DIPOLE-STRENGTH FUNCTIONS STUDIED IN PHOTON-SCATTERING EXPERIMENTS AT ELBE

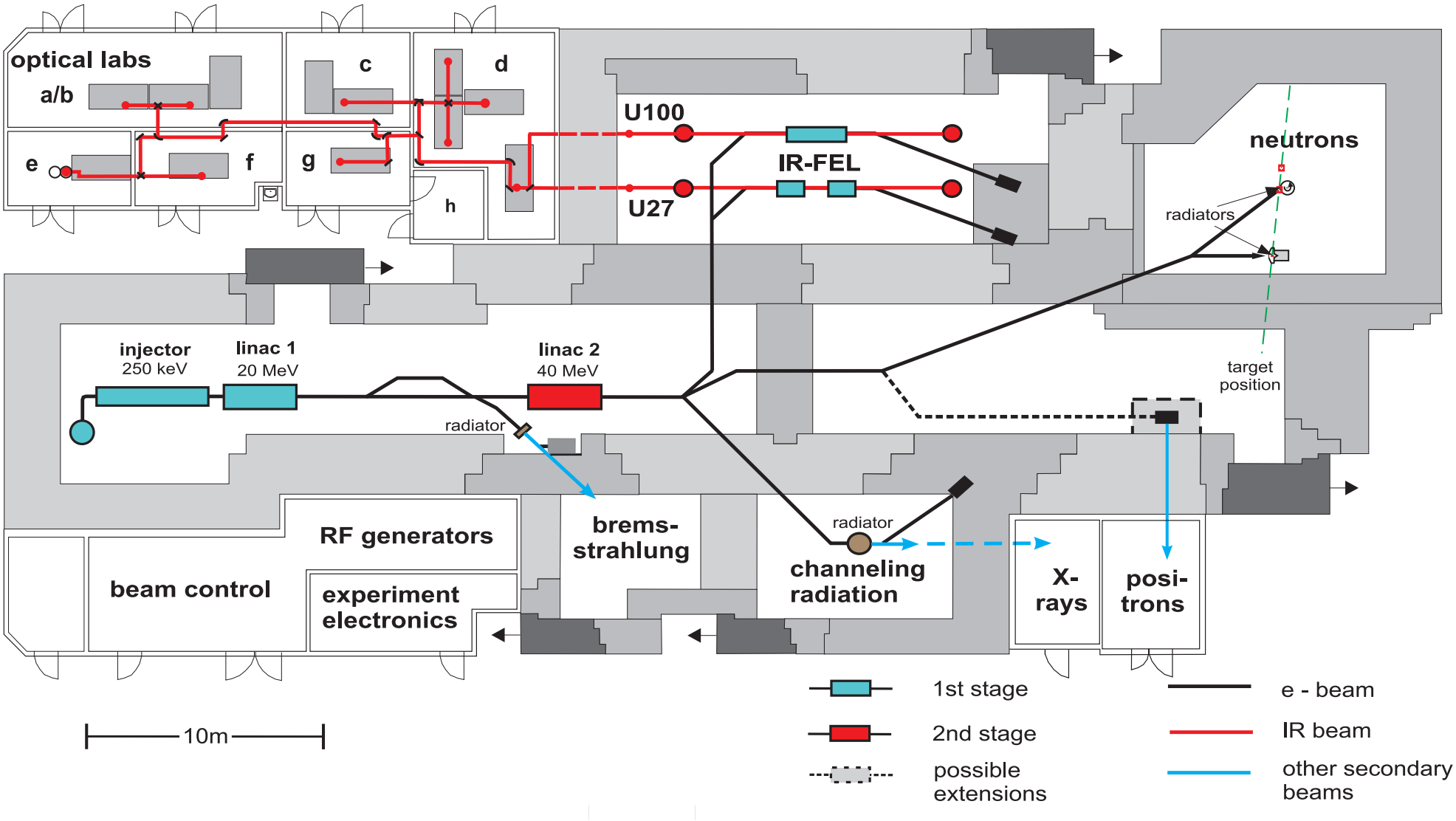
R. Schwengner[1], G. Rusev[1], N. Benouaret[1,2], R. Beyer[1], F. Dönau[1], M. Erhard[1], E. Grosse[1,3], A. R. Junghans[1], K. Kosev[1], J. Klug[1], C. Nair[1], N. Nankov[1,4], K. D. Schilling[1], A. Wagner[1]

[1] *Institut für Strahlenphysik, Forschungszentrum Dresden-Rossendorf, 01314 Dresden, Germany*
[2] *Faculté de Physique, Université des Sciences et de la Technologie d'Alger, 16111 Bab-Ezzouar-Alger, Algerie*
[3] *Institut für Kern- und Teilchenphysik, Technische Universität Dresden, 01062 Dresden, Germany*
[4] *Institute for Nuclear Research and Nuclear Energy, BAS, 1784 Sofia, Bulgaria*

- The bremsstrahlung facility
- Photon-scattering experiments
- Data analysis and results
- Comparison with model predictions

Supported by Deutsche Forschungsgemeinschaft

Electron Linear accelerator of high Brilliance and low Emittance

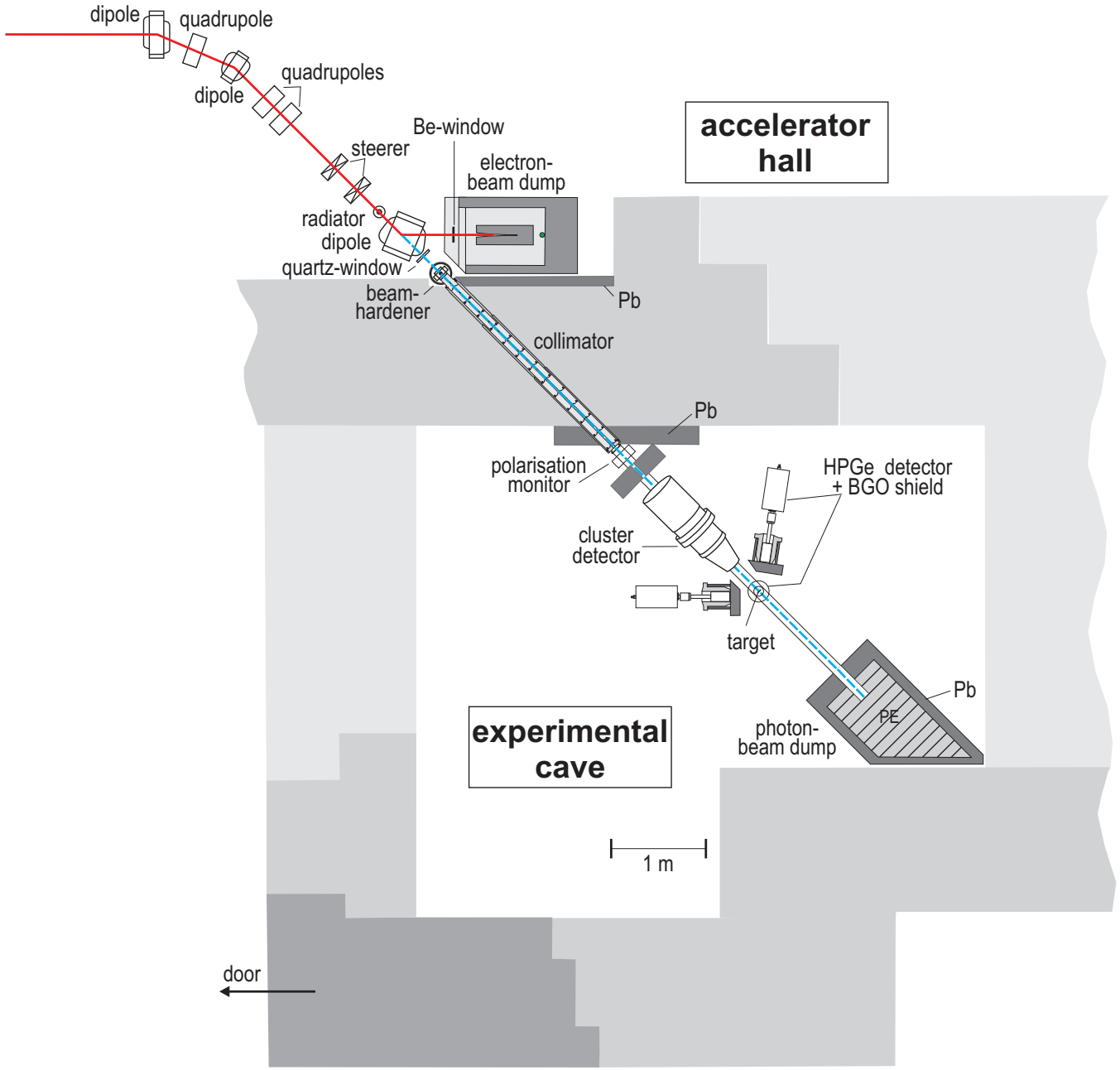


The bremsstrahlung facility at the electron accelerator ELBE

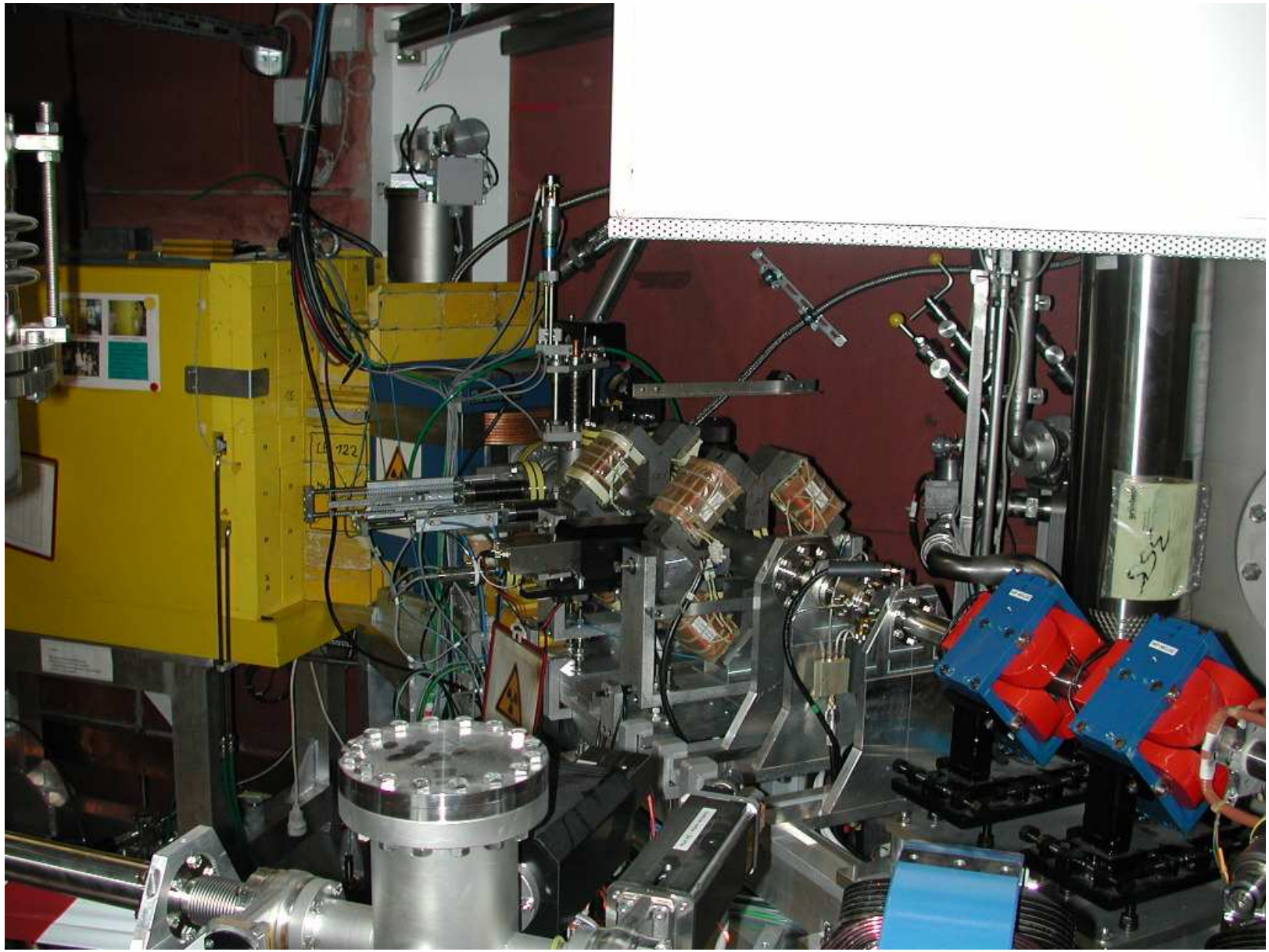
R.S. et al., NIM A 555 (2005) 211

Accelerator parameters:

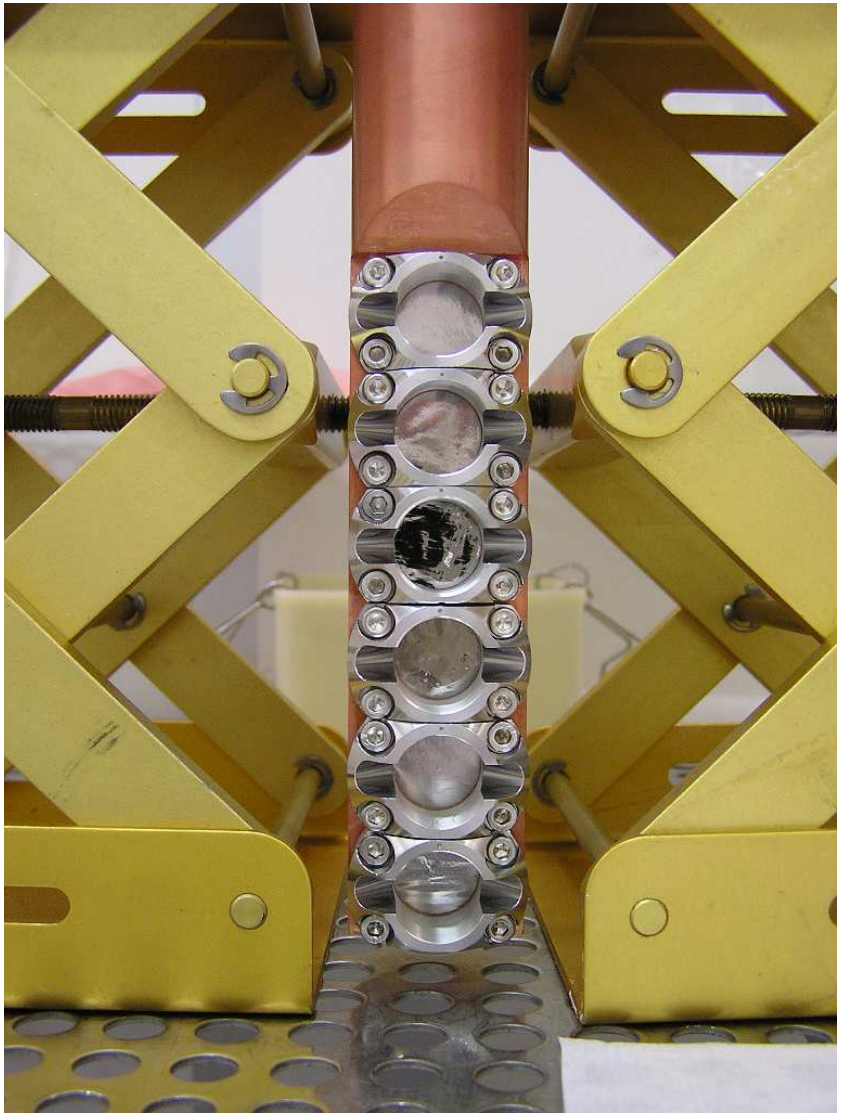
- Maximum electron energy:
  18 MeV
- Maximum average current:
  1 mA
- Micro-pulse rate:
  13 MHz
- Micro-pulse length:
  $\approx$ 5 ps



Electron-beam line



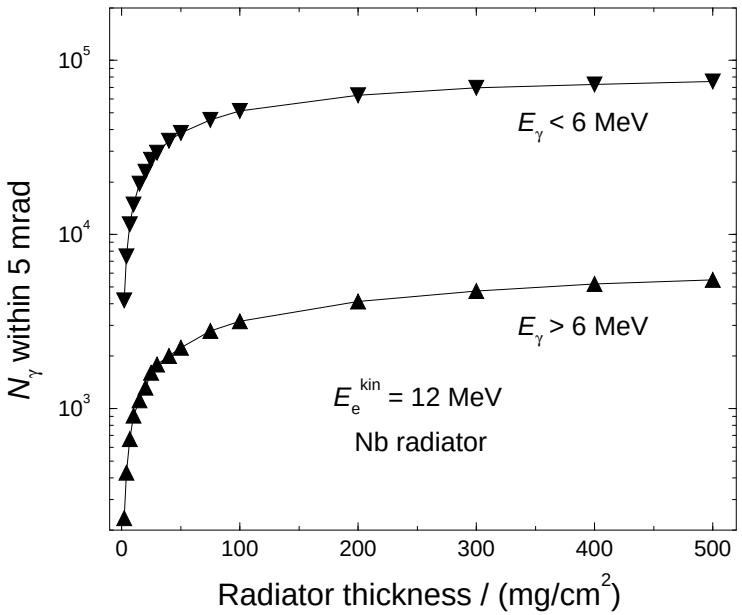
Radiator

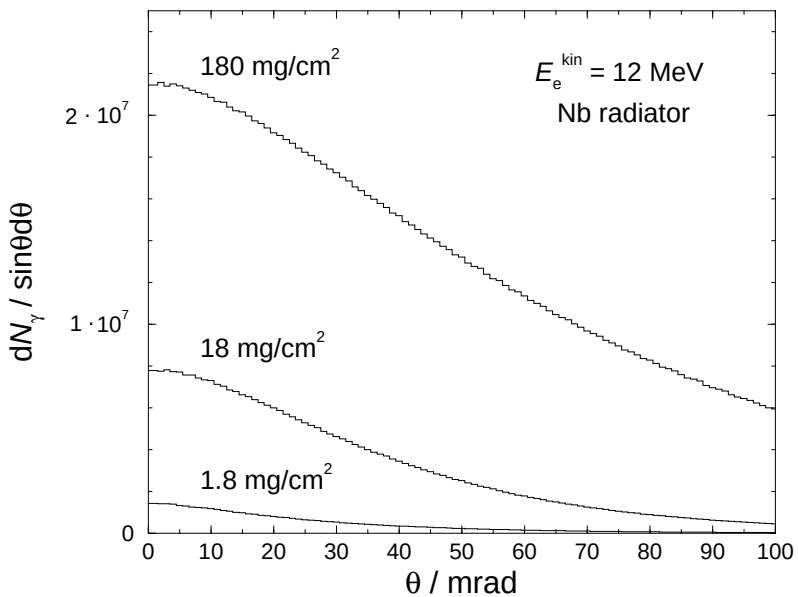


Niobium radiators:

- Six radiator foils of 16 mm diameter mounted on a water-cooled copper rod
- Thicknesses of 2, 3, 4, 5, 7 and 12.5 μm, corresponding to $2 \cdot 10^{-4}$ to 10^{-3} radiation lengths
- Radiator holder can be moved by a DC motor drive to select a radiator without breaking the vacuum

Simulation of the flux of photons passing the collimator





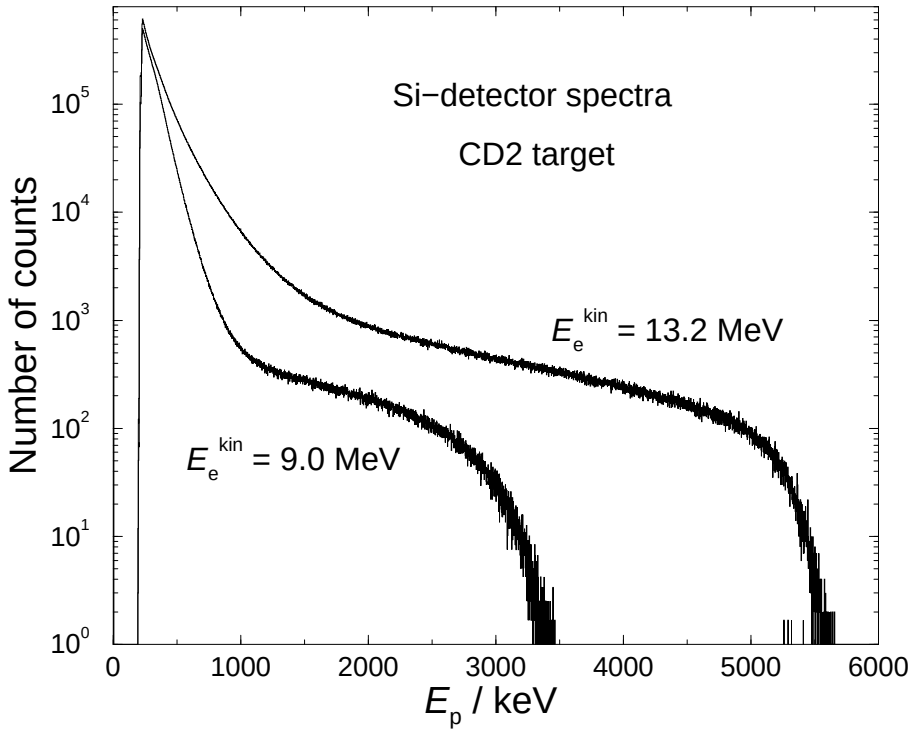
Simulations with GEANT4:

- Number of photons produced by 10^9 electrons of $E_e^{kin} = 12$ MeV in a cone with an opening angle of 5 mrad as a function of the niobium-radiator thickness.

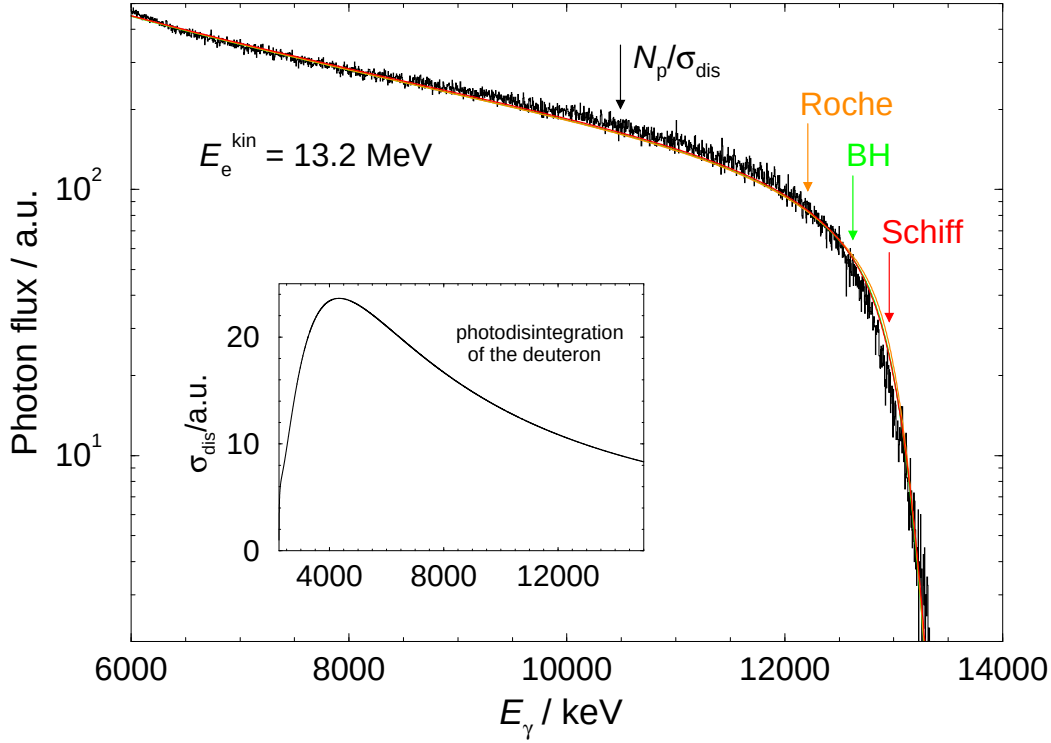
- Number of photons produced by 10^9 electrons of $E_e^{kin} = 12$ MeV in niobium radiators of different thicknesses as a function of the angle between electron beam and photon.

Detector setup

Measurement of the electron energy via photodisintegration of deuterons



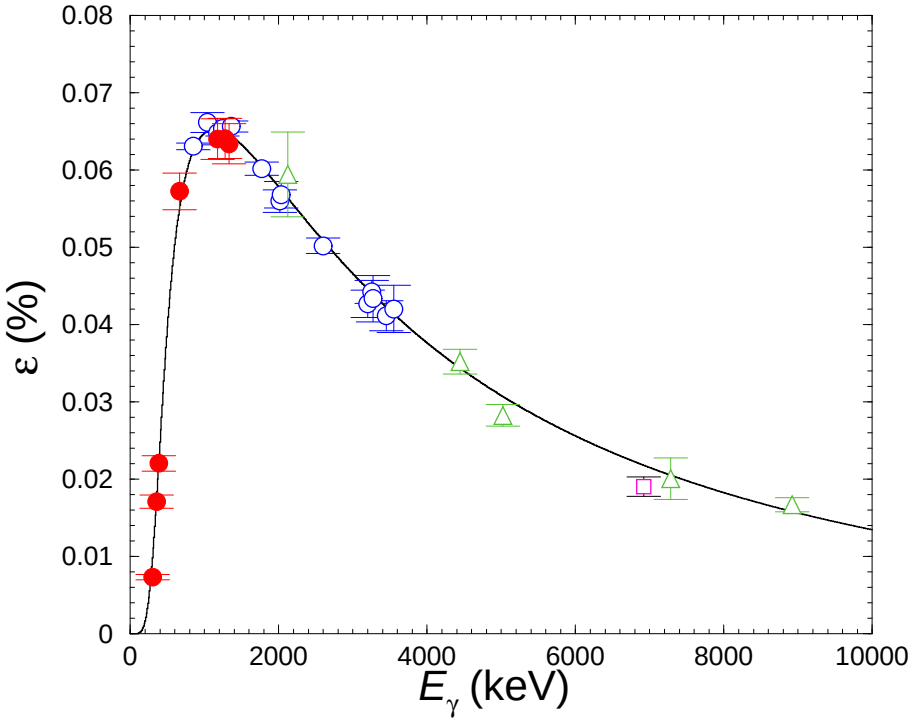
Spectra measured with Si detectors of 300 μm thickness during the irradiation of a deuterated polyethylene film with bremsstrahlung.



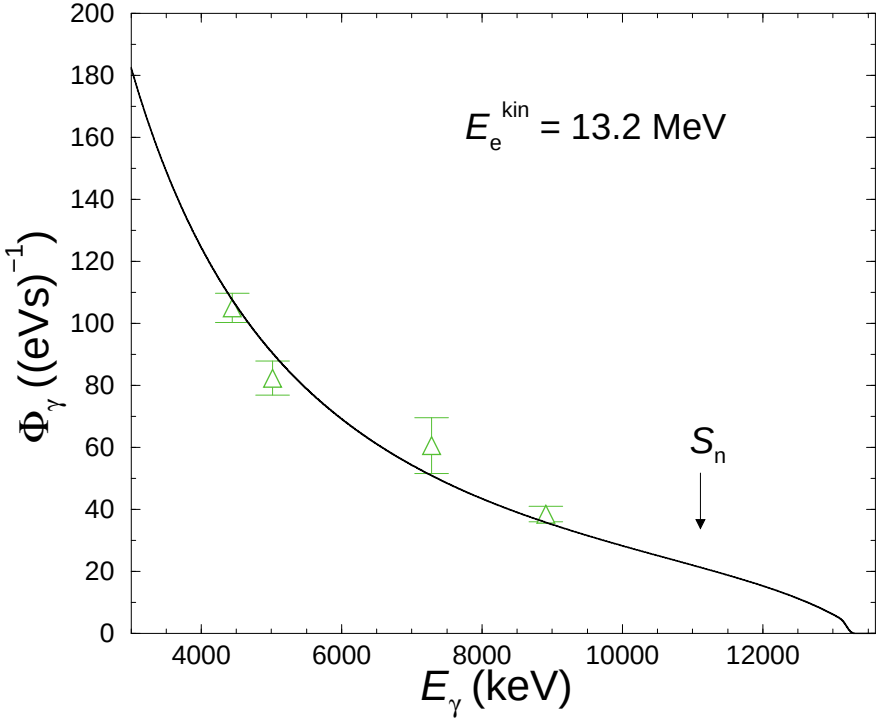
Spectrum of incident photons recalculated from the proton spectrum and the cross section for the disintegration of the deuteron.

σ_{dis}: H. Bethe, C. Longmire, Phys. Rev. 77 (1950) 647
Roche: G. Roche *et al.*, Phys. Rev. A 5 (1972) 2403
BH: H. Bethe, W. Heitler, Proc. Roy. Soc. A 146 (1934) 83
Schiff: L.I. Schiff, Phys. Rev. 83 (1951) 252

Absolute detector efficiency and photon flux

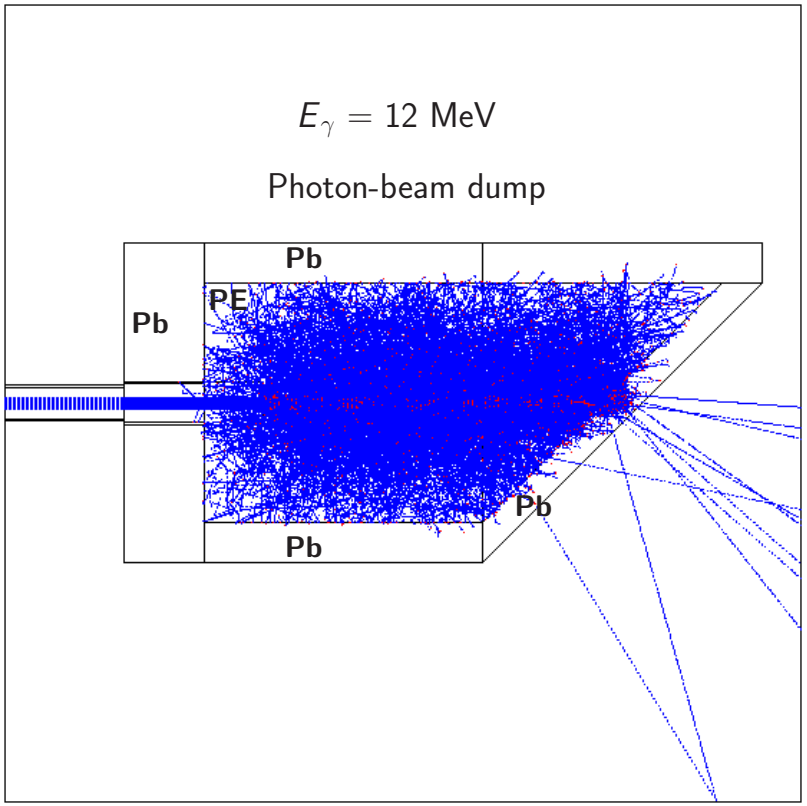


Absolute efficiency of two detectors at 127° deduced from ^{22}Na, ^{60}Co, ^{133}Ba, (filled circles) and simulated with GEANT3 (solid line). Relative efficiencies deduced from ^{56}Co (open circles), ^{11}B (open triangles) and ^{16}O (open square).



Absolute photon flux deduced from transitions in ^{11}B (open triangles) using the calculated efficiency shown in the left panel and relative photon flux calculated according to G. Roche et al. (code by E. Haug, Rad. Phys. Chem. 77 (2008) 207).

Beam dump

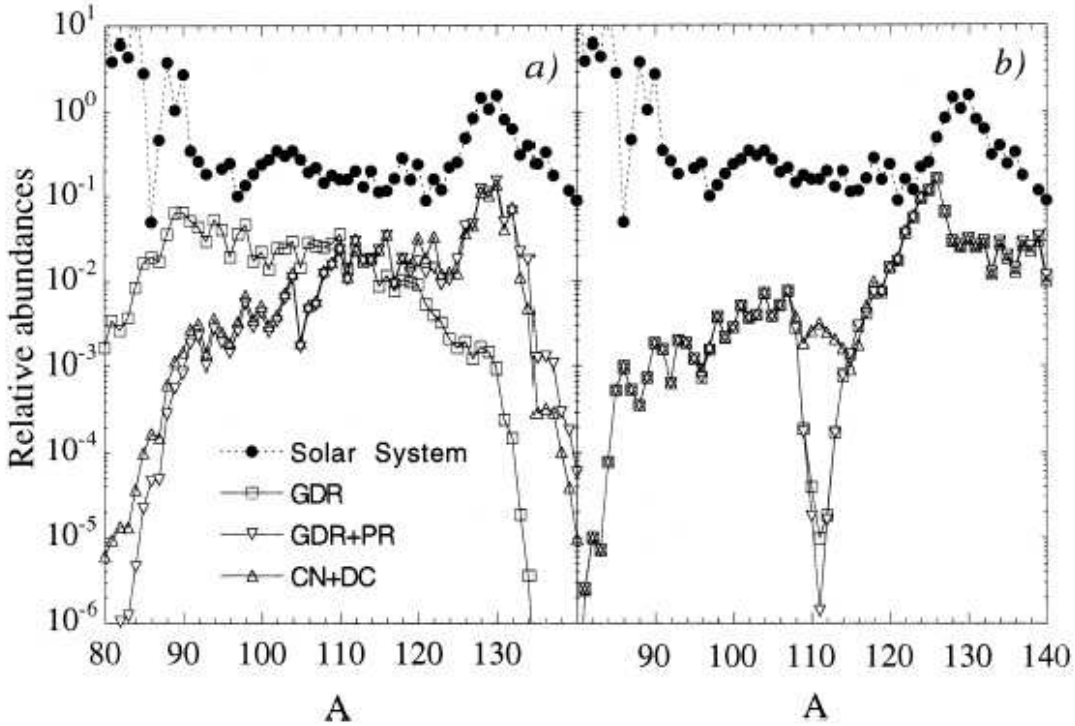


GEANT3 simulation with 1000 trajectories of 12 MeV photons.

About 0.3 % of the photons are scattered back towards the detectors.

Dipole strength close to the particle-separation energy

- Understanding of astrophysical processes:
  - Influence on (γ,n) reaction rates in the p-process.
  - Influence on (n,γ) reaction rates in the s-process.
- Studies for transmutation:
  - Analysis of (n,γ) reactions.
- Open problems:
  - Precise knowledge of the $E1$ strength on the low-energy tail of the Giant Dipole Resonance.
  - Properties of the $E1$ strength functions at varying proton and neutron numbers: shell effects, deformation etc.

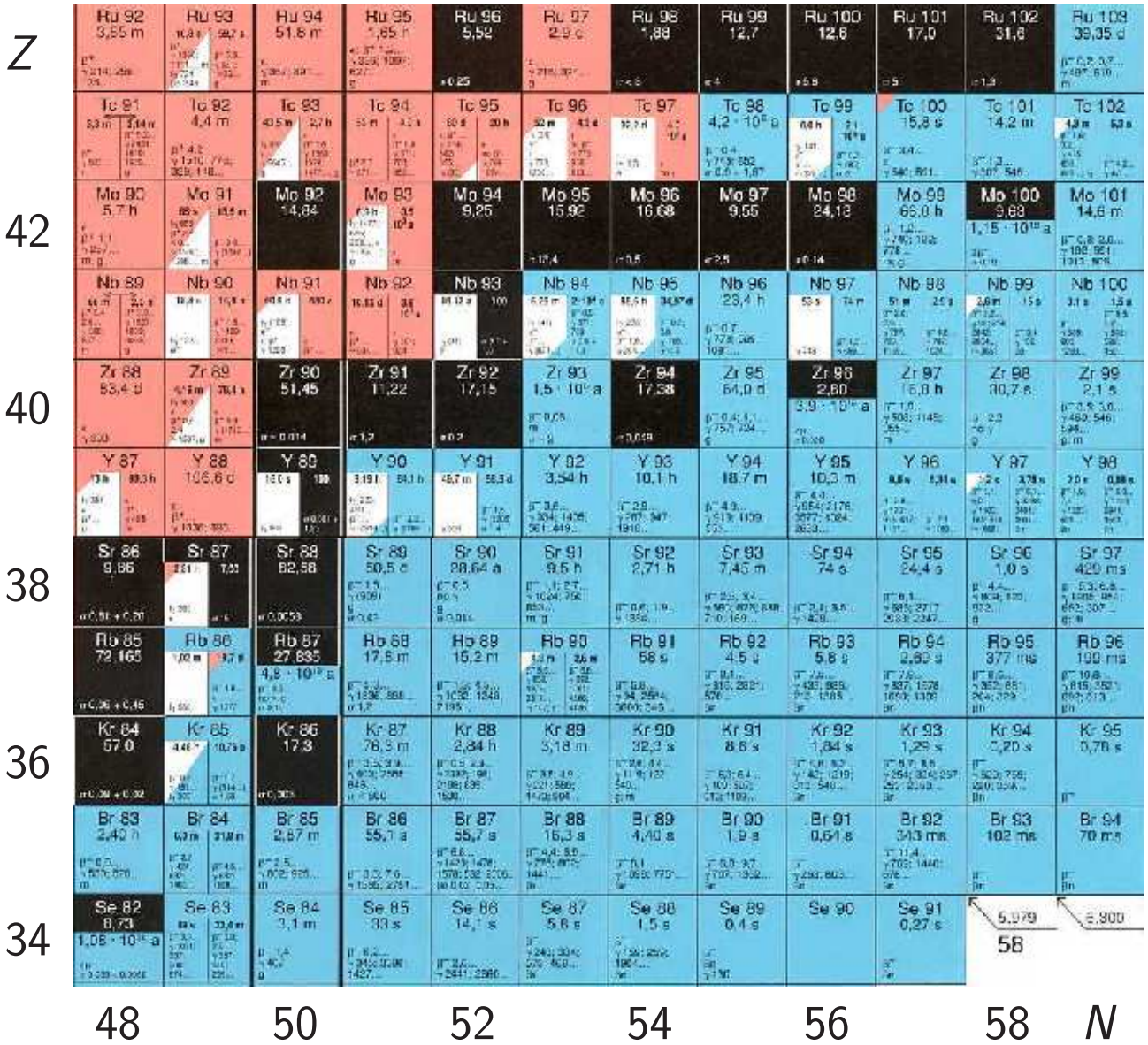


$T = 1.0 \times 10^9$ K $\quad$ $T = 1.5 \times 10^9$ K

$N_n = 10^{20}$ cm^2 $\quad$ $N_n = 10^{28}$ cm^2

S. Goriely, PLB 436 (1998) 10

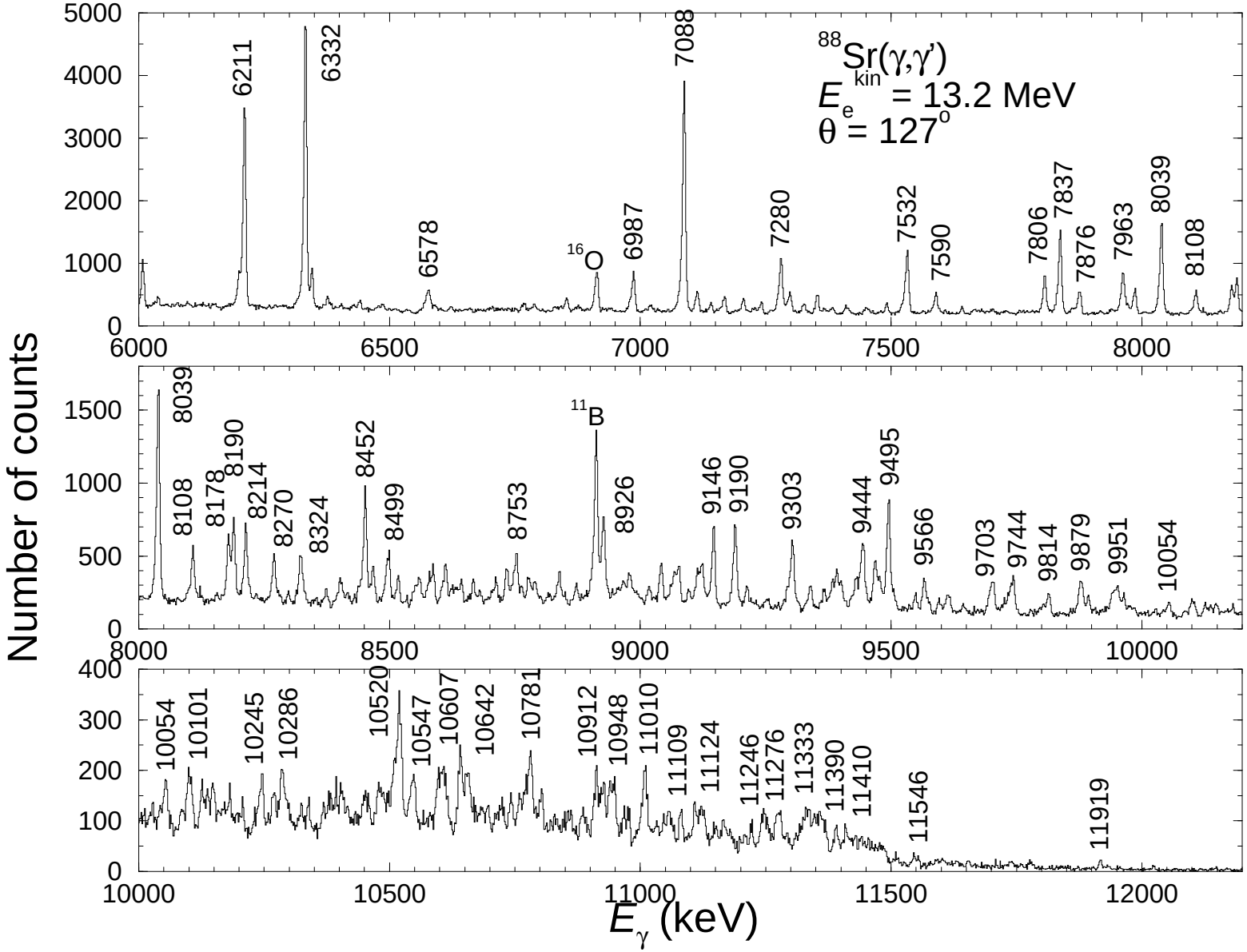
Nuclides under investigation in photon-scattering experiments



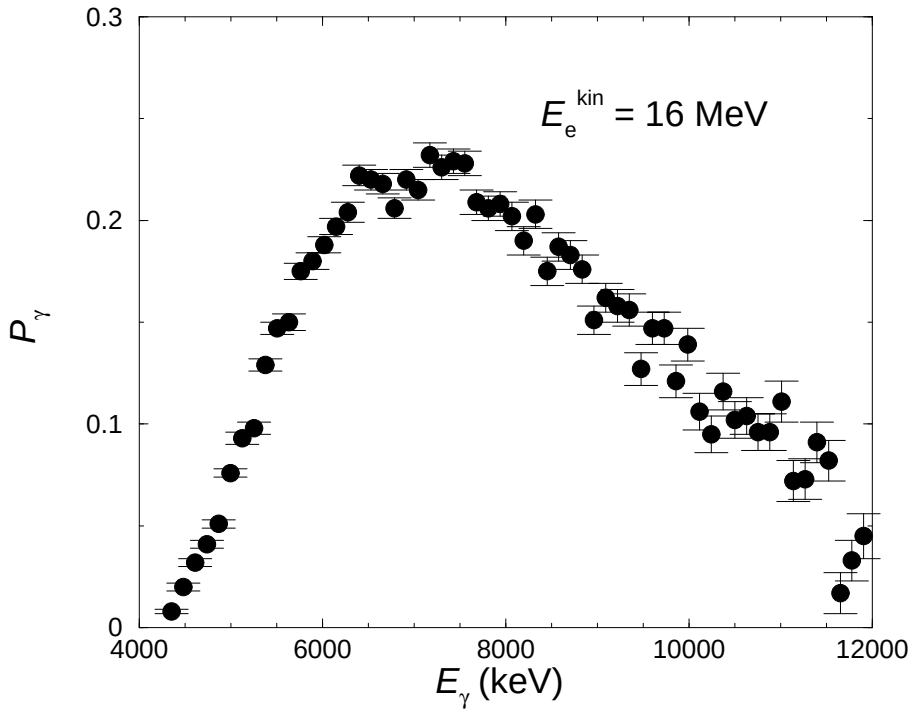
nuclide	S_n MeV	E_e^{kin} (MeV) ELBE
^{92}Mo	12.7	6.0[a], 13.2[b,c]
^{94}Mo	9.7	13.2
^{96}Mo	9.2	13.2
^{98}Mo	8.6	(3.3, 3.8)[a,d], 8.5, 13.2[b,c]
^{100}Mo	8.3	(3.2, 3.4, 3.8)[a] 7.8, 13.2[b,c]
^{90}Zr	12.0	7.0, 9.0, 12.8
^{89}Y	11.5	7.0[e], 9.5, 13.2
^{88}Sr	11.1	6.8[f], 9.0, 13.2, 16.0[g]
^{87}Rb	9.9	4.0[h], 13.2
^{86}Kr	9.9	

[a] G. Rusev et al., PRC 73 (2006) 044308
[b] G. Rusev et al., EPJA 27 (2006) s01, 171
[c] R. Schwengner et al., NPA 788 (2007) 331c
[d] G. Rusev et al., PRL 95 (2005) 062501
[e] J. Reif et al., NPA 620 (1997) 1
[f] L. Käubler et al., PRC 70 (2004) 064307
[g] R. Schwengner et al., PRC 76 (2007) 034321
[h] L. Käubler et al., PRC 65 (2002) 054315

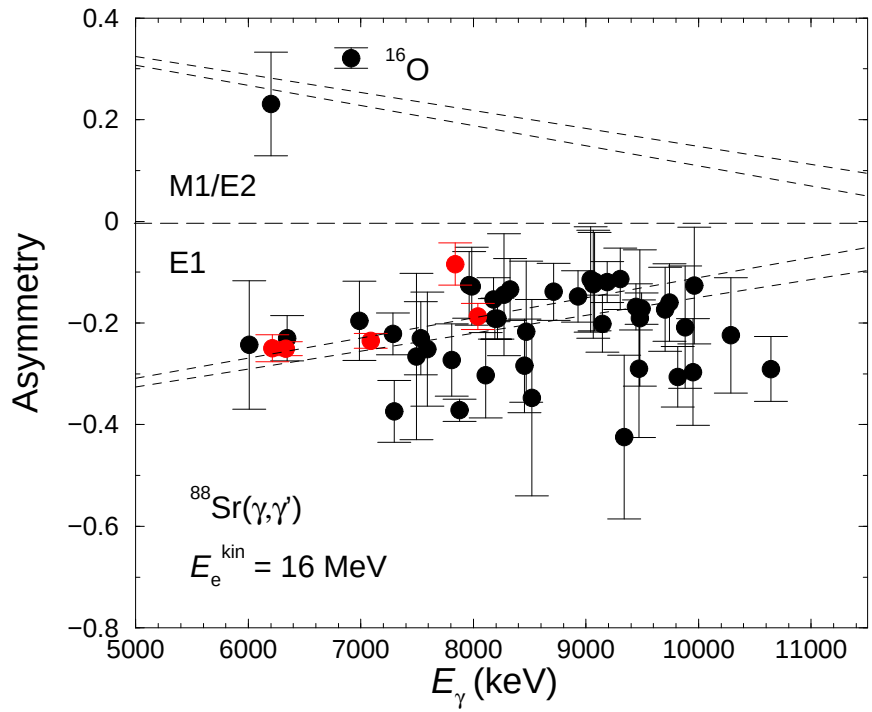
Photon scattering from ^{88}Sr



Measurement with polarised photons

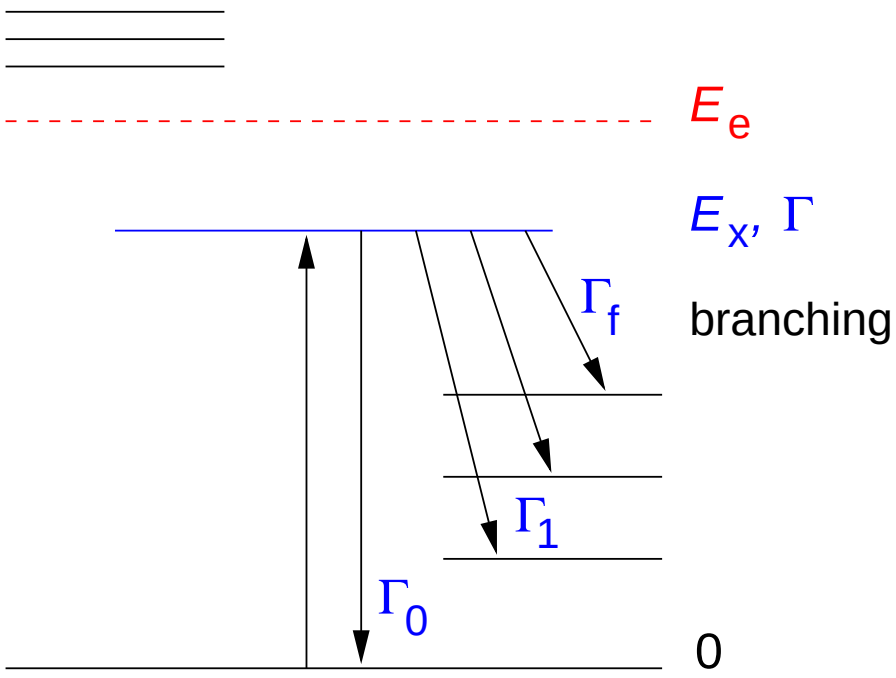


Degree of polarisation as deduced from spectra of protons emitted in the disintegration of deuterons $d(\vec{\gamma}, p)n$.



Asymmetries $(N_{\gamma\parallel} - N_{\gamma\perp})/(N_{\gamma\parallel} + N_{\gamma\perp})$ *of intensities of* γ *rays in* ^{88}Sr.

Problem of feeding and branching



Measured intensity of a γ transition:

$$I_\gamma(E_\gamma, \Theta) = I_s(E_x)\, \Phi_\gamma(E_x)\, \epsilon(E_\gamma)\, N_{at}\, W(\Theta)\, \Delta\Omega$$

Scattering cross section integral:

$$I_s = \int \sigma_{\gamma\gamma}\, dE = \frac{2J_x + 1}{2J_0 + 1} \left(\frac{\pi\hbar c}{E_x}\right)^2 \frac{\Gamma_0}{\Gamma}\, \Gamma_0$$

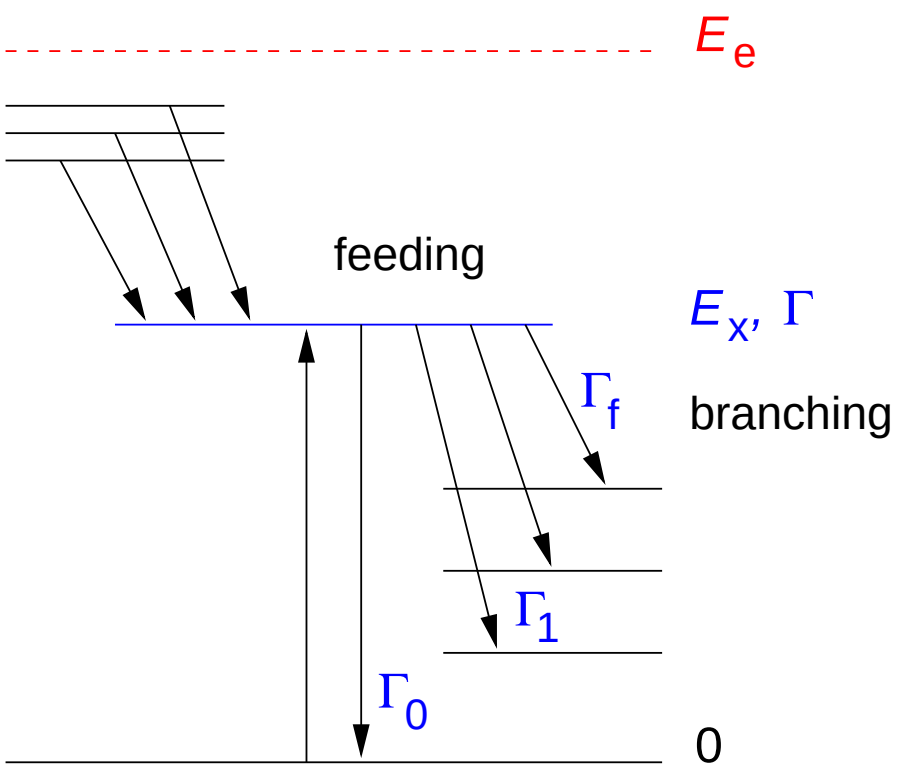
Absorption cross section:

$$\sigma_\gamma = \sigma_{\gamma\gamma} \left(\frac{\Gamma_0}{\Gamma}\right)^{-1}$$

E1 strength:

$$B(E1) \sim \Gamma_0 / E_\gamma^3$$

Problem of feeding and branching



Measured intensity of a γ transition:

$$I_\gamma(E_\gamma, \Theta) > I_s(E_x)\, \Phi_\gamma(E_x)\, \epsilon(E_\gamma)\, N_{at}\, W(\Theta)\, \Delta\Omega$$

Scattering cross section integral:

$$I_s = \int \sigma_{\gamma\gamma}\, dE = \frac{2J_x + 1}{2J_0 + 1} \left(\frac{\pi\hbar c}{E_x}\right)^2 \frac{\Gamma_0}{\Gamma}\, \Gamma_0$$

Absorption cross section:

$$\sigma_\gamma = \sigma_{\gamma\gamma} \left(\frac{\Gamma_0}{\Gamma}\right)^{-1}$$

E1 strength:

$$B(E1) \sim \Gamma_0 / E_\gamma^3$$

Problem of feeding and branching

Correction of the strength function by using statistical methods (G. Rusev, Dissertation):

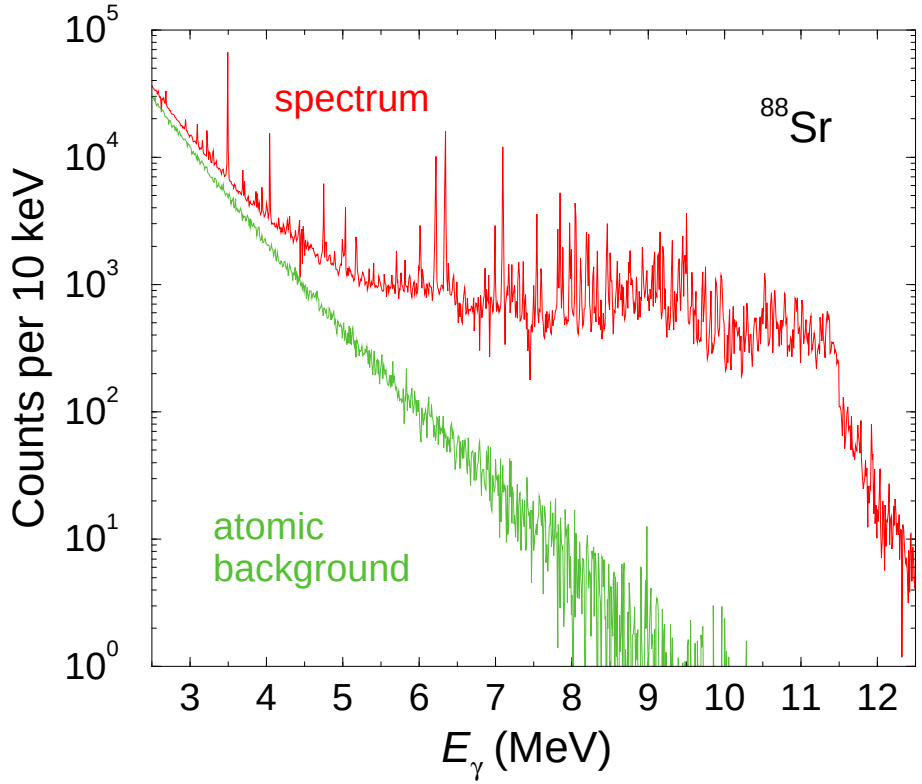
⇒ Monte Carlo simulations of γ-ray cascades from groups of levels in 100 keV bins over the whole energy range.

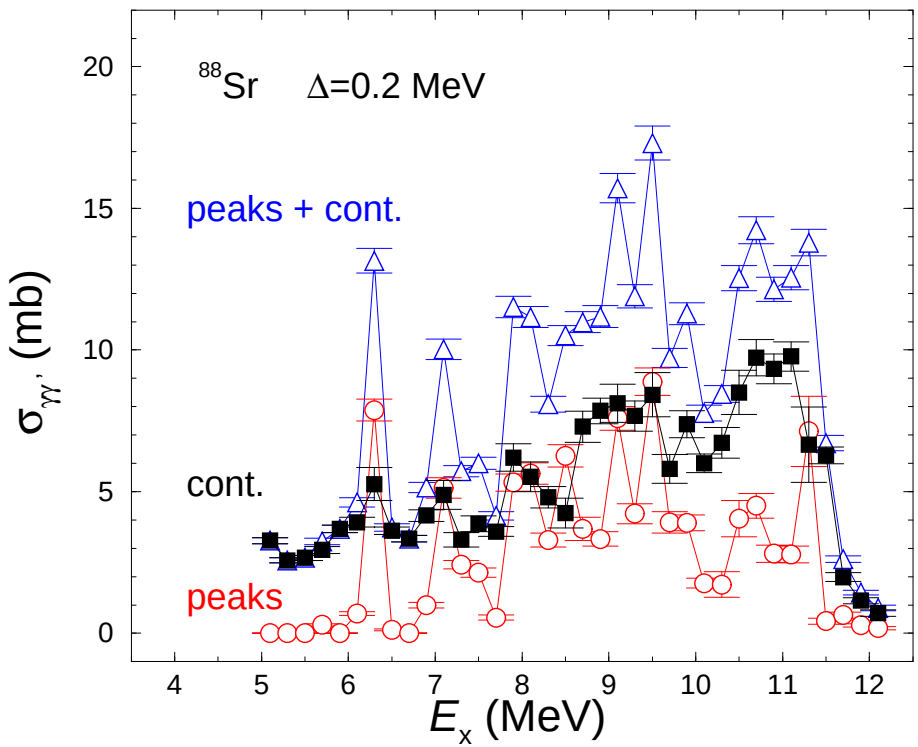
⇒ Level scheme of $J = 0$, 1 and 2 states constructed using:
- Backshifted Fermi-Gas Model with level-density parameters given in:
  T. v. Egidy, D. Bucurescu, PRC 72 (2005) 044311
- Wigner level-spacing distributions

⇒ Partial decay widths calculated by using:
- Photon strength functions approximated by Lorentzian parametrisations.
  - $E1$: parameters determined from a fit to (γ,n) data
  - $M1$: global parametrisation of $M1$ spin-flip resonances
  - $E2$: global parametrisation of $E2$ isoscalar resonances
  (www-nds.iaea.org/RIPL-2)
- Porter-Thomas distributions of decay widths.

⇒ Feeding intensities subtracted and intensities of g.s. transitions corrected with calculated branching ratios Γ_0/Γ.

Unresolved strength in the continuum

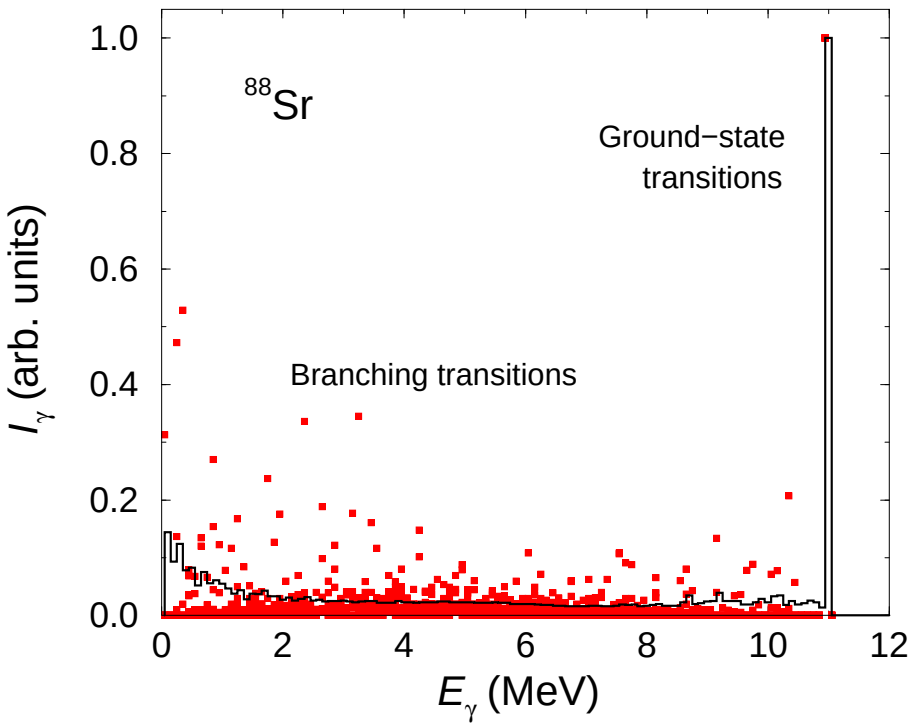




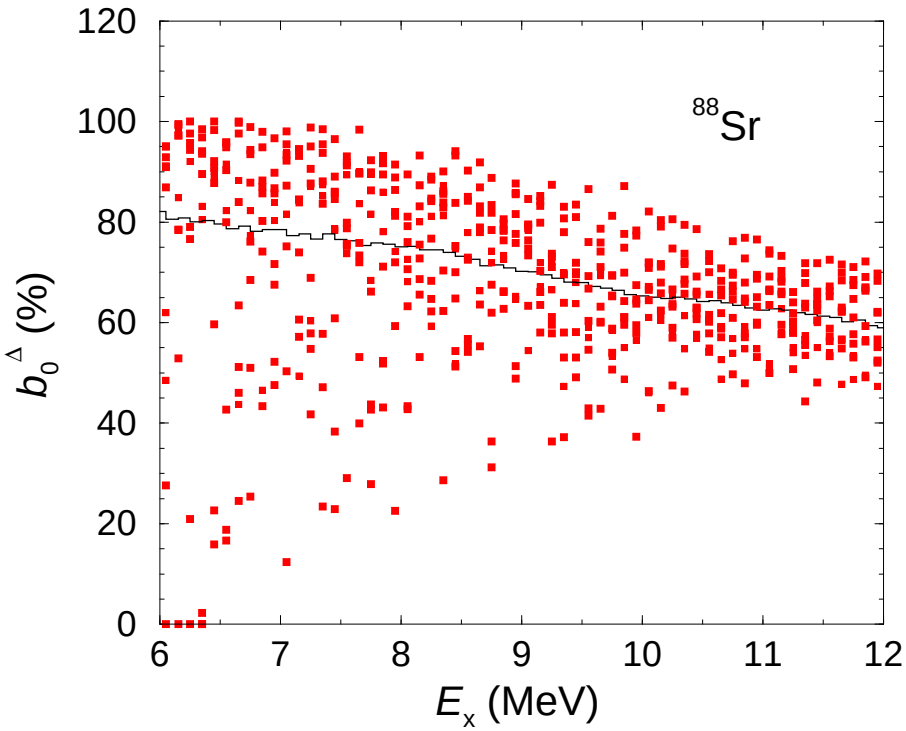
Experimental spectrum of ^{88}Sr (corrected for room background, detector response, efficiency, measuring time) and simulated spectrum of atomic background.

Dipole strengths in ^{88}Sr, not corrected for branching and averaged over energy bins of 0.2 MeV, as derived from the difference of the experimental spectrum and the atomic background (triangles) and from the isolated peaks only (circles).

Correction for feeding and branching by using statistical methods

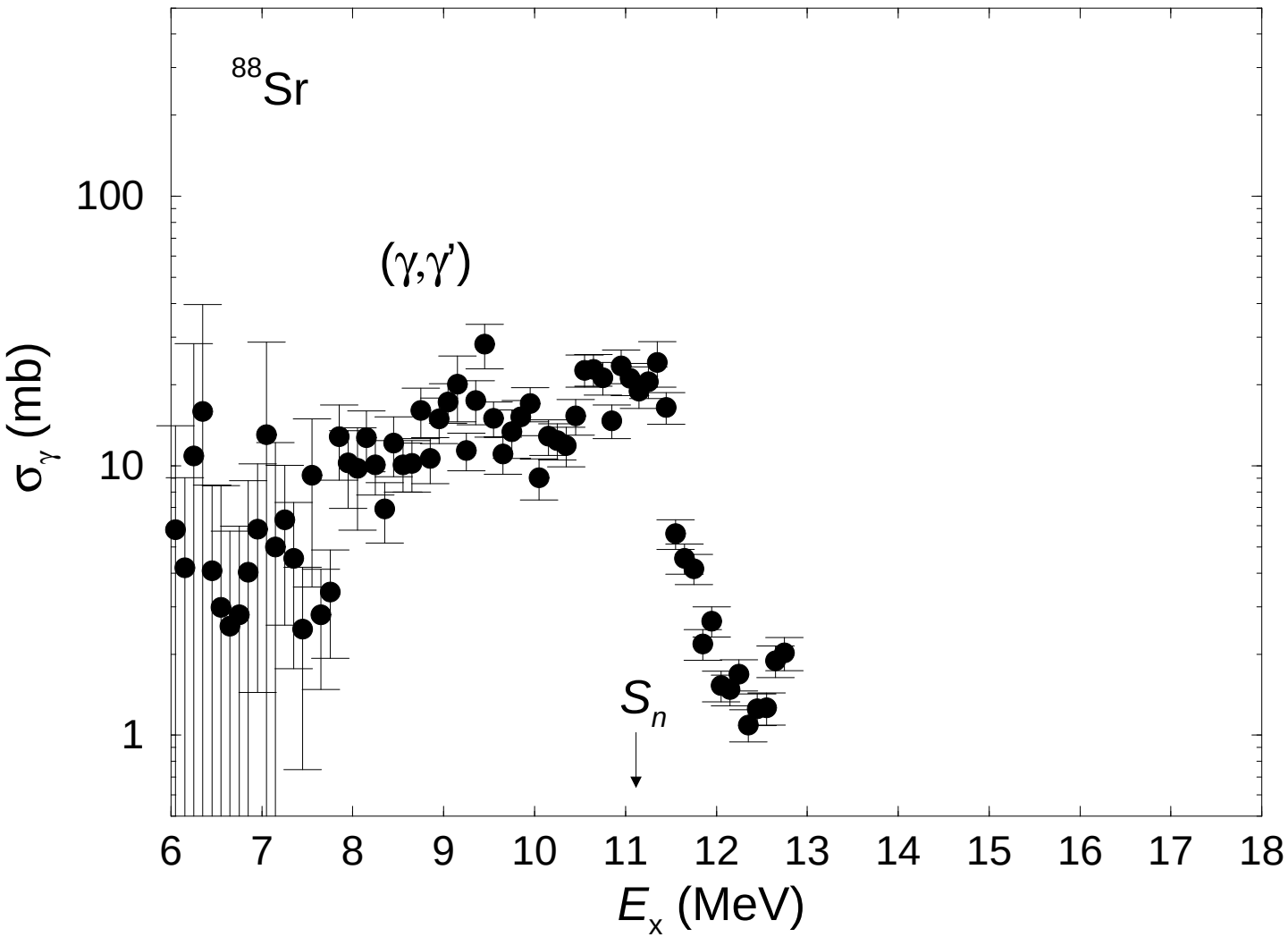


Simulated intensity distribution of transitions depopulating levels in a 100 keV bin around 11 MeV.



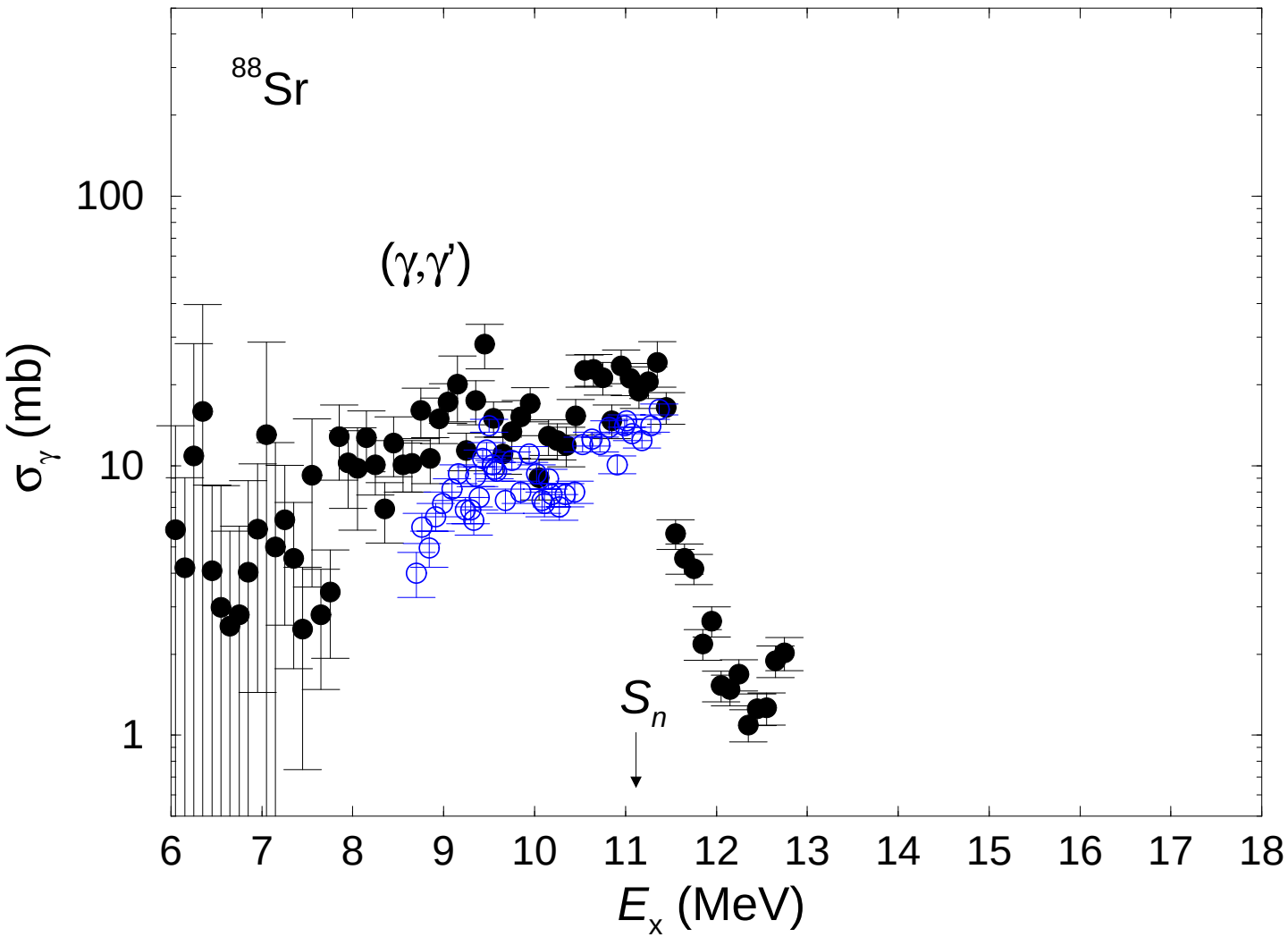
Distribution of branching ratios $b_0 = \Gamma_0/\Gamma$ versus the excitation energy as obtained from the simulations of γ-ray cascades for ^{88}Sr. Solid line: mean values of b_0. Dashed lines: maximum uncertainties of b_0 resulting from the various nuclear realizations.

Absorption cross section in ^{88}Sr



Present (γ, γ) data

Absorption cross section in ^{88}Sr

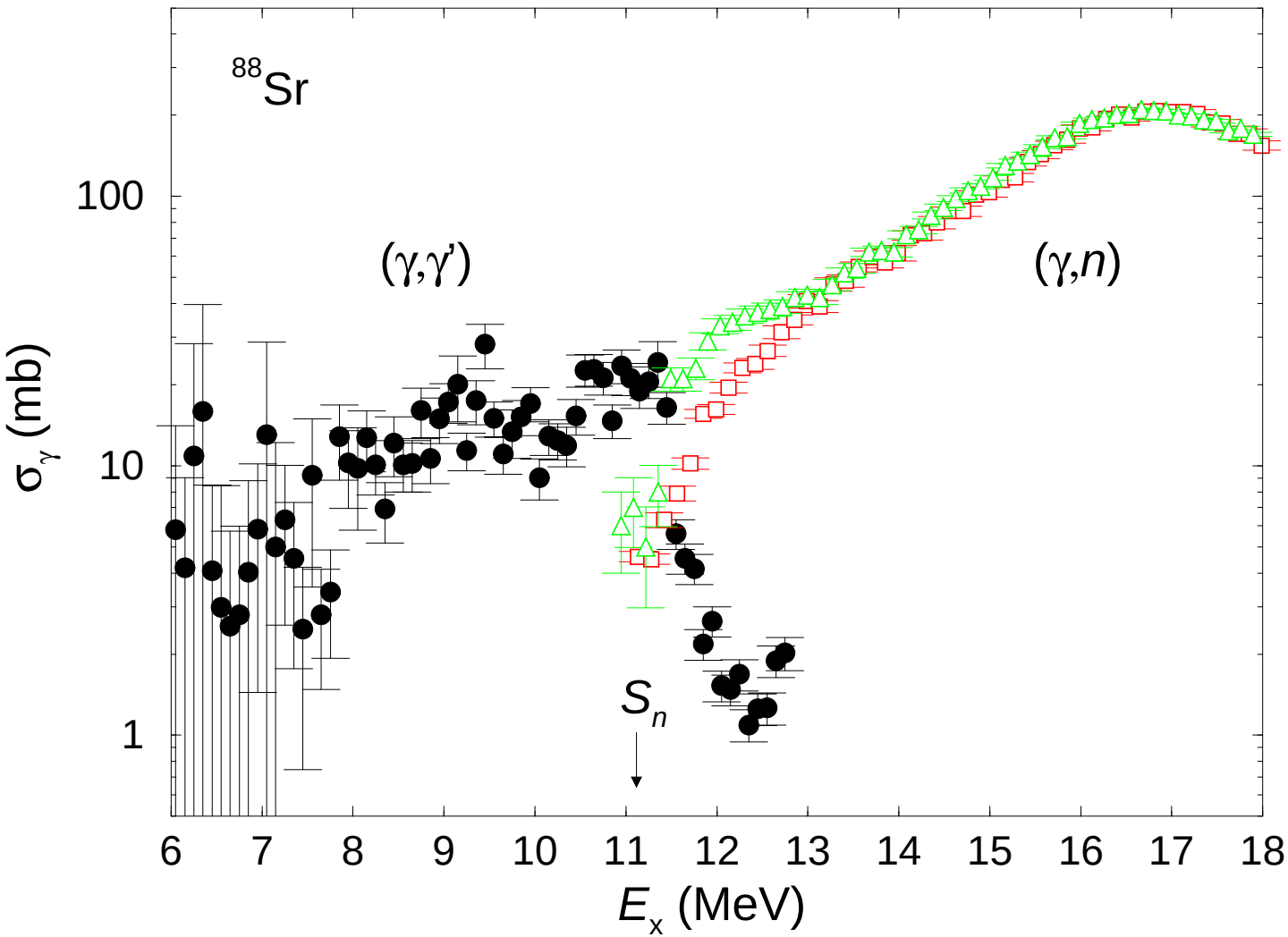


Present (γ, γ) data

Monoenergetic photons

PRC 8 (1973) 1421

Absorption cross section in ^{88}Sr

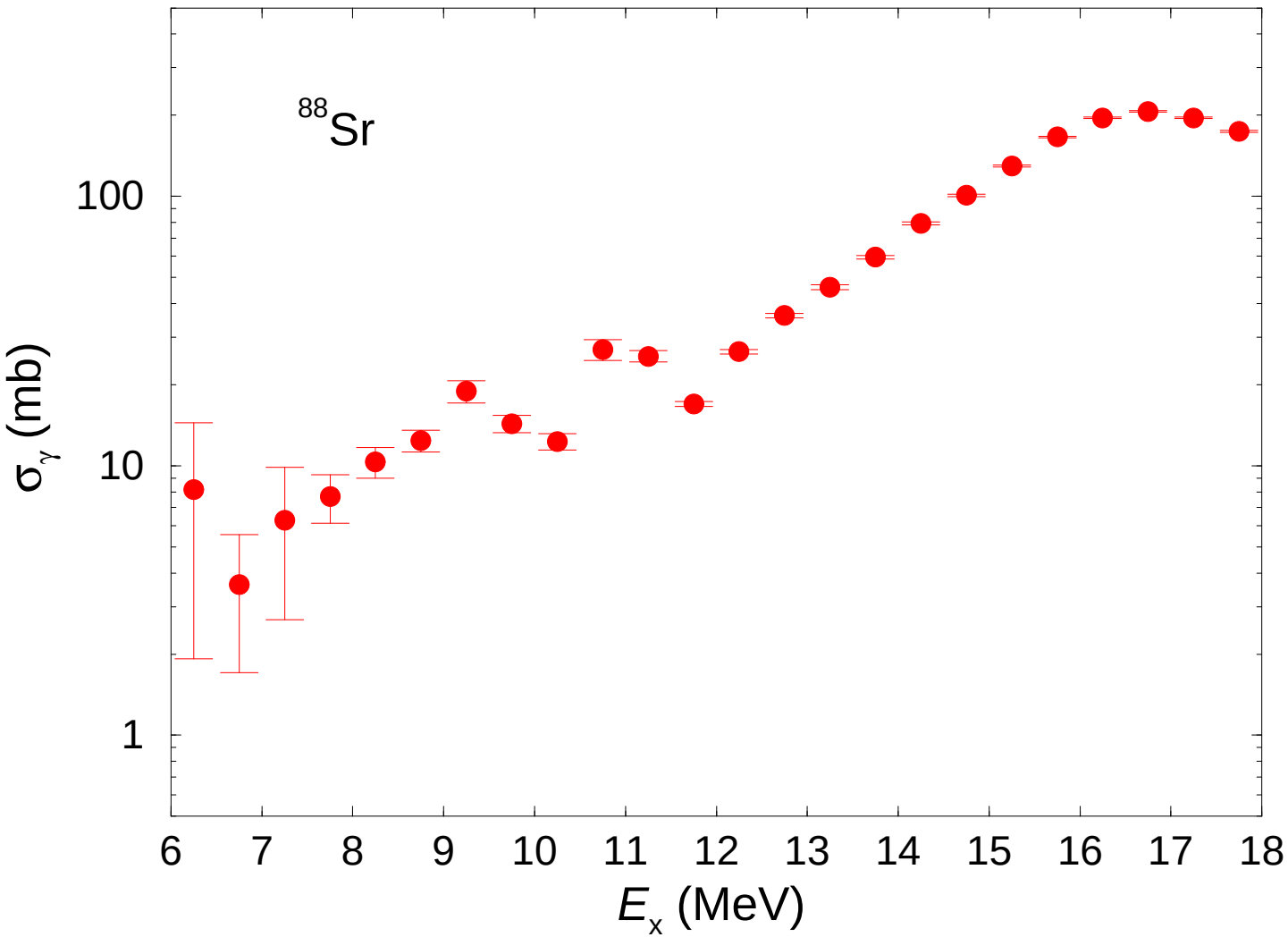


Present (γ, γ) data

(γ, n) data
NPA 175 (1971) 609

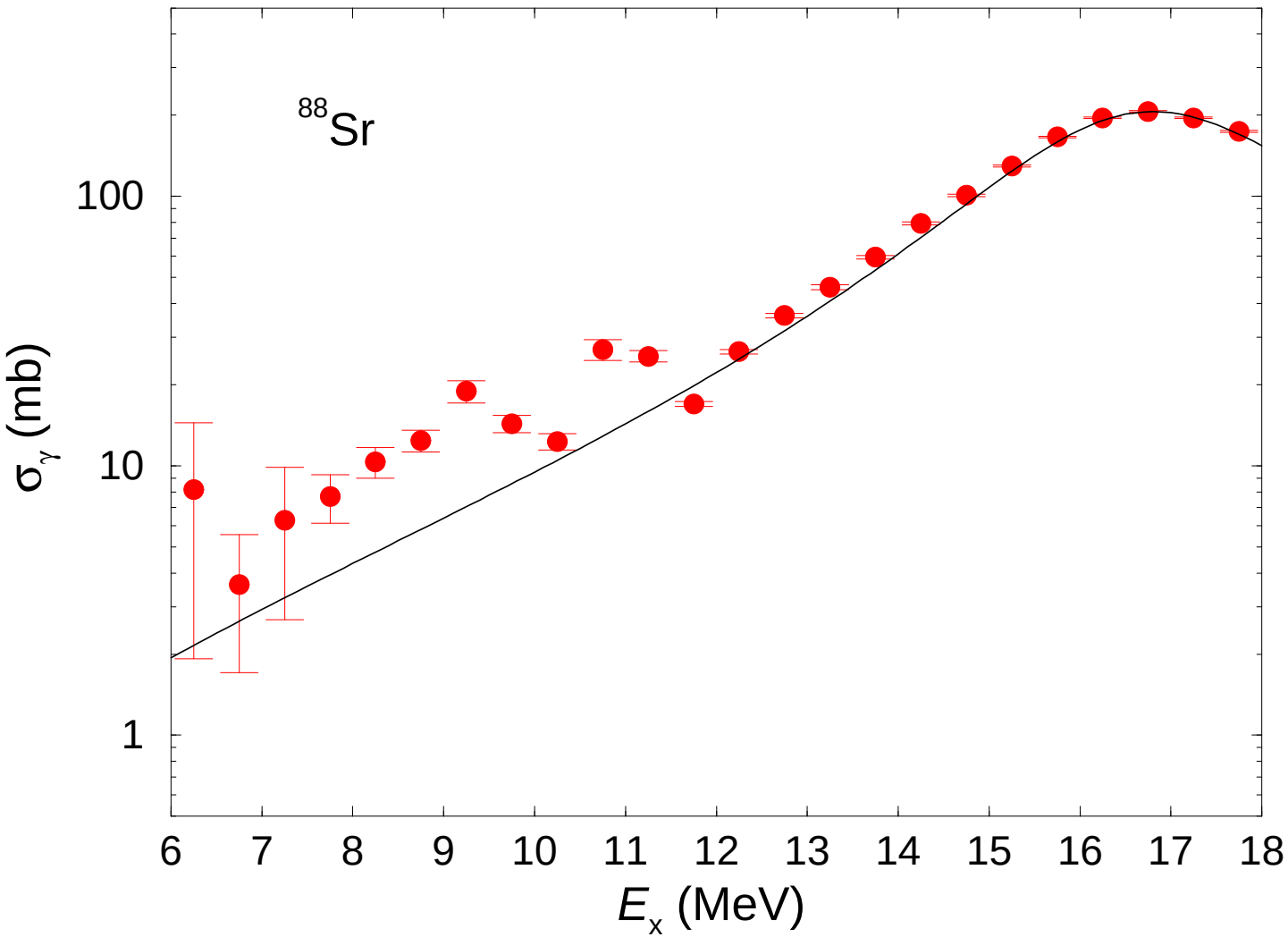
(γ, n) data
VTYF 8 (1982) 121

Absorption cross section in ^{88}Sr



Present (γ, γ) data
$+ (\gamma, n)$ data

Absorption cross section in ^{88}Sr



Present (γ, γ) data
$+ (\gamma, n)$ data

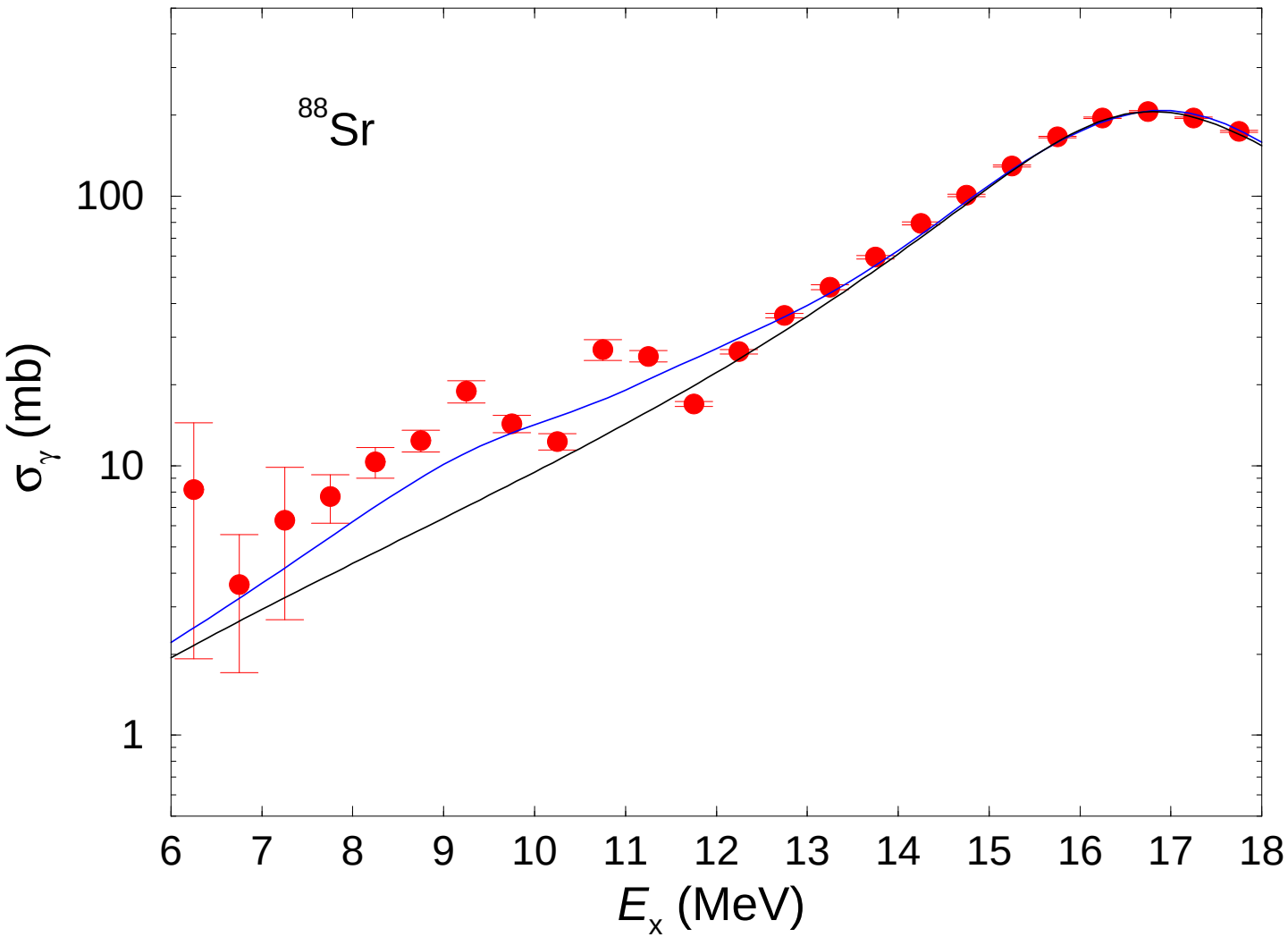
Lorentz curve:

$E_0 = 16.8$ MeV

$\Gamma = 4.0$ MeV

$\frac{\pi}{2}\sigma_0\Gamma = 60\ \frac{NZ}{A}$ MeV mb

Absorption cross section in ^{88}Sr

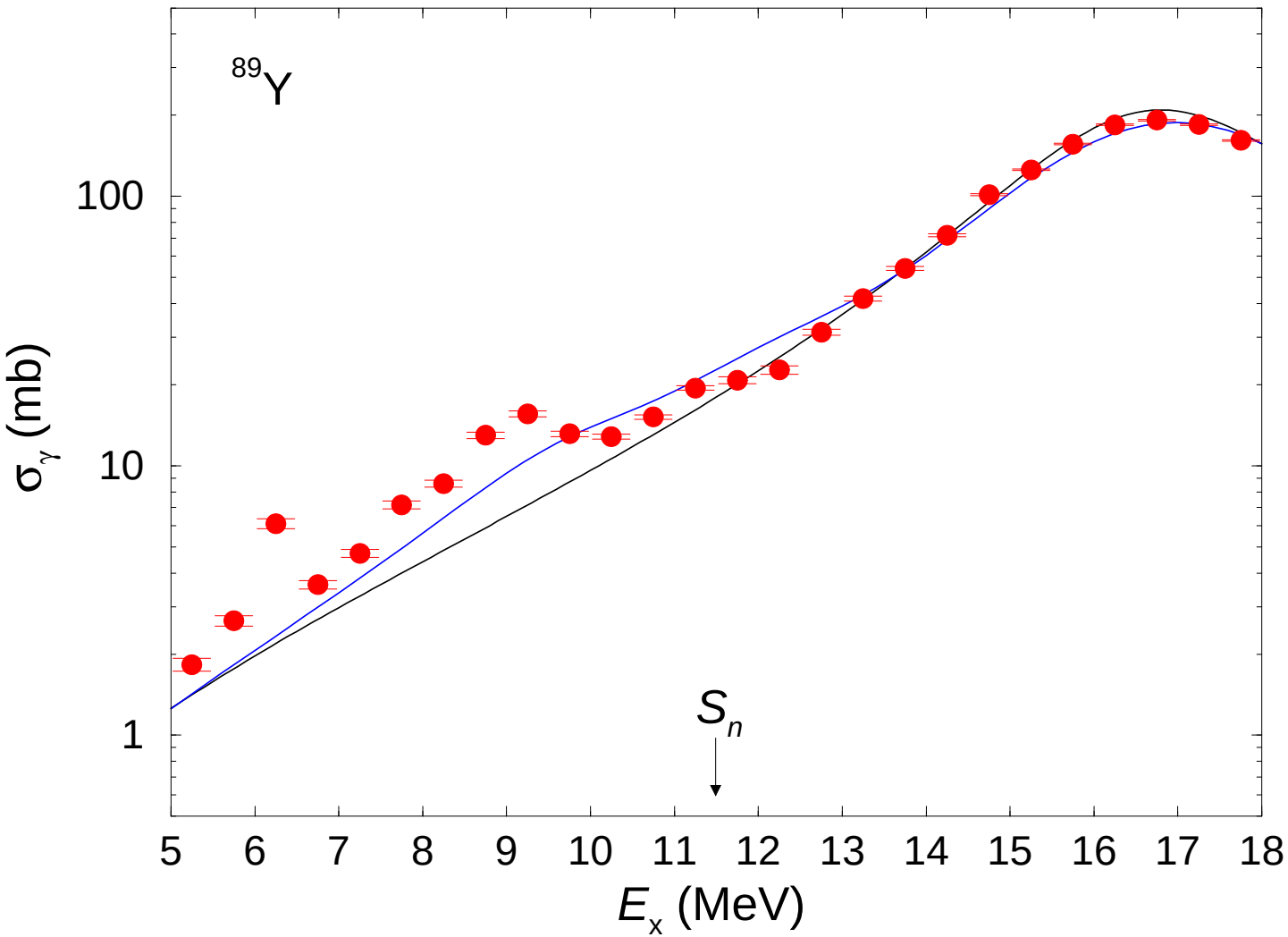


Present (γ, γ) data
$+ (\gamma, n)$ data

Lorentz curve:
$E_0 = 16.8$ MeV
$\Gamma = 4.0$ MeV
$\frac{\pi}{2}\sigma_0\Gamma = 60\ \frac{NZ}{A}$ MeV mb

QRPA
Woods-Saxon basis:
$\Gamma = 3.2$ MeV

Absorption cross section in ^{89}Y

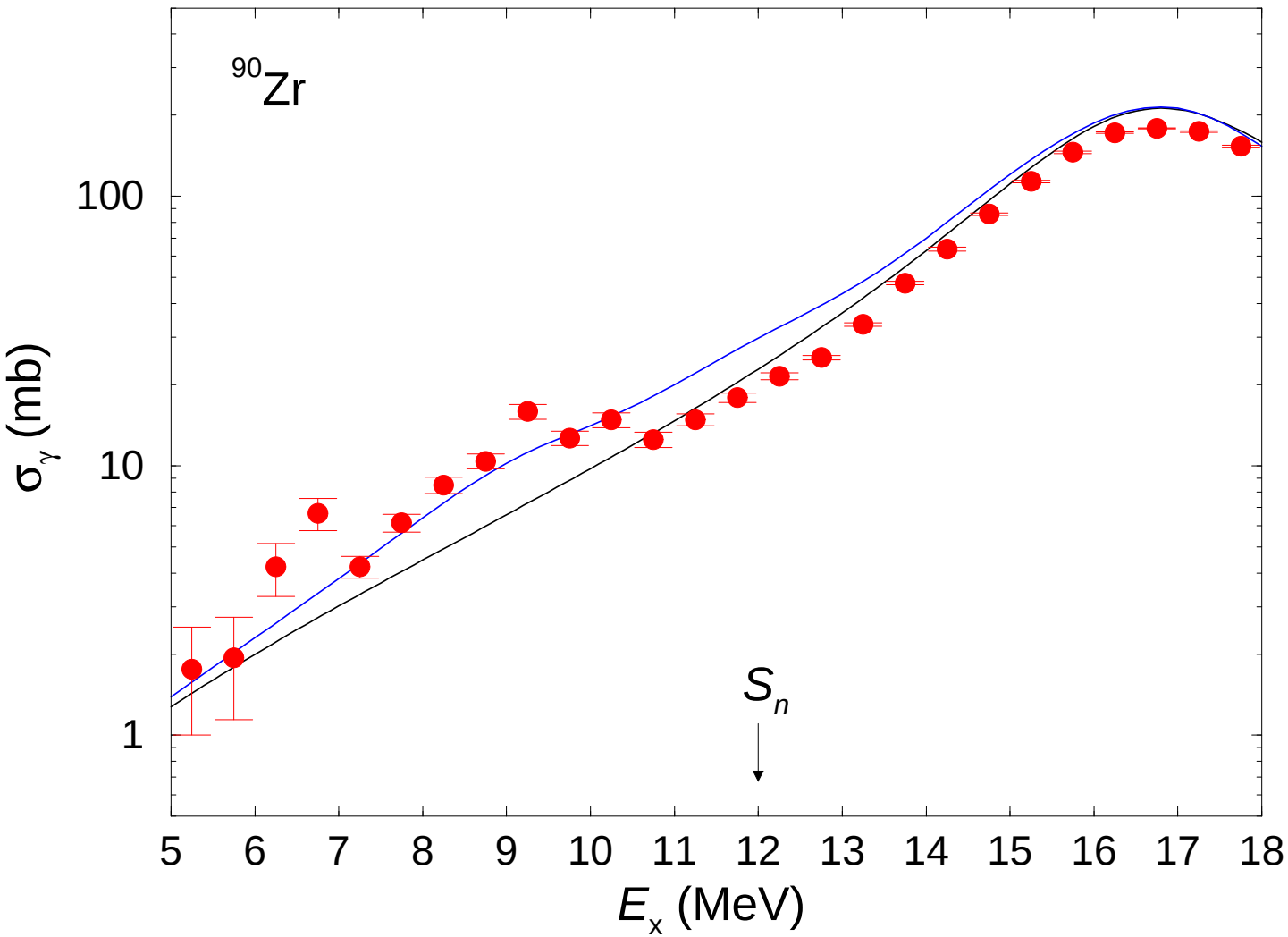


Present (γ, γ) data
$+ (\gamma, p)$ data
$+ (\gamma, n)$ data

Lorentz curve:
$E_0 = 16.8$ MeV
$\Gamma = 4.0$ MeV
$\frac{\pi}{2}\sigma_0\Gamma = 60\ \frac{NZ}{A}$ MeV mb

QRPA
Woods-Saxon basis:
$\Gamma = 3.2$ MeV

Absorption cross section in ^{90}Zr

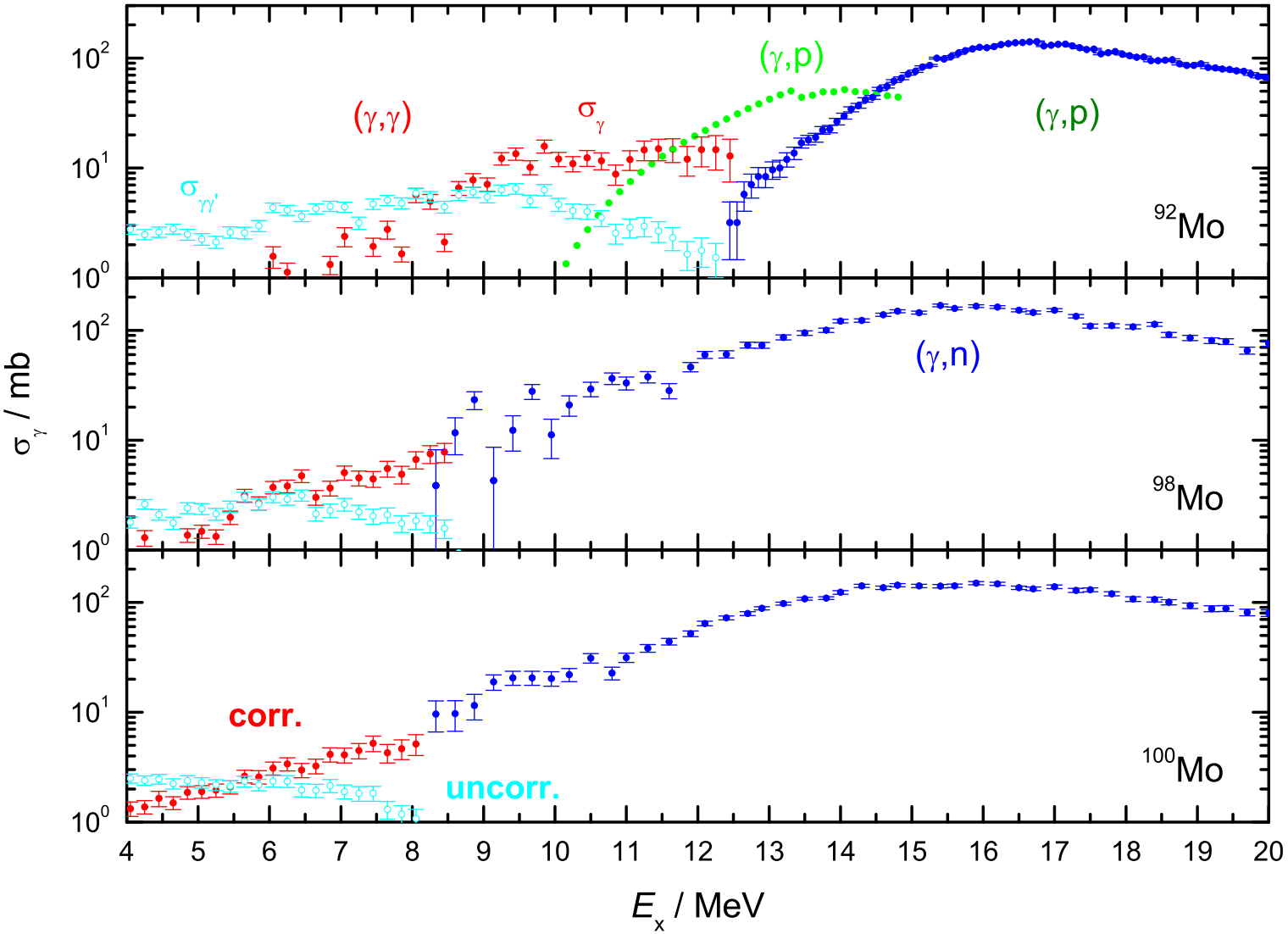


Present (γ, γ) data
$+ (\gamma, p)$ data
$+ (\gamma, n)$ data

Lorentz curve:
$E_0 = 16.8$ MeV
$\Gamma = 4.0$ MeV
$\frac{\pi}{2}\sigma_0\Gamma = 60\ \frac{NZ}{A}$ MeV mb

QRPA
Woods-Saxon basis:
$\Gamma = 3.2$ MeV

Absorption cross sections in ^{92}Mo, ^{98}Mo and ^{100}Mo



(γ, n) - experiment:
H. Beil et al.,
NPA 227 (1974) 427

(γ, p) - theory:
T. Rauscher and
F.-K. Thielemann,
ADNDT 88 (2004) 1

QRPA calculations for deformed nuclei

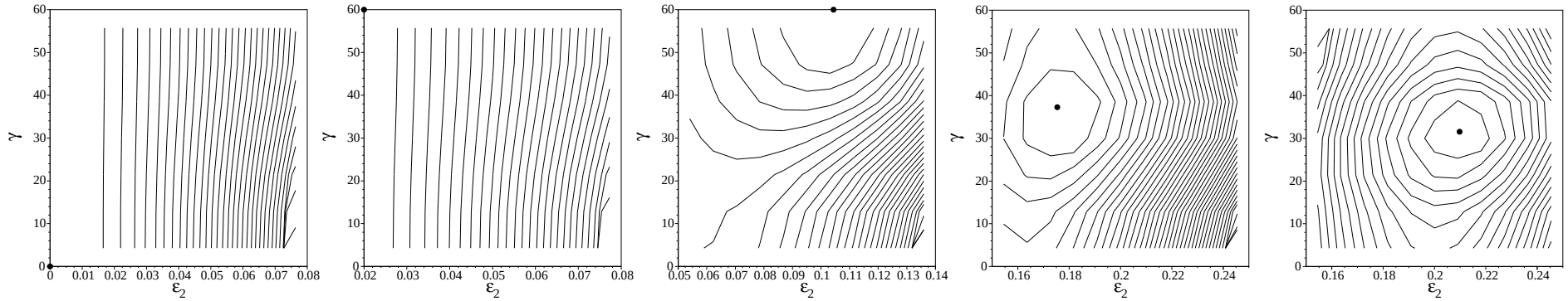
Hamiltonian for 1^- states:

- Nilsson or Woods-Saxon mean field plus monopole pairing
- isoscalar and isovector dipole-dipole and octupole-octupole interactions

F. Dönau, PRL 94 (2005) 092503

F. Dönau et al., PRC 76 (2007) 014317

Total energy as a function of the quadrupole deformation ε_2 and the triaxiality γ:

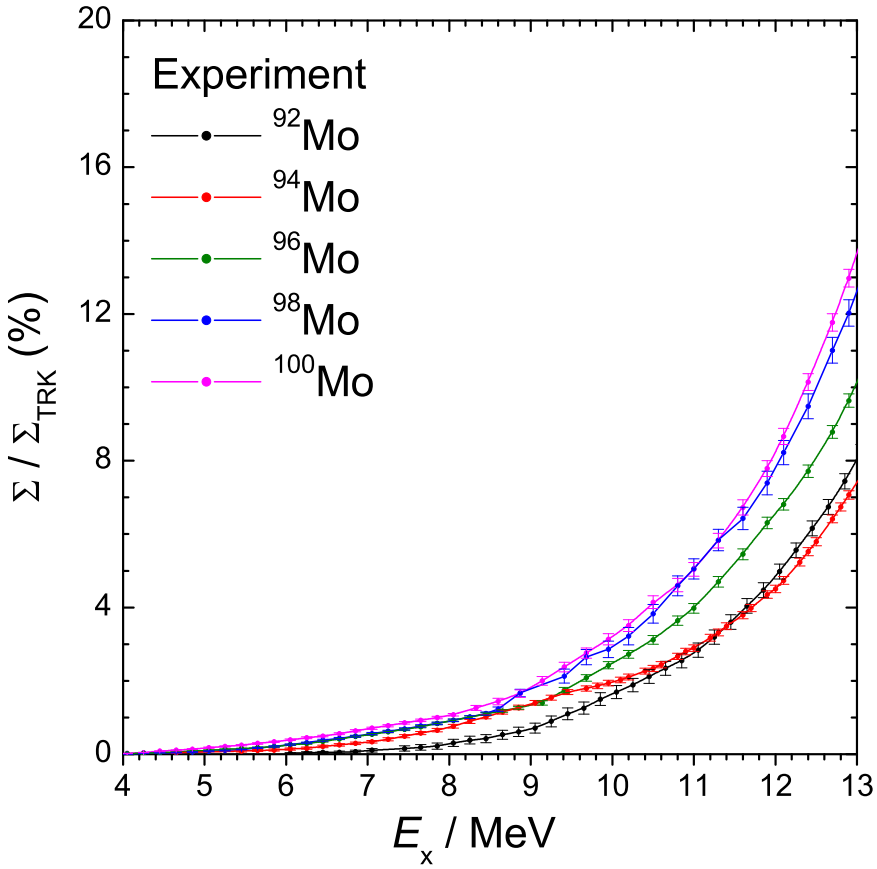


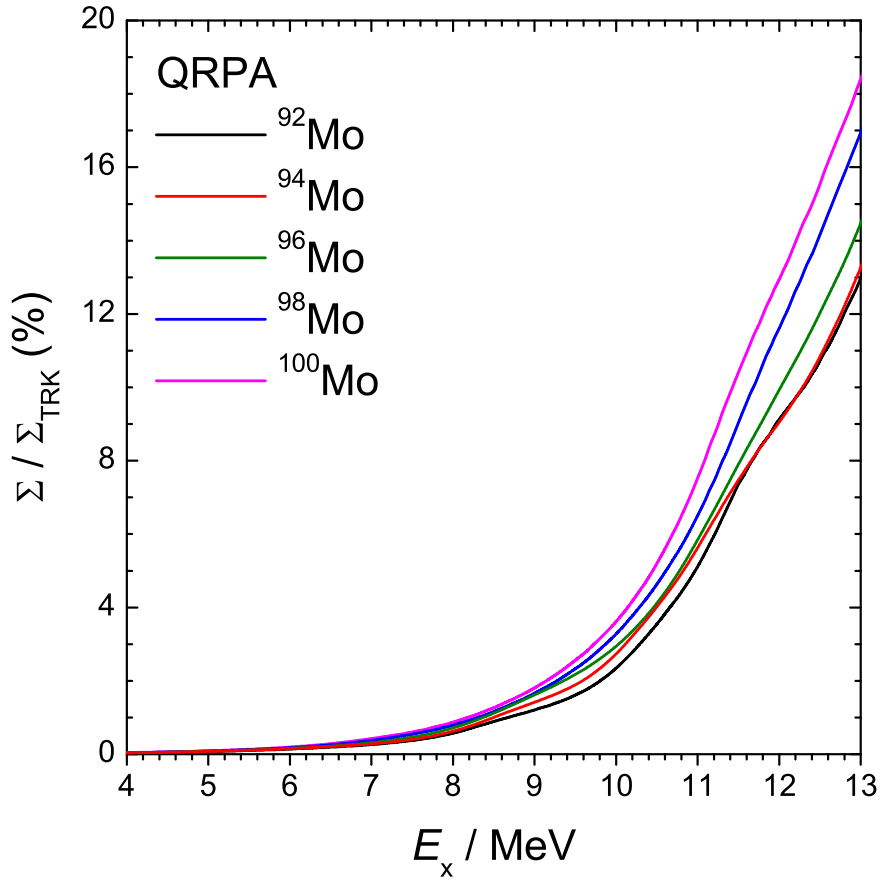
$^{92}Mo_{50}$	$^{94}Mo_{52}$	$^{96}Mo_{54}$	$^{98}Mo_{56}$	$^{100}Mo_{58}$
$\varepsilon_2 = 0.0$	$\varepsilon_2 = 0.02$	$\varepsilon_2 = 0.10$	$\varepsilon_2 = 0.18$	$\varepsilon_2 = 0.21$
		$\gamma = 60°$	$\gamma = 37°$	$\gamma = 32°$

TAC model with shell-correction method:

S. Frauendorf, NPA 557 (1993) 259c, NPA 667 (2000) 115

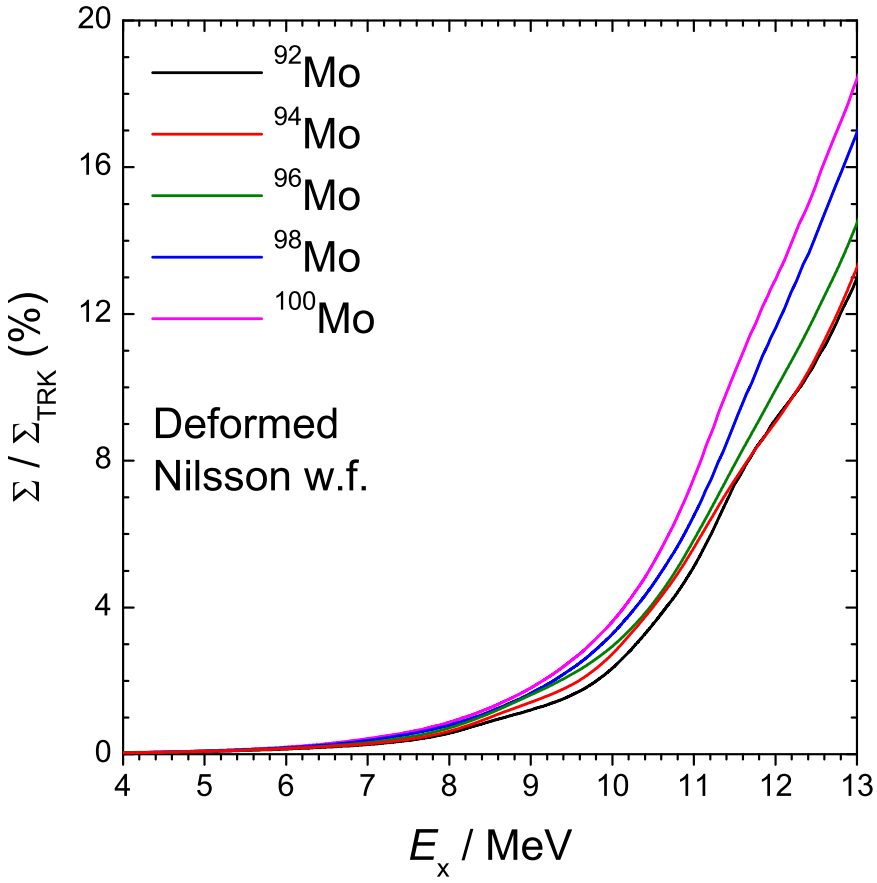
Experiments and QRPA calculations for deformed Mo isotopes

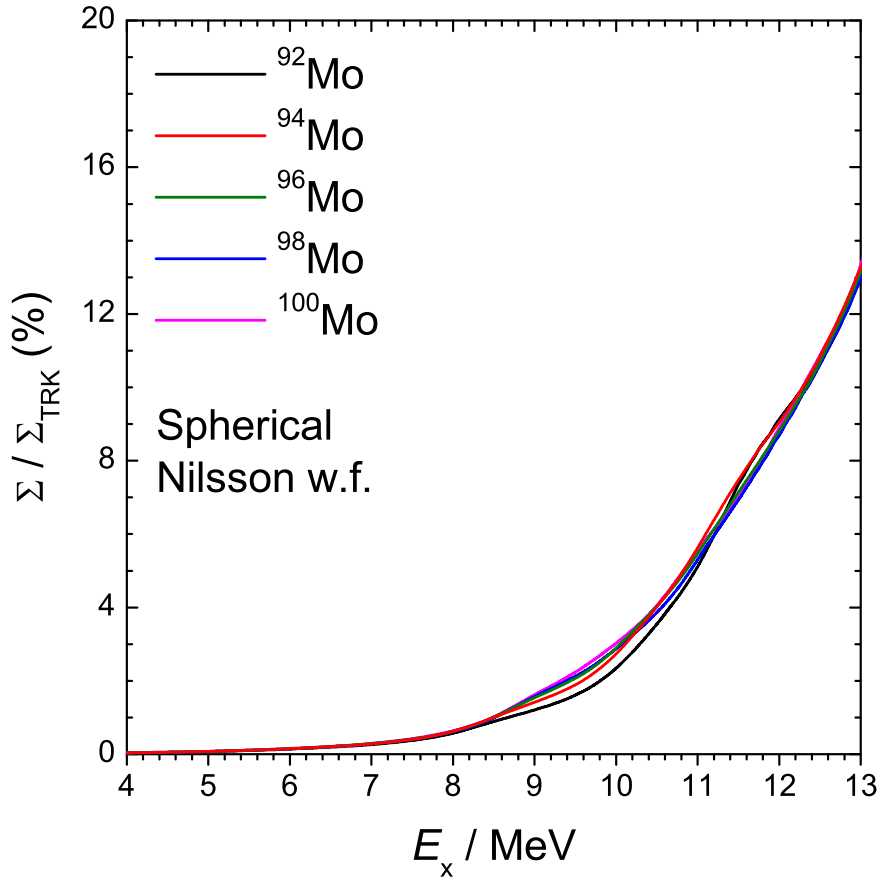




$$\Sigma(E_x) = \sum_{i}^{E_x} \sigma_\gamma(E_i)\ \Delta E \qquad \Sigma_{TRK} = 60\ NZ/A\ \ \text{MeV mb}$$

Deformed and spherical QRPA calculations for Mo isotopes





$$\Sigma(E_x) = \sum_{i}^{E_x} \sigma_\gamma(E_i)\ \Delta E \qquad \Sigma_{TRK} = 60\ NZ/A\ \ \text{MeV mb}$$

Summary

- Study of dipole-strength functions of N=50 isotones and of even-even Mo isotopes up to the neutron-separation energies at the photon-scattering facility of ELBE.
- Measurement with polarised photons for ^{88}Sr: Multipolarity $E1$ deduced for 50 g.s. transitions above 6 MeV including 63% of the total $E1$ strength of all g.s. transitions.
- Comparison of measured spectrum with calculated atomic background: 30 – 40% of the total dipole strength in resolved peaks and 70 – 60% in continuum.
- Simulations of statistical γ cascades: Estimate of intensities of branching transitions.
- The reconstructed σ_γ connect smoothly with (γ,n) data.

⇒ For the first time in photon-scattering experiments:
(i) Correct determination of the dipole-strength function at high excitation energy.
(ii) Information on the photoabsorption cross section over the whole energy range up to the GDR.

- QRPA calculations:
(i) Reproduction of observed extra strength in the energy range from 6 – 12 MeV.
(ii) The increase of the dipole strength towards the heavier Mo isotopes is correlated with increasing deformation.