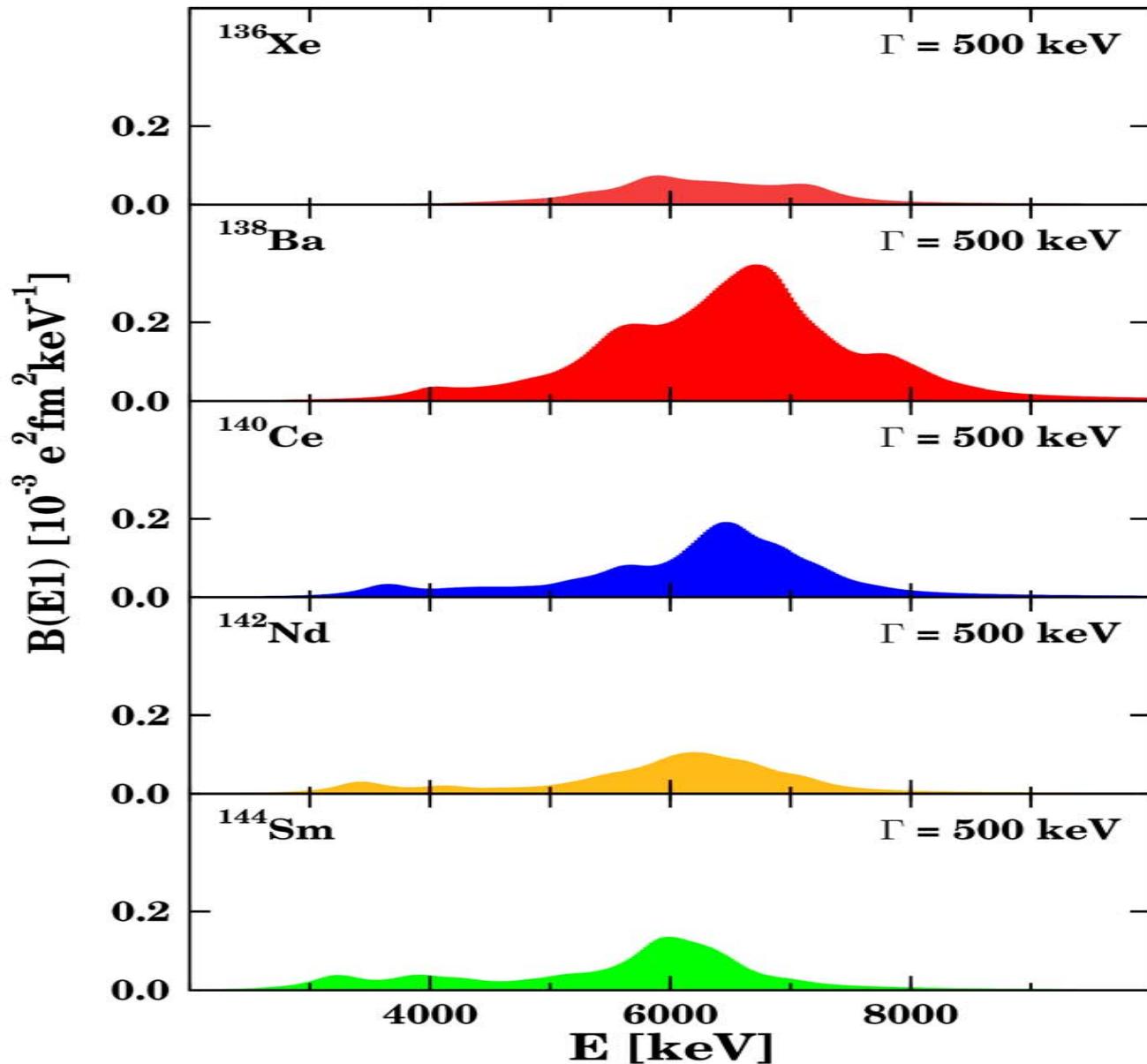


# E1 strength below 9 MeV in N=82 nuclei



A. Z. et al., Phys. Lett. B **542** (2002) 43, and  
S. Volz et al., to be published

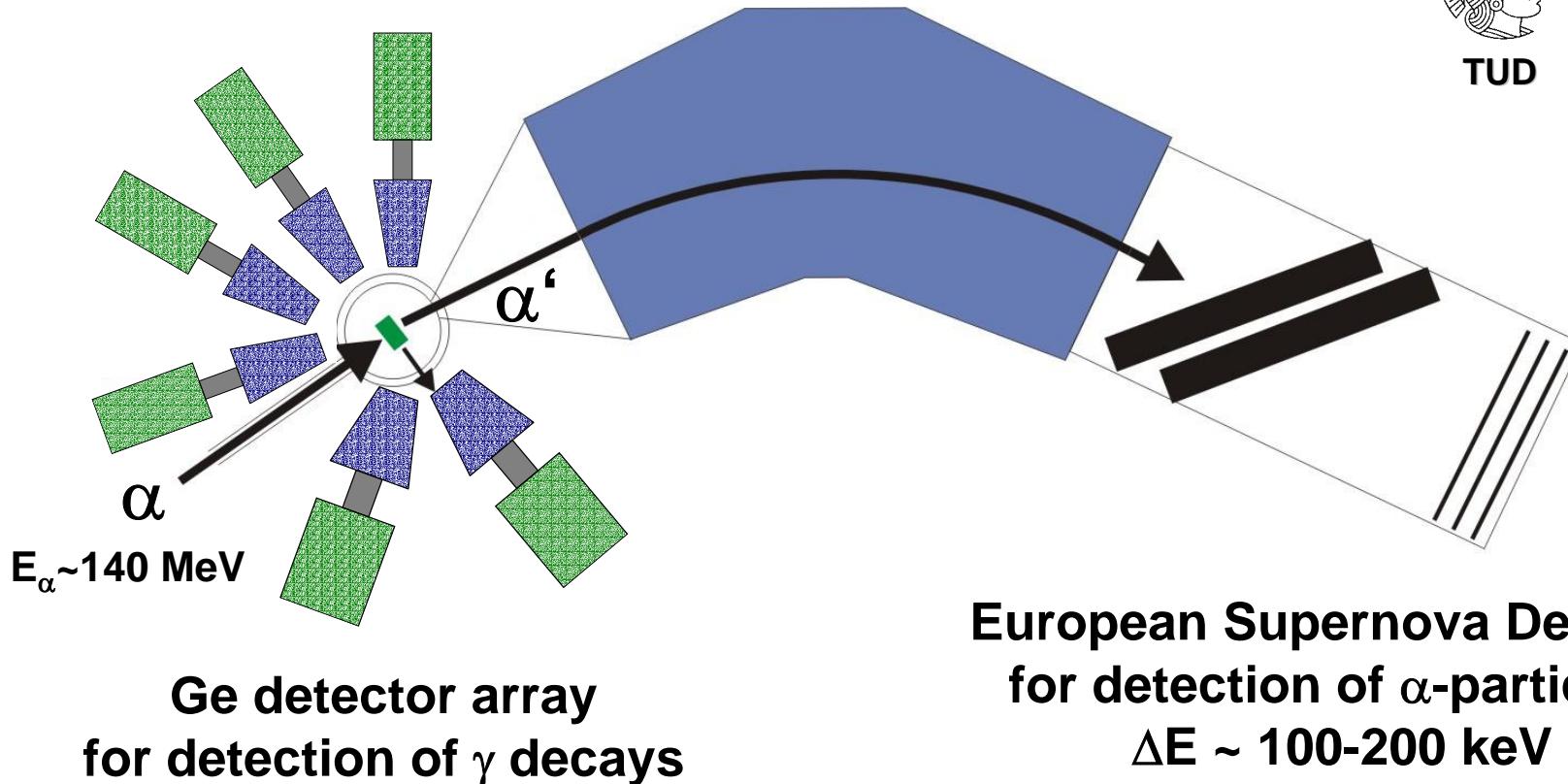
# Substructure within the PDR ?



F. Iachello

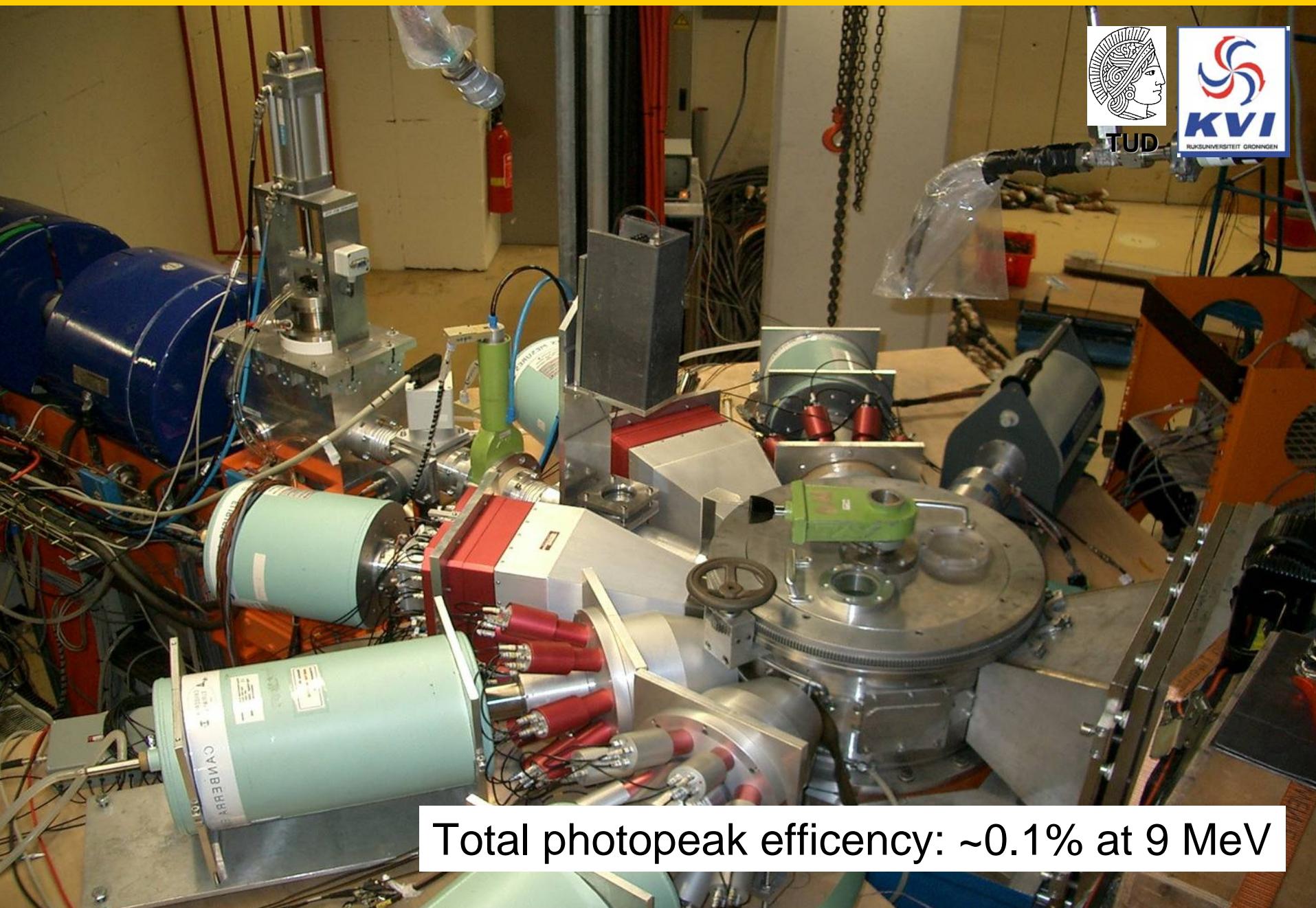
# Investigating the PDR with $\alpha$ -particles

Big Bite Spectrometer (BBS)



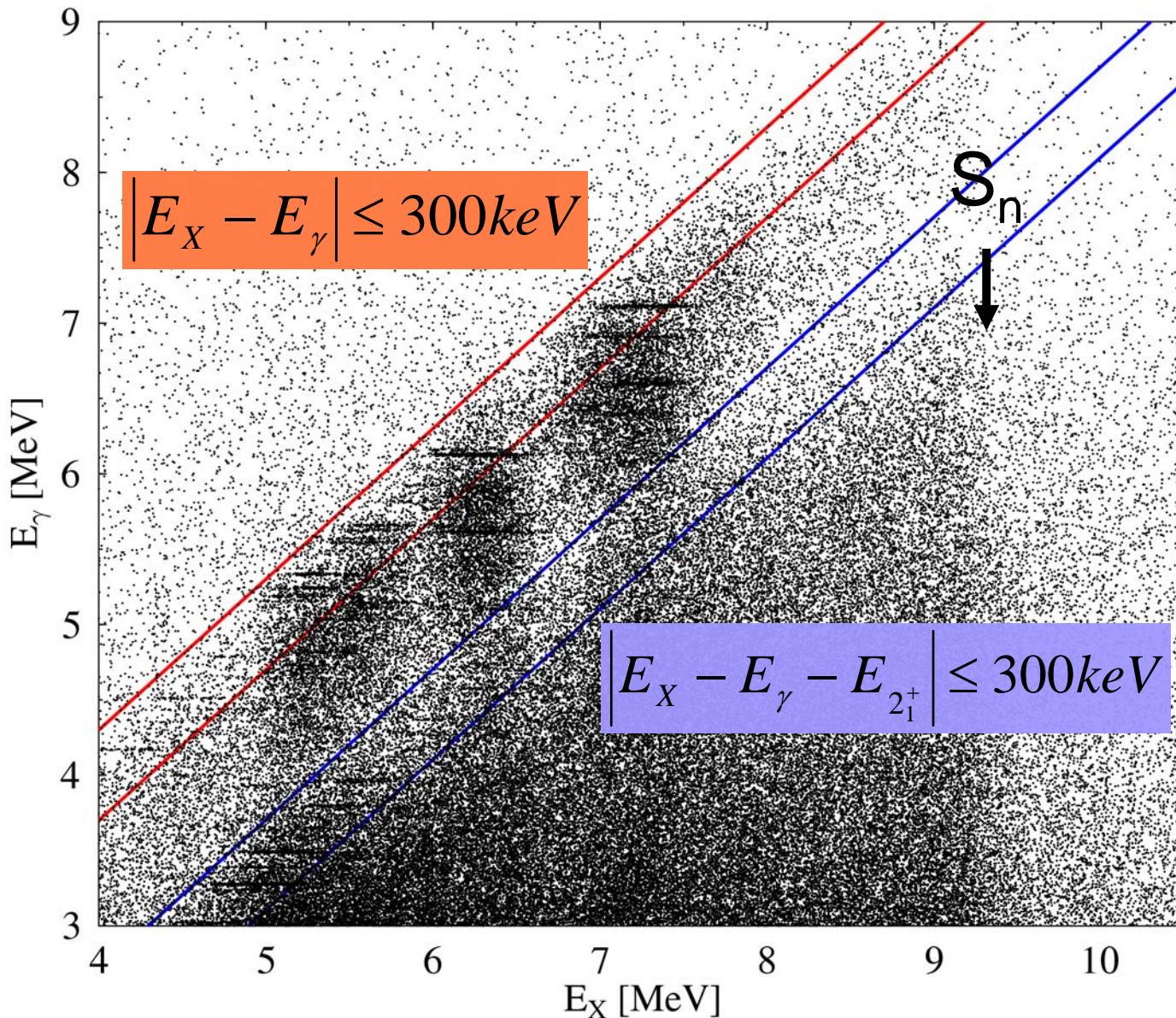
This setup combines isospin selectivity and skin sensitivity of  $\alpha$ -particles with spin selectivity and energy resolution of  $\gamma$ -spectroscopy

# The new ISOSPIN setup at KVI

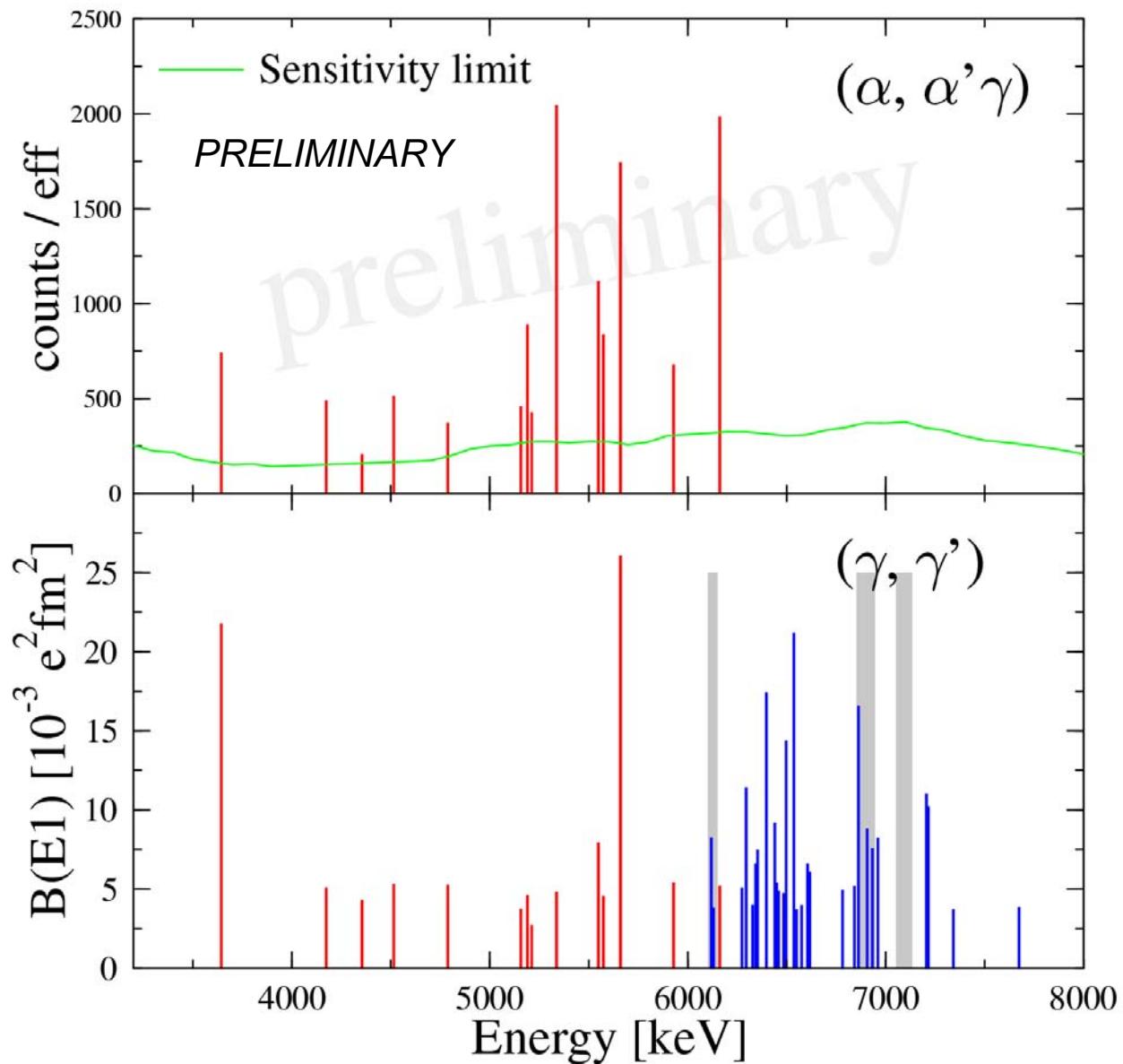


Total photopeak efficiency: ~0.1% at 9 MeV

# 2D-energy matrix: $(\alpha, \alpha'\gamma)$ on $^{140}\text{Ce}$



# E1 strength in $^{140}\text{Ce}$ : $(\alpha, \alpha'\gamma)$ vs. $(\gamma, \gamma')$

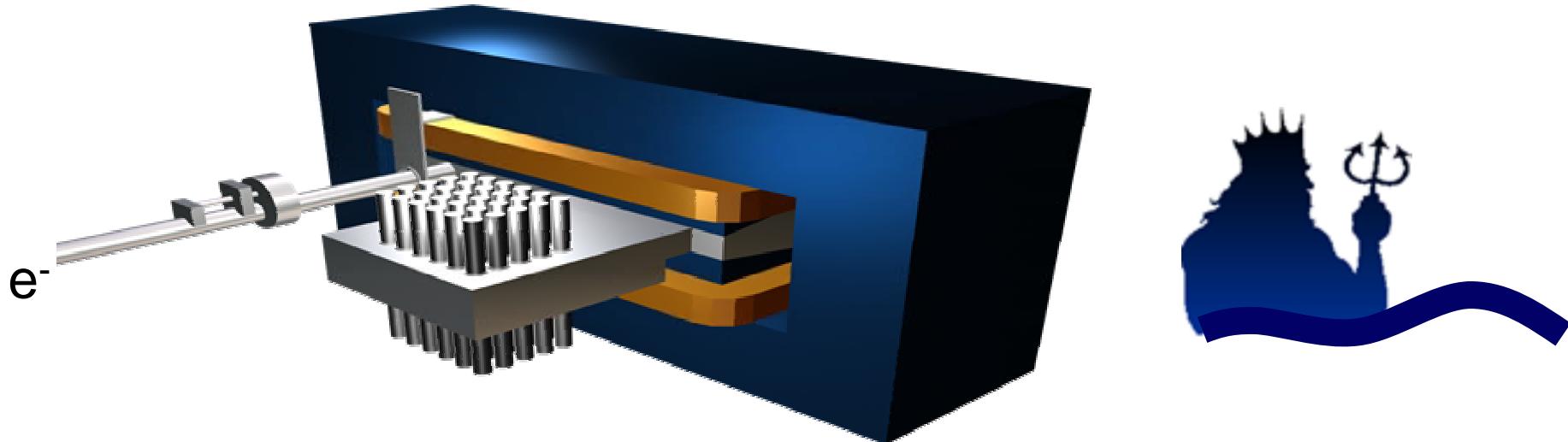


# Summary

- An E1 resonance exhausting up to 1% of the EWSR is observed in all examined stable nuclei around about 7 MeV
- The strength seems to split up into two parts with different underlying isospin structure and/or different nuclear surface content
- More resonance like strength is found above the particle threshold in n-rich systems
- We do not understand the connection between the strength below and above the threshold and between the strength in stable and exotic nuclei

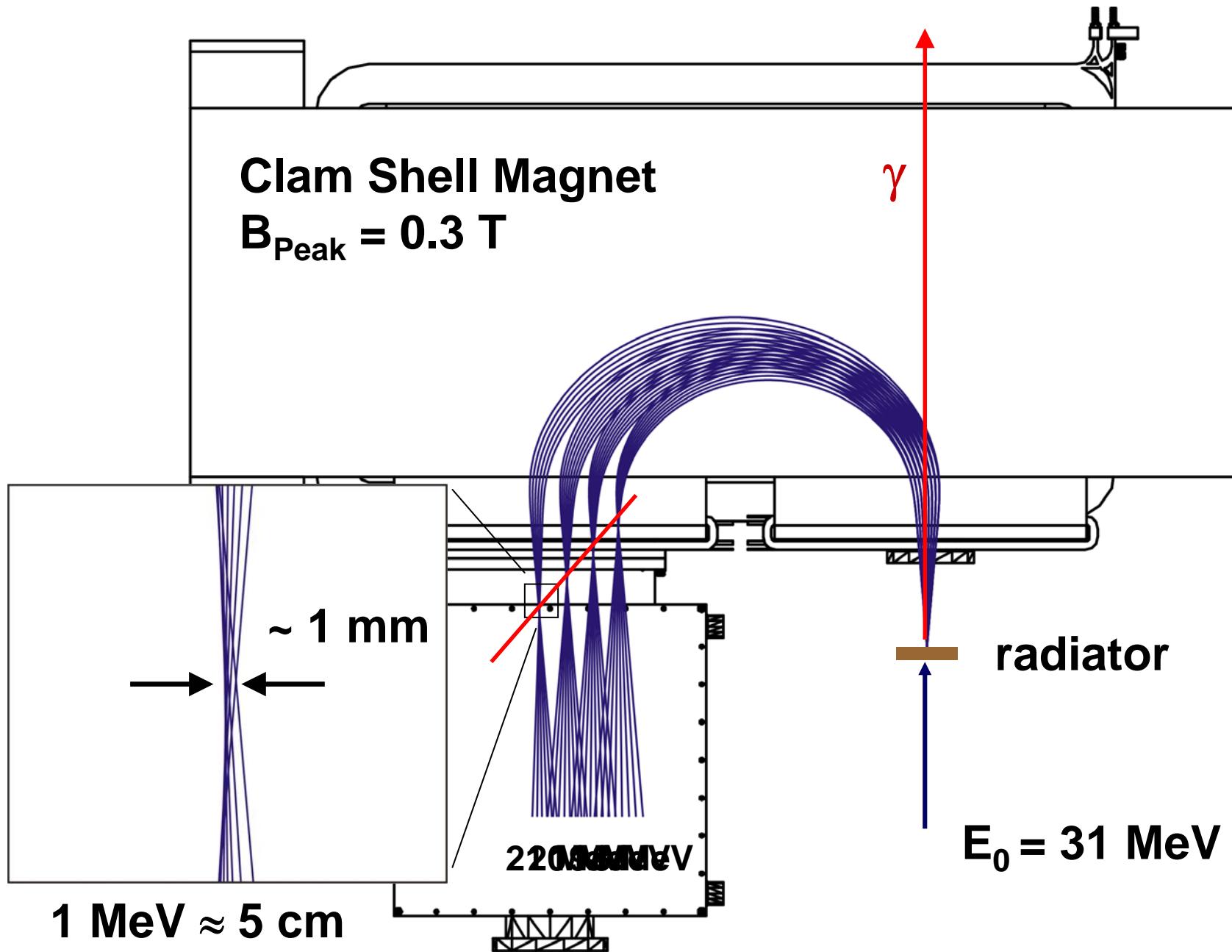
# Connection to E1 strength above the threshold in stable nuclei

Low Energy Photon Tagger @ S-DALINAC  
**NiederEnergiePhotonenTagger**

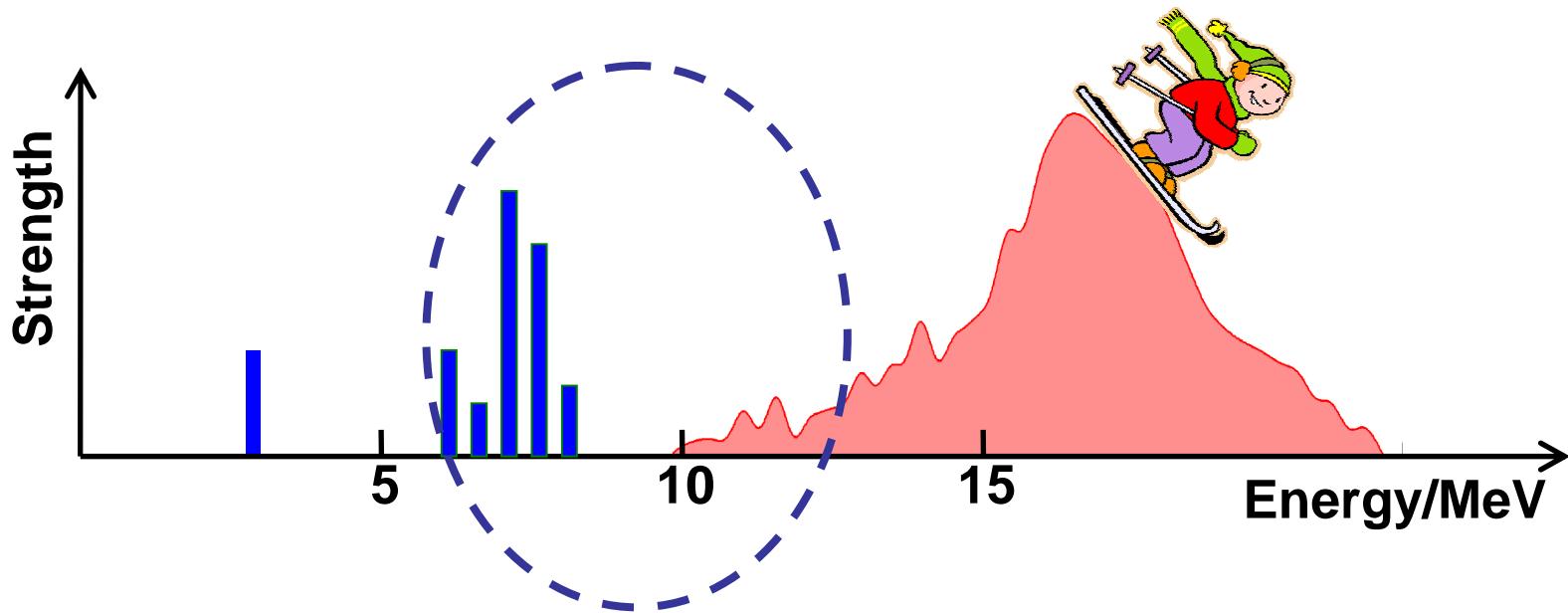


High resolution measurement ( $<0.25\%$ )  
of photon induced reaction rates in the  
energy range  $8 \text{ MeV} < E_\gamma < 20 \text{ MeV}$

# NEPTUN at S-DALINAC



# The photoresponse of heavy nuclei – some implications on nucleosynthesis



- Complete photoresponse ( $\gamma, \gamma'$ ), ( $\gamma, n$ ), ( $\gamma, \alpha$ ), ( $\gamma, p$ ) can be measured in stable nuclei at S-DALINAC
- Additional information about structure from ( $\alpha, \alpha' \gamma$ ) and ( $e, e'$ ) experiments

# The photoresponse of heavy nuclei – some implications on nucleosynthesis

**M. Elvers, J. Endres, M. Fritzsch, J. Hasper,  
L. Kern, K. Lindenberg, S. Müller,  
D. Savran, C. Siegel, K. Sonnabend, S. Volz**

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More information and references: [www.zilges.de](http://www.zilges.de)