Electromagnetic excitations in nuclei: from photon scattering to photodisintegration

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- The bremsstrahlung facility
- Photon-scattering experiments
- Photoactivation experiments

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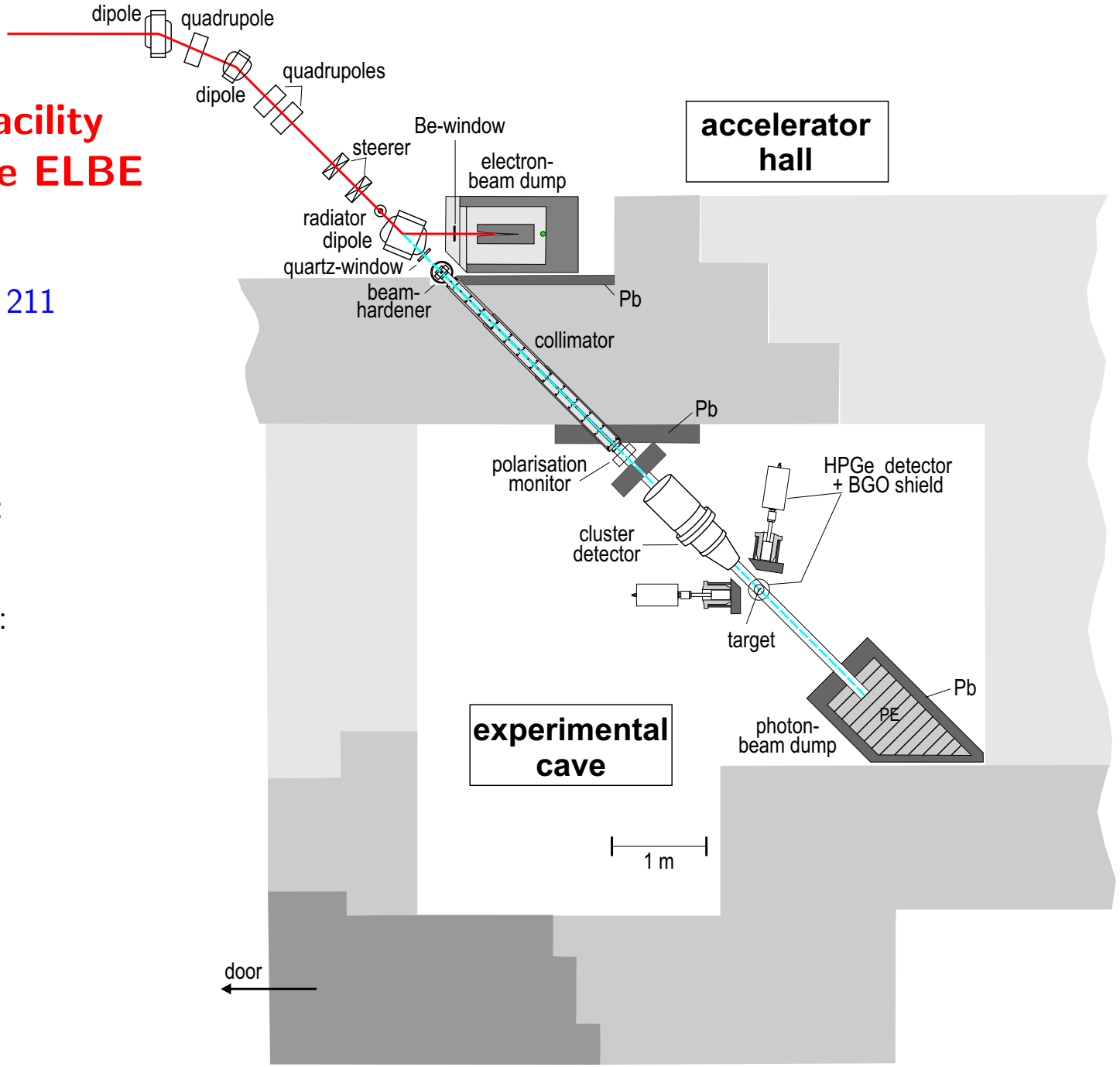
The bremsstrahlung facility at the radiation source ELBE

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:
  < 10 ps

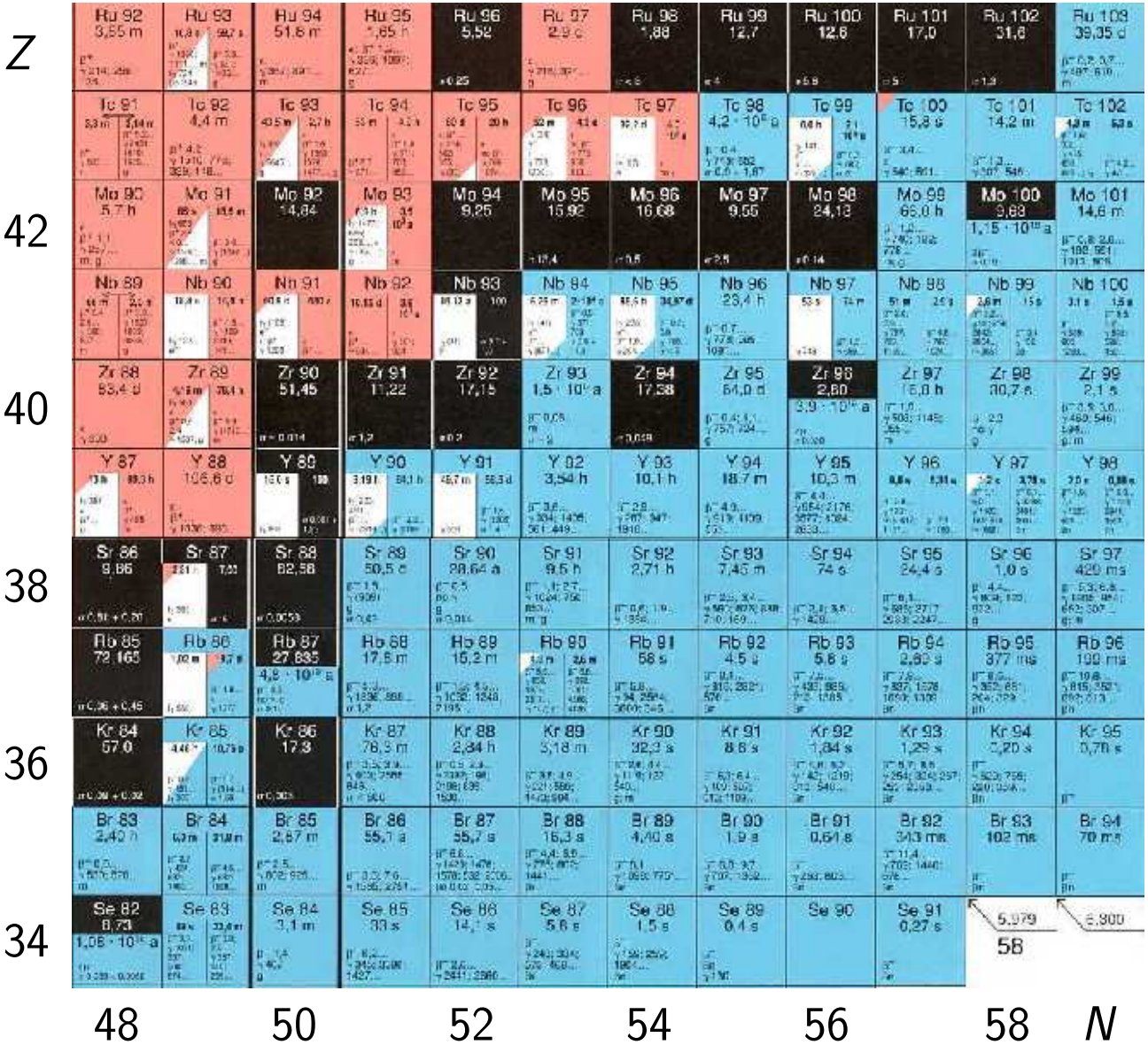


Detector setup

Dipole strength close to the particle-separation energy

- Importance for the understanding of astrophysical processes.
  $\Rightarrow$ Influence on (γ,n) reaction rates for the production of particular neutron-deficient nuclei in the so-called p-process.
- Open problems:
  - The precise knowledge of $E1$ strength on the low-energy tail of the Giant Dipole Resonance
  - The properties of the Pygmy Dipole Resonance, a concentration of $E1$ strength in the energy range between about 5 MeV and 11 MeV.

Nuclides under investigation in photon-scattering experiments



nuclide	S_n MeV	E_e^{kin} MeV
^{92}Mo	12.7	6.0, 13.2
^{98}Mo	8.6	3.3[a], 3.8[a], 13.2
^{100}Mo	8.3	3.2[a], 3.4[a], 3.8[a] 7.8, 13.2
^{88}Sr	11.1	6.8[b], 9.0, 13.2, 16.0
^{89}Y	11.5	7.0[c], 13.2
^{90}Zr	12.0	7.0, 9.0, 12.8

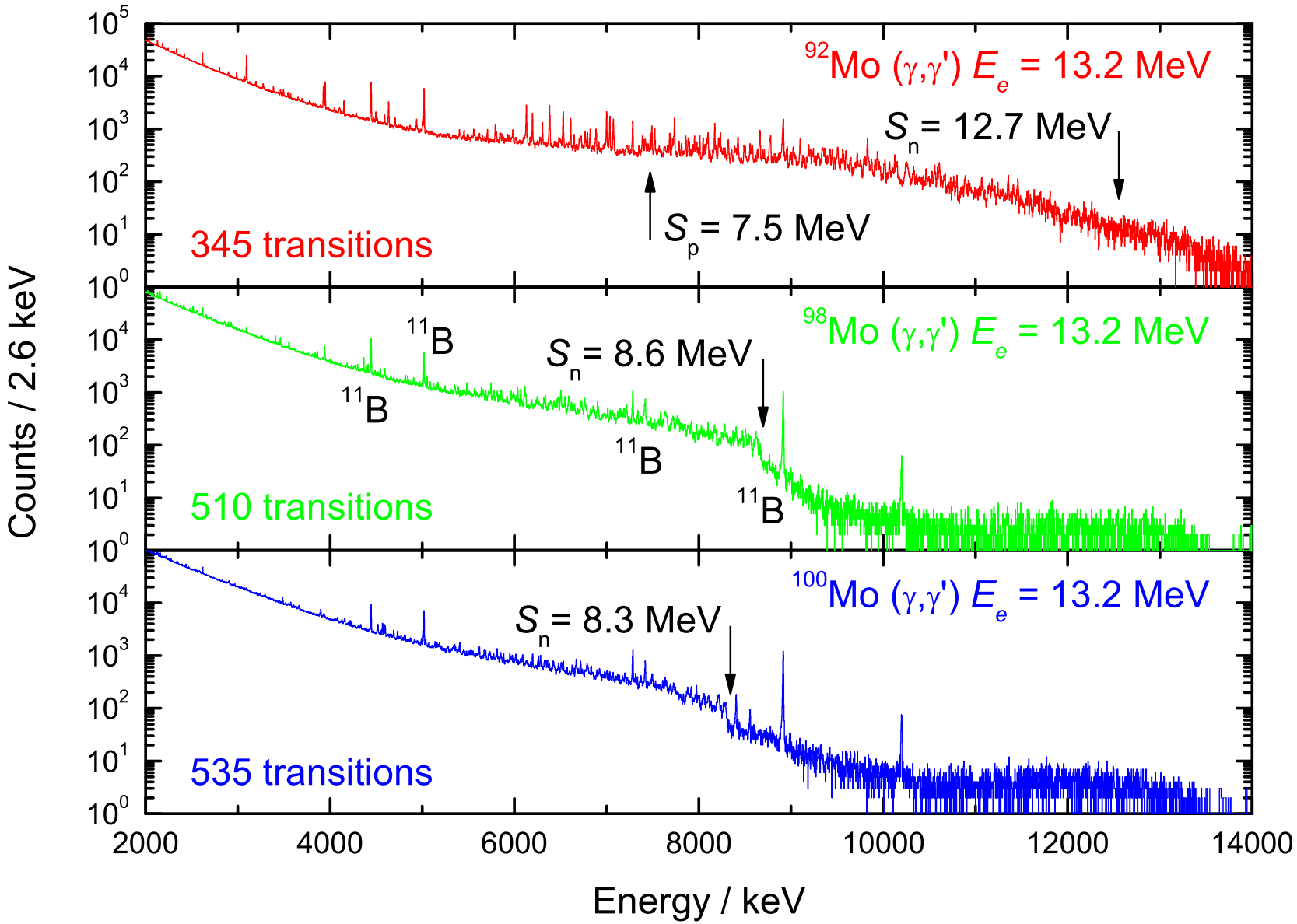
ELBE experiment

[a] Dynamitron experiment, PRL 95 (2005) 062501

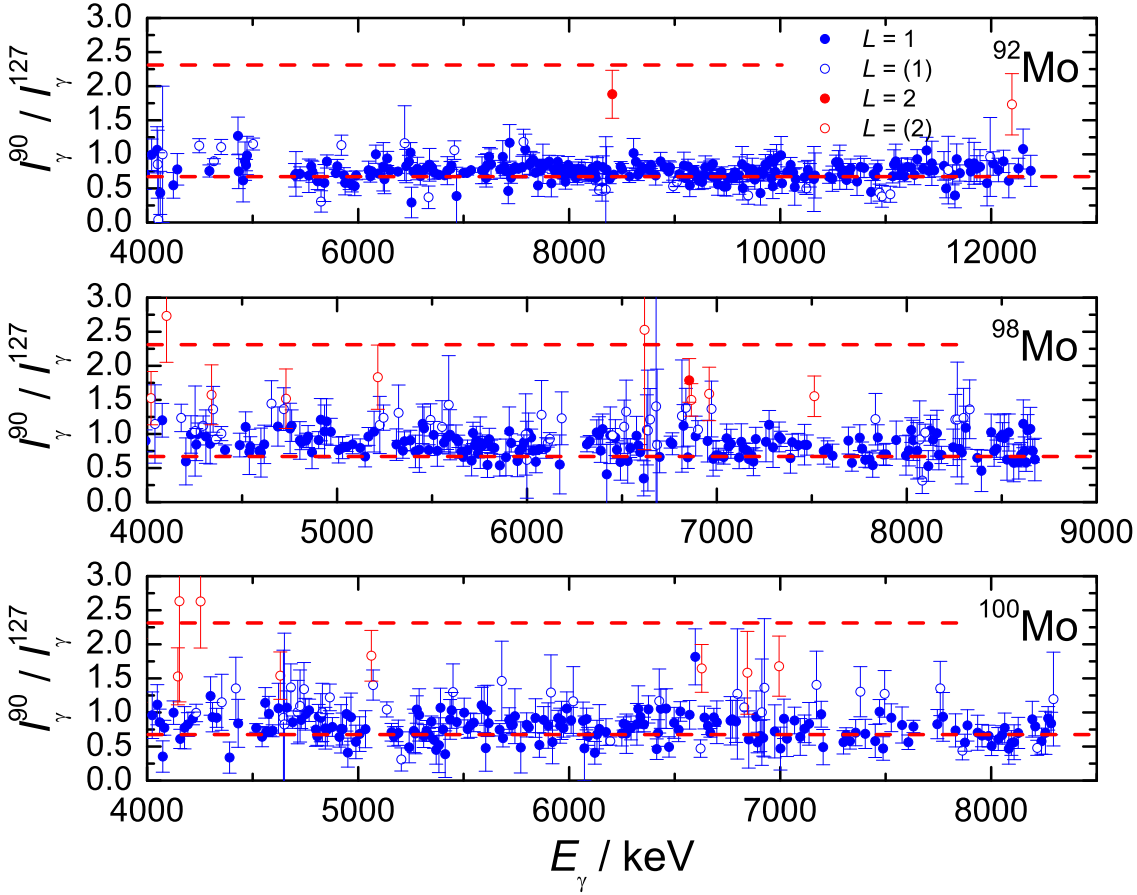
[b] S-Dalinac experiment, PRC 70 (2004) 064307

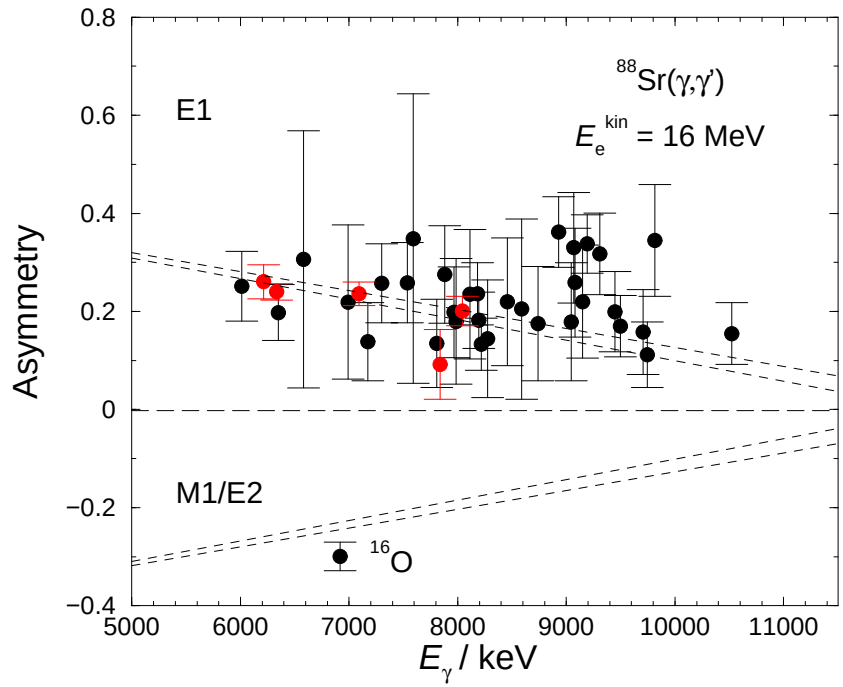
[c] S-Dalinac experiment, NPA 620 (1997) 1

Photon scattering from ^{92}Mo, ^{98}Mo and ^{100}Mo



Angular distributions of transitions in ^{92}Mo, ^{98}Mo and ^{100}Mo
Linear polarisations of transitions in ^{88}Sr



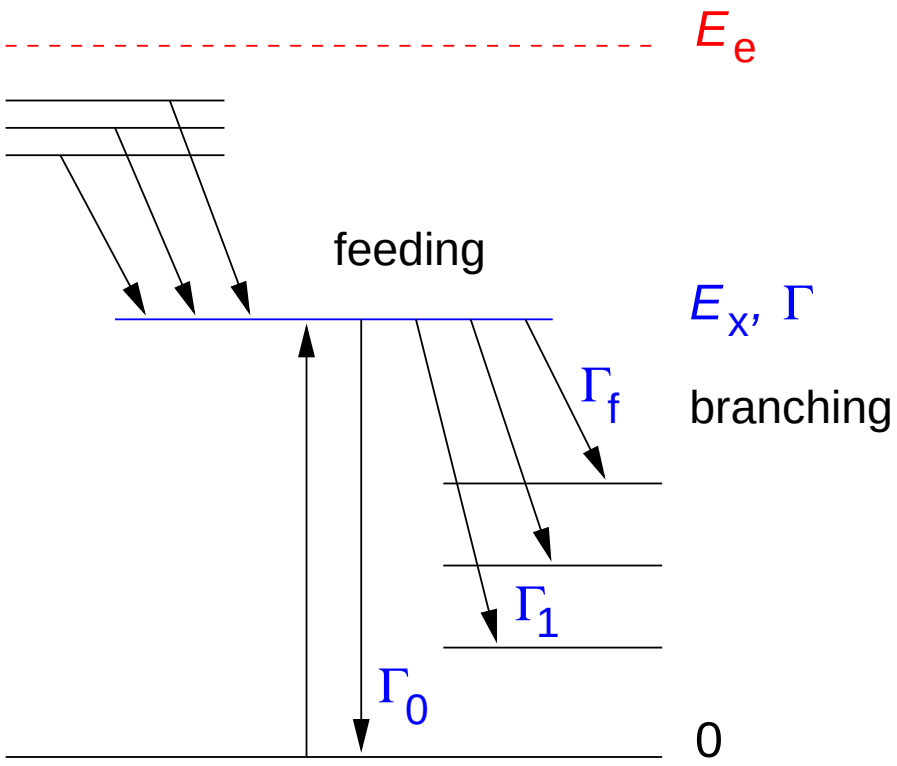


$L = 1$: $I_\gamma(90°)/I_\gamma(127°) = 0.73$

$L = 2$: $I_\gamma(90°)/I_\gamma(127°) = 2.28$

Experimental asymmetries of transitions in ^{88}Sr.

Problem of feeding and branching



Measured intensity of a γ transition:

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

Energy-integrated cross section:

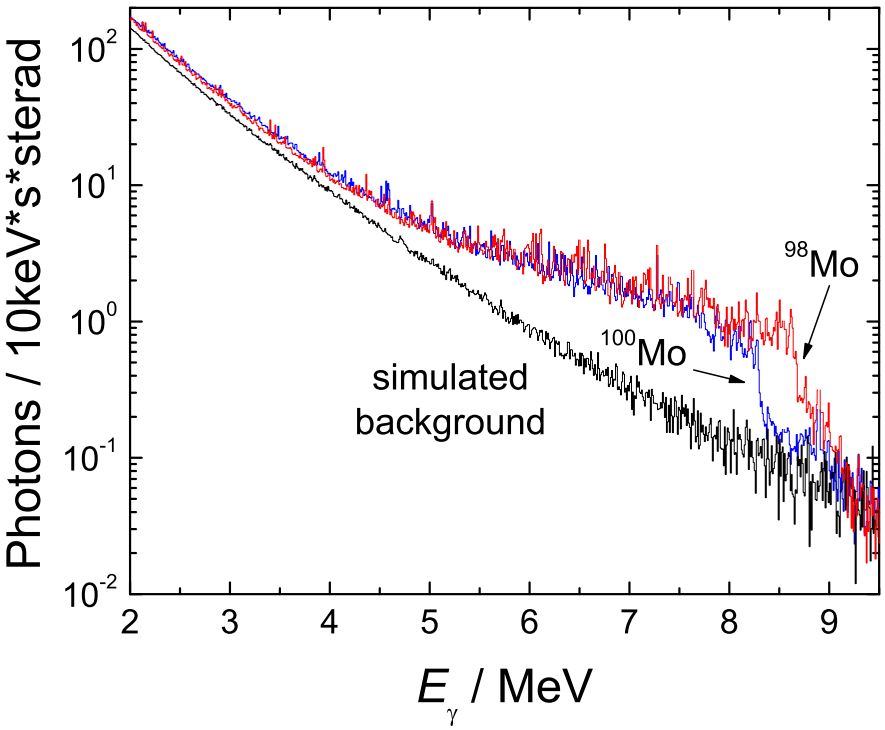
$$I_s = \int \sigma_{\gamma\gamma_0} \, dE$$

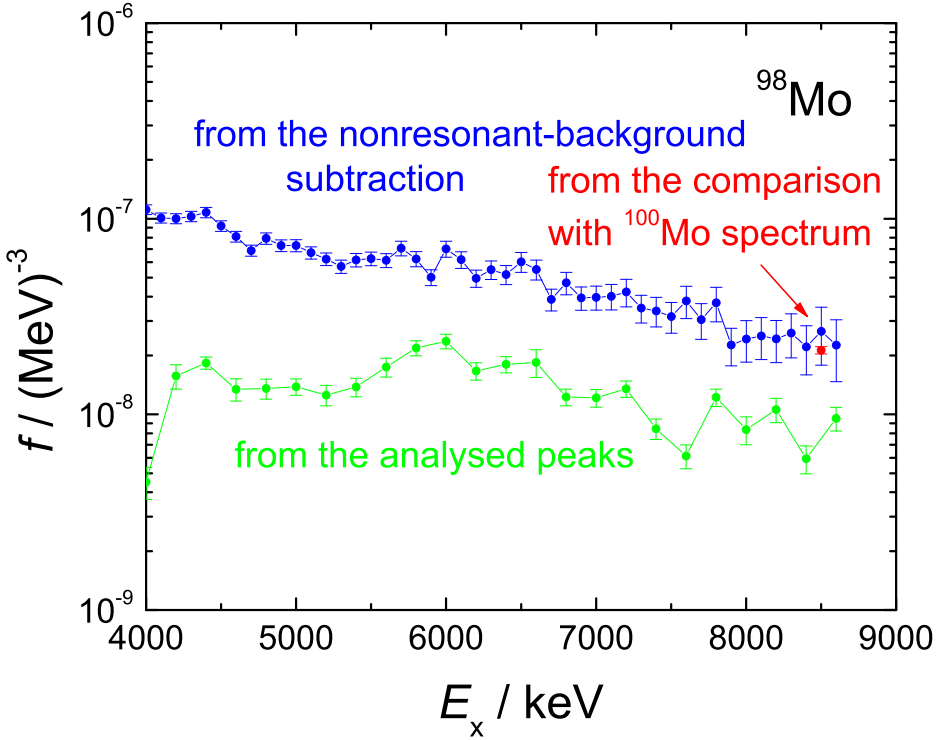
$$I_s = \frac{2J_x + 1}{2J_0 + 1} \left(\frac{\pi\hbar c}{E_x}\right)^2 \frac{\Gamma_0}{\Gamma} \Gamma_0; \quad \Gamma = \frac{\hbar}{\tau}$$

E1 strength:

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

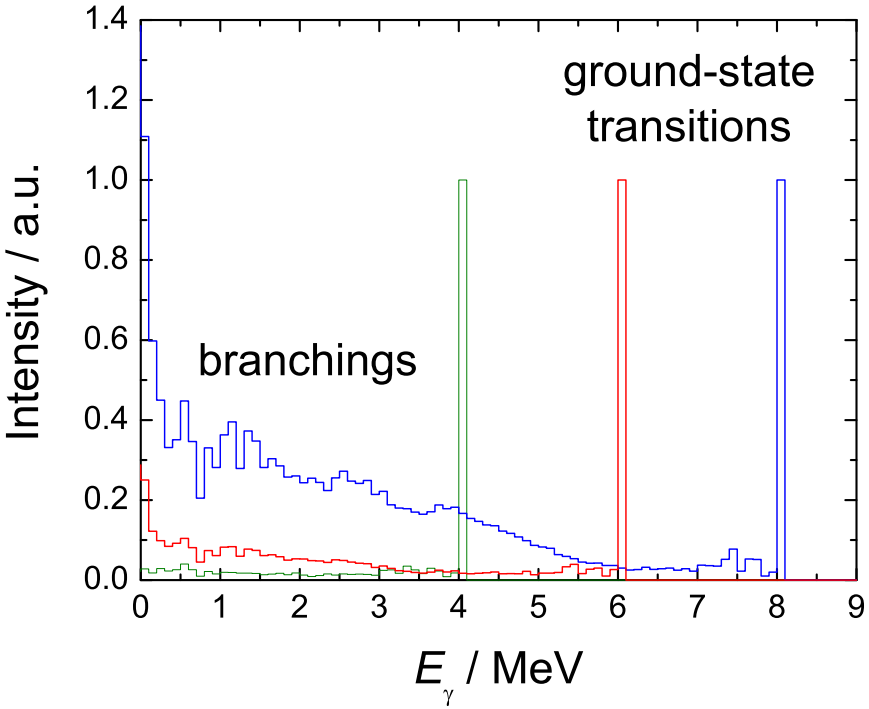
Unresolved strength in the continuum



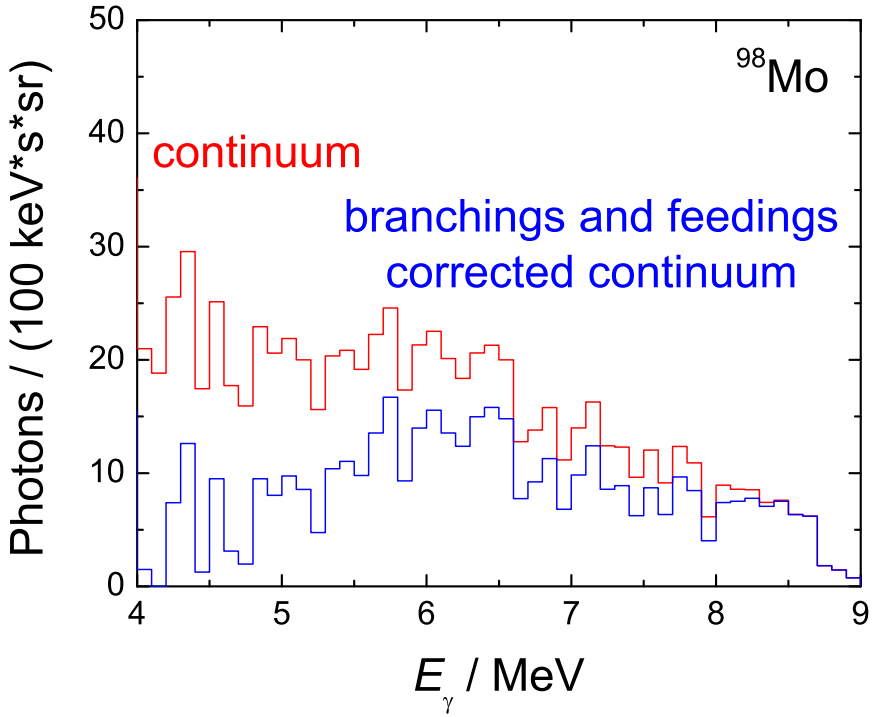


$$f_1(E) = \frac{1}{\Delta} \sum_{\Delta} \frac{\Gamma_0}{E^3}$$

Correction of feeding and branching

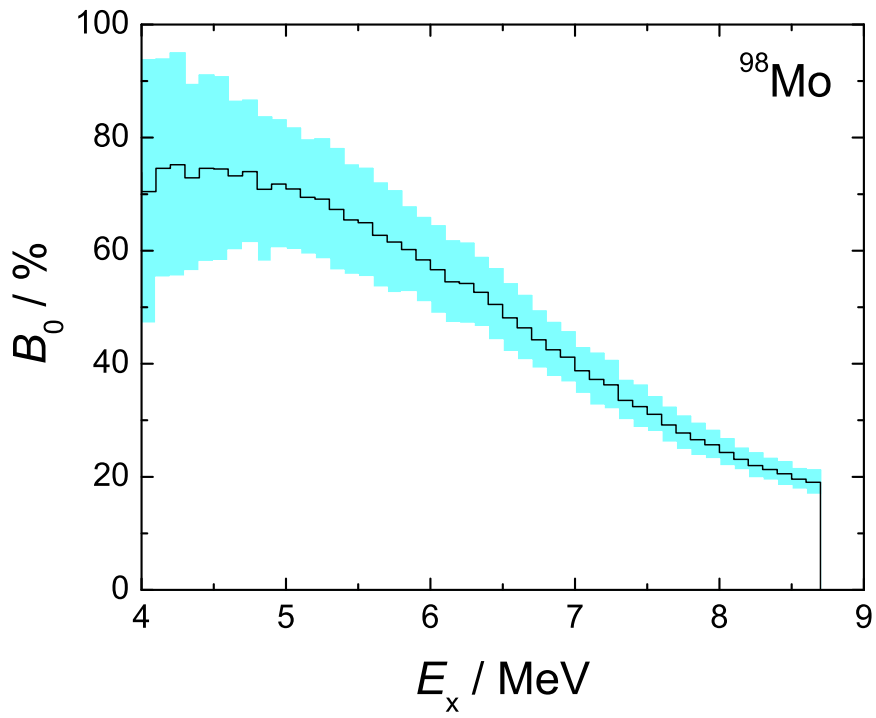


Simulation of the intensity distribution of ground-state and branching transitions.

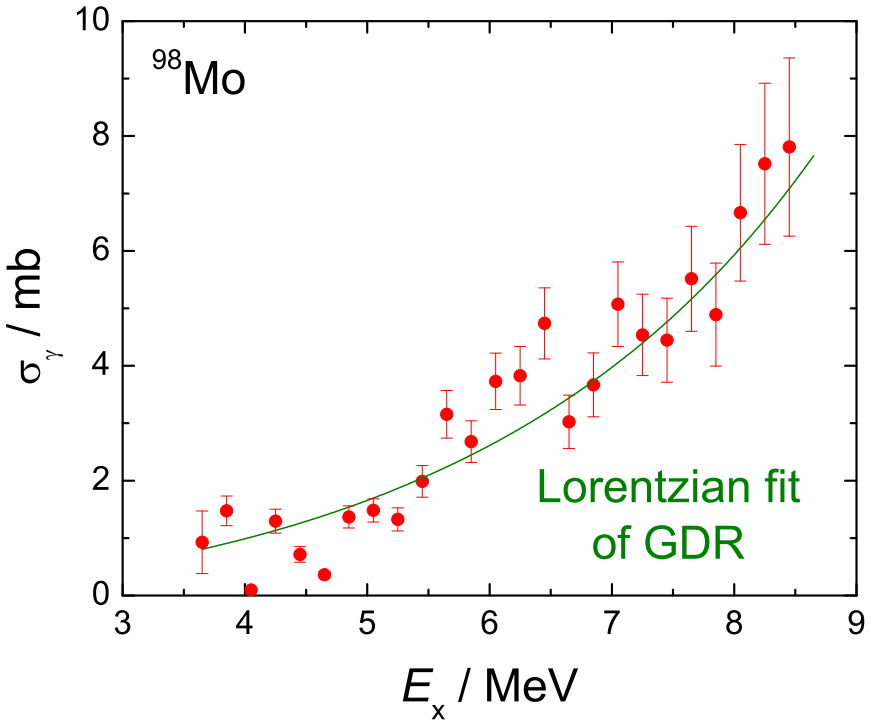


Intensity distribution of ground-state transitions after correction for branchings and feedings.

Correction of feeding and branching

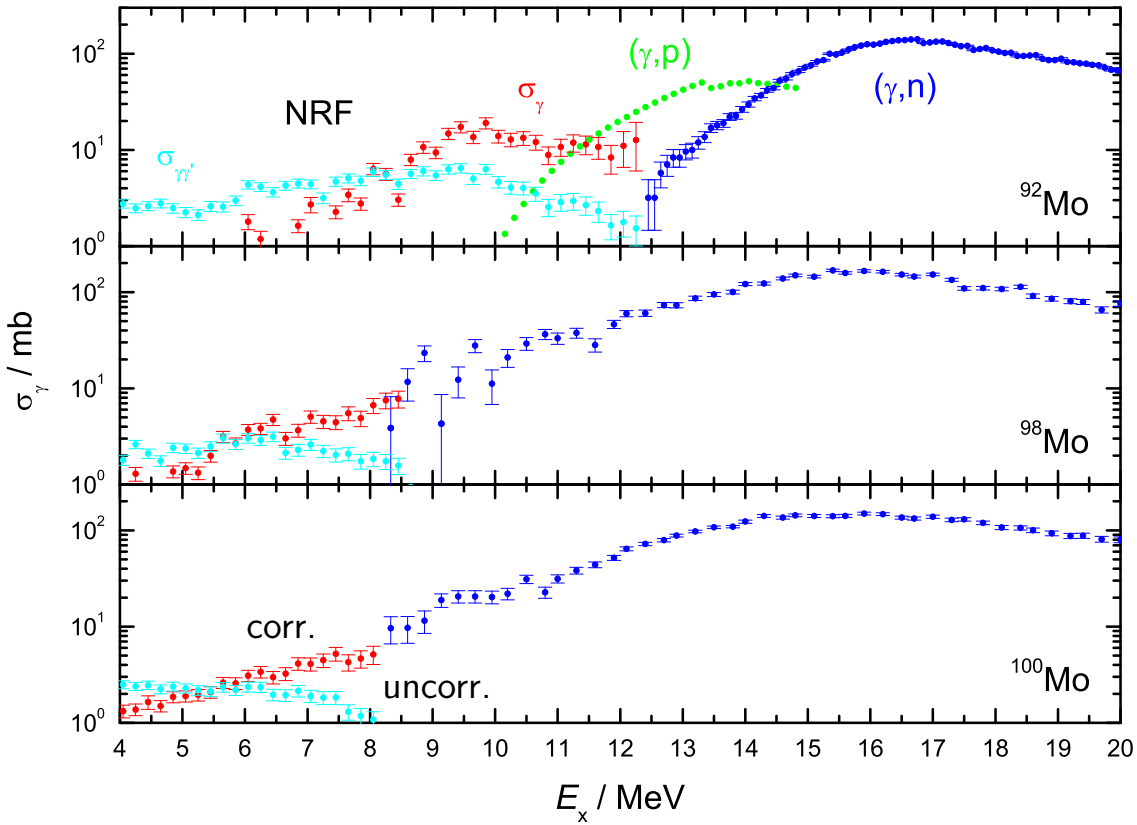


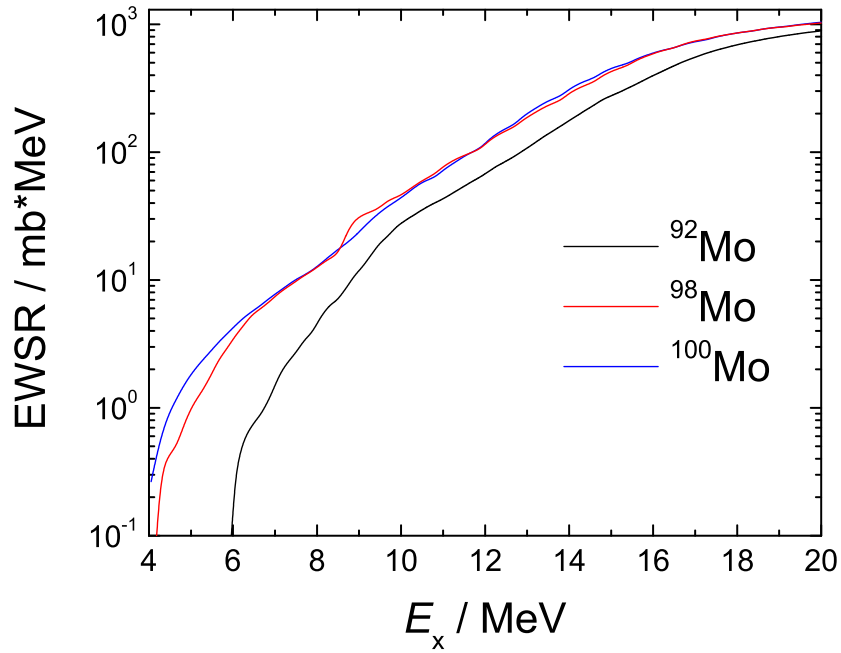
Simulated distribution of branching ratios $B_0 = \Gamma_0/\Gamma$.



Absorption cross section $\sigma_\gamma \sim \Gamma_0/E_\gamma^2$.

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



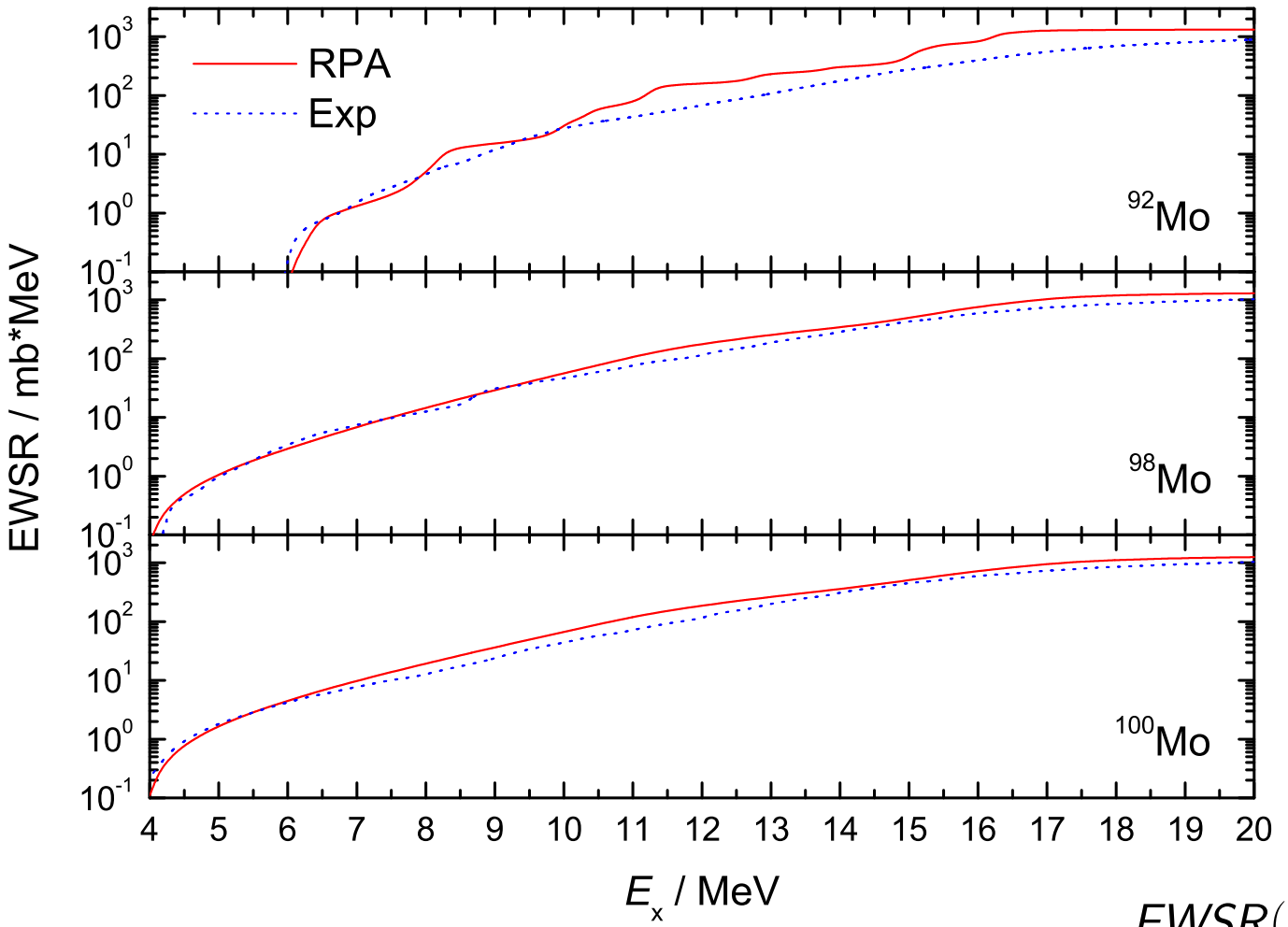


(γ, n) - experiment:
H. Beil et al.,
NPA 227 (1974) 427

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

RPA calculations for deformed nuclei

Energy-weighted sum rule from experiments and RPA calculations:



$$EWSR(E_x) = \sum_{i}^{E_x} \sigma_\gamma(E_i)\ \Delta E$$

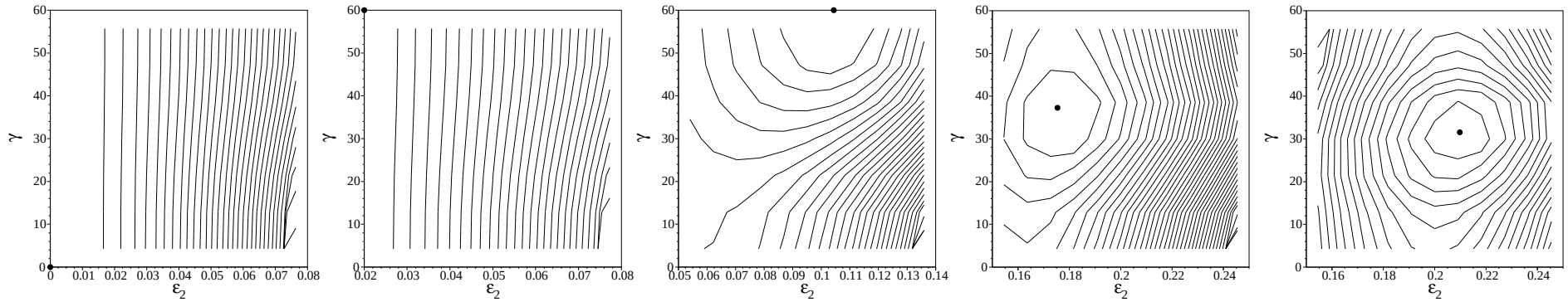
RPA calculations for deformed nuclei

Hamiltonian for 1^- states:

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

F. Dönau, PRL 94 (2005) 092503

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



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

TAC model with shell-correction method

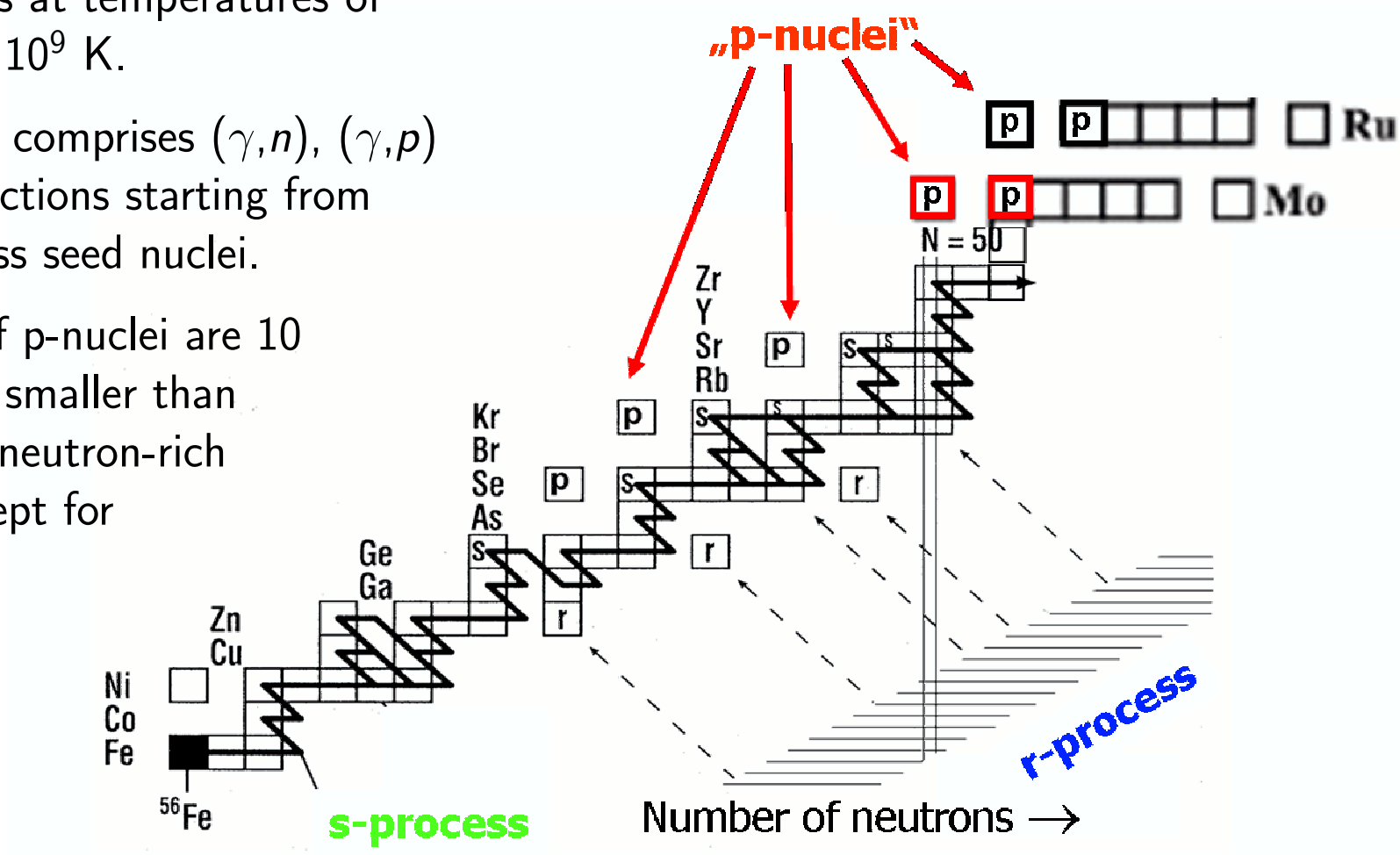
S. Frauendorf, NPA 557 (1993) 259c, NPA 667 (2000) 115

Summary

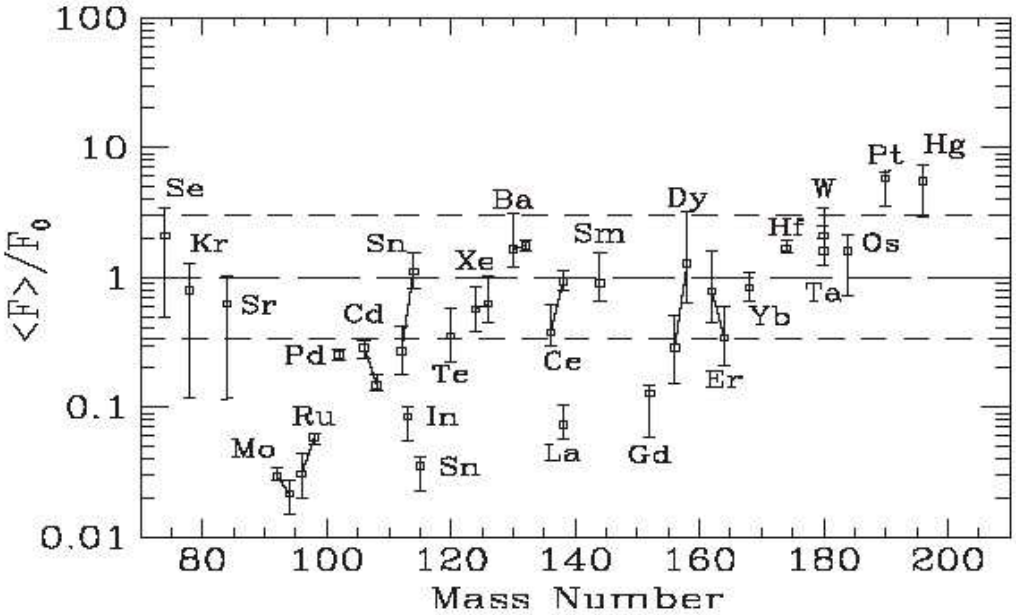
- Dipole-strength distributions of even-even Mo isotopes studied up to neutron-separation energies at the photon-scattering facility of the ELBE accelerator.
- Simulations of γ cascades from excited levels:
  $\Rightarrow$ Estimate of branchings and feedings.
- The reconstructed dipole-strength distributions connect smoothly with the low-energy tails of the Giant Dipole Resonances.
- RPA calculations in a deformed basis reproduce the dipole-strength distributions in the series of Mo isotopes.

P-nuclei and the γ-process

- 35 p-nuclei from ^{74}Se to ^{196}Hg cannot be produced in the s- or r-processes.
- They are produced and destroyed by the p- or γ-process at temperatures of $T \approx (2 - 3) \cdot 10^9$ K.
- The γ-process comprises (γ,n), (γ,p) and (γ,α) reactions starting from s- and r-process seed nuclei.
- Abundances of p-nuclei are 10 to 1000 times smaller than those of their neutron-rich isotopes - except for Mo and Ru.



Calculation of abundances of p-nuclei

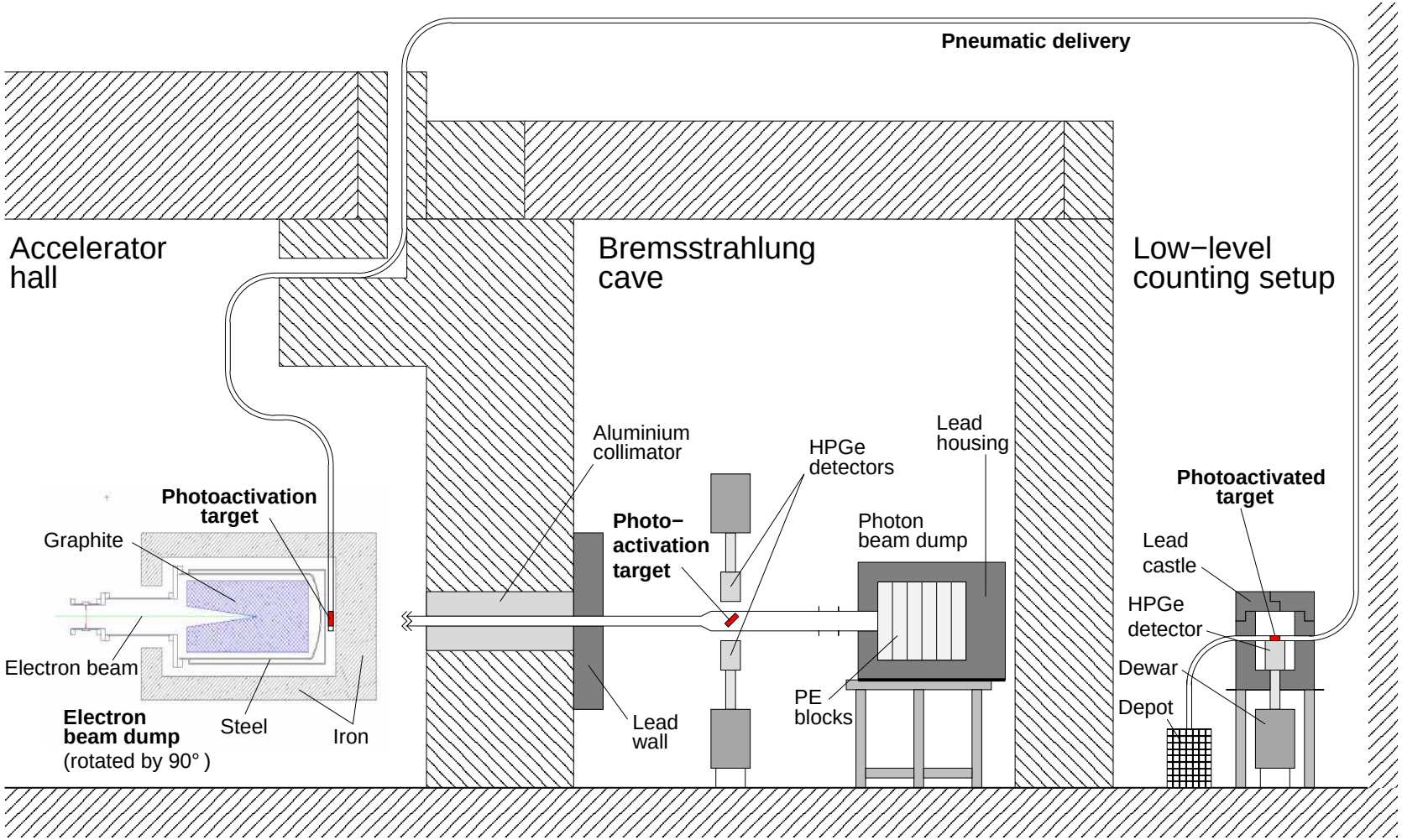


M. Arnould, S. Goriely,
PR 384 (2003) 1

- The abundances of Mo and Ru are underestimated by network calculations.
- Are the reaction rates correct?

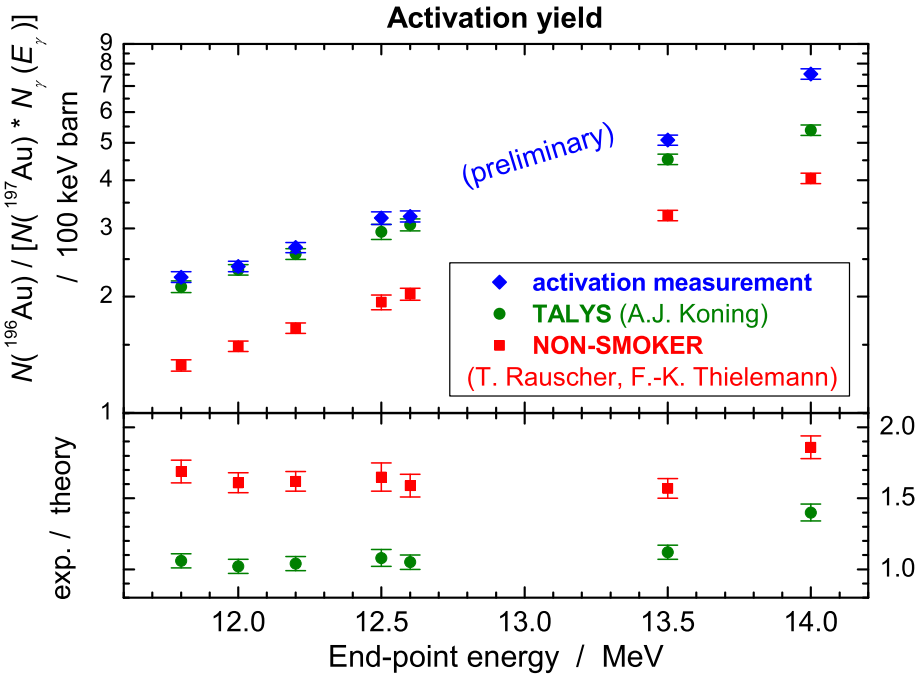
⇒ Study of the photodisintegration of ^{92}Mo

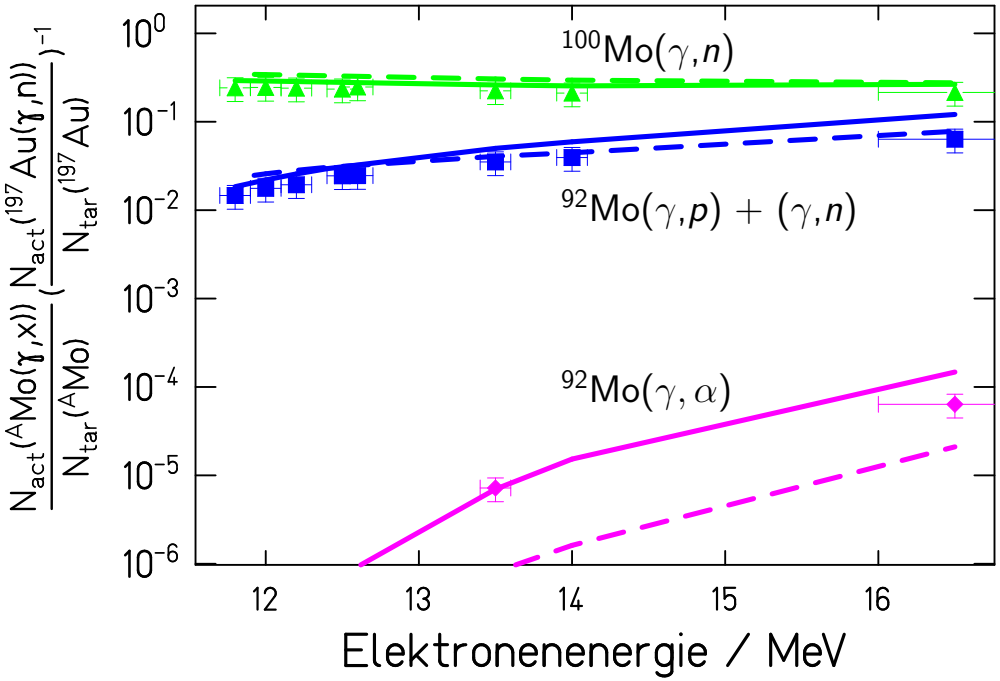
Setup for photoactivation experiments



Setup for photoactivation experiments

Activation yield





Activation yield of the $^{197}Au(\gamma, n)$ reaction. The yield is normalised to the number of ^{197}Au atoms and to the absolute photon flux at $E_x = 8921$ keV.

Activation yields of Mo isotopes normalised to the activation yield of the $^{197}Au(\gamma, n)$ reaction.

Solid lines: T. Rauscher and F.-K. Thielemann, ADNDT 88 (2004) 1
Dashed lines: A. Koning et al., AIP Conf. Proc. 769 (2005) 177

Summary

- Endpoint energy derived from the photodisintegration of ^{2}H.
- Photon-flux distribution from known widths in ^{11}B.
- Determination of the photon flux in the electron-beam dump by means of the ^{197}Au(γ, n) reaction.
- Rough agreement of the activation yield with theoretical predictions.
- ^{92}Mo$(\gamma, \alpha)^{88}$Zr observed for the first time.