



IAEA

International Atomic Energy Agency

Lecture 17:

Low-energy nuclear reactions – Part 2

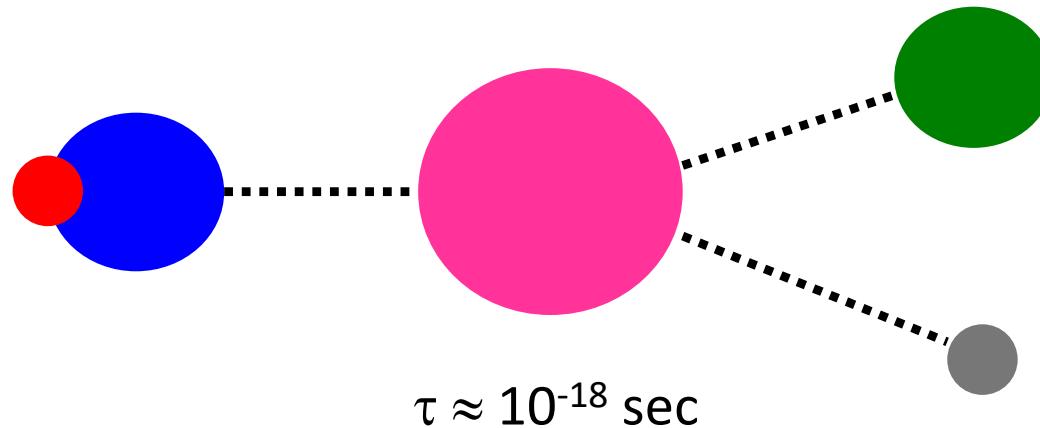
Sotirios Charisopoulos

Physics Section,
NAPC/NA, IAEA, Vienna

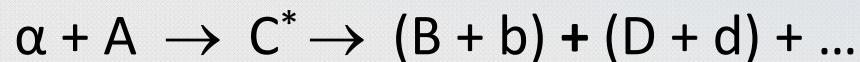
Joint ICTP-IAEA Workshop on
Electrostatic Accelerator Technologies, Basic Instruments and Analytical Techniques | (smr 3331)
ICTP, Trieste, October 28, 2019

<http://indico.ictp.it/event/8728/>

Capture reactions : a special case of compound-nucleus (CN) reactions



Capture reaction (via compound nucleus formation)



$$\sigma_{bB} = \frac{\pi\lambda^2}{(2J_\alpha + 1)(2J_A + 1)} \sum_{J^\pi} (2J_C + 1) T_{\alpha A}^{J^\pi} \frac{T_{bB}^{J^\pi}}{\sum_i T_i^{J^\pi}}$$

$T_{\alpha A}^{J^\pi}$:= probability that α will cross the surface of A to form a compound state of C having spin J . It depends on the orbital momentum of α

$T_{bB}^{J^\pi}$:= probability that b escapes from a state of the compound nucleus C with spin J .

$\sum_i T_i^{J^\pi}$:= sum of probabilities over all exit channels i .

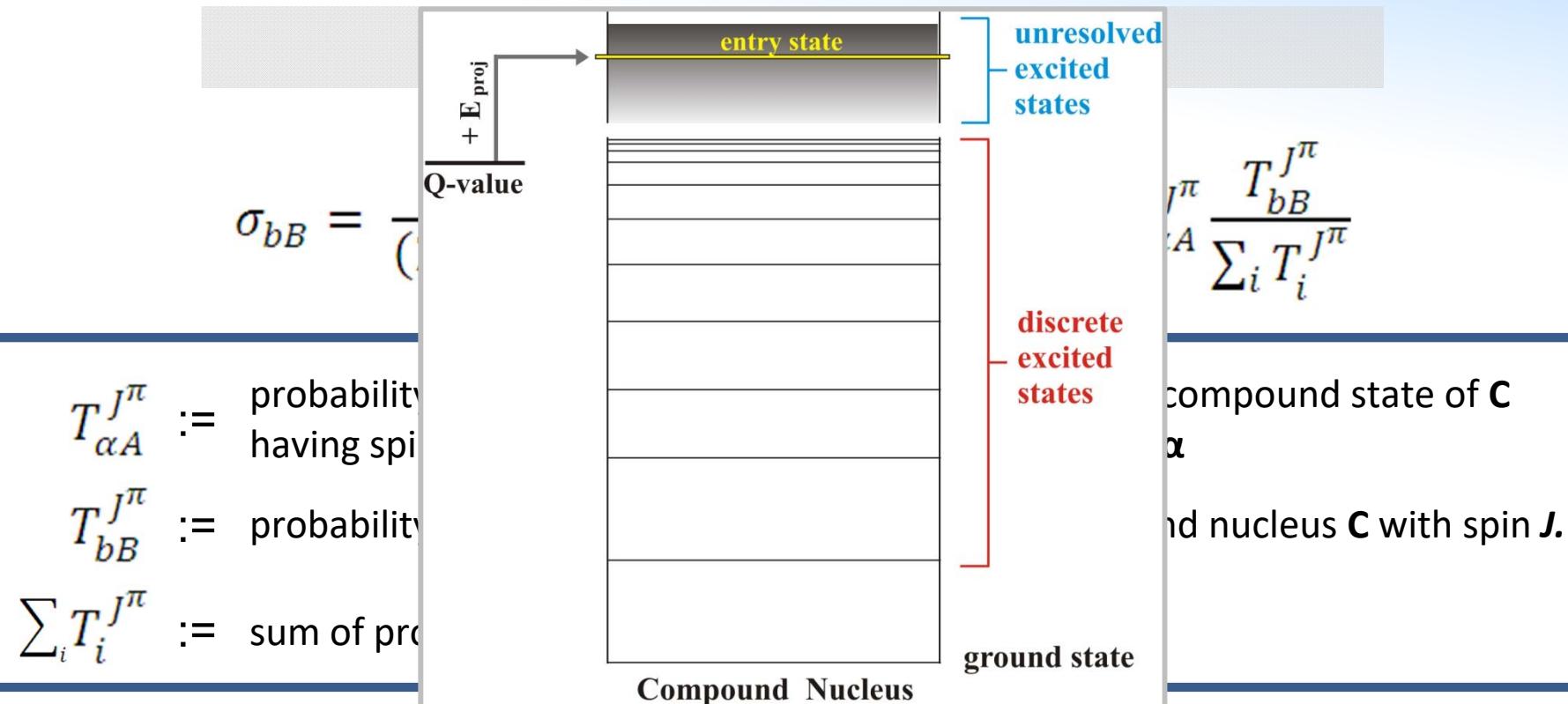
If γ emission then T from **Giant Dipole de-excitation (GDR)**

If particle emission then T from **Optical Model Potentials (OMP)**

CN is excited to continuum => Ts have to be averaged

$$\bar{T}_{\alpha A} = \sum_I \int \rho(E_\alpha, I) T_{\alpha A}^I(E_\alpha) dE_\alpha$$

Nuclear Level Density (NLD)



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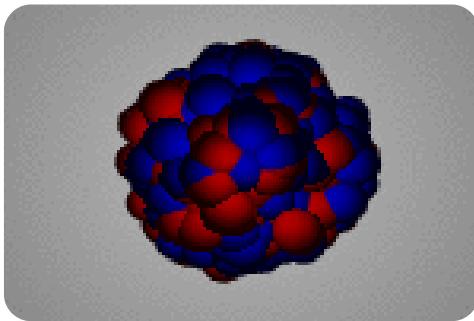
Nuclear Level Density (NLD)

Giant Resonances in nuclei

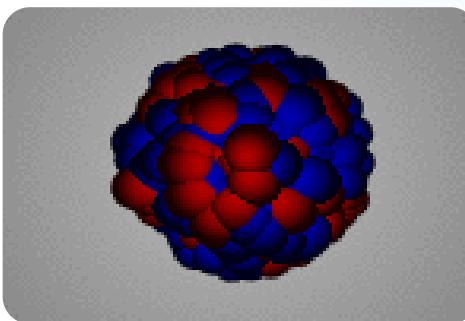
$(\gamma \rightarrow {}^A X)$



Monopole

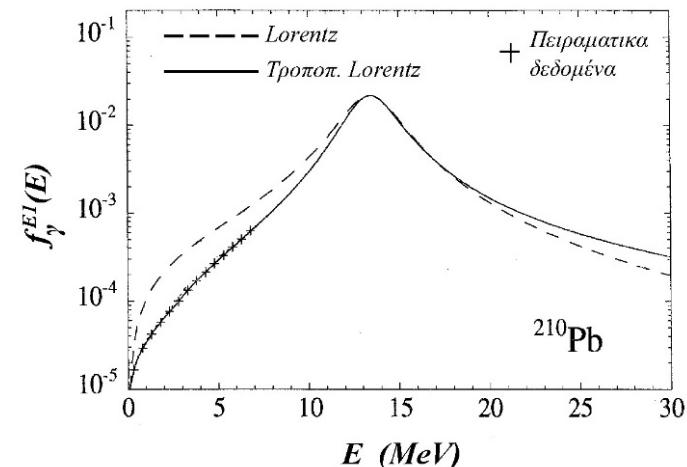
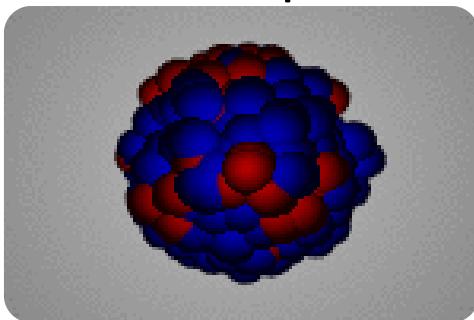


Dipole

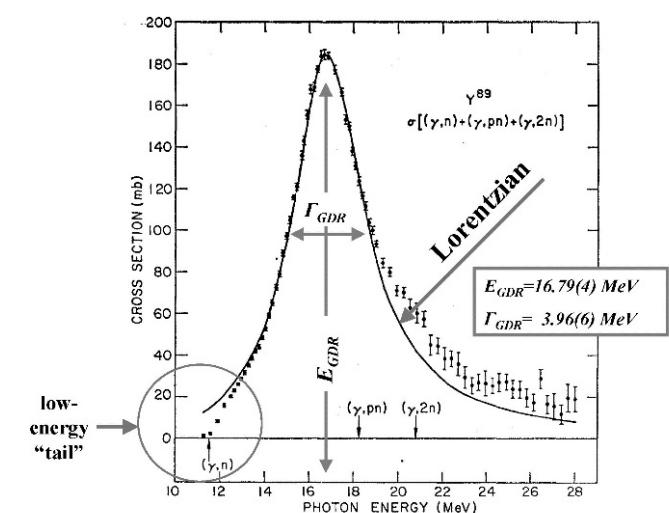
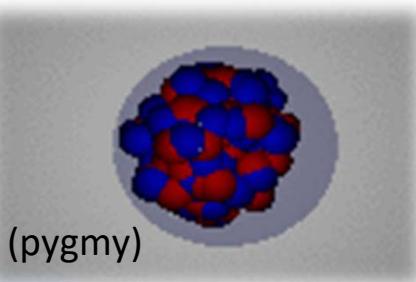
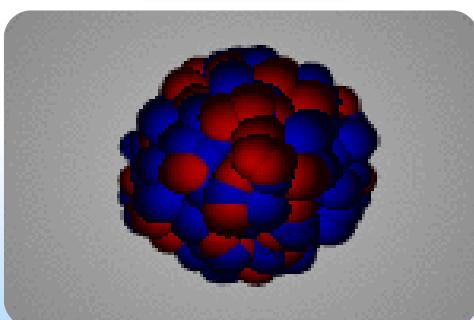


$$T_\gamma^{X1}(\varepsilon_\gamma) = 2\pi\varepsilon_\gamma^{2L+1}f_\gamma^{X1}(\varepsilon_\gamma) = 2\pi\varepsilon_\gamma^3f_\gamma^{X1}(\varepsilon_\gamma)$$

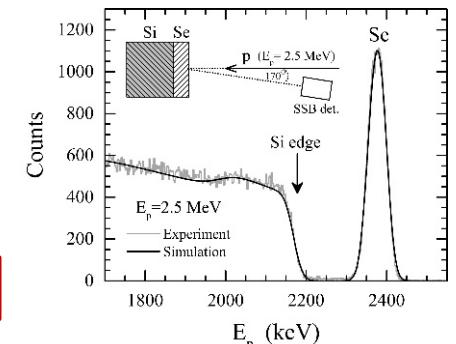
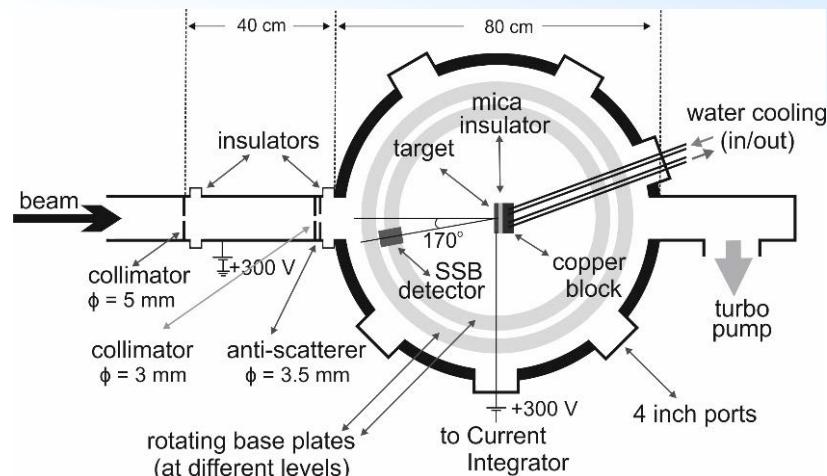
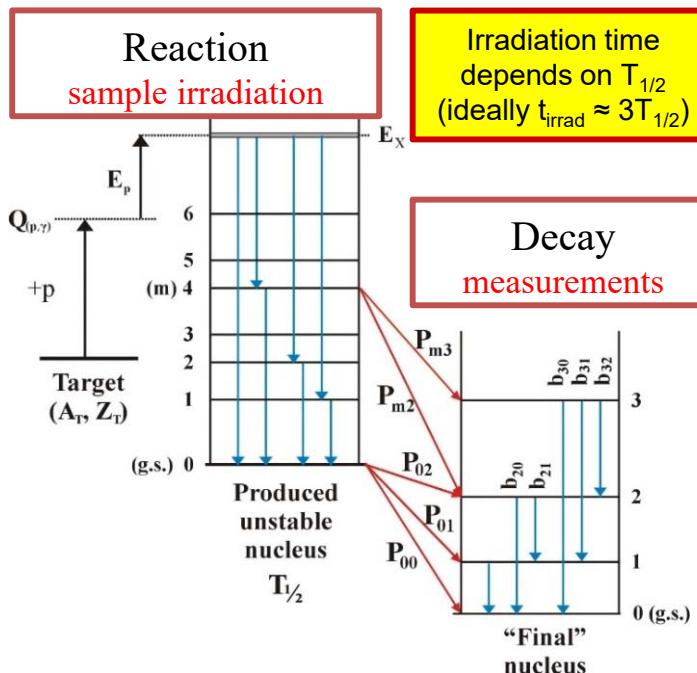
Quadrupole



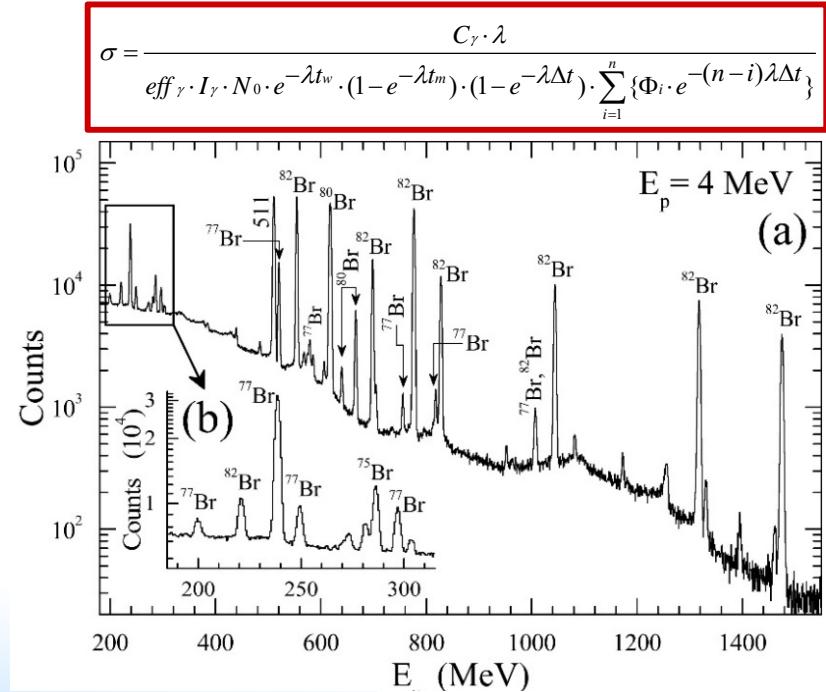
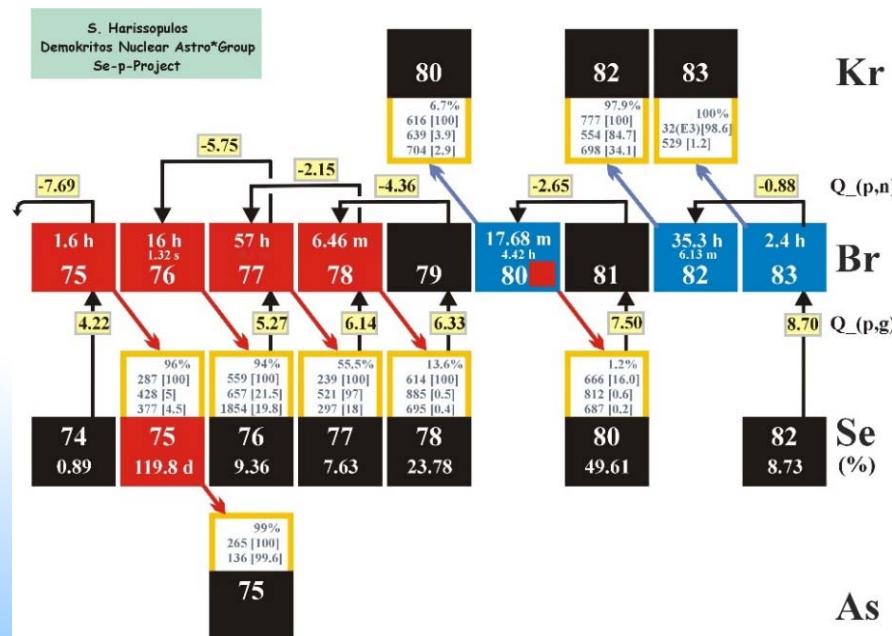
$$f_\gamma^{E1}(\varepsilon_\gamma) = 8.68 \times 10^{-8} (mb^{-1} MeV^{-2}) \times \frac{\sigma_{GDR} \varepsilon_\gamma \Gamma_{GDR}^2}{(\varepsilon_\gamma^2 - E_{GDR}^2)^2 + \varepsilon_\gamma^2 \Gamma_{GDR}^2}$$



Cross section measurements (The activation technique)

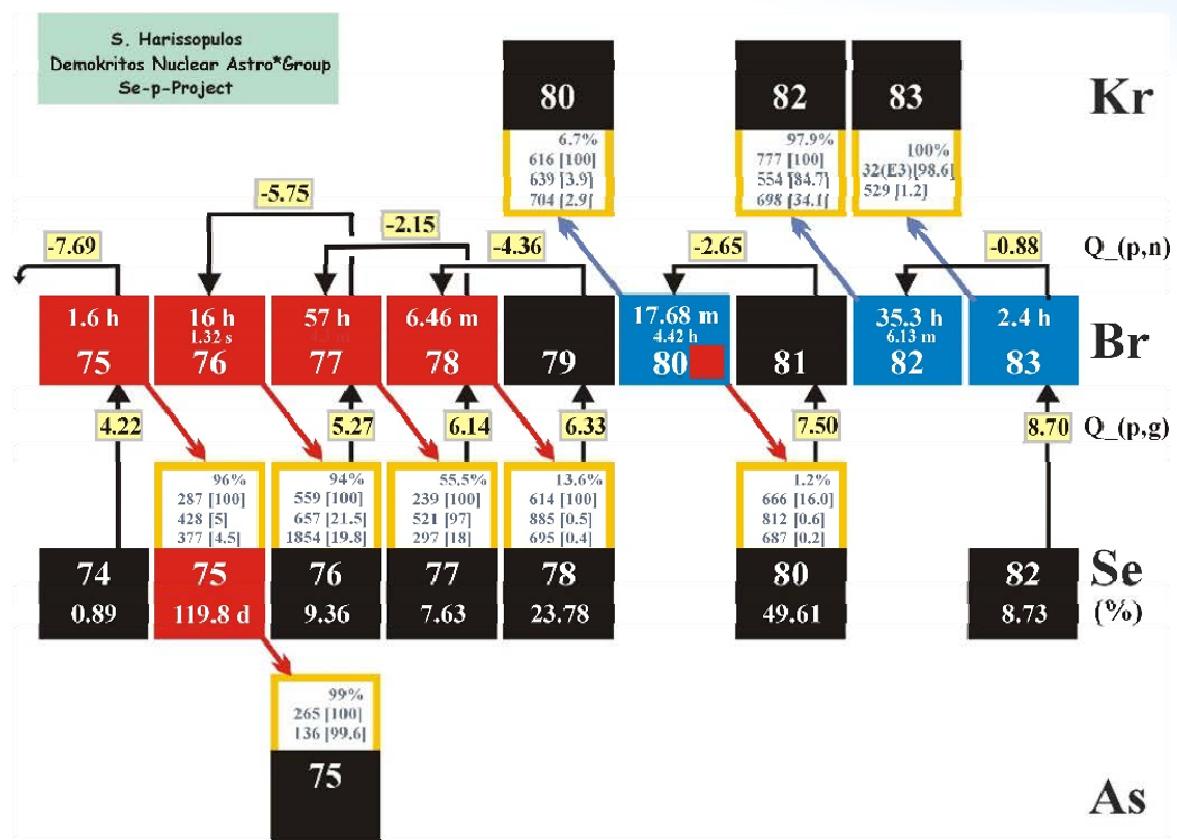
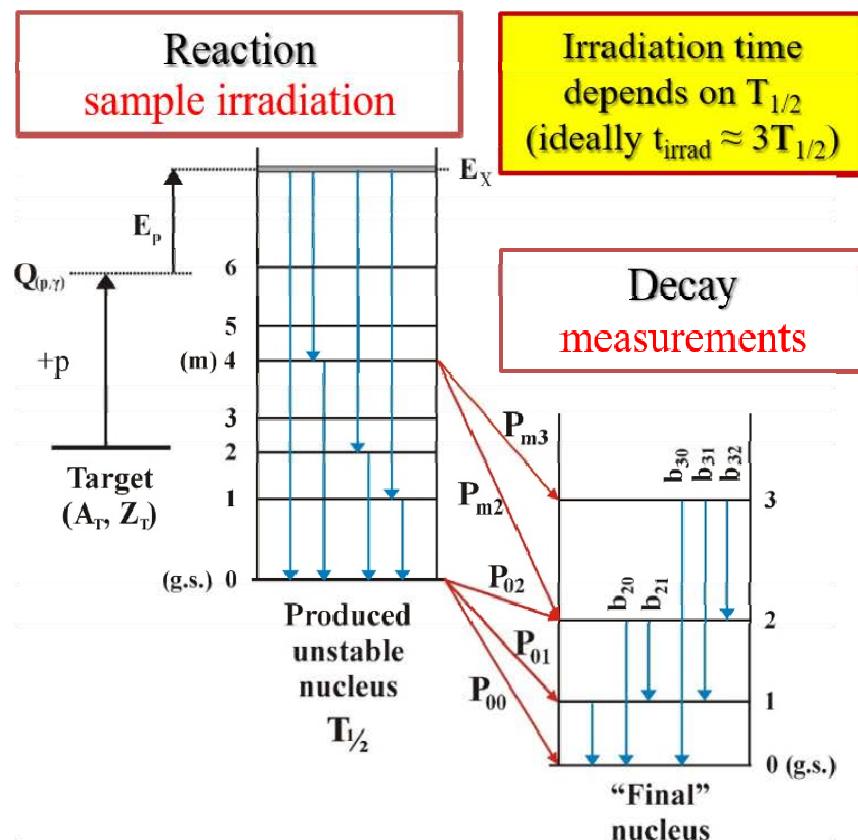


The irradiation chamber at INPP/Demokritos



Cross section measurements

(The activation technique-1)

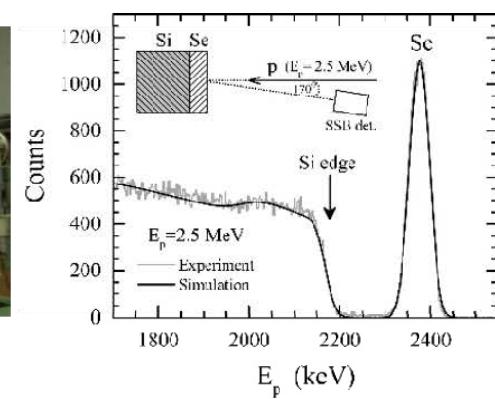
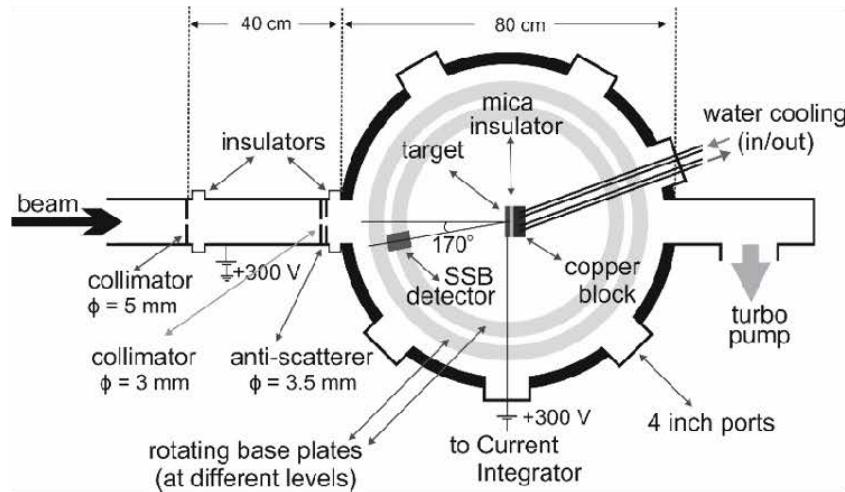


Cross section measurements

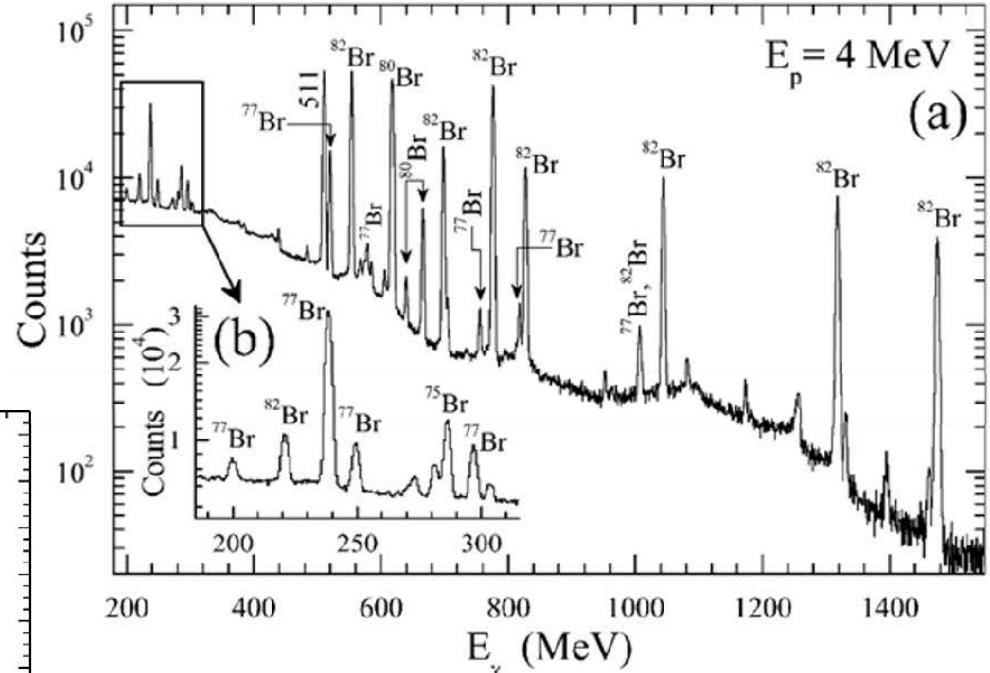
(The activation technique-2)



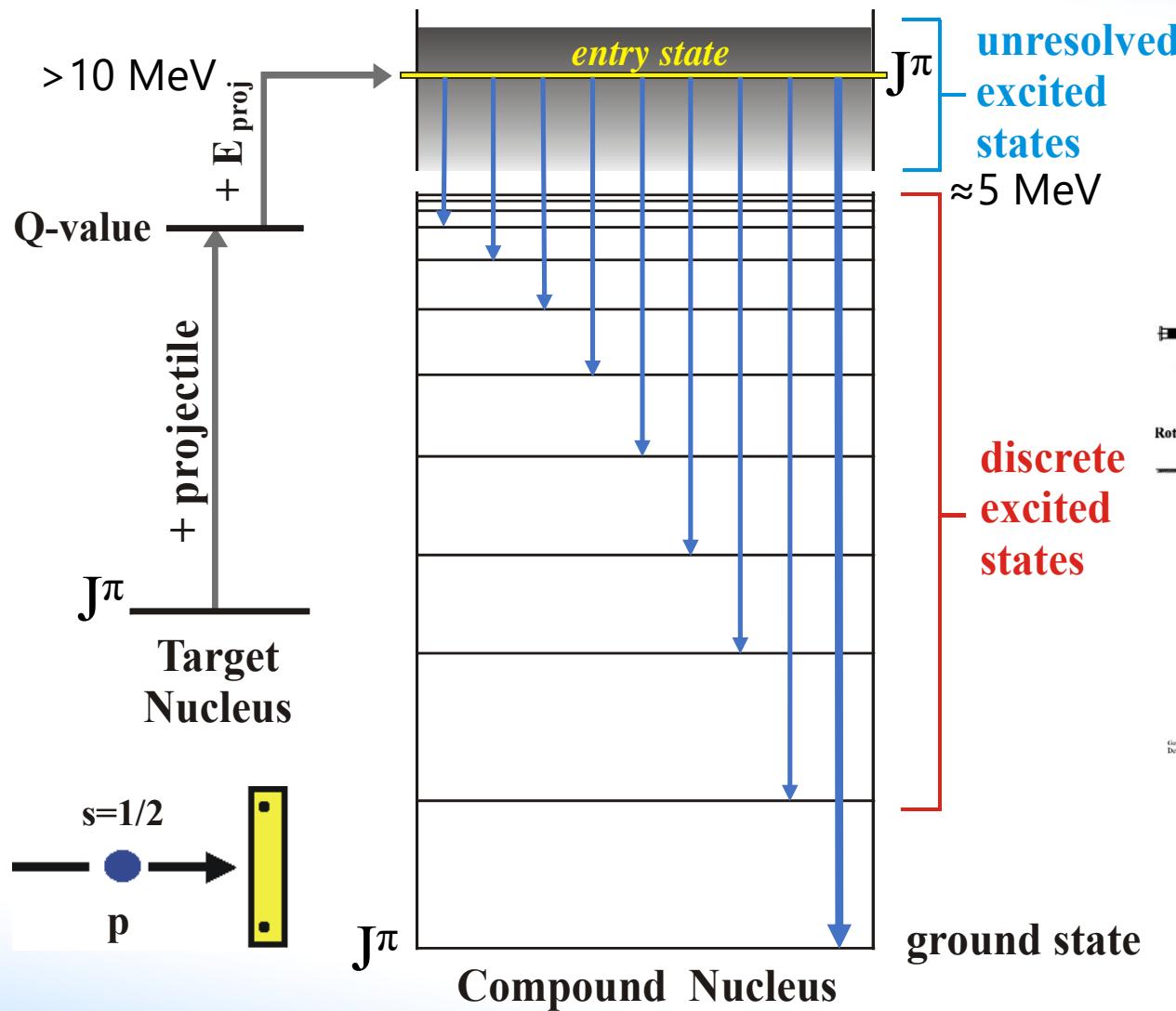
The irradiation chamber at INPP/Demokritos



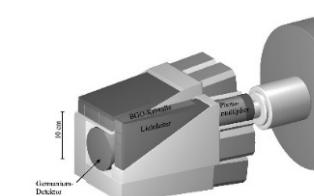
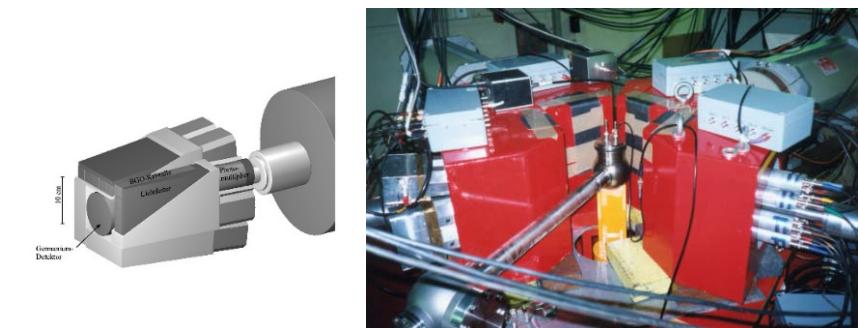
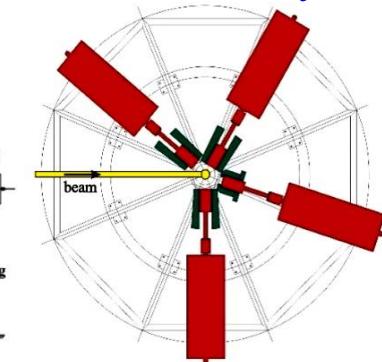
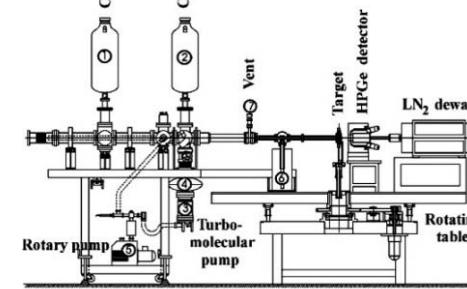
$$\sigma = \frac{C_\gamma \cdot \lambda}{e_{\text{eff}} \cdot I_\gamma \cdot N_0 \cdot e^{-\lambda t_w} \cdot (1 - e^{-\lambda t_m}) \cdot (1 - e^{-\lambda \Delta t}) \cdot \sum_{i=1}^n \{\Phi_i \cdot e^{-(n-i)\lambda \Delta t}\}}$$



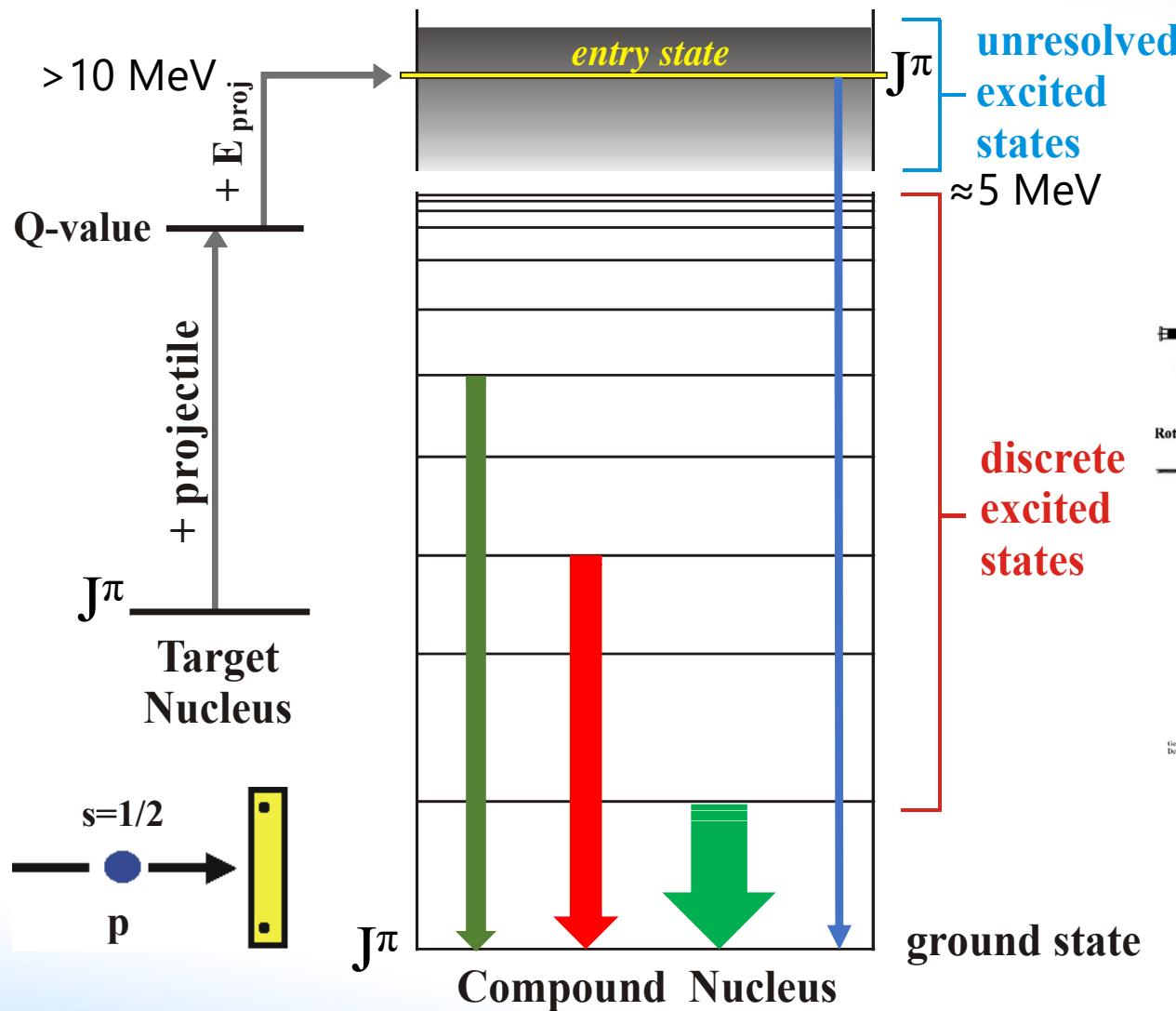
Cross sections from γ -angular distribution measurements -1



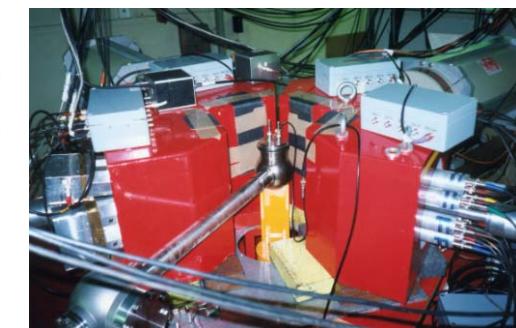
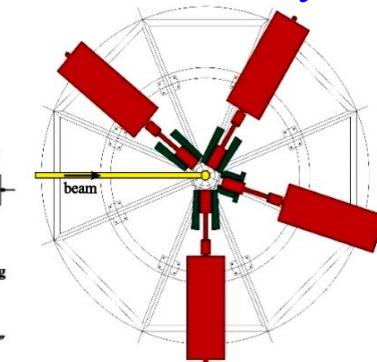
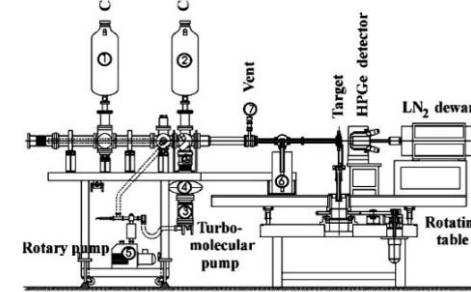
The Stuttgart HPGe-detector array



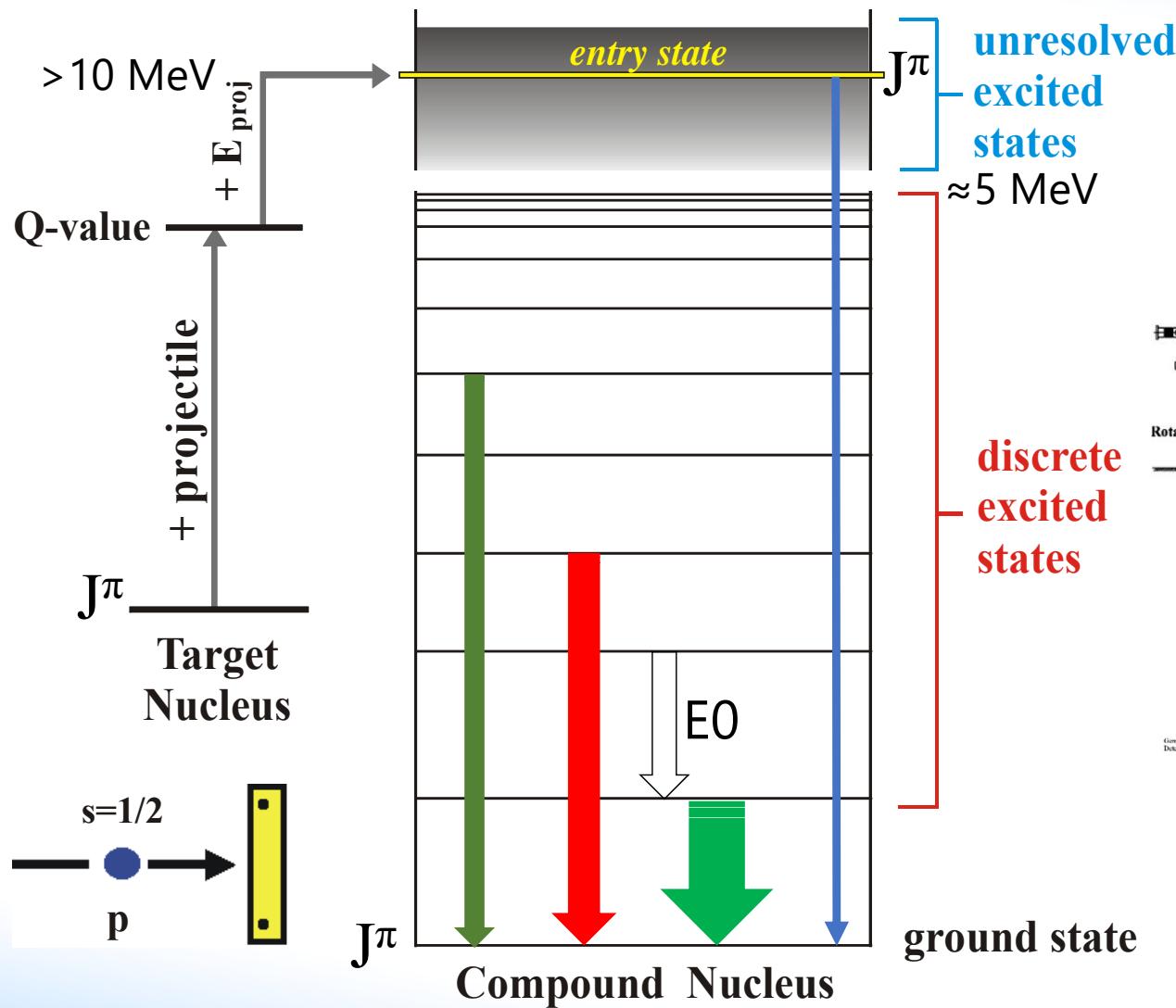
Cross sections from γ -angular distribution measurements



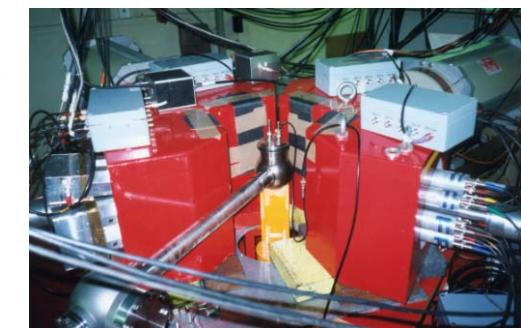
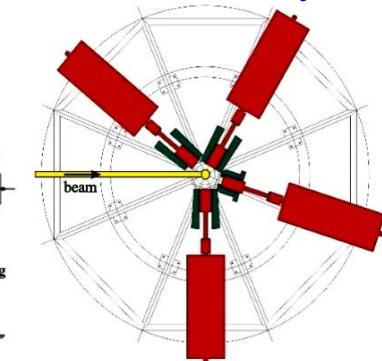
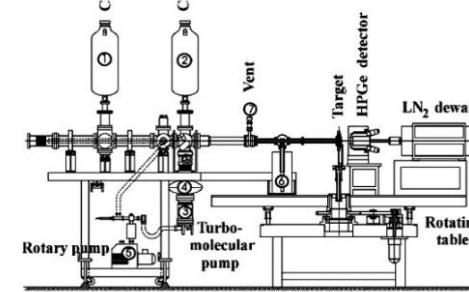
The Stuttgart HPGe-detector array



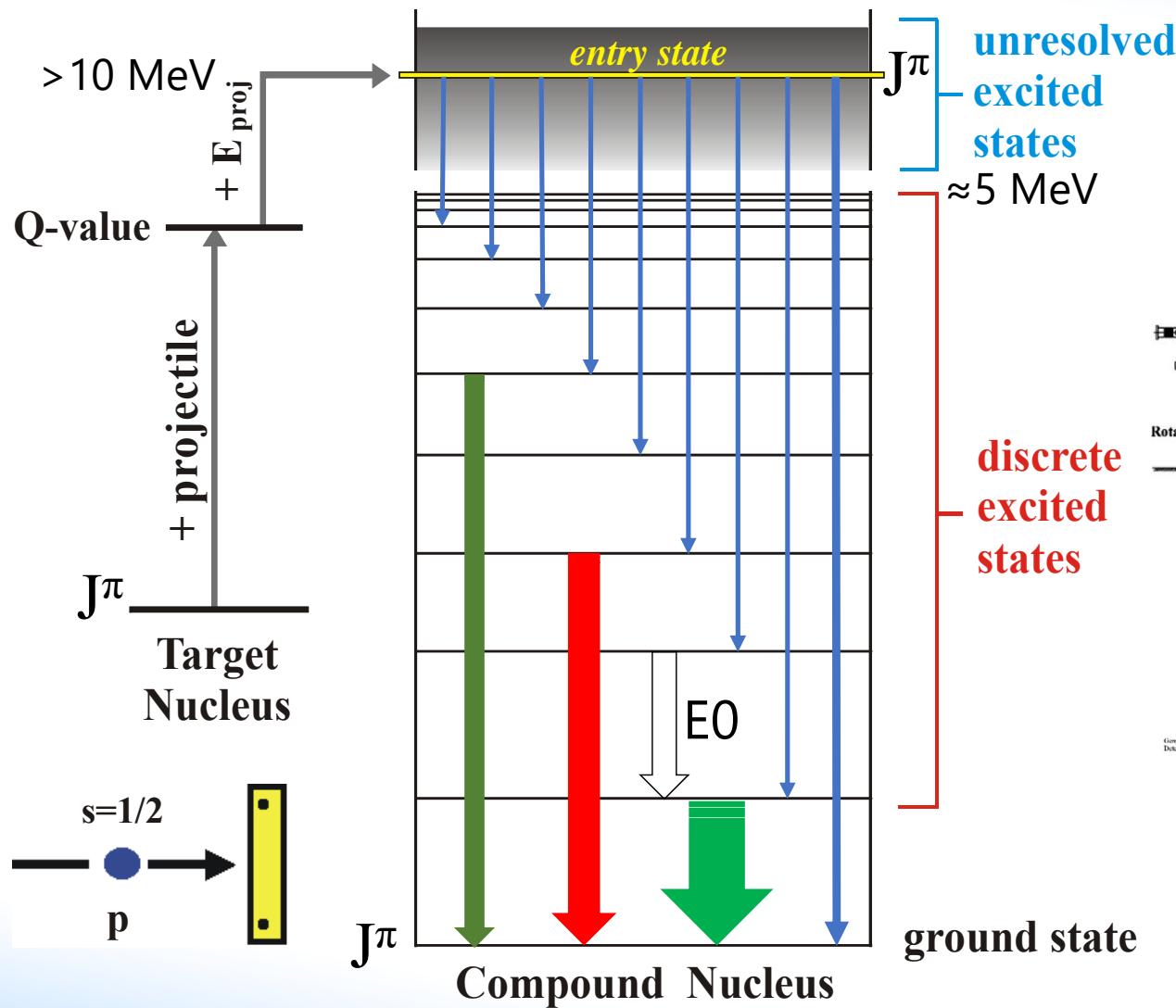
Cross sections from γ -angular distribution measurements



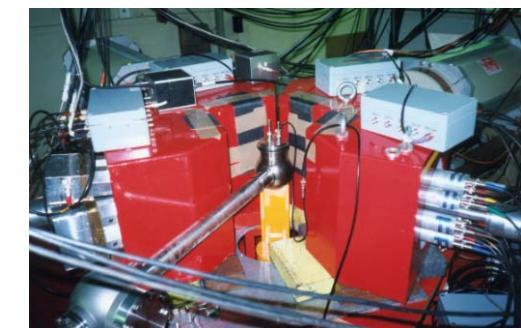
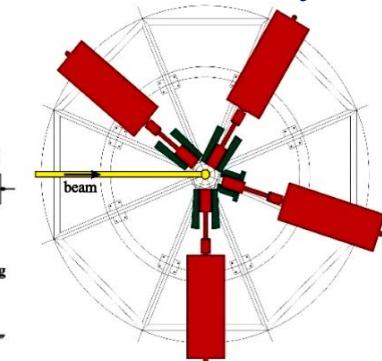
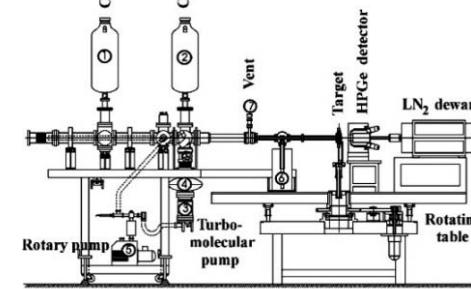
The Stuttgart HPGe-detector array



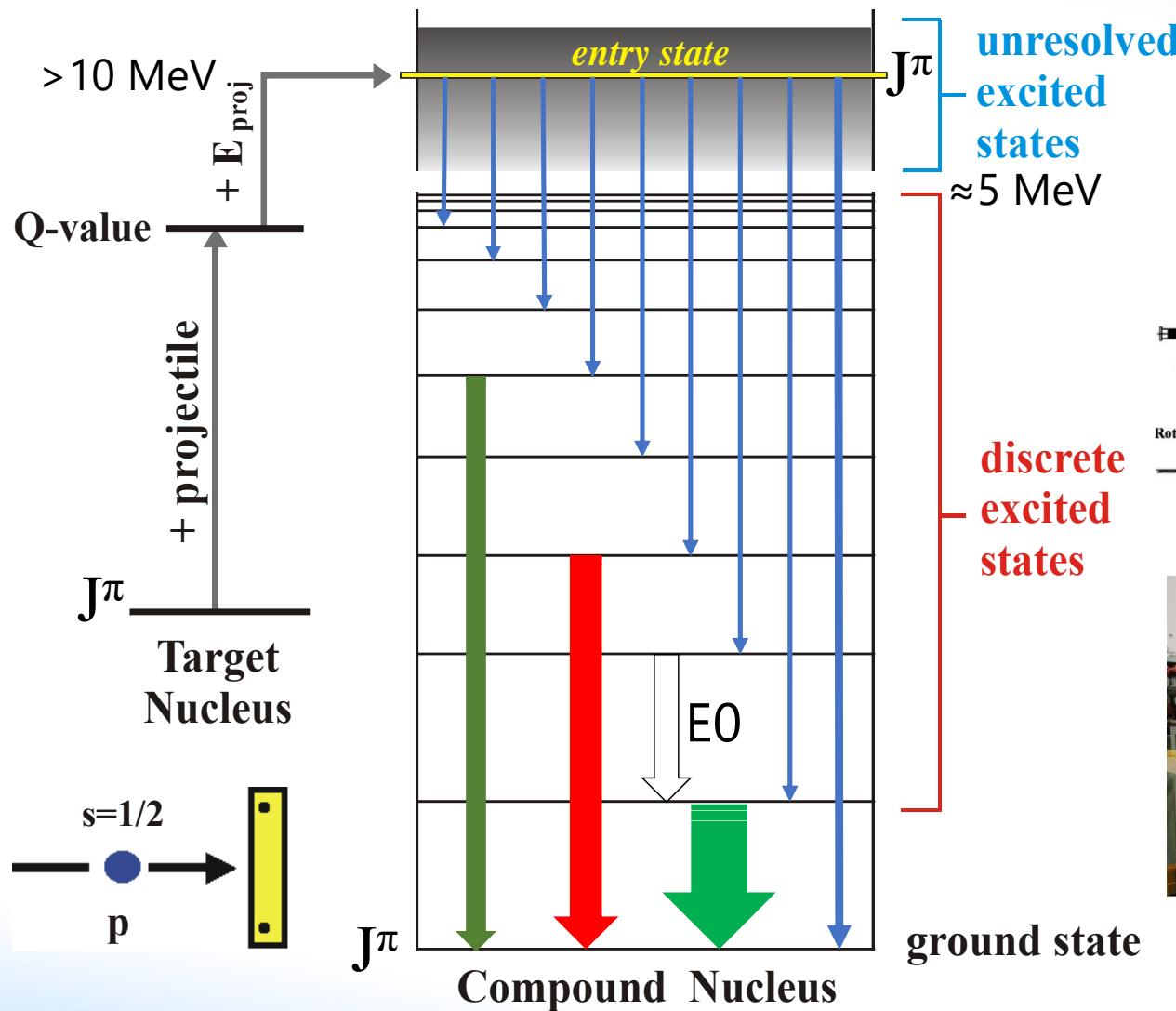
Cross sections from γ -angular distribution measurements



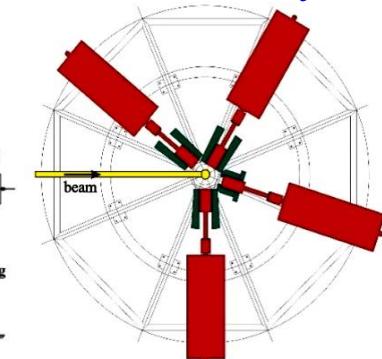
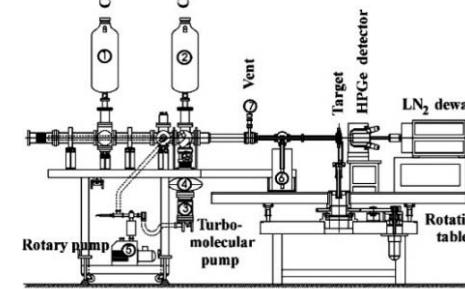
The Stuttgart HPGe-detector array



Cross sections from γ -angular distribution measurements -1



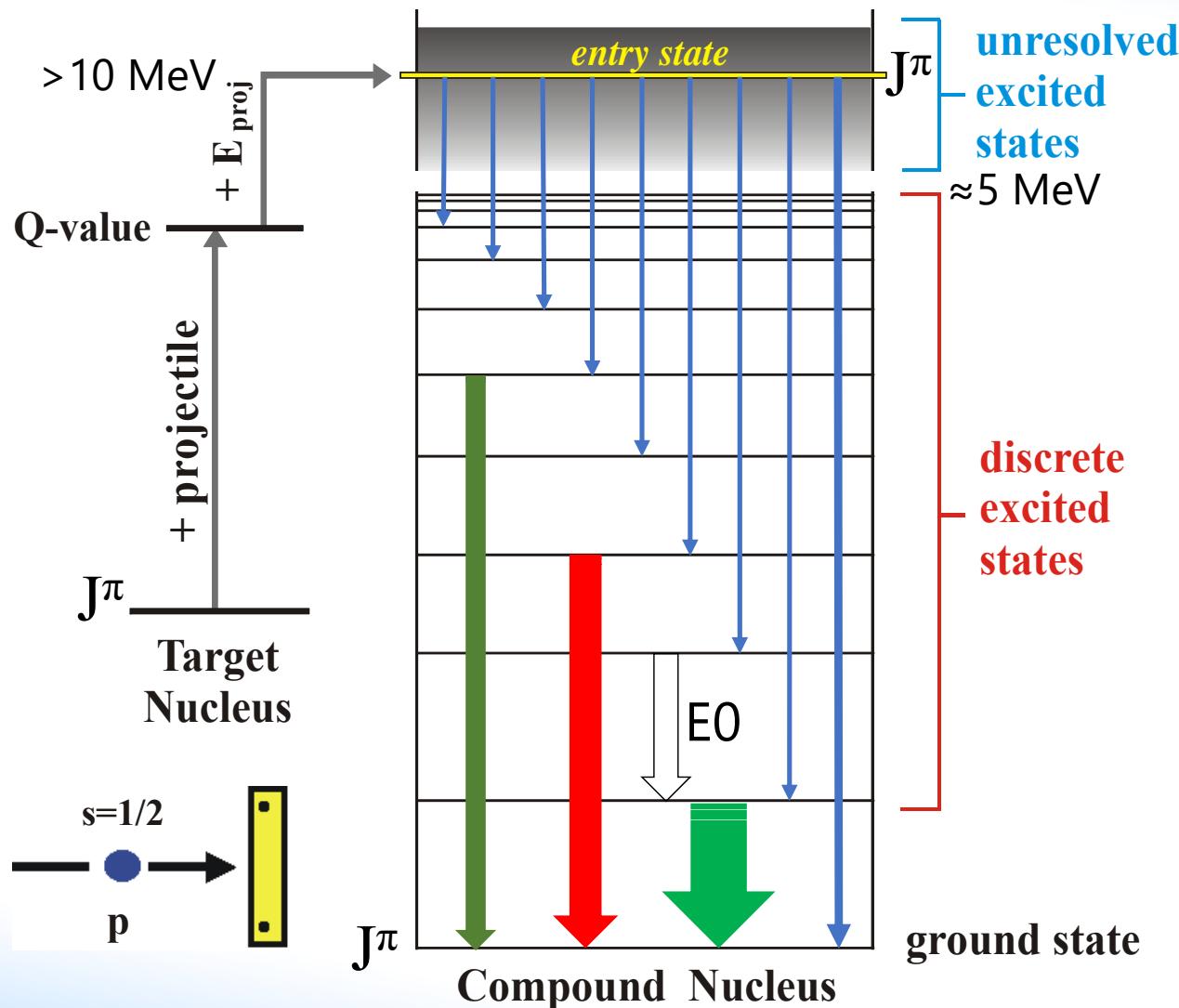
The Stuttgart HPGe-detector array



... now at “Demokritos” (no BGOs)



Cross sections from γ -angular distribution measurements -2



entry-state parity:
 $\pi(\text{gs})_{\text{TARGET}} * (-1)^{L_p} - \pi(\text{exc. state})_{\text{CS}}$

entry-state spin:
 $|J_T - J_p| \leq J_{\text{ENTRY}} \leq |J_T + J_p|$

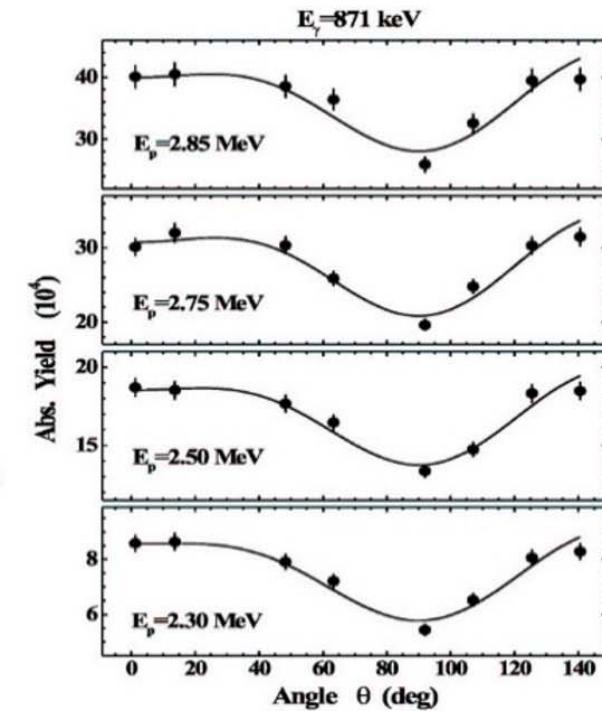
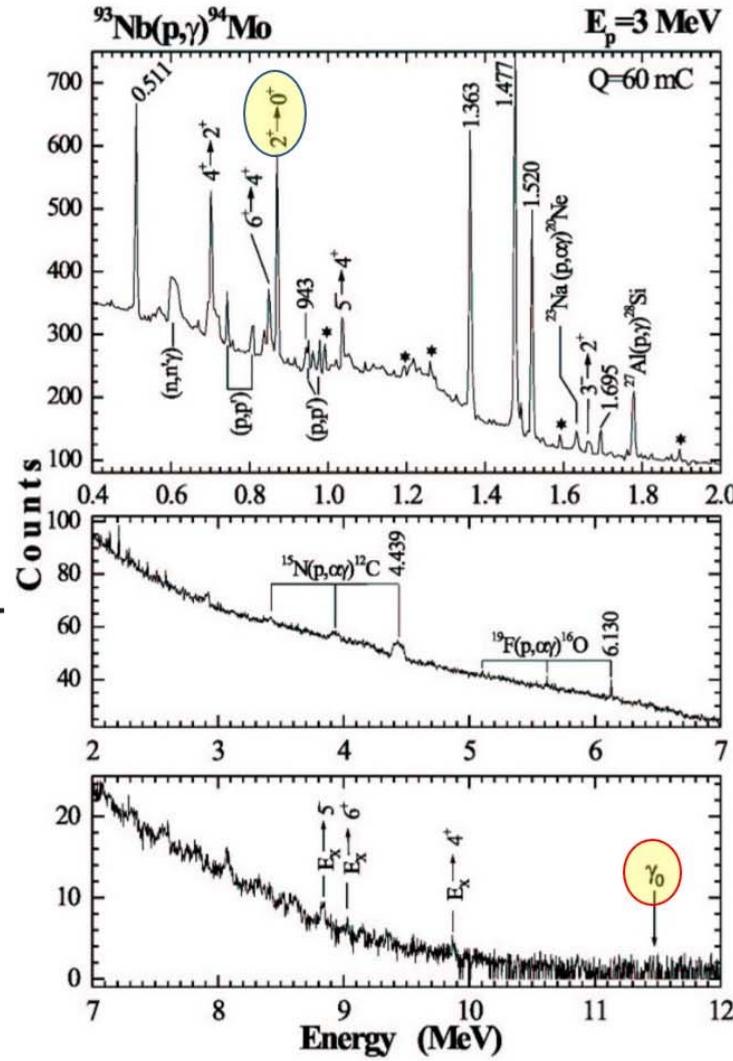
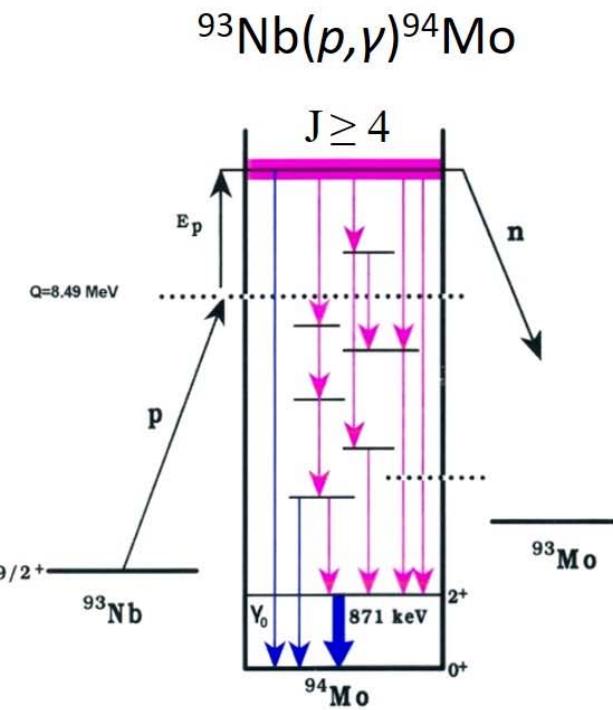
TARGET : even -odd nucleus

J_{TARG}	$L_p=0$	$L_p=1$
	J_{ENTRY}	J_{ENTRY}
1/2	0, 1	0, 1, 2
3/2	1, 2	0, 1, 2, 3
5/2	2, 3	1, 2, 3, 4
7/2	3, 4	2, 3, 4, 5
9/2	4, 5	3, 4, 5, 6

TARGET : even -even nucleus

J_{TARG}	$L_p=0$	$L_p=1$
	J_{ENTRY}	J_{ENTRY}
0	1/2	1/2, 3/2

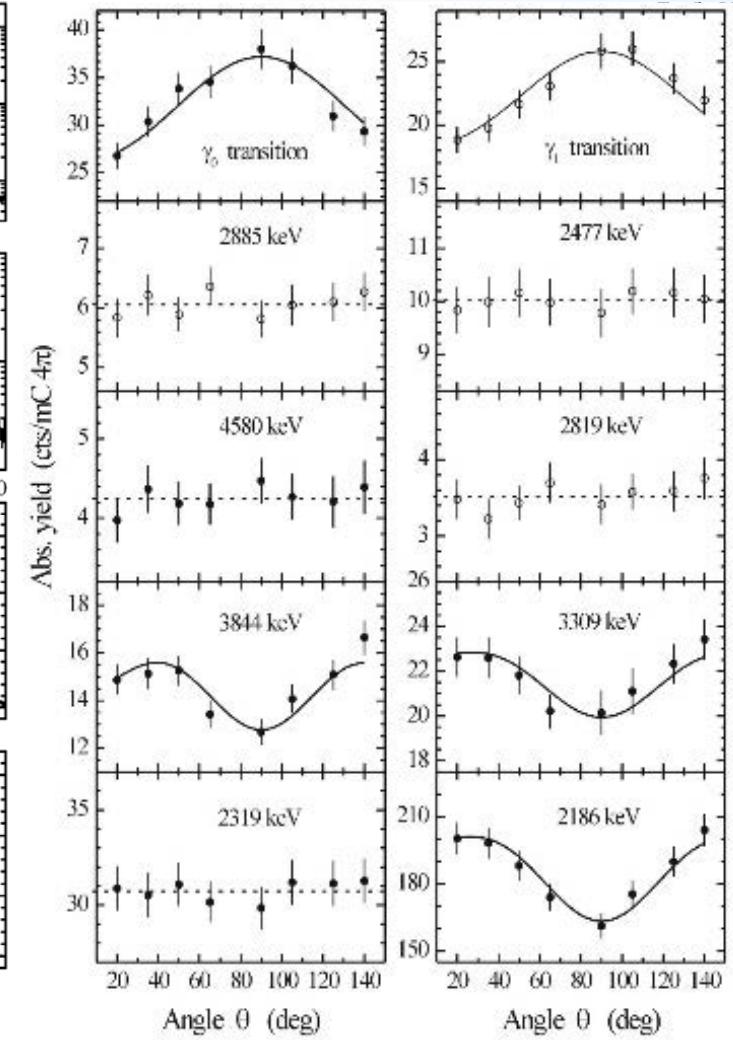
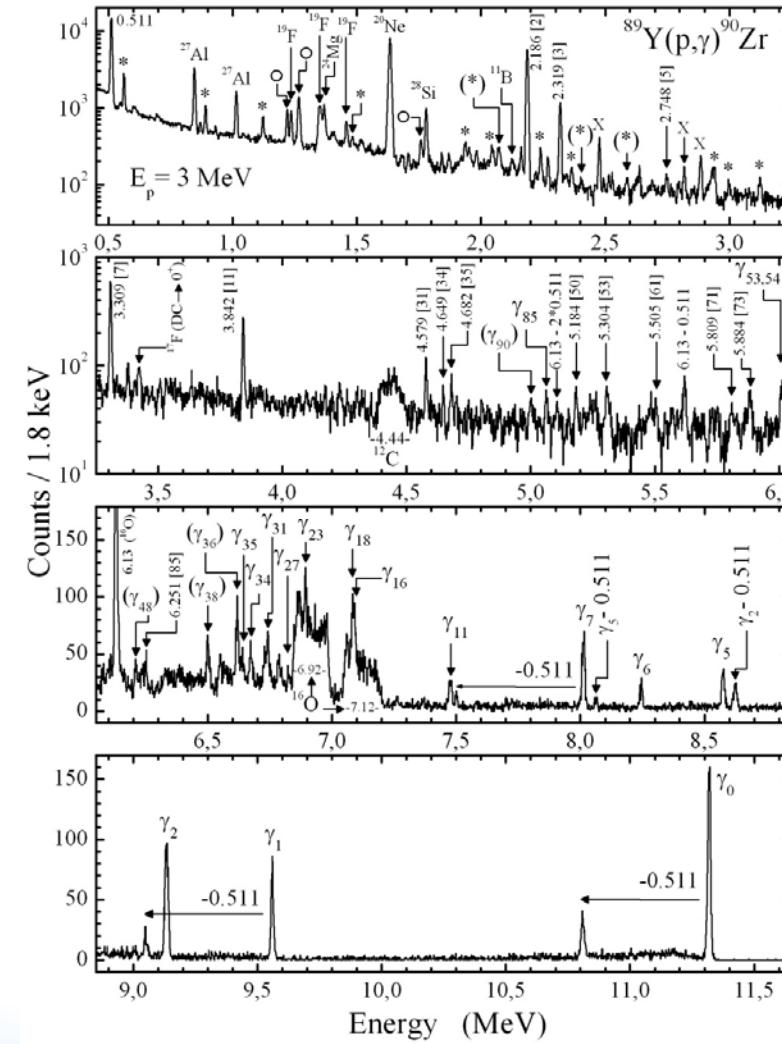
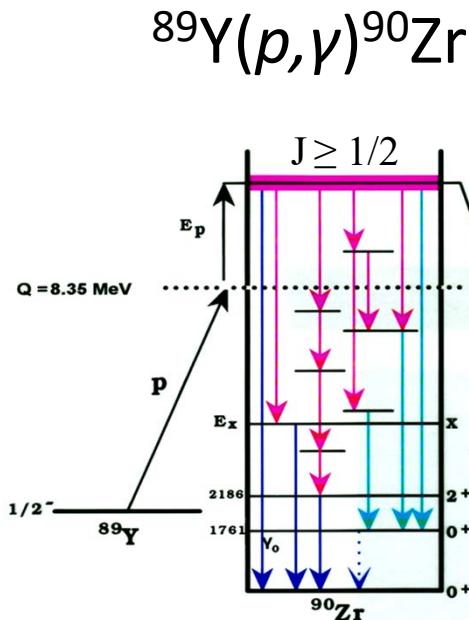
Cross sections from γ -angular distribution measurements -3



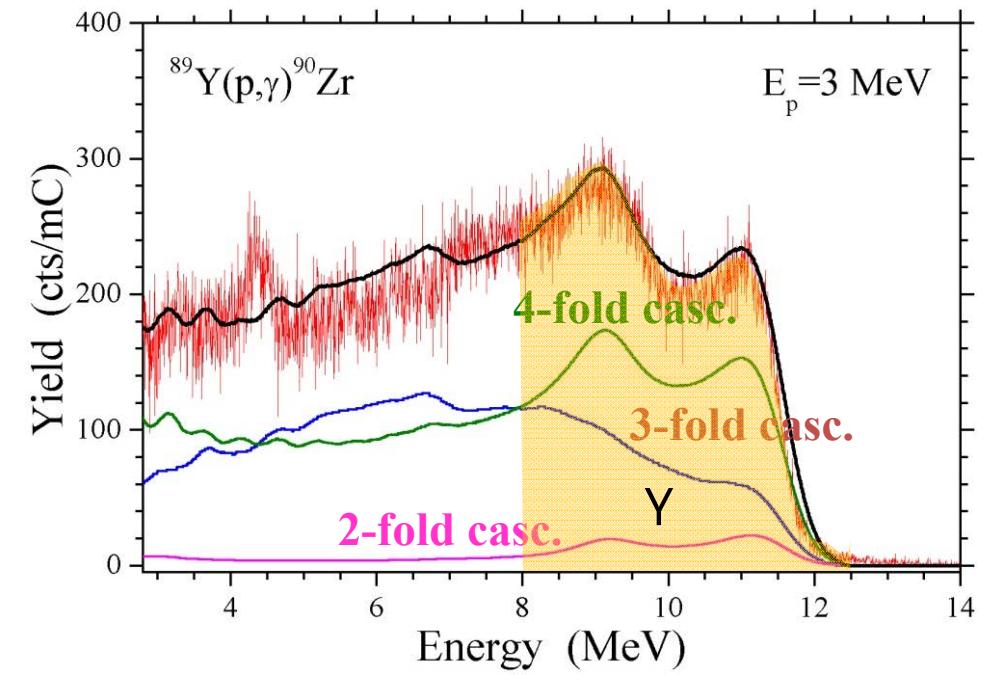
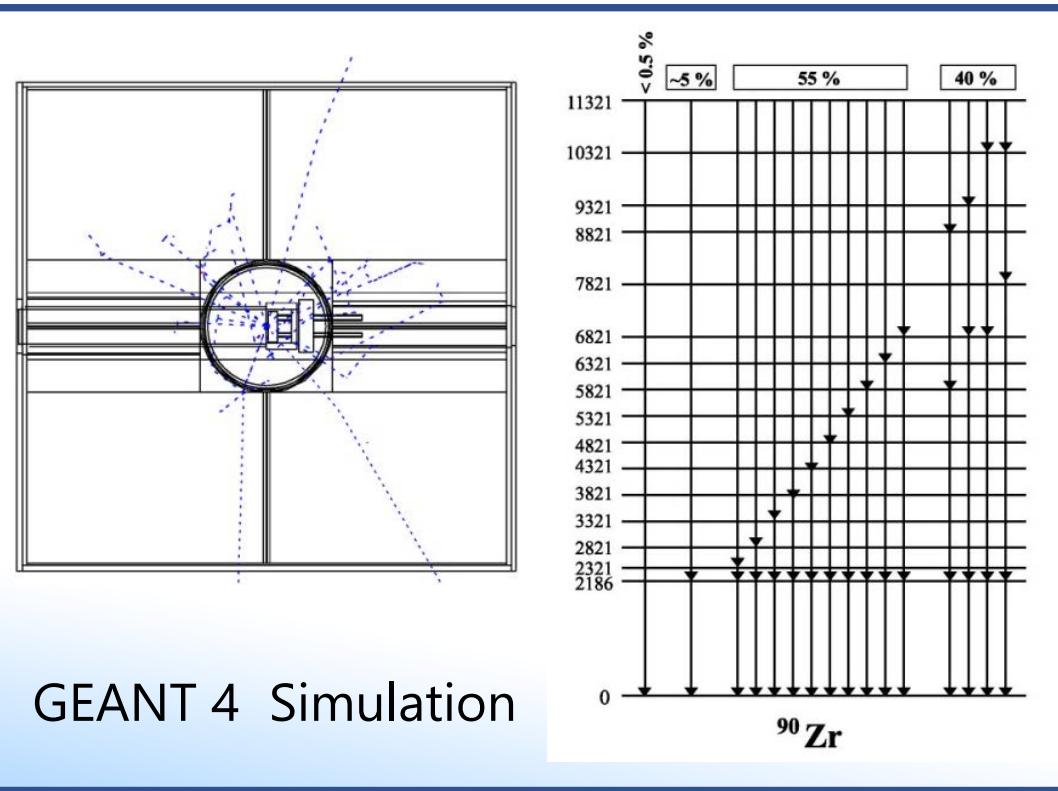
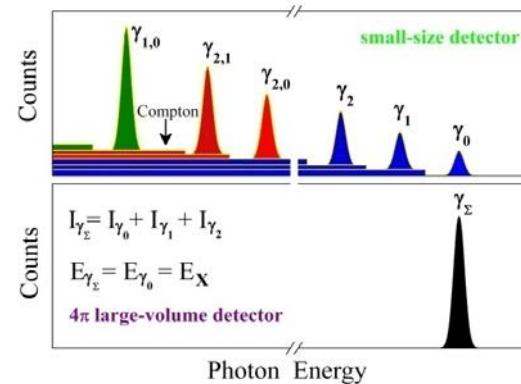
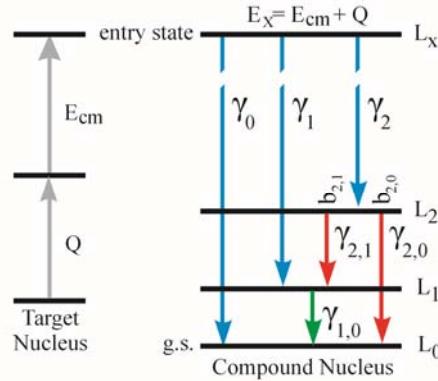
$$W(\vartheta) = A_0 (1 + a_2 P_2(\cos \vartheta) + a_4 P_4(\cos \vartheta))$$

$$\sigma = \frac{A}{N_A N_p \xi} \sum_j (A_0)_j$$

Cross sections from γ -angular distribution measurements -4

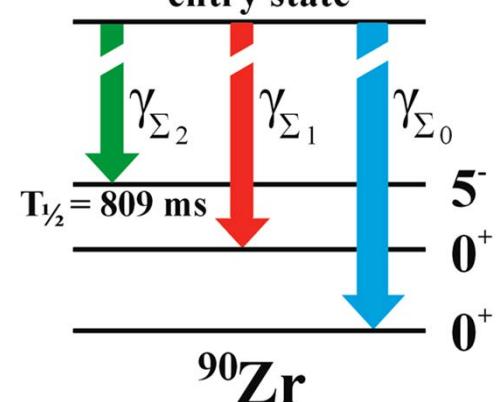
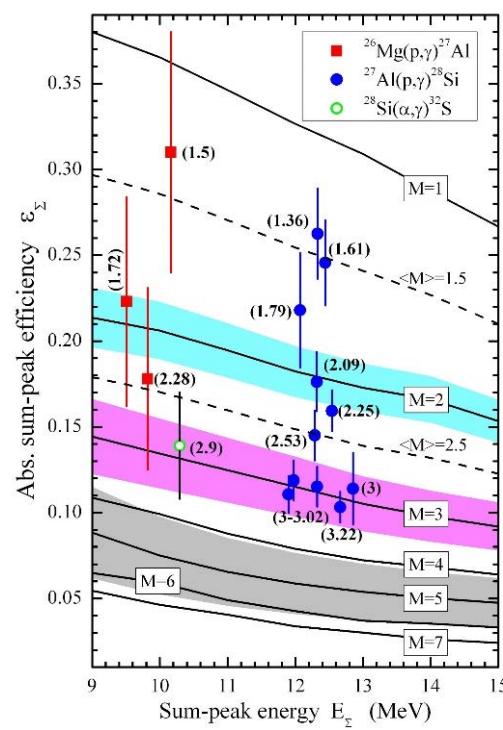
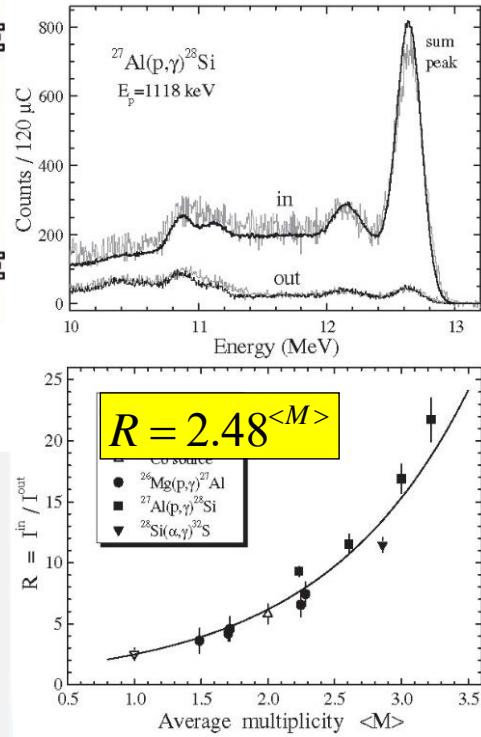
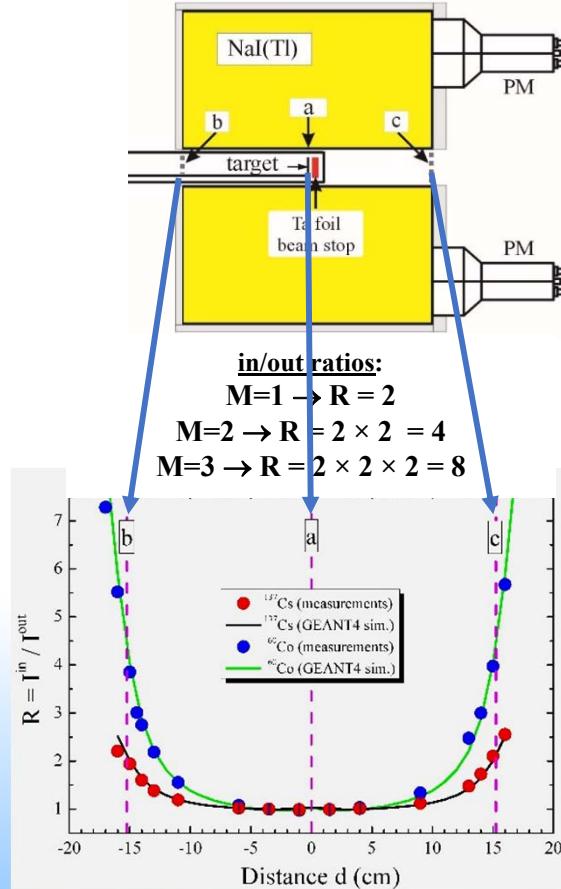
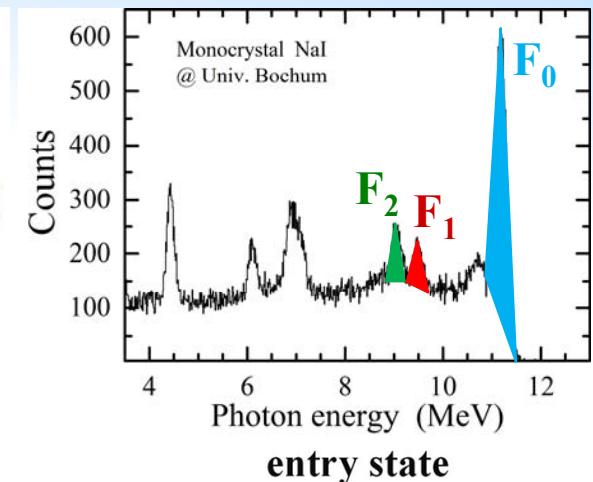
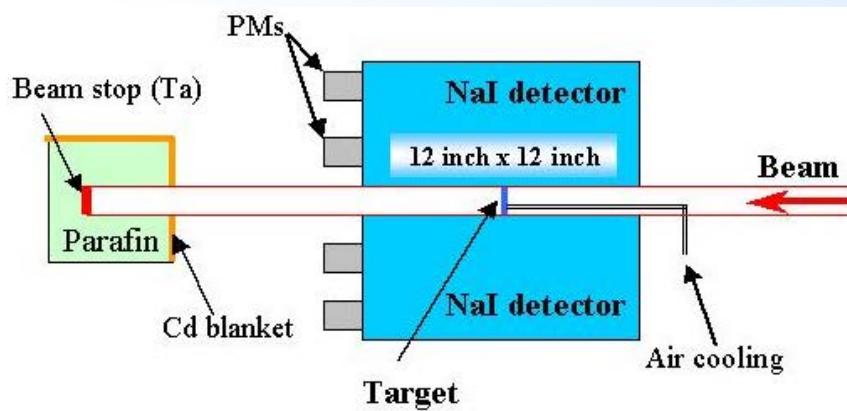
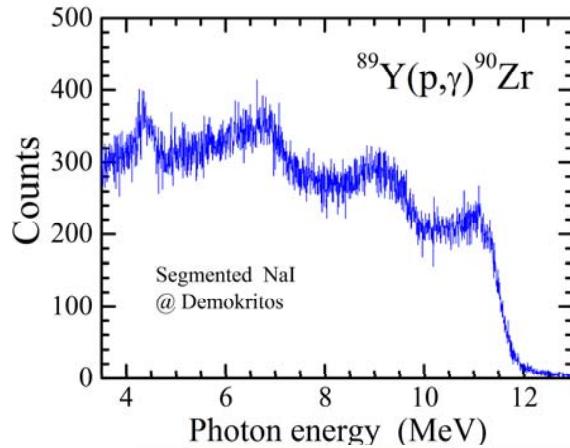


Cross sections from angle-integrated γ -spectra / 1



$$\sigma = (\gamma/\varepsilon) * (1/\xi) * (A/N_A)$$

Cross sections from angle-integrated γ -spectra / 2



$$Y_0 = F_0 / (N_{\text{proj}} \times \varepsilon_0)$$

$$Y_1 = F_1 / (N_{\text{proj}} \times \varepsilon_1)$$

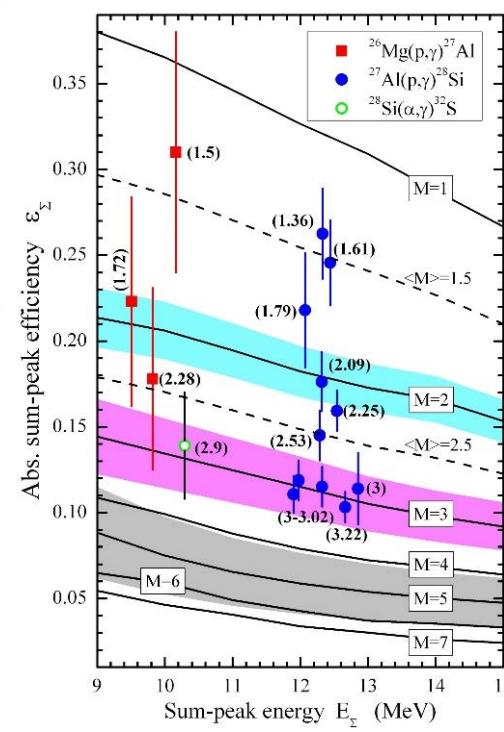
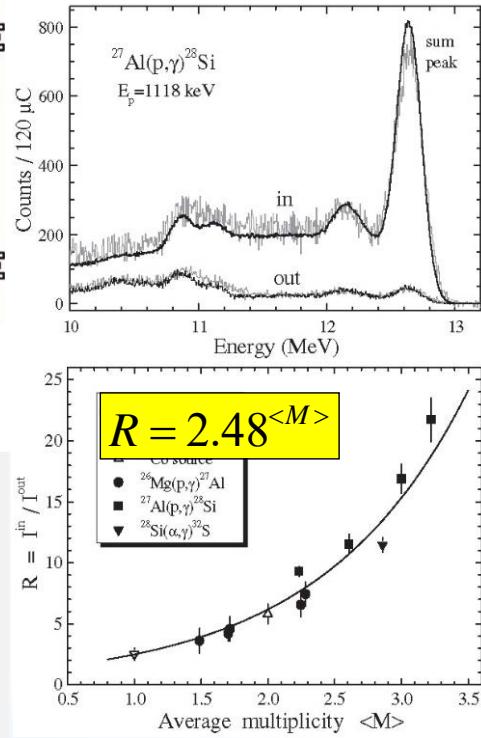
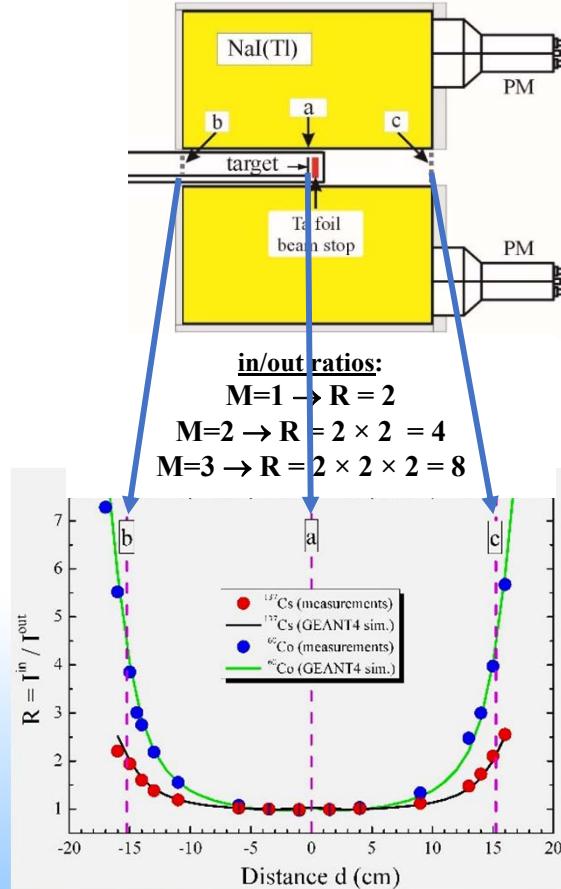
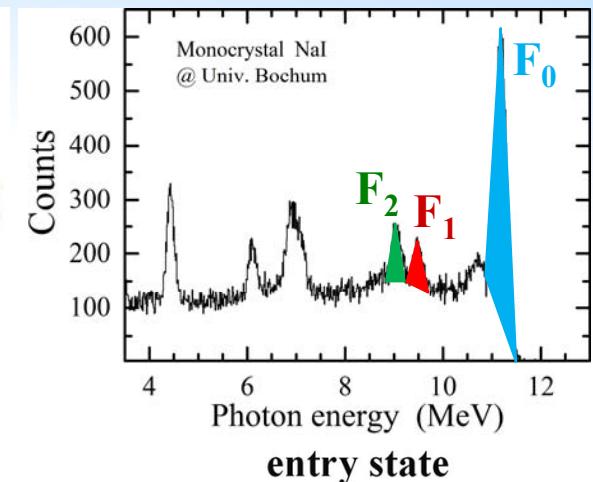
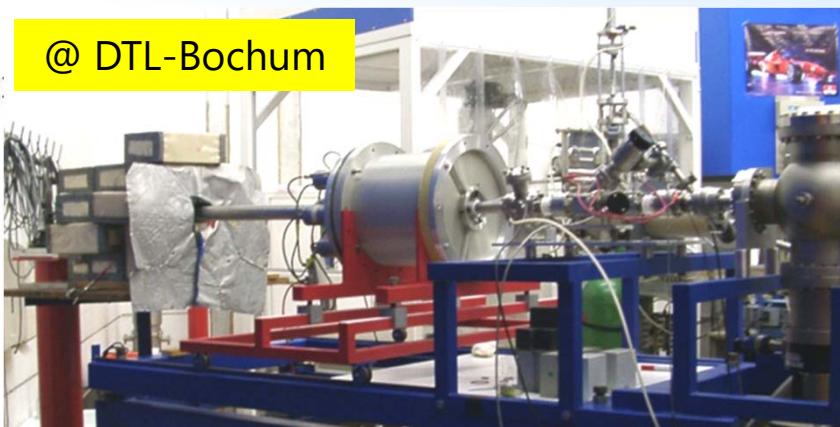
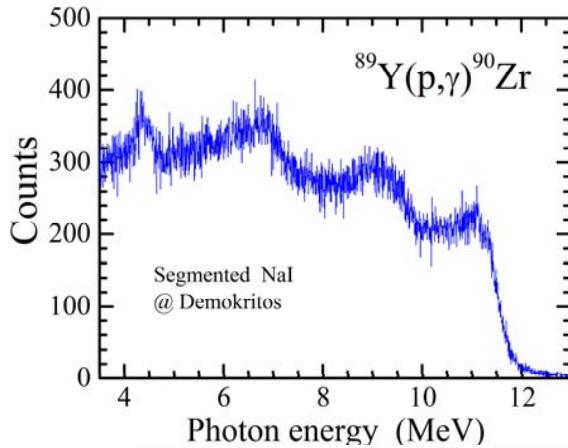
$$Y_2 = F_2 / (N_{\text{proj}} \times \varepsilon_2)$$

$$Y_{\text{TOT}} = Y_0 + Y_1 + Y_2$$

$$\varepsilon_{\Sigma} = \varepsilon_0 + \alpha \cdot \exp(-E_{\Sigma} / b)$$

$$\sigma_T = (A/N_A) (Y_{\text{TOT}} / \xi)$$

Cross sections from angle-integrated γ -spectra / 2



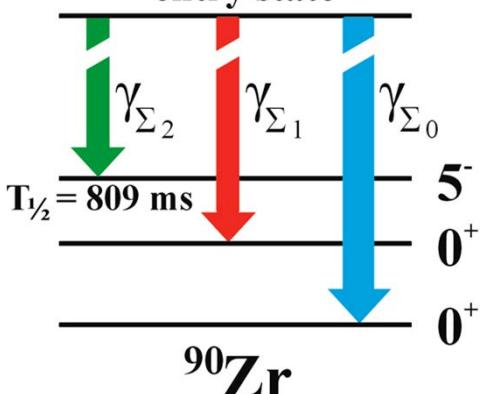
$Y_0 = F_0 / (N_{\text{proj}} \times \varepsilon_0)$

$Y_1 = F_1 / (N_{\text{proj}} \times \varepsilon_1)$

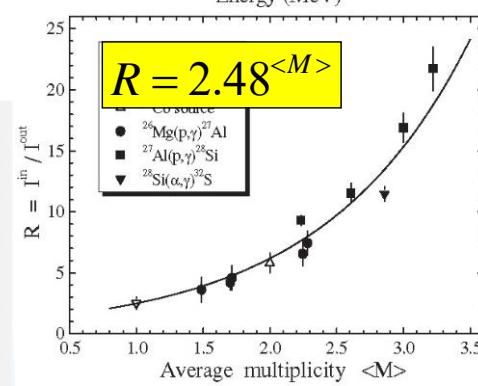
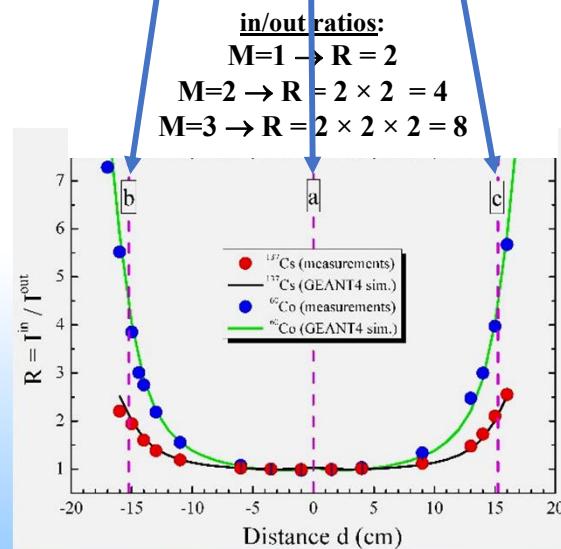
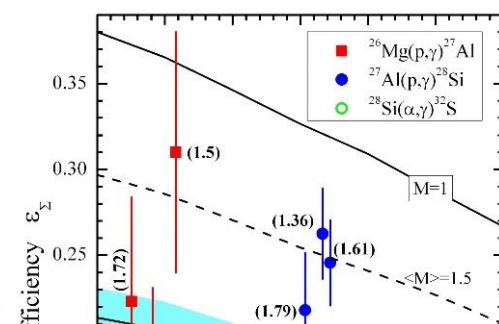
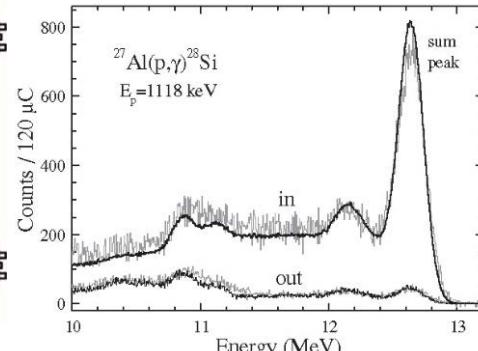
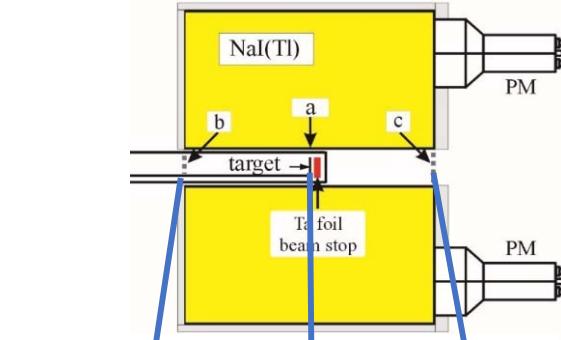
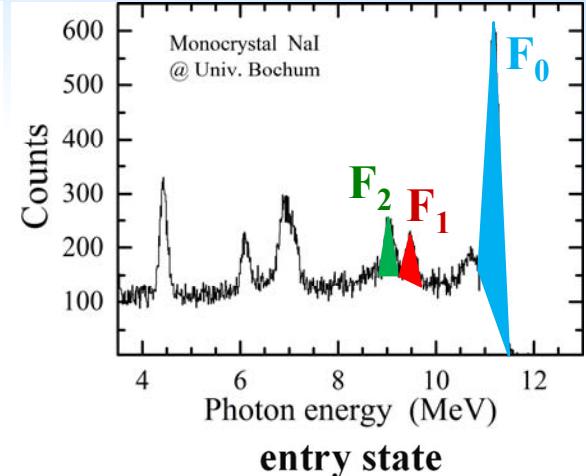
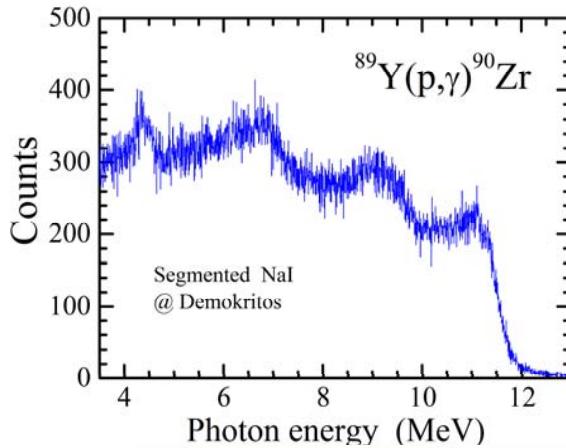
$Y_2 = F_2 / (N_{\text{proj}} \times \varepsilon_2)$

$Y_{\text{TOT}} = Y_0 + Y_1 + Y_2$

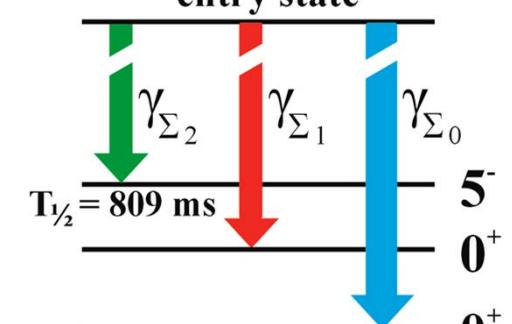
$\sigma_T = (A/N_A) (Y_{\text{TOT}} / \xi)$



Cross sections from angle-integrated γ -spectra / 2



$$\varepsilon_{\Sigma} = \varepsilon_0 + \alpha \cdot \exp(-E_{\Sigma} / b)$$



$$Y_0 = F_0 / (N_{\text{proj}} \times \varepsilon_0)$$

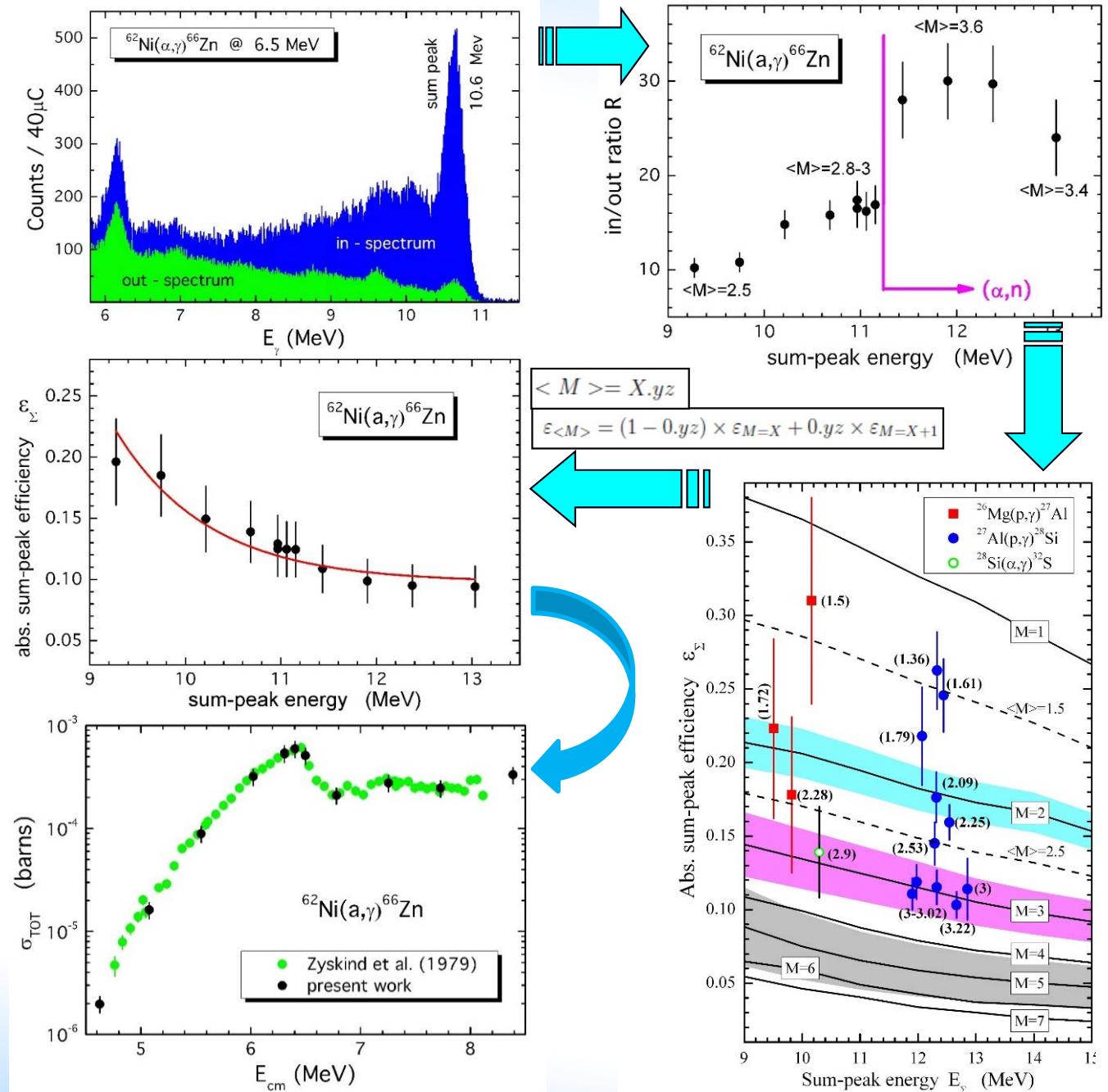
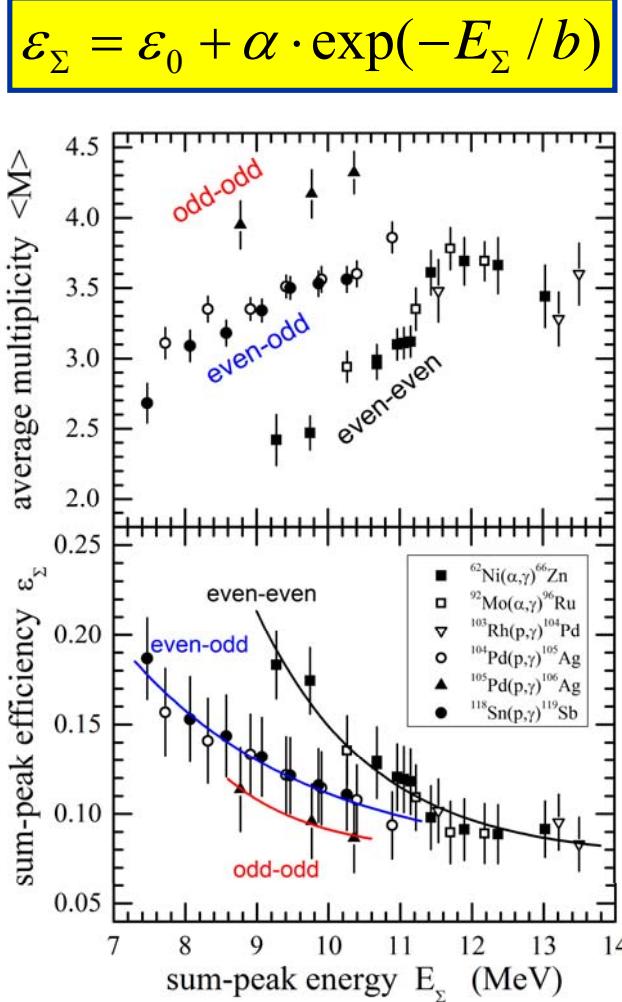
$$Y_1 = F_1 / (N_{\text{proj}} \times \varepsilon_1)$$

$$Y_2 = F_2 / (N_{\text{proj}} \times \varepsilon_2)$$

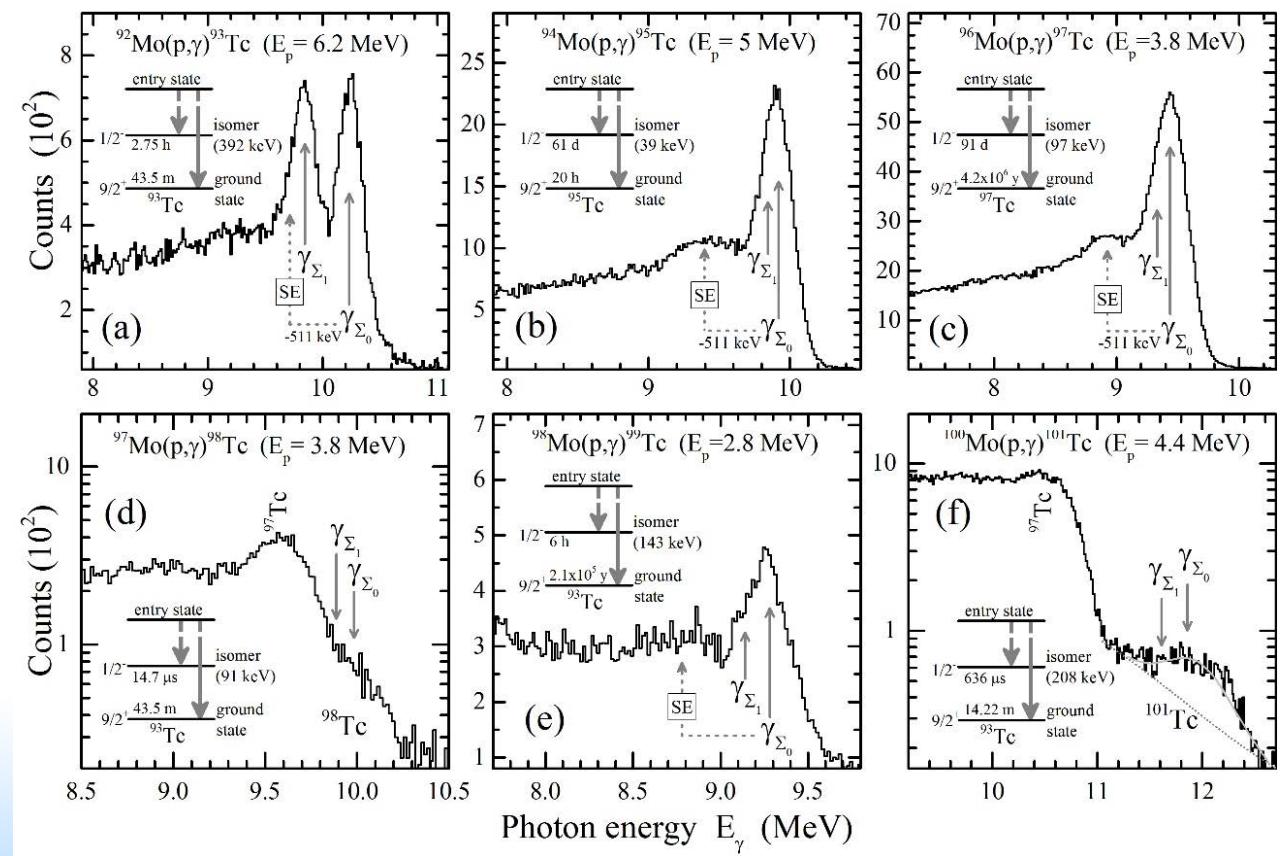
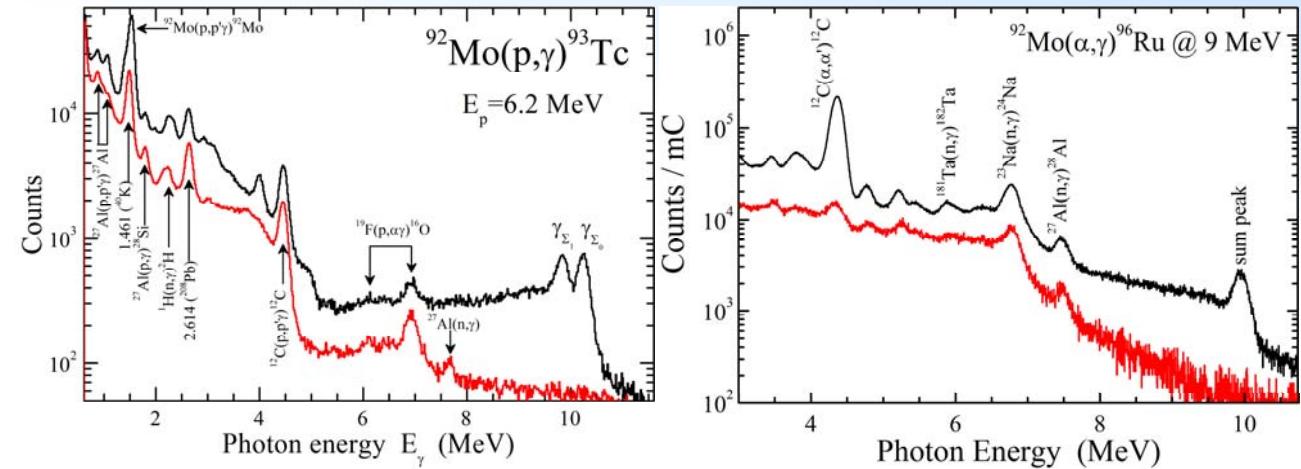
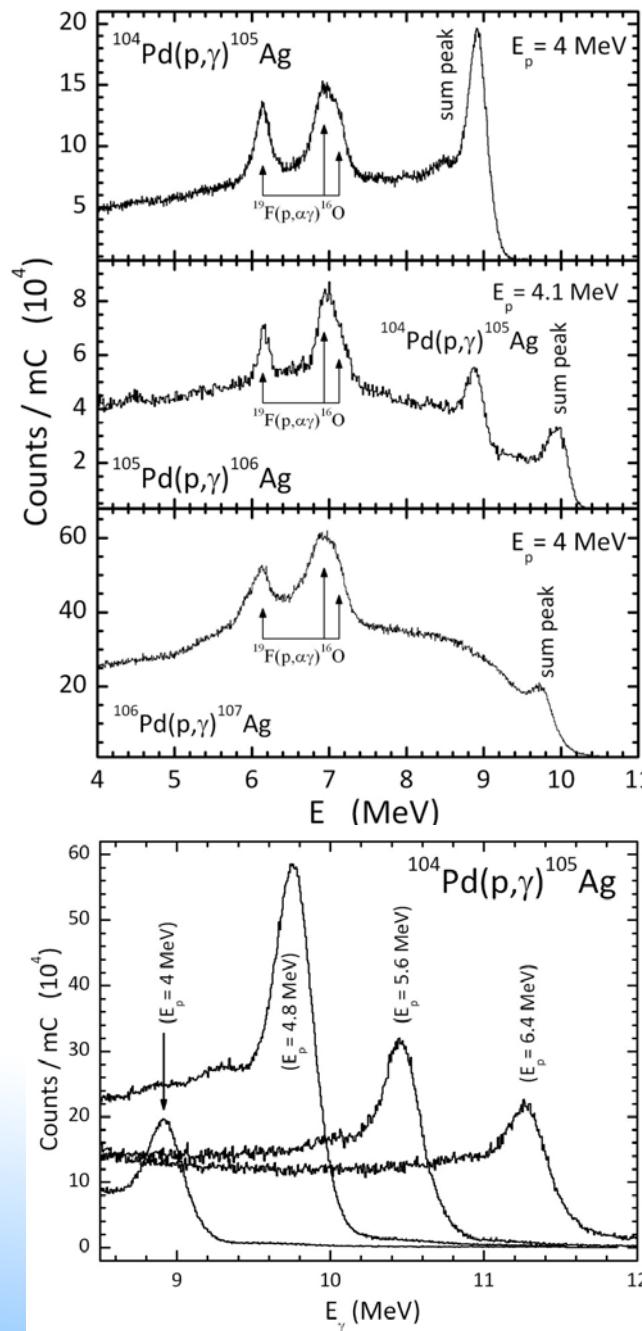
$$Y_{\text{TOT}} = Y_0 + Y_1 + Y_2$$

$$\sigma_T = (A/N_A) (Y_{\text{TOT}} / \xi)$$

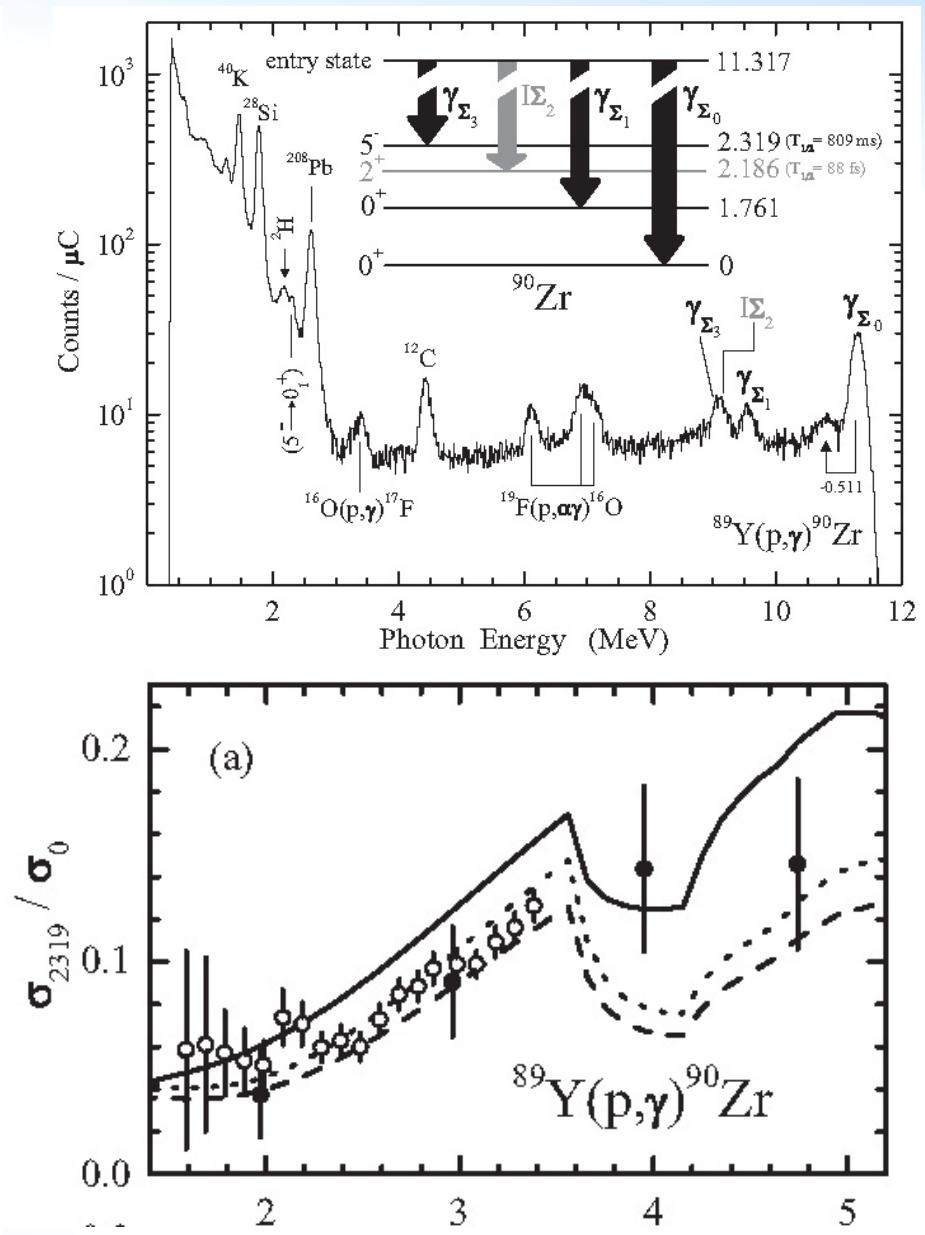
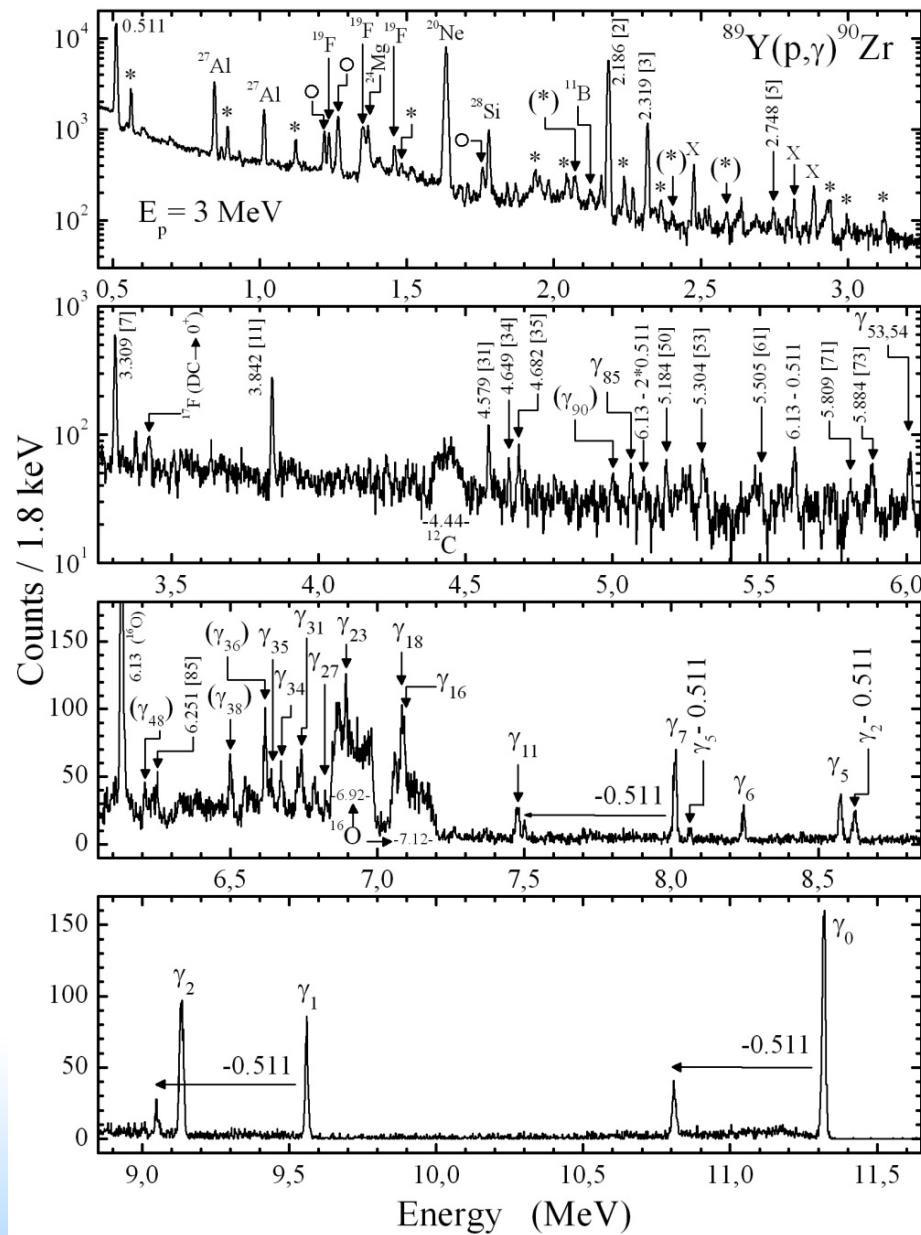
Cross sections from angle-integrated γ -spectra / 3



Typical $4\pi \gamma$ -summing (angle-integrated) γ -spectra



Spectra comparison



Direct cross-section measurement methods for captures



	OFF-BEAM activation measurements	IN-BEAM γ -angular distribution measurements	IN-BEAM angle-integrated measurements
reaction to study	final nucleus must be unstable	any	any
target	enriched or natural	enriched	enriched
backing	If, then low-Z (C, Al, Si ...)	If, then high-Z (Ta, Au, ...)	If, then mostly high-Z (Ta, Au, ...)
detectors	normal size HPGe ($\varepsilon \approx 30\%$)	large-volume HPGe (arrays) ($\varepsilon \geq 70\%$)	4π calorimeters [large NaI(Tl)] ($\varepsilon \approx 100\%$)
γ rays to detect	in most cases $E_\gamma \leq 2$ MeV	up to $E_\gamma \approx 15$ MeV	up to $E_\gamma \approx 15$ MeV

Thank you!
Ευχαριστώ !

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