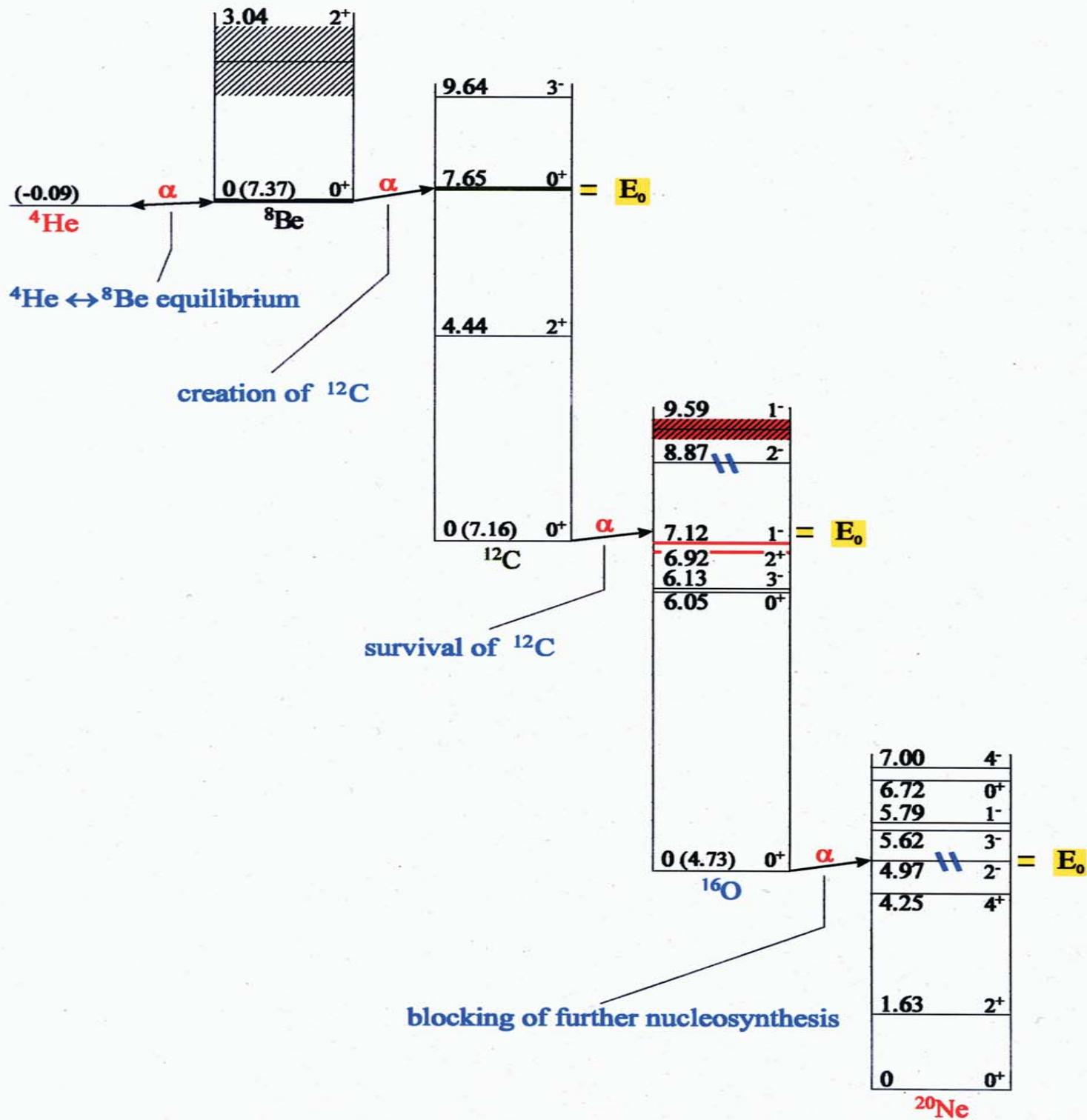


The key reaction $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$

J.W. Hammer
University of Stuttgart

Seminar talk at the occasion of the JINA R-Matrix workshop
at Notre Dame University, Oct. 12th, 2004





Influence on:

-  Carbon/Oxygen Ratio
-  Nucleosynthesis of Most Heavier Elements
-  Composition of White Dwarfs
-  Mechanism of Supernovae
-  Formation of Black Holes in Massive Stars



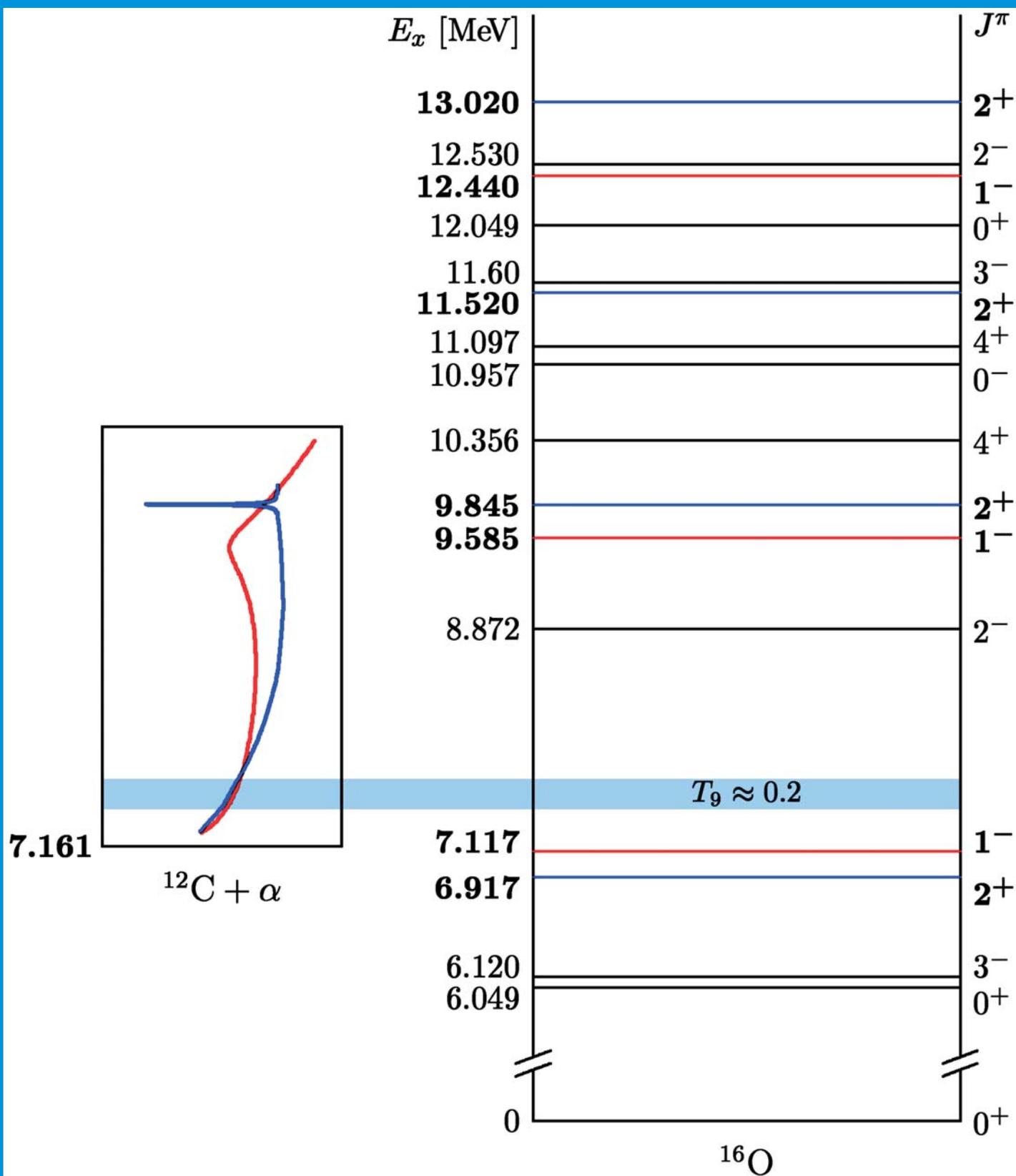
Why > 30 years of research ?

$$\sigma \approx 10^{-17} \text{ b}$$

- ▶ *Resonances, Interferences*
- ▶ *Modelling, Extrapolation*
- ▶ *Separation E1, E2, Rest*



^{16}O level scheme



Stuttgart Approach to C12ag :

γ - angular Distribution

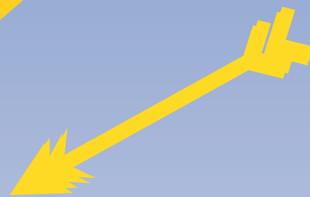


$\delta_{\alpha\alpha}$

Separation of E1,E2 + Phase Φ_{12}
Modelling by R-Matrix



$\delta_{\alpha\alpha}$



^{16}N

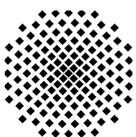
S-Factor Curves



Extrapolation



Reaction Rate



Experimental Ingredients

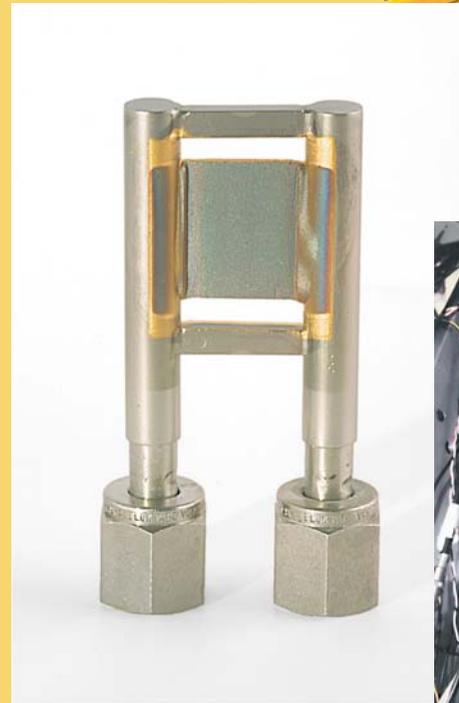
Ion beam :

- ▶ Intensity 0.5 mA He⁺
- ▶ Stability
- ▶ Beam induced background



Targets :

- ▶ Isotope separation
- ▶ Purity
- ▶ Homogeneity
- ▶ Standing time

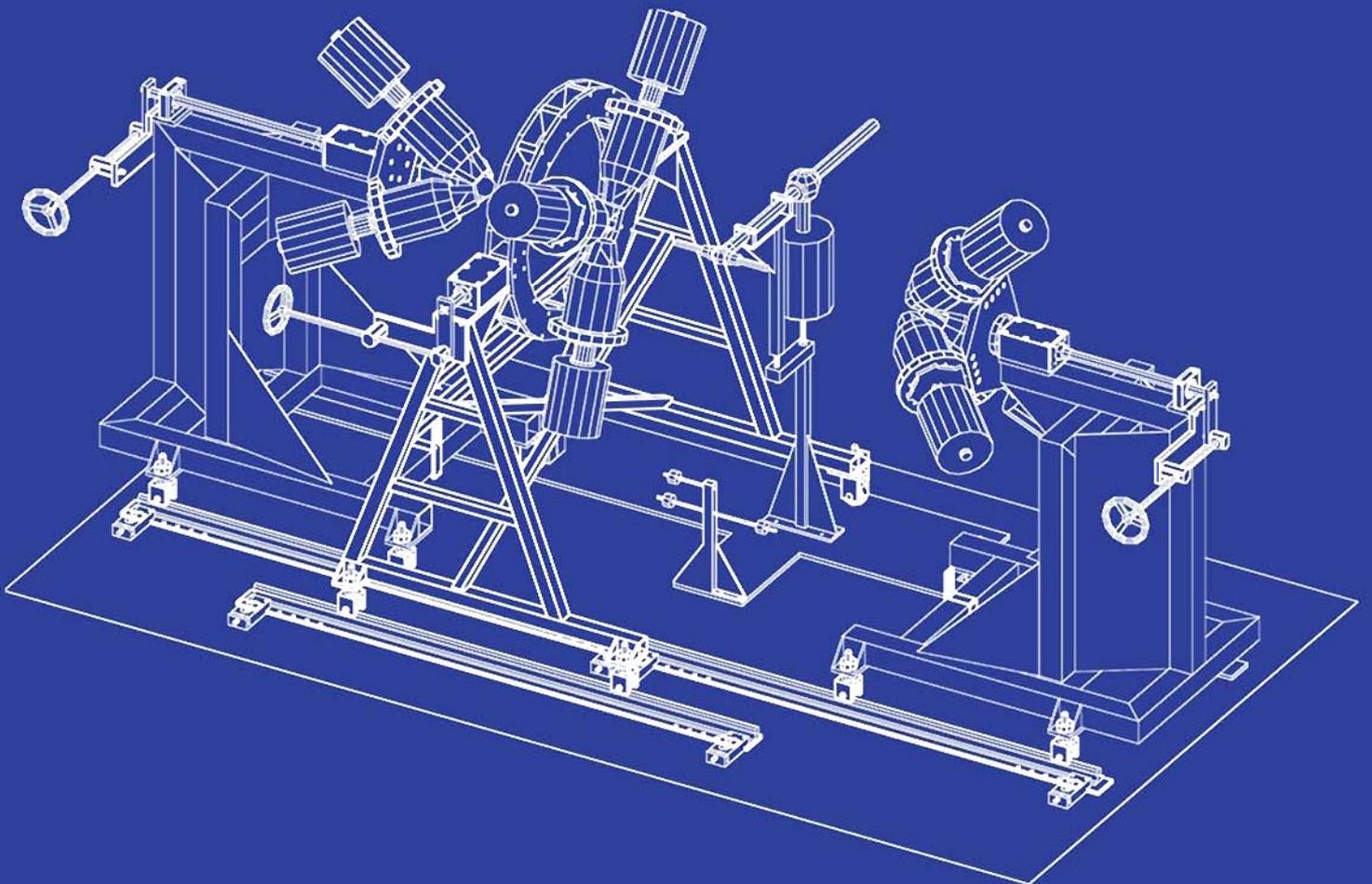
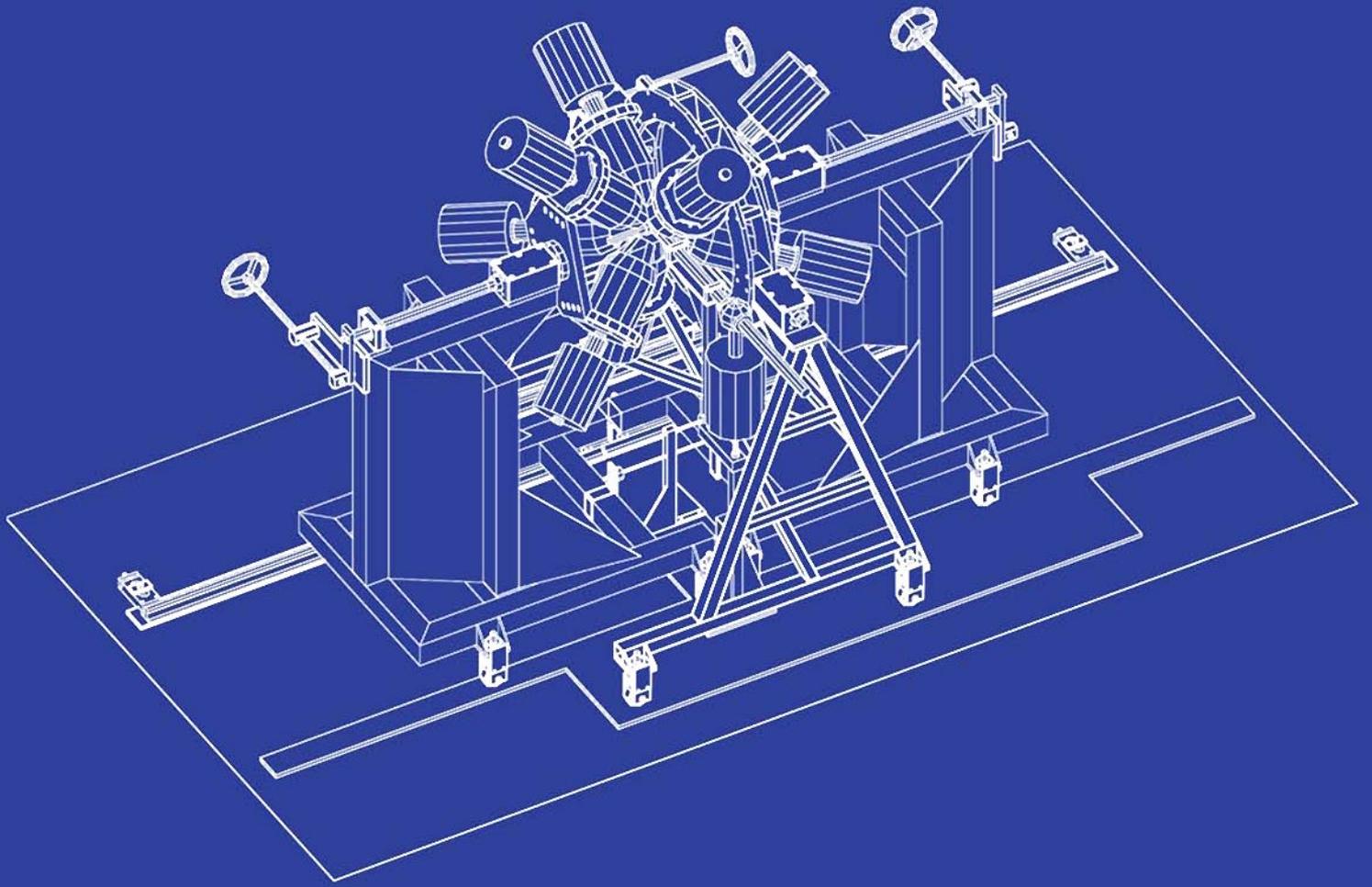


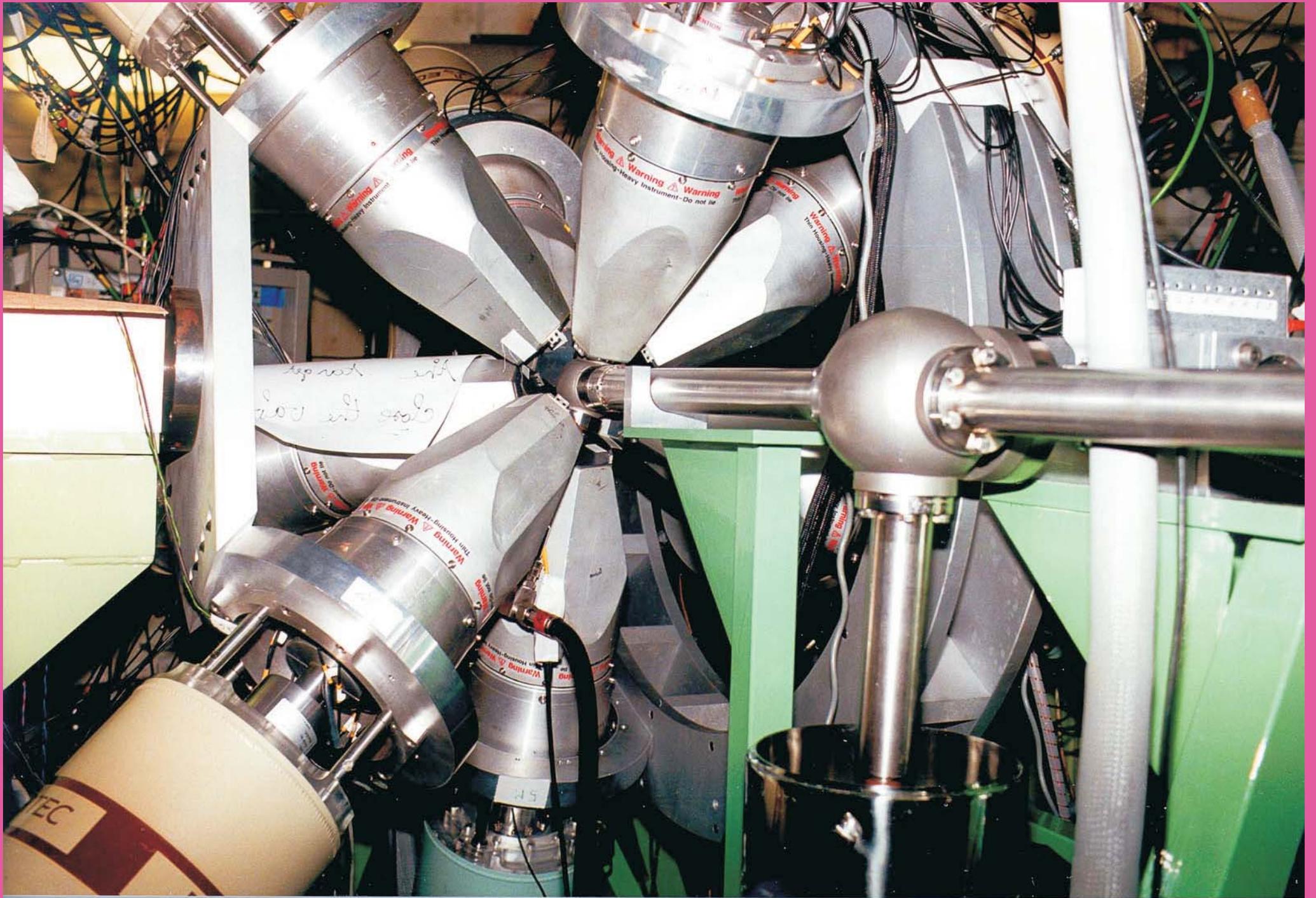
Measuring time

Detectors :

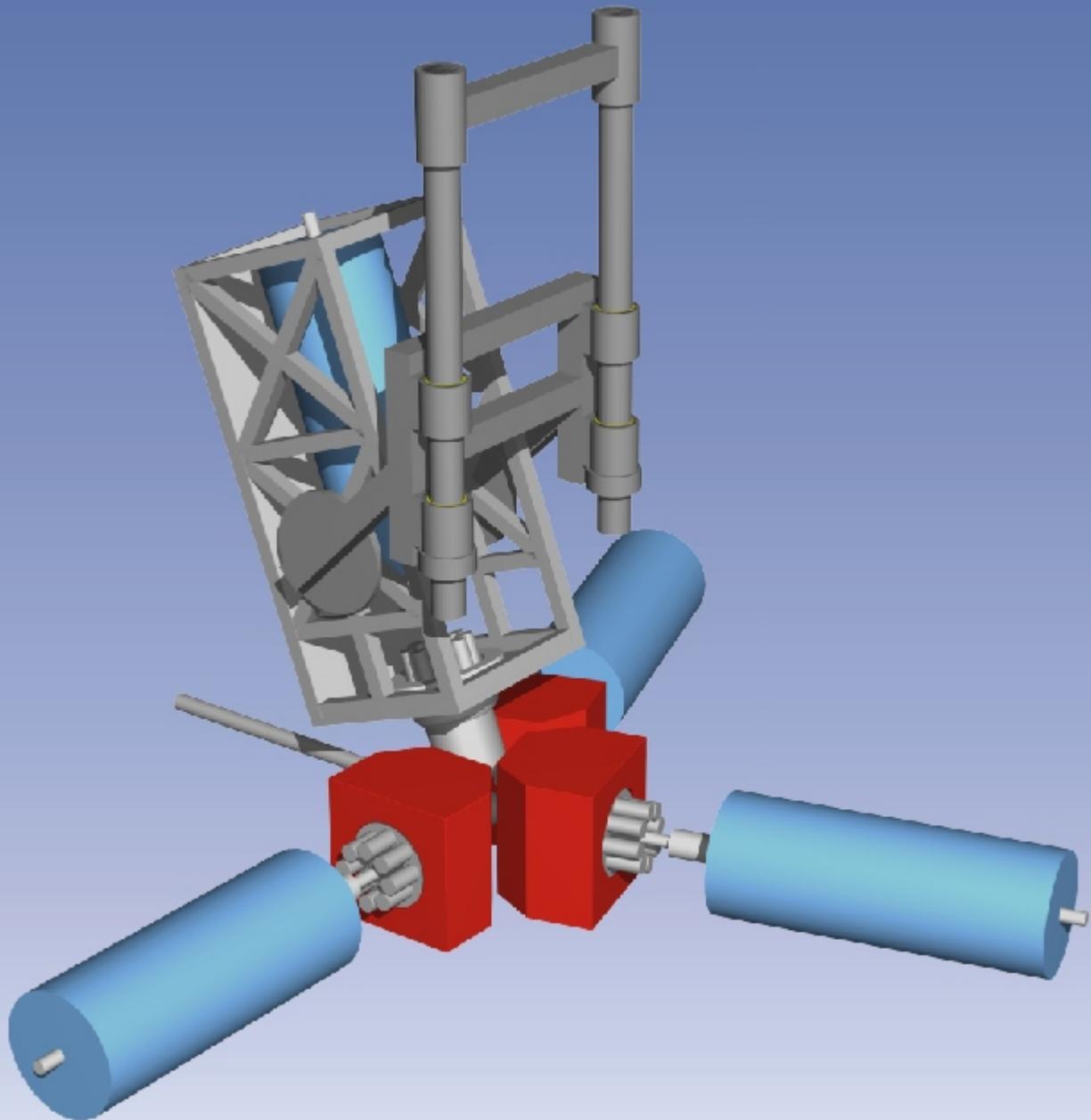
- ▶ Efficiency
- ▶ Background suppression
- ▶ Granularity



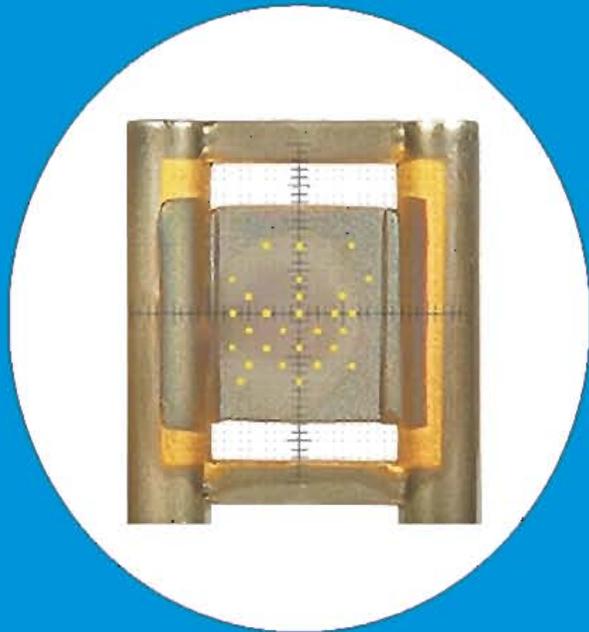




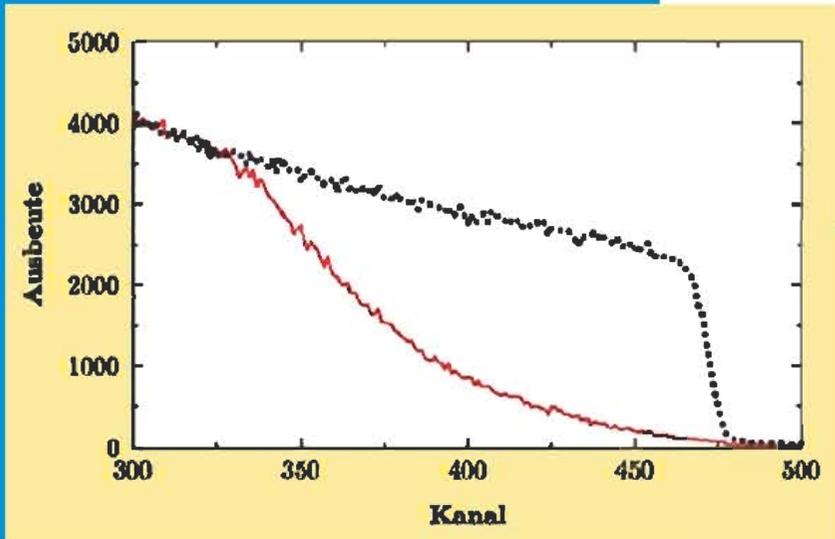
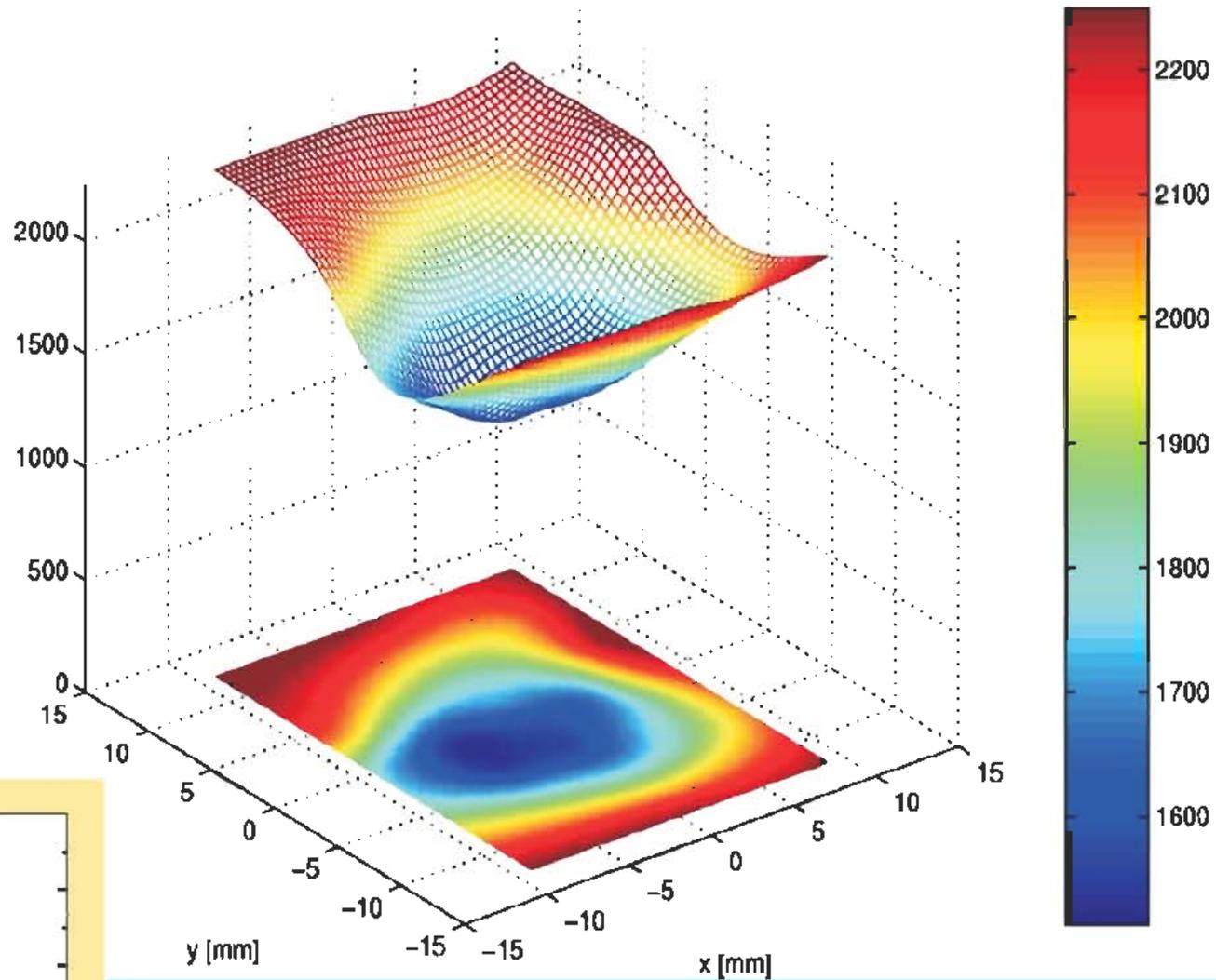
The Stuttgart GANDI Array

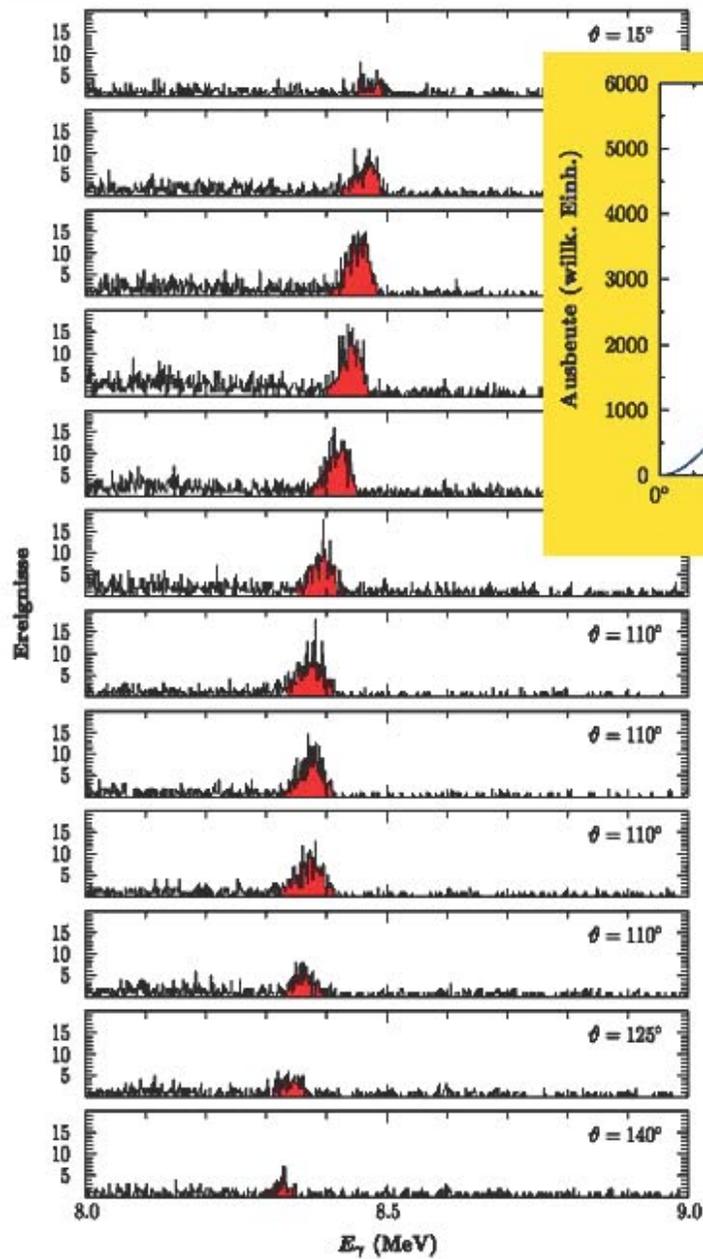




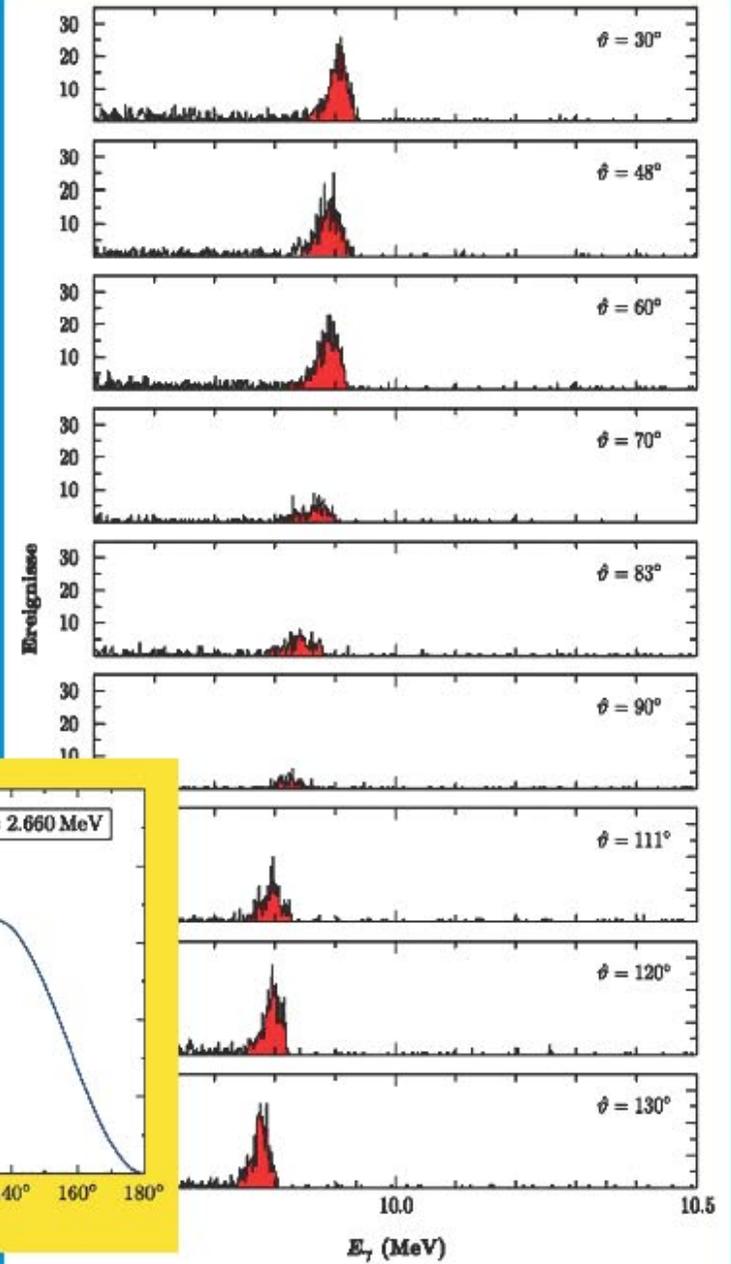
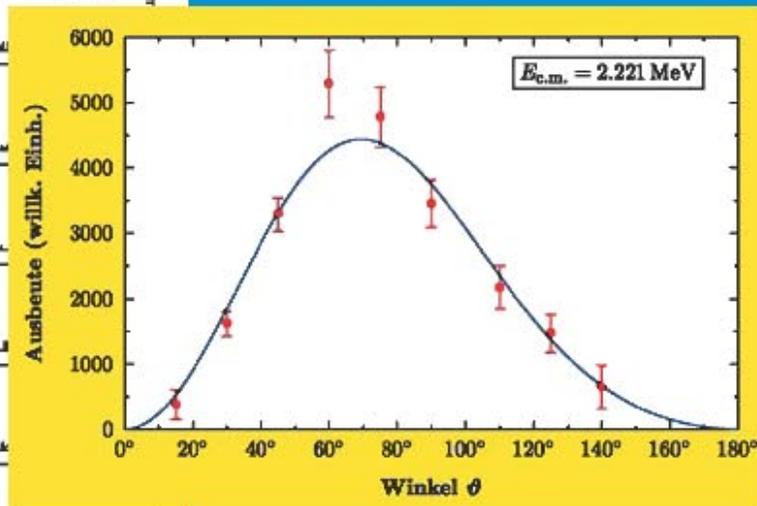


^{12}C Flächenbelegung [10^{15} Atome cm^{-2}]

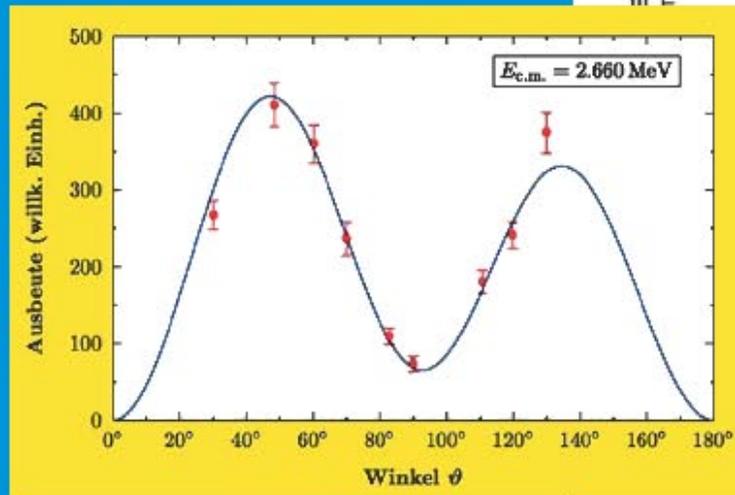




γ -Spektren bei $E_{c.m.} = 2.221$ MeV.



γ -Spektren bei $E_{c.m.} = 2.660$ MeV.



Efforts for the two C12ag - experiments :

Target production

70 days

Target development

41 days

3.300 spectra

C12ag - reaction

121 days

32.000 spectra

RBS-target-analysis

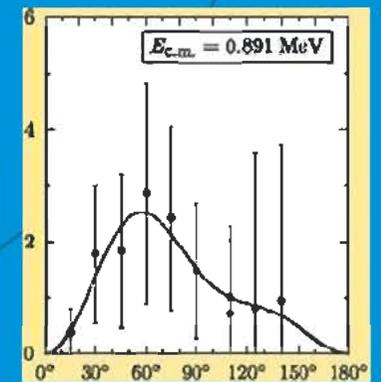
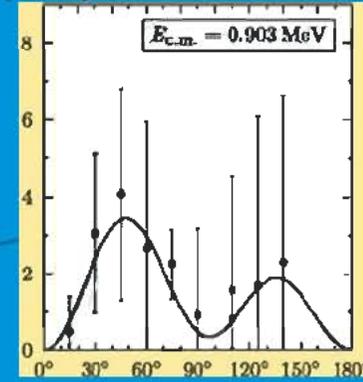
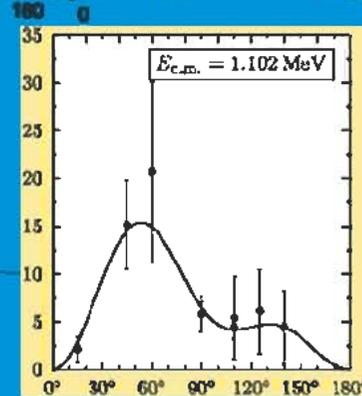
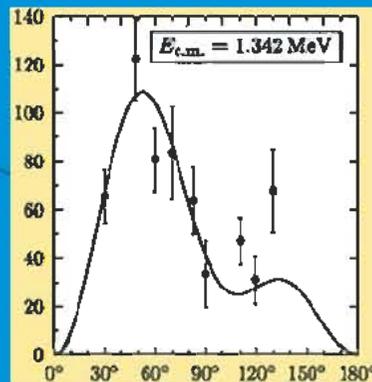
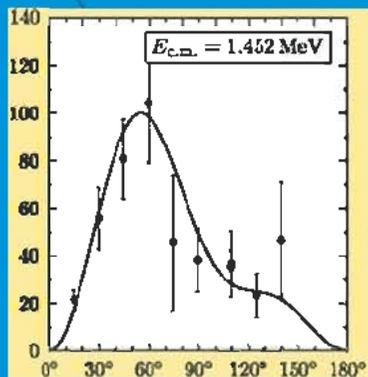
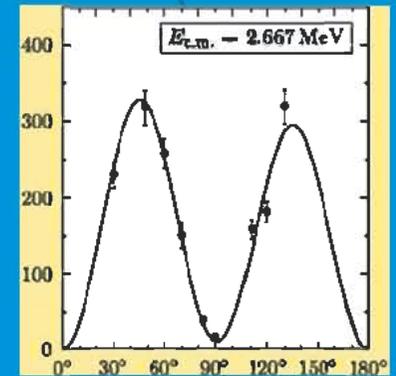
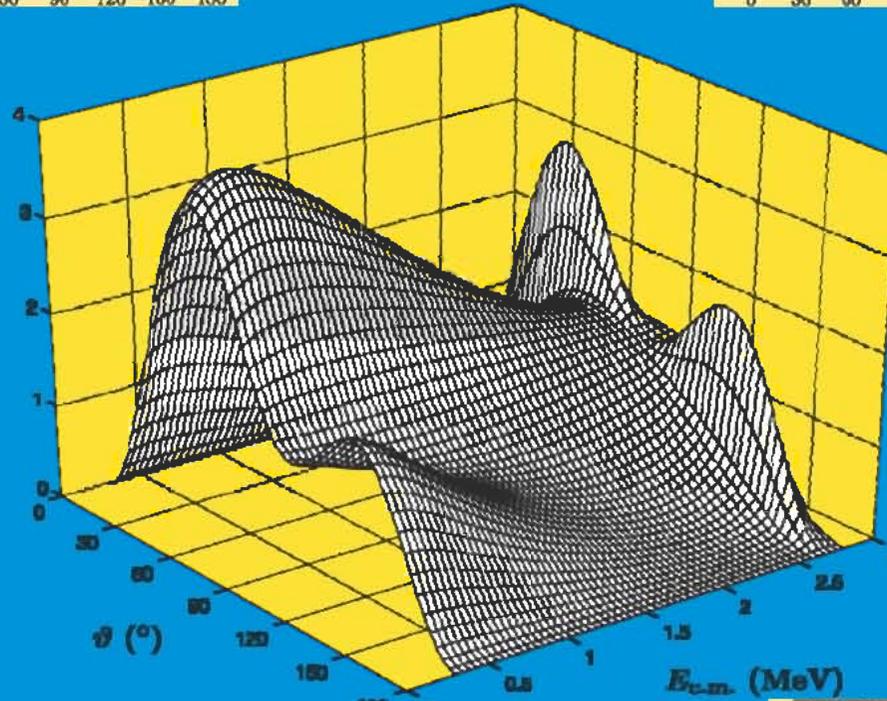
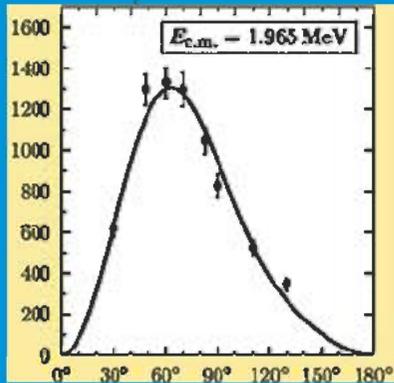
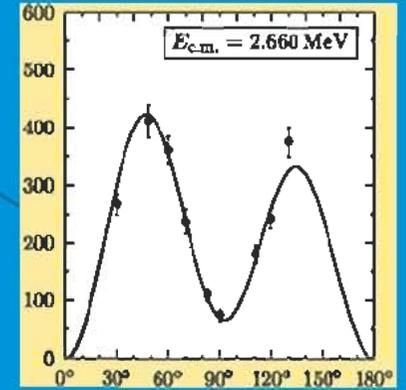
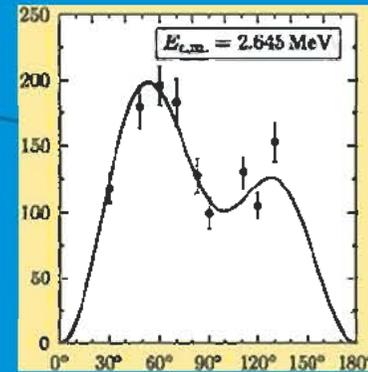
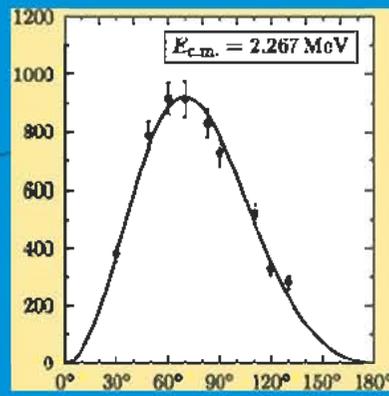
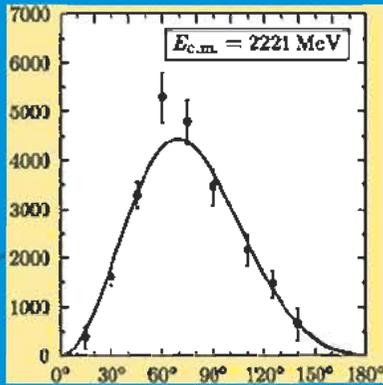
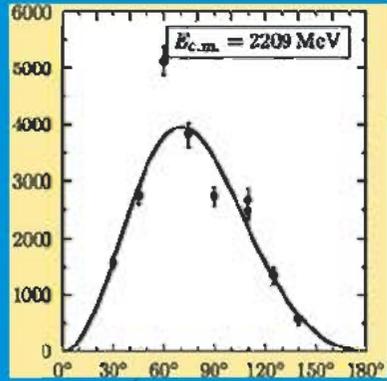
30 days

800 spectra



full beam days !





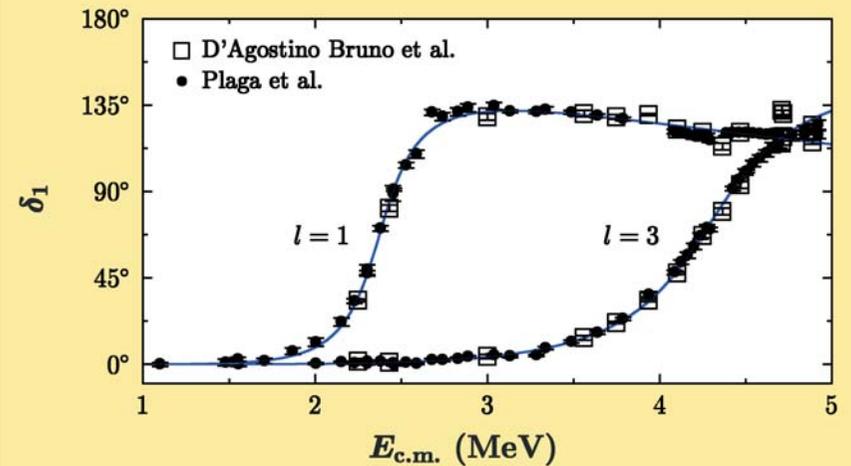
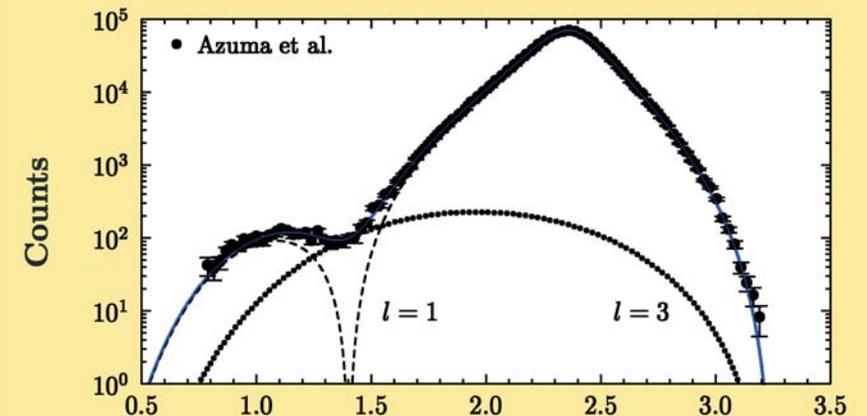
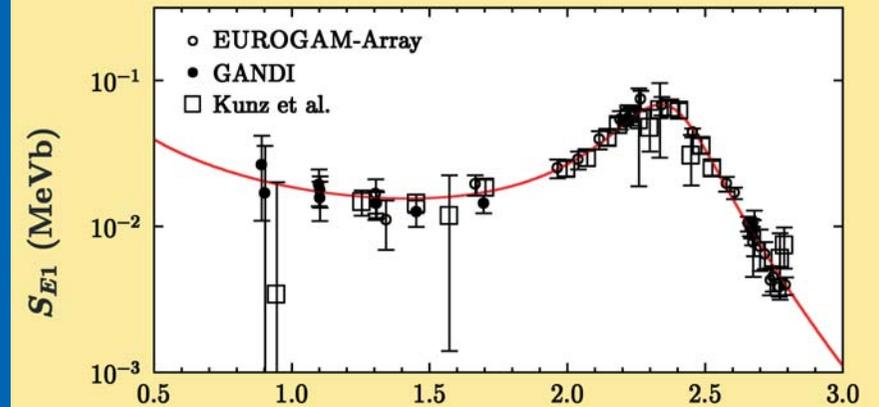
R - Matrix Fits E1

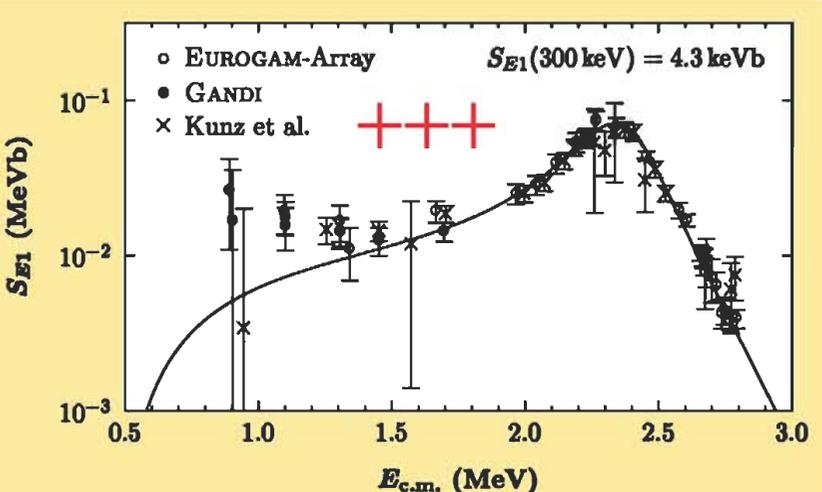
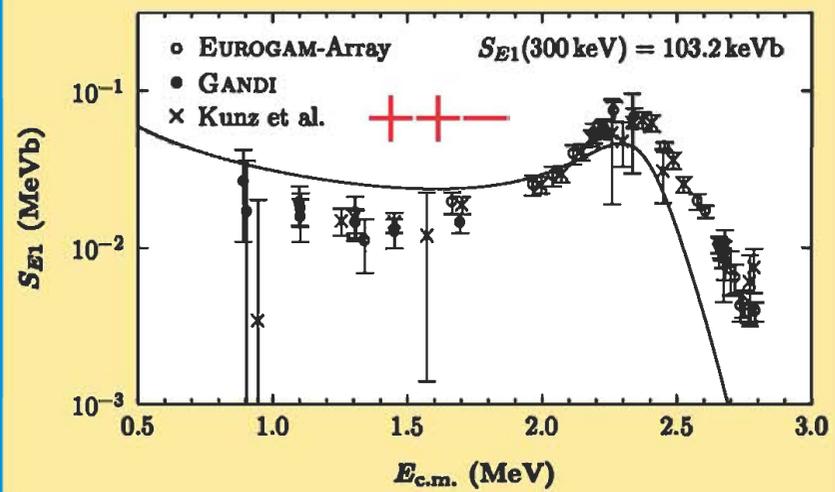
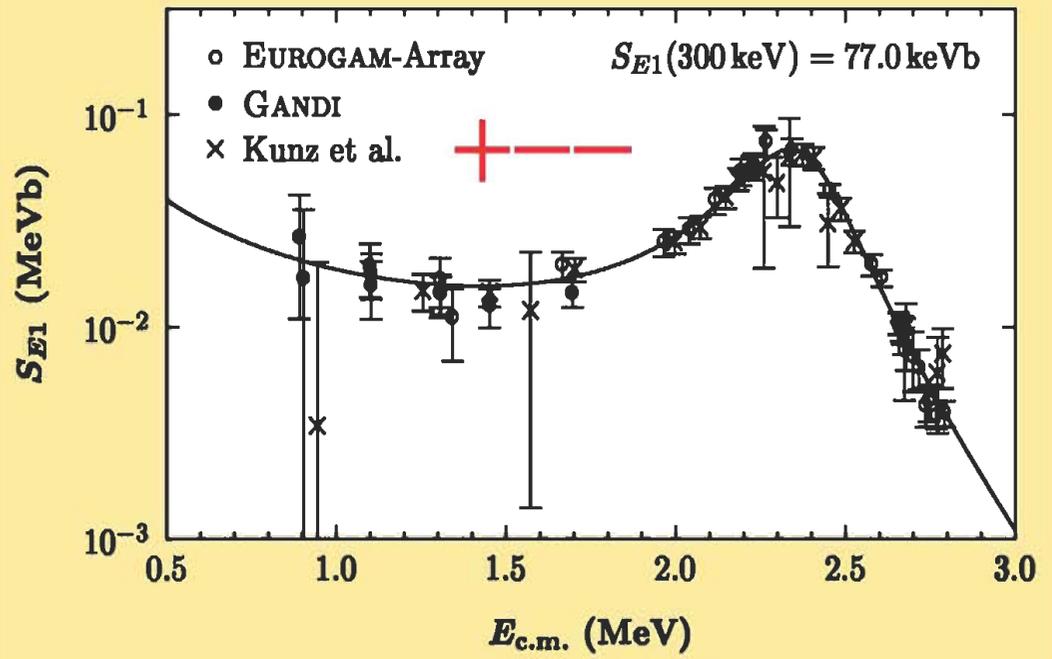
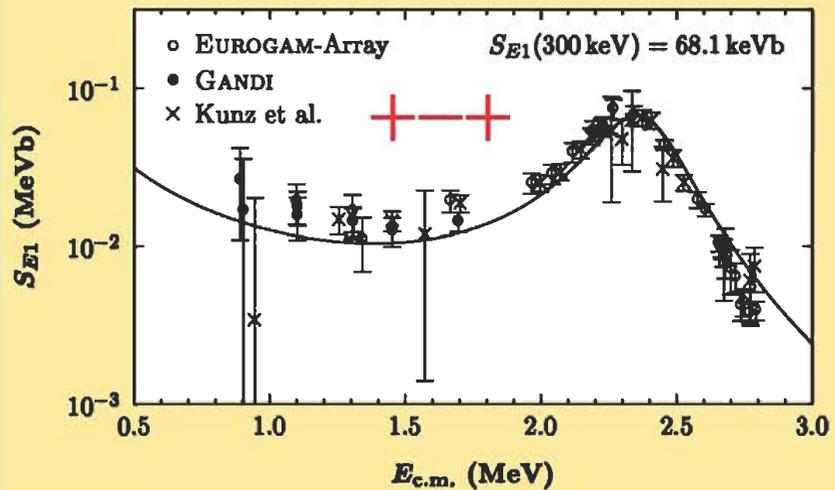
Fit of ...

- ▶ Capture data
- ▶ ^{16}N data
- ▶ α -scattering data

3-level-fit

- ▶ 4 interference-combinations





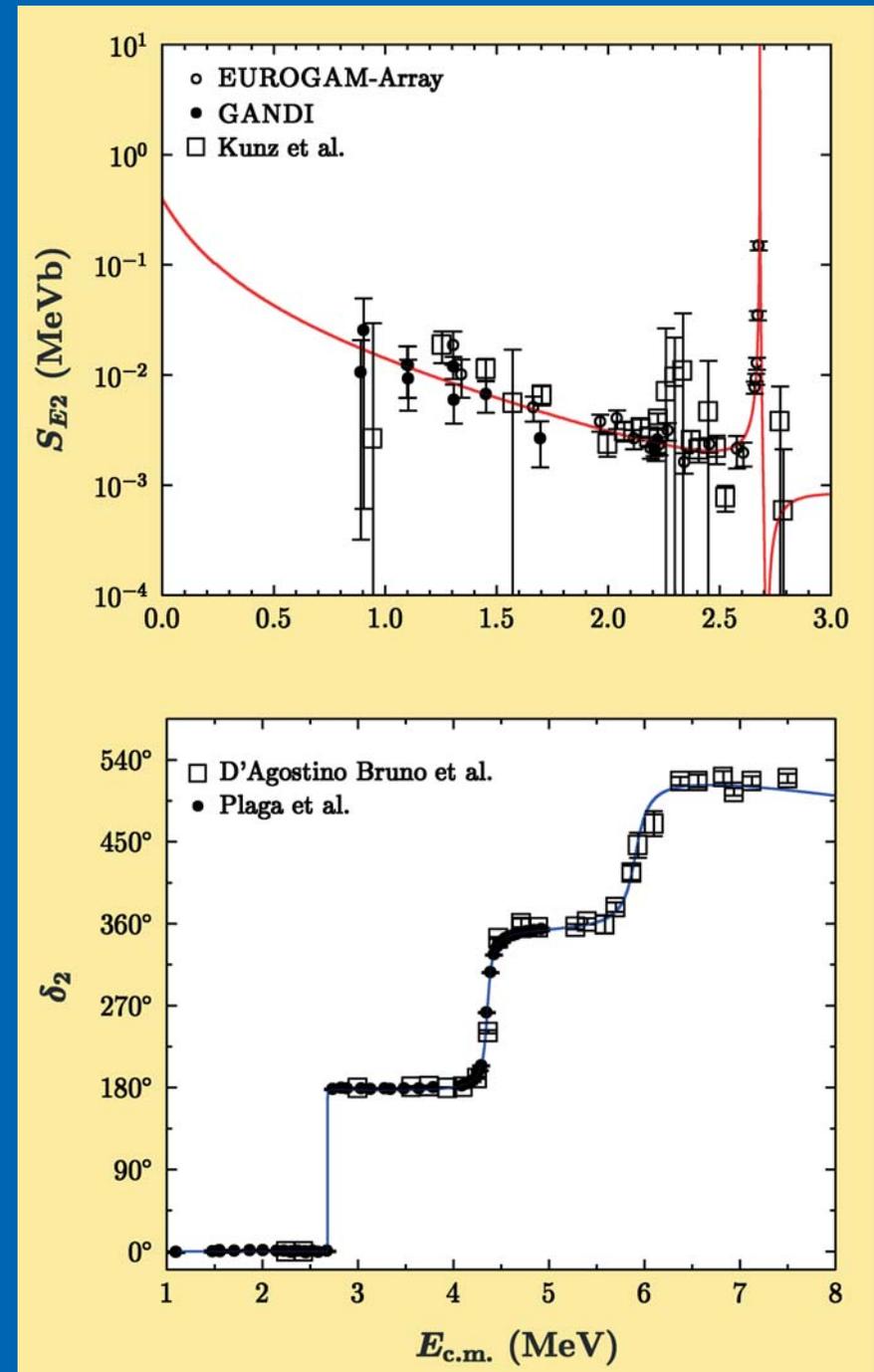
R - Matrix Fits E2

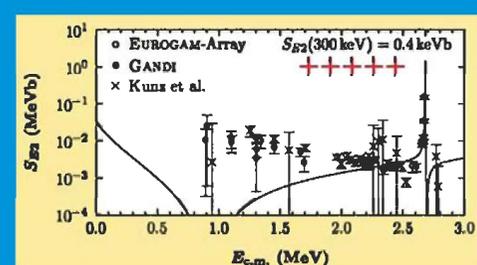
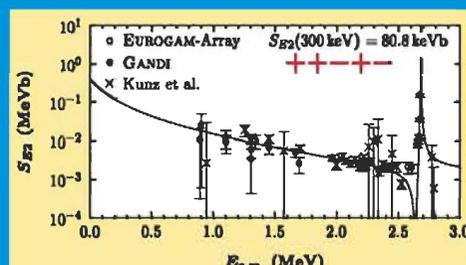
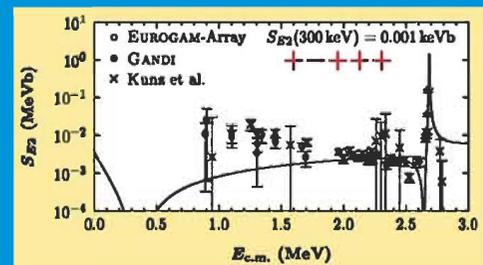
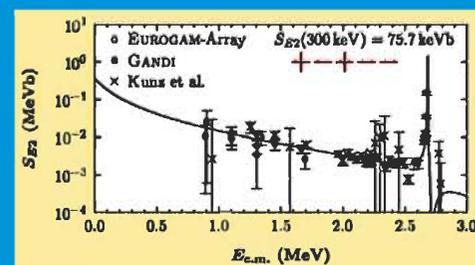
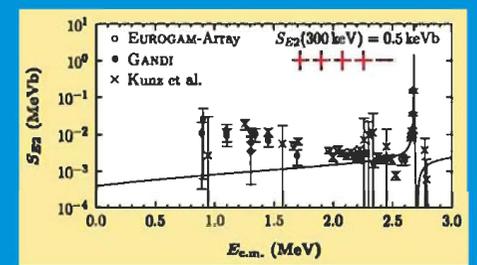
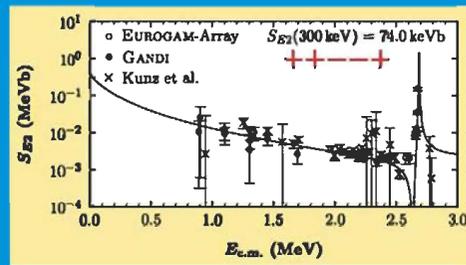
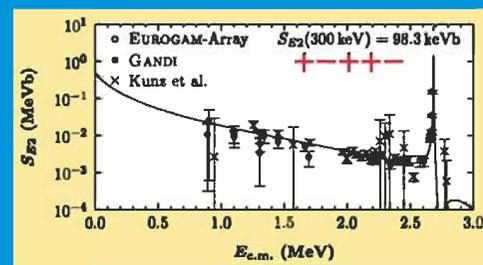
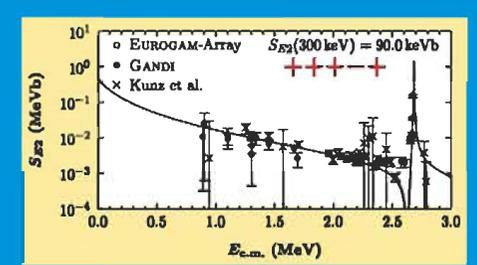
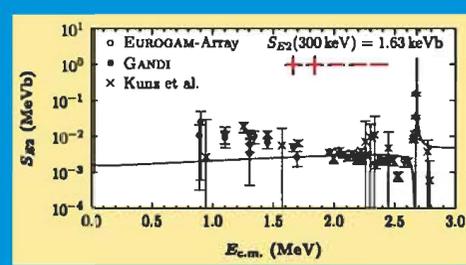
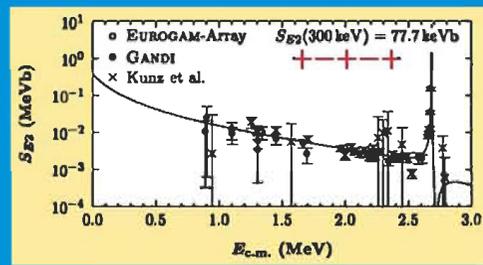
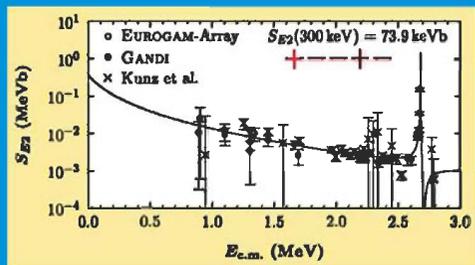
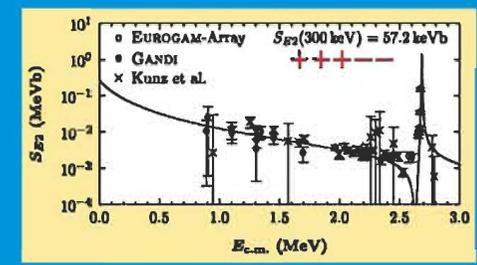
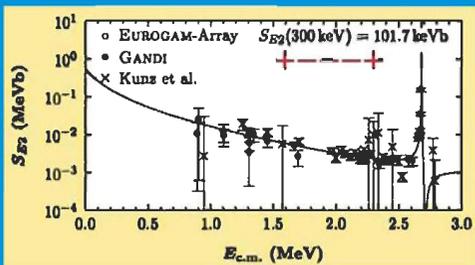
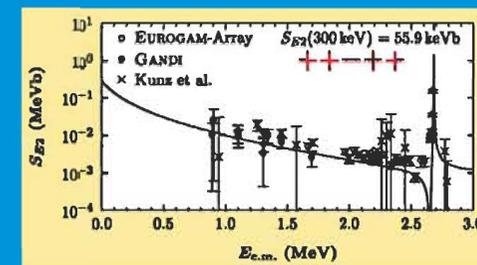
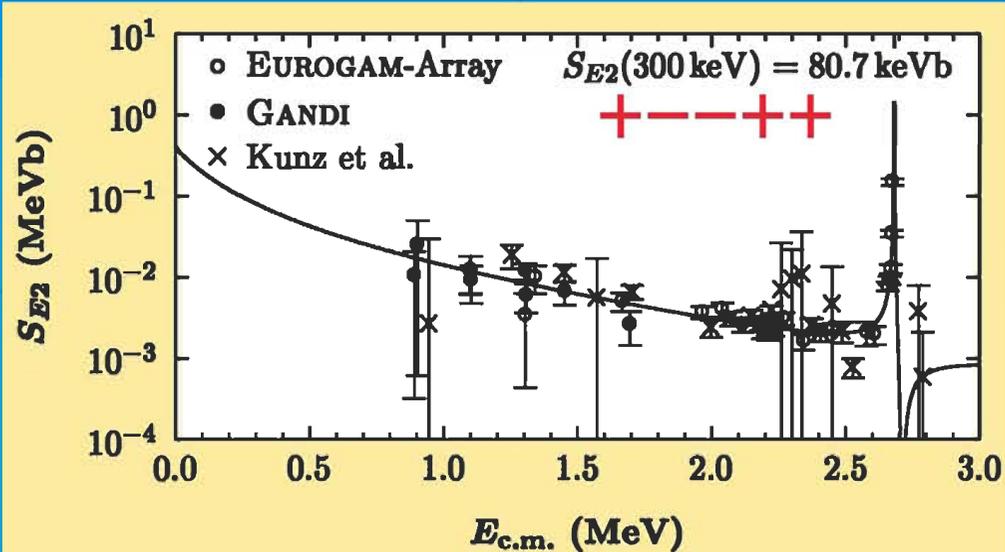
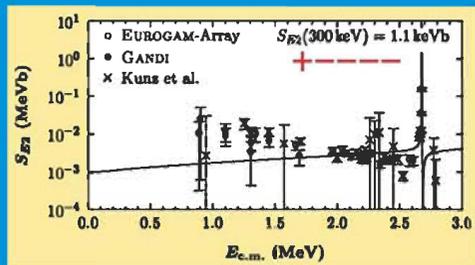
Fit of ...

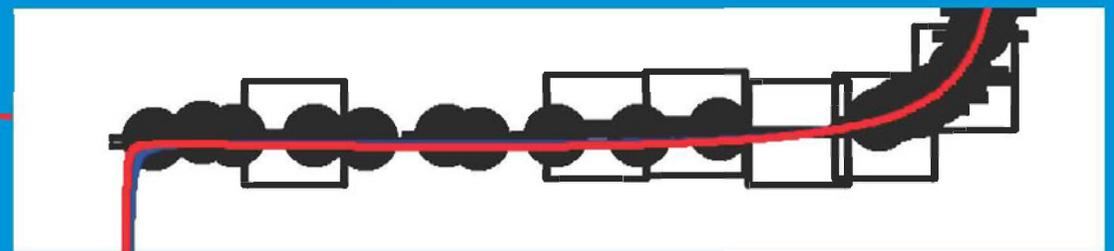
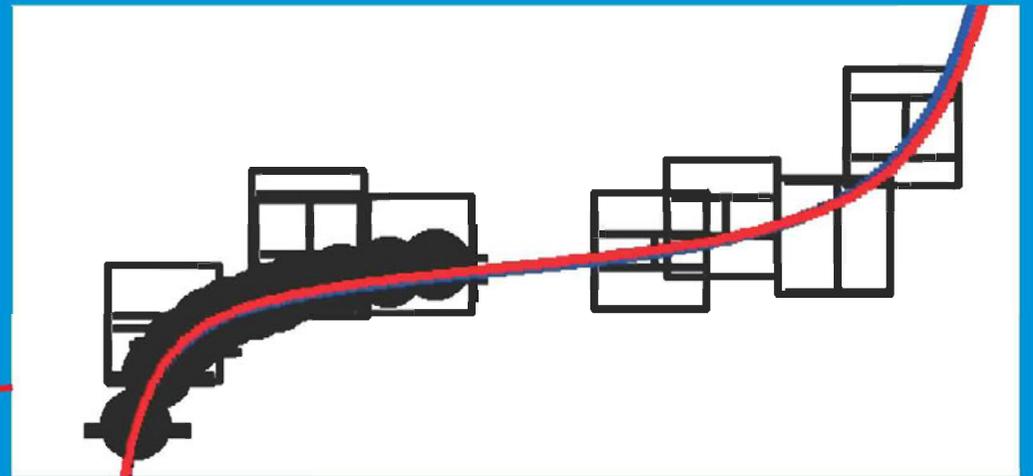
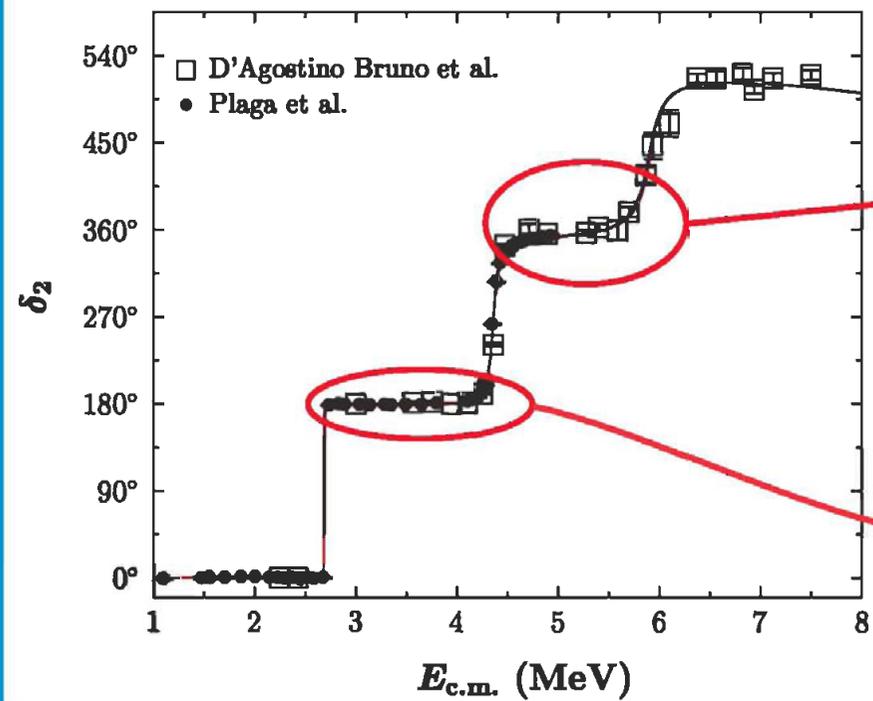
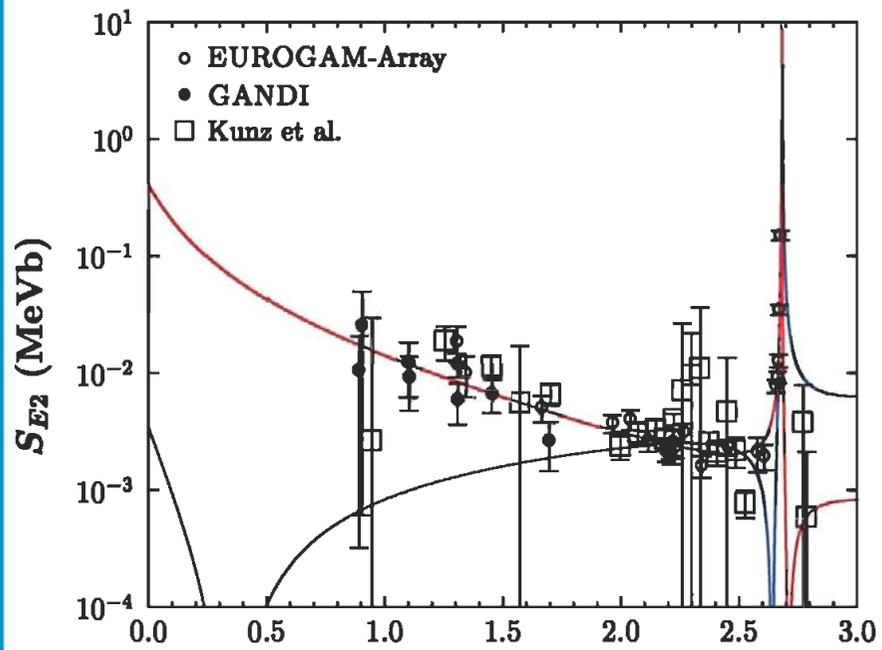
- Capture data
- α -scattering data

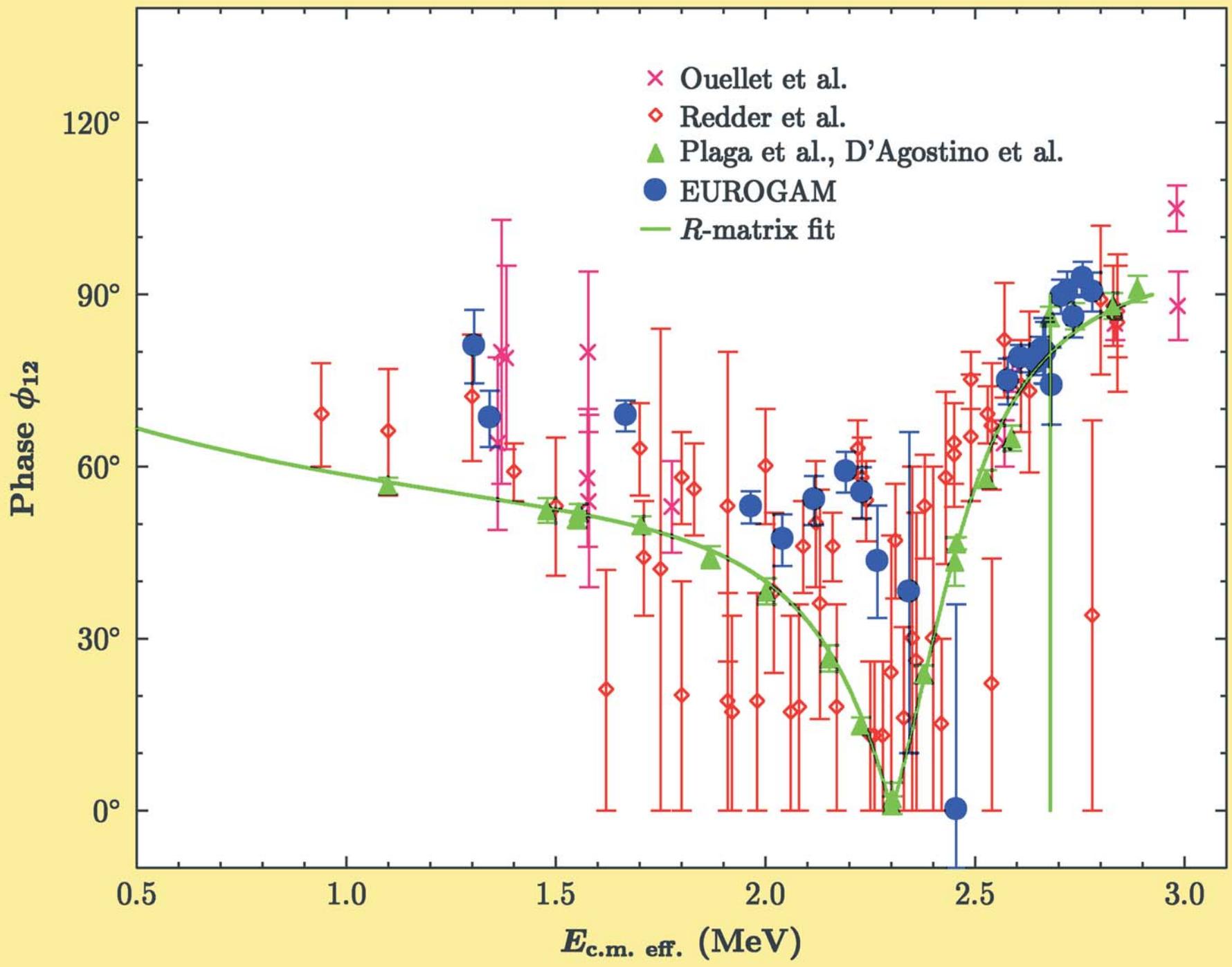
5-level-fit

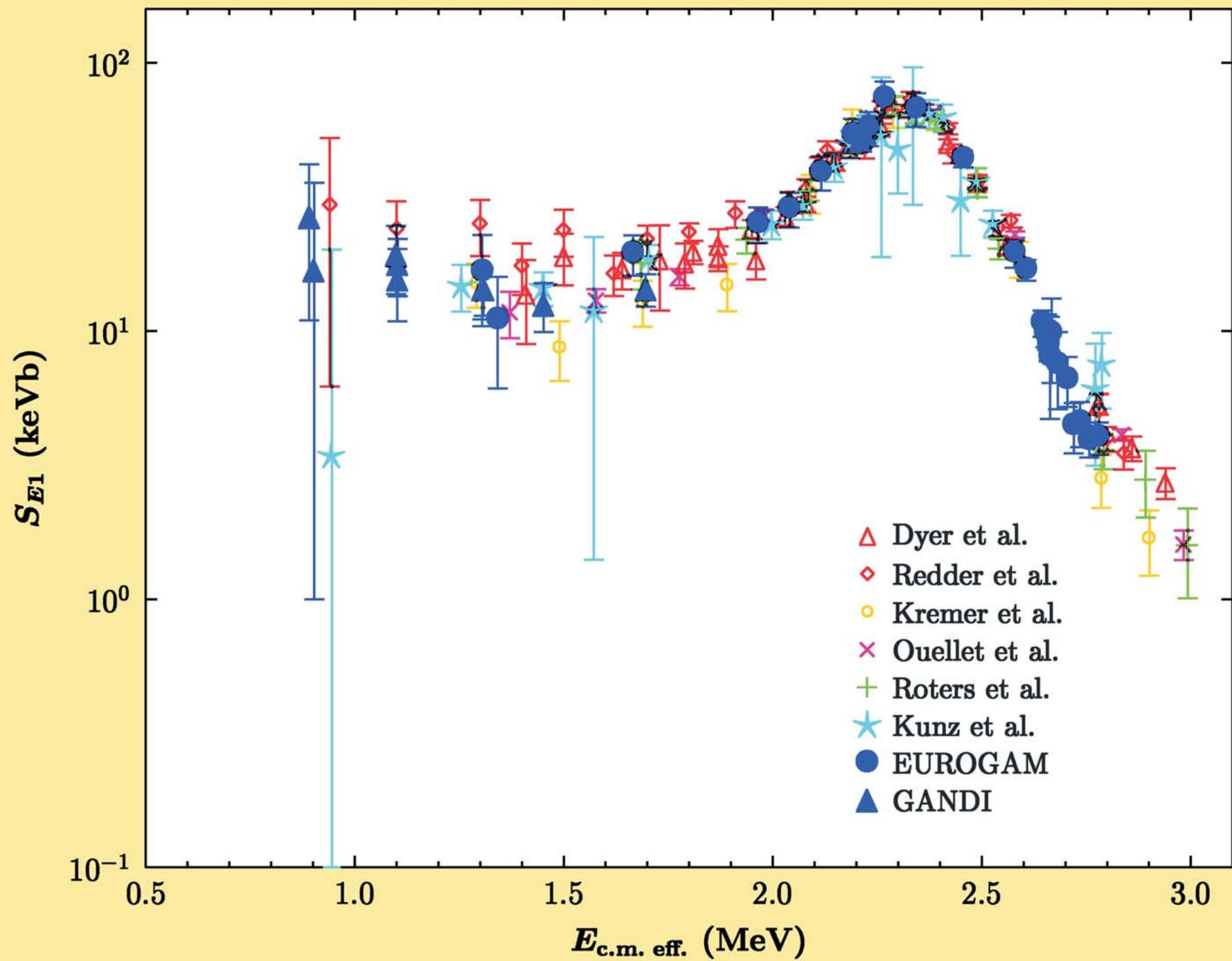
- 16 interference-combinations



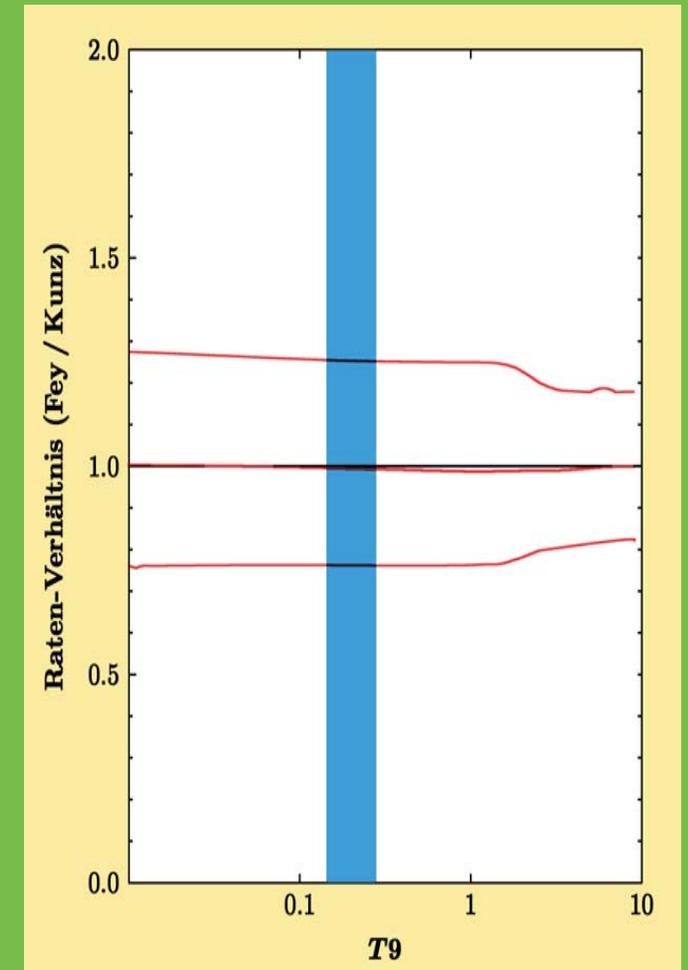
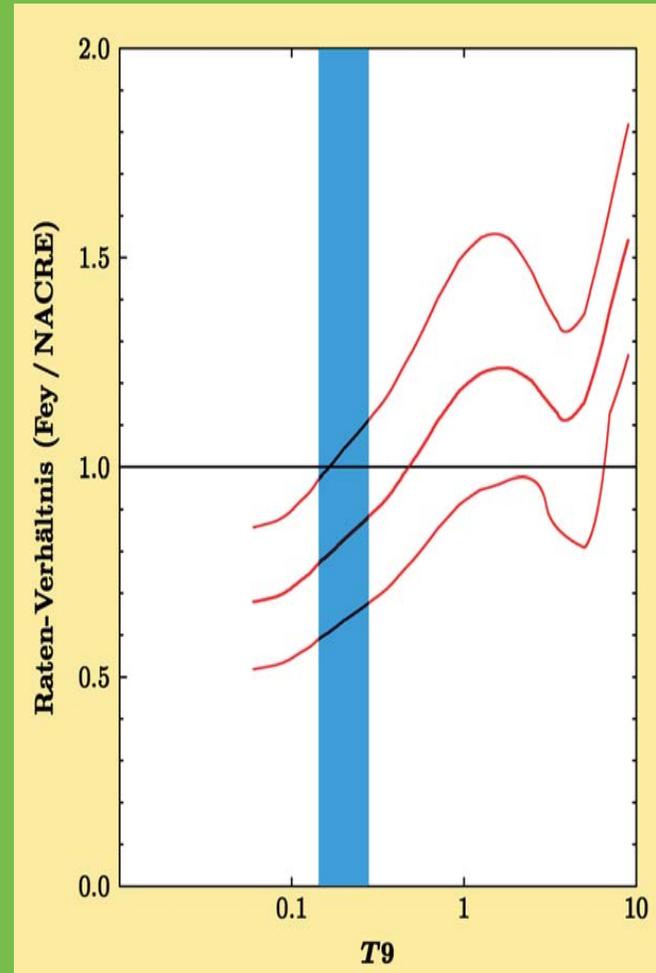
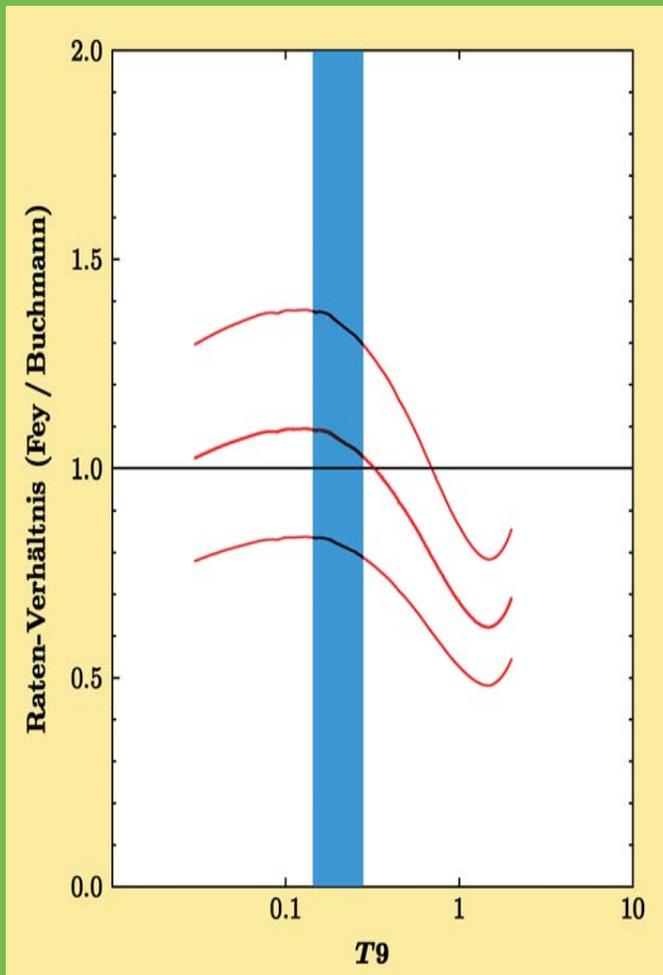




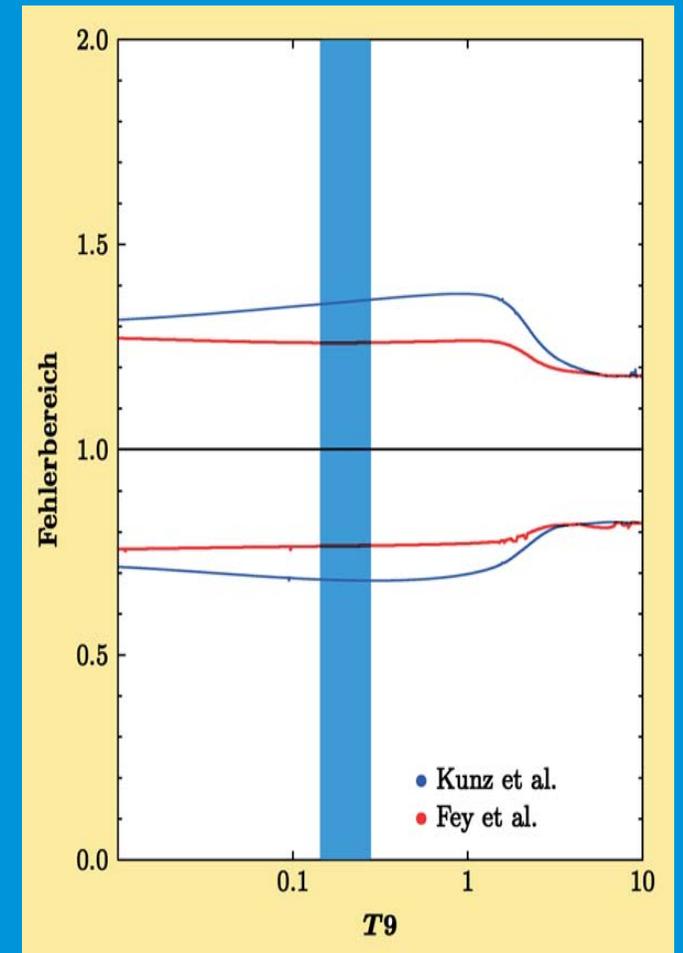
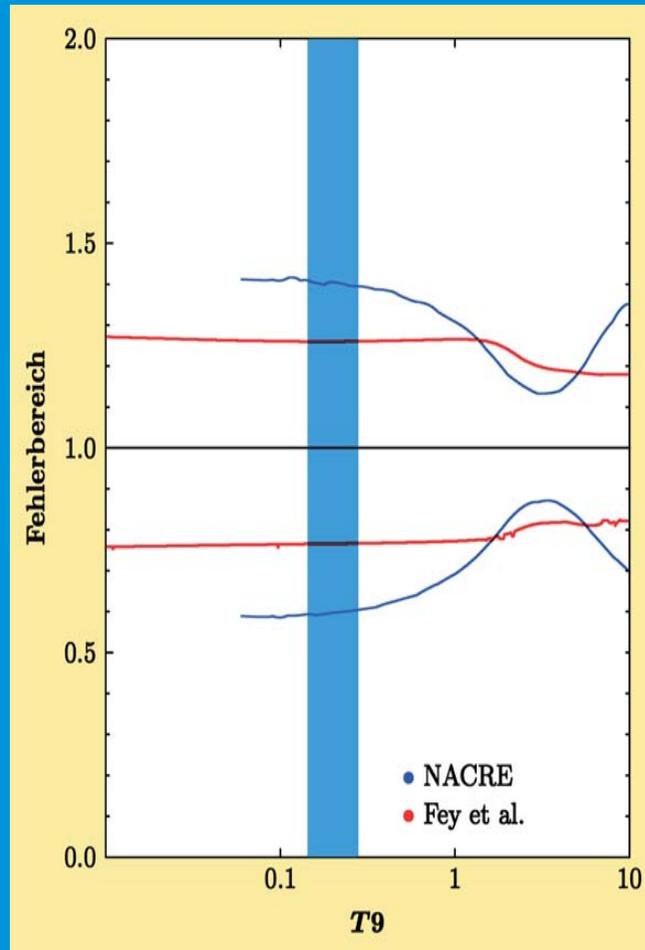
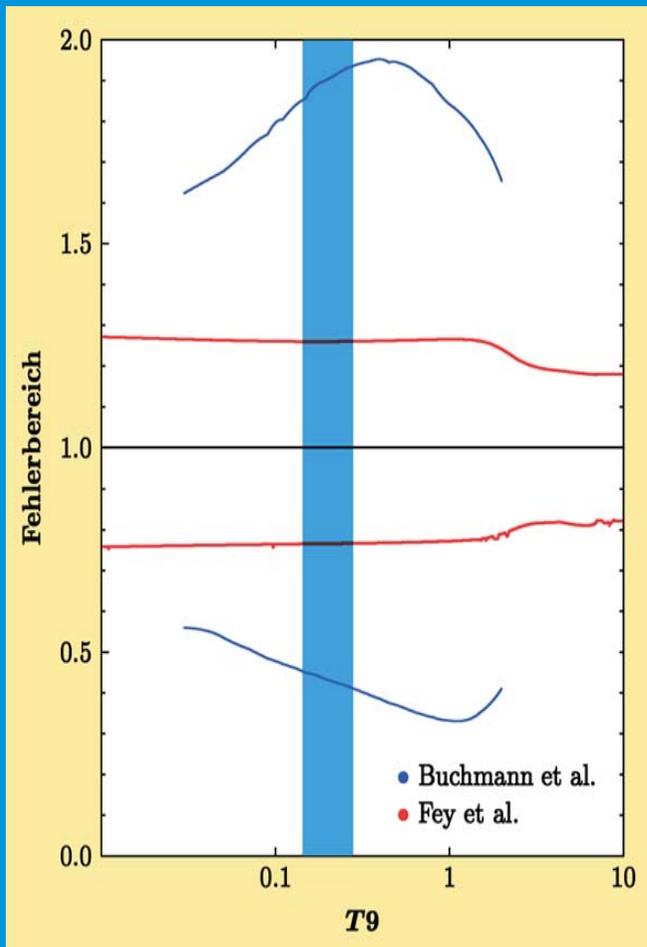


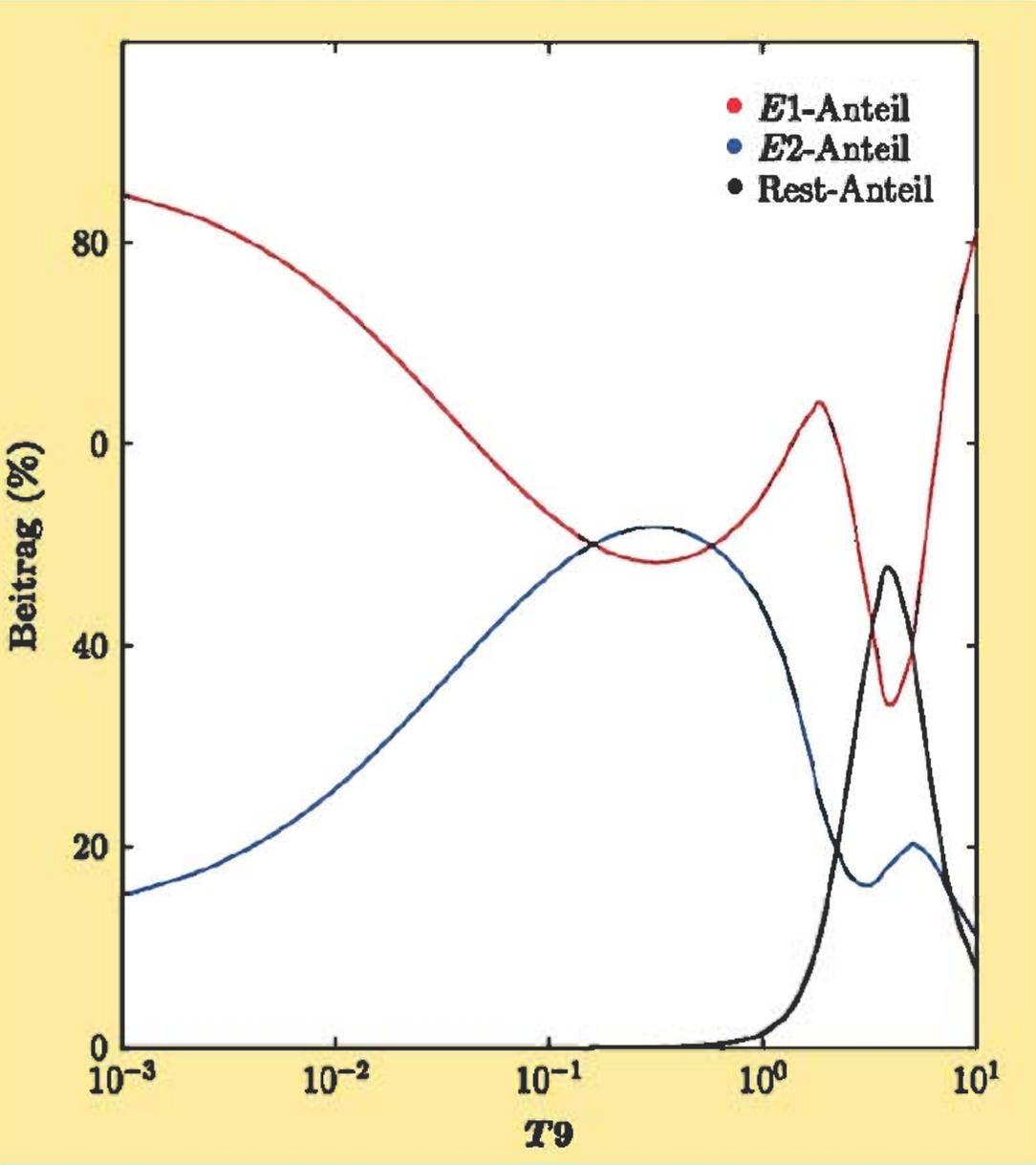
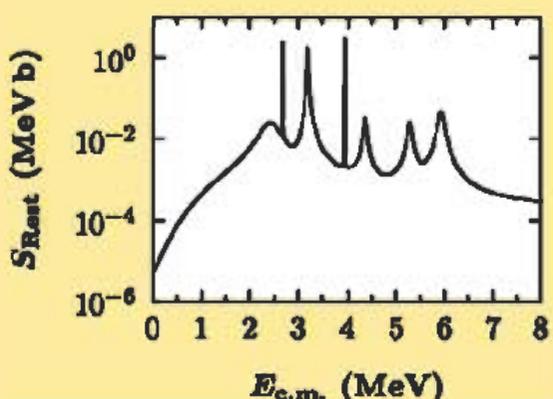
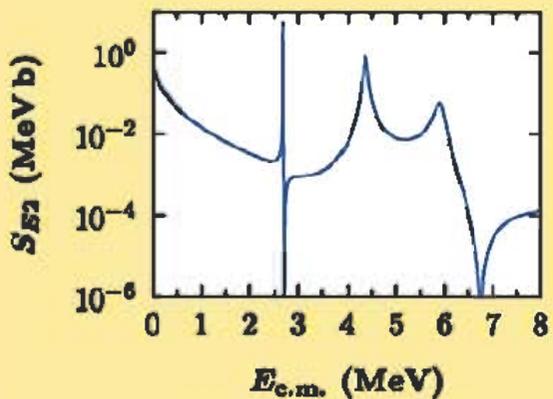
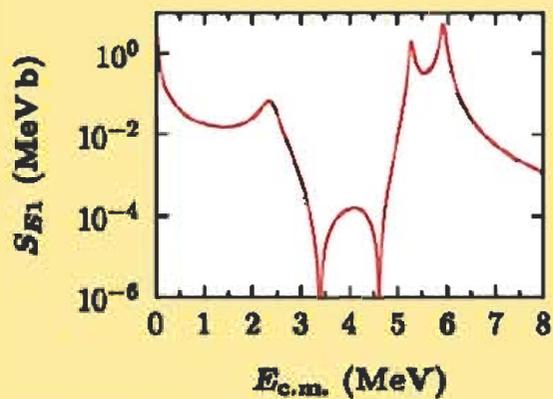


Comparison of the ratio of reaction rates : Fey : Buchmann / NACRE / Kunz



Comparison of the uncertainties given for the $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ reaction rate





Experiment(s)	$S_{E1}(300)$ [keV b]	$S_{E2}(300)$ [keV b]
EUROGAM	81 (20)	80 (27)
GANDI	77 (19)	78 (26)
Kunz et al.	76 (20)	85 (30)
E + G	77 (19)	80 (25)
G + K	76 (18)	81 (23)
E + G + K	77 (17)	81 (22)

SUMMARY and CONCLUSION

2 experiments : $E_{\text{cm}} = 0.89 - 2.8 \text{ MeV}$

Interference combinations excluded

$$S_{E1}^{300} = (77 \pm 17) \text{ keVb}$$

$$S_{E2}^{300} = (81 \pm 22) \text{ keVb}$$

$$S_{\text{casc}}^{300} = (4 \pm 4) \text{ keVb}$$

$$S_{\text{total}}^{300} = (162 \pm 39) \text{ keVb}$$

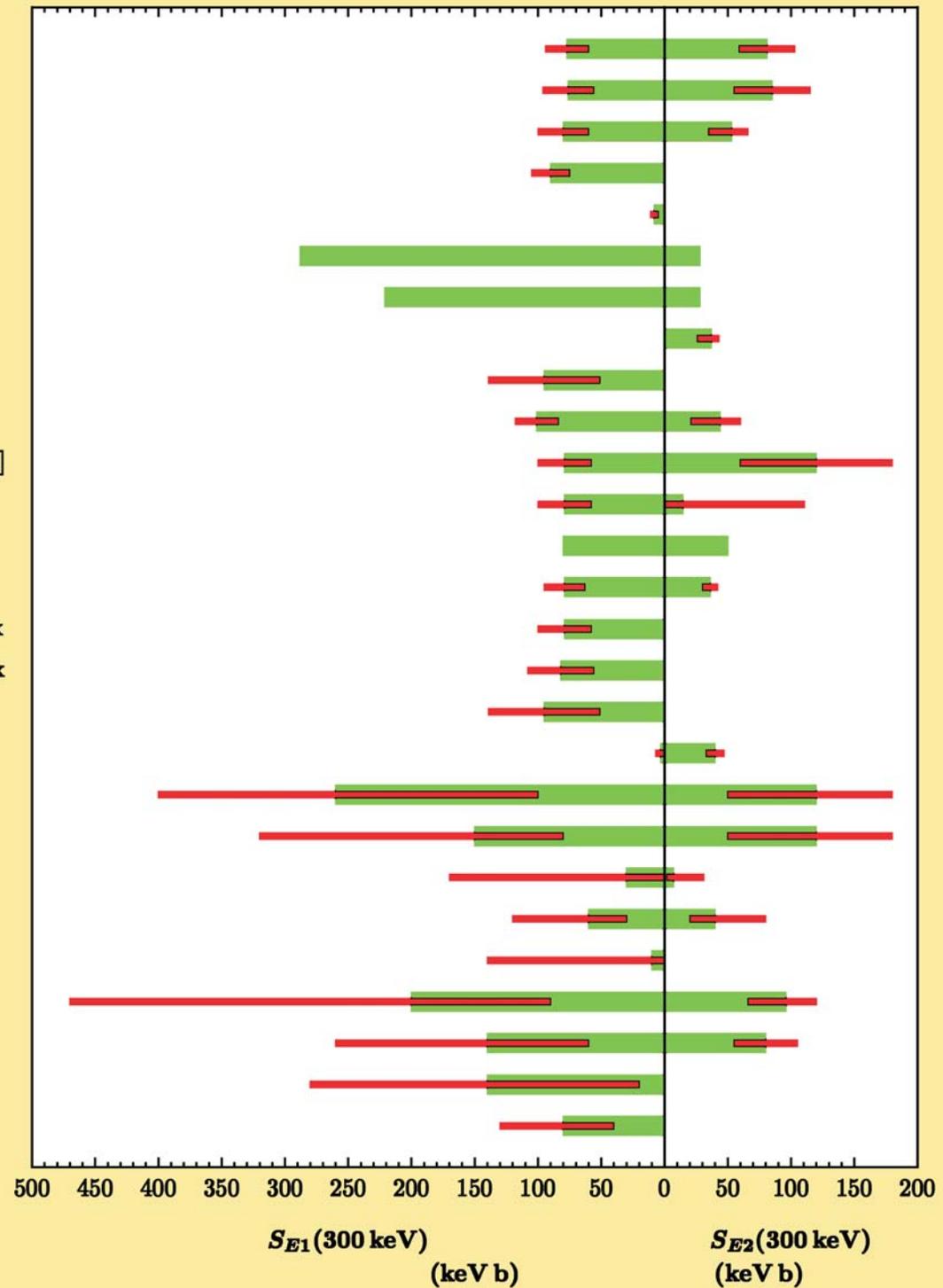
Reaction Rate with $\pm 25\%$ uncertainty

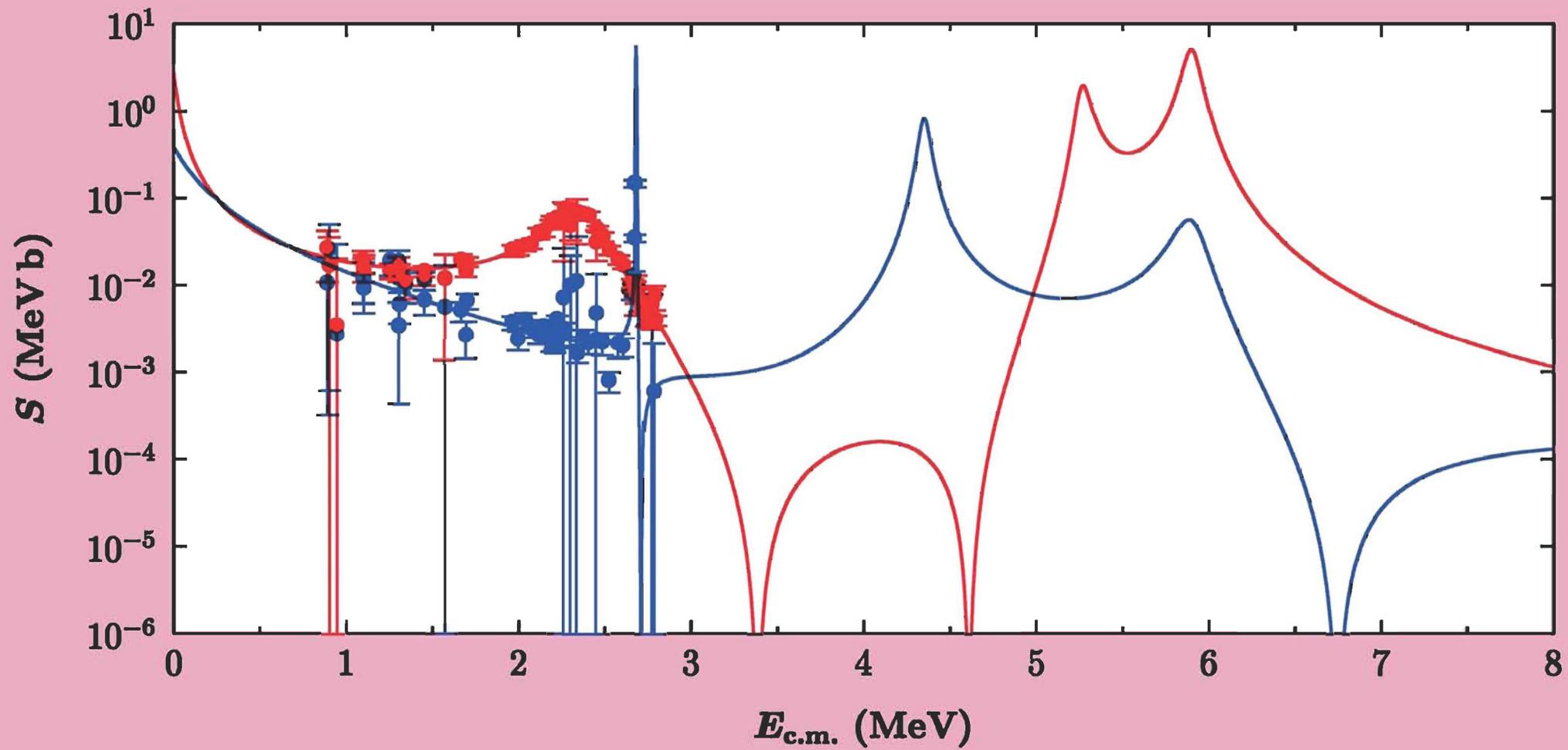
Table + 2 Analytical Expressions

Lowest Measured Energy up to Now

Most Precise Reaction Rate

- This Work**
- [Kun02a]
- [Tis02]
- [Gia01b], Set I
- [Gia01b], Set II
- [Bra01], Set I
- [Bra01], Set II
- [Buc01a]
- [Rot99]
- [Bru99]
- „NACRE“ [Ang99]
- [Tra97]
- [Buc96a]
- [Oue96]
- [Azu94], *R*-Matrix
- [Azu94], *K*-Matrix
- [Zha93]
- [Oue92]
- [Bar91], Fit 1
- [Bar91], Fit 2
- [Fil89]
- „CF88“ [Cau88]
- [Kre88]
- [Red87], A
- [Red87], B
- [Dye74], A
- [Dye74], B





Collaboration

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F. Hammache

Gesellschaft für Schwerionenforschung mbH (GSI), Darmstadt, Germany

G. Staudt

Physikalisches Institut, Universität Tübingen, Germany

....like listening to a nightingale

*whilst the
home team
scores a
goal !*



Material for discussion

NUCLEAR PHYSICS NEWS Int. 14 No.1, p.35, (2004) :

NuPECC recommends with high priority the installation of a compact, high-current 5-MV accelerator for light ions equipped with a high efficiency 4π -array of Ge-detectors at the underground laboratory of Gran Sasso.

Direct Methods :

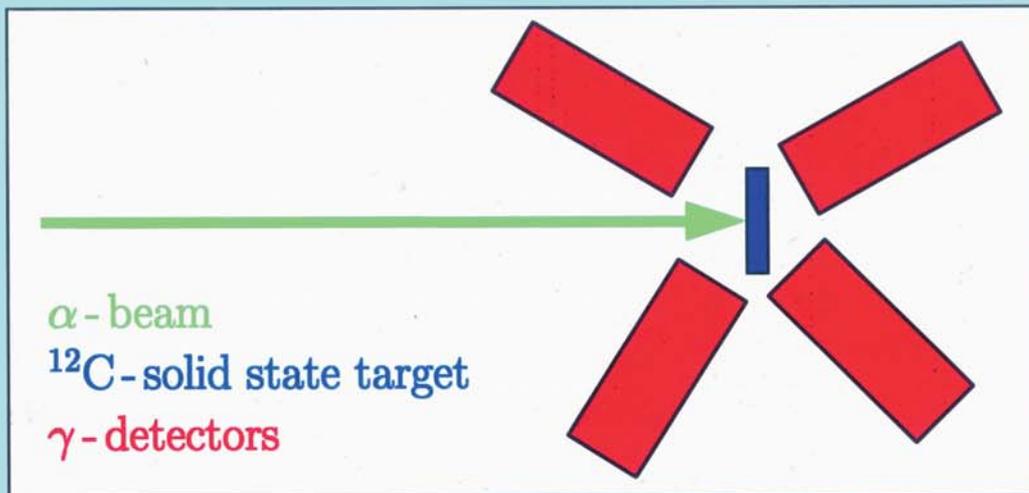
- ▶ γ -angular distribution meas.
- ▶ ^{16}O -recoil measurement
- ▶ Simple γ -detection, inverse kin.
- ▶ Full 4π γ -detection

Indirect Methods :

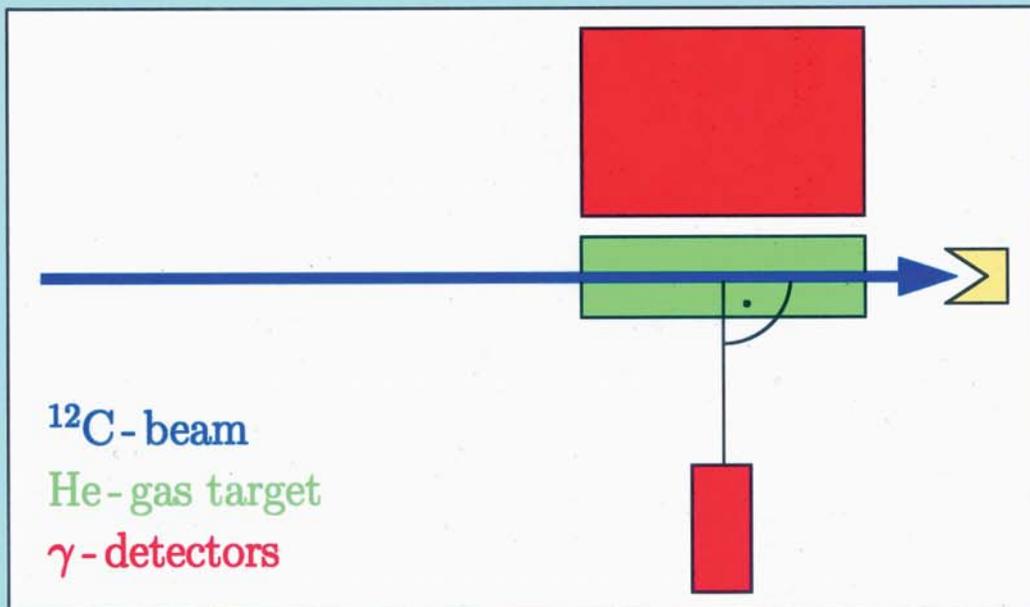
- ▶ β -delayed α -decay of ^{16}N
- ▶ Elastic α -scattering off ^{12}C
- ▶ Coulomb break up of ^{16}O
- ▶ γ -induced break up of ^{16}O
- ▶ Transfer reaction, ANC-method
- ▶ Trojan horse method
- ▶ β -delayed p-decay of ^{17}Ne

$^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ – direct methods

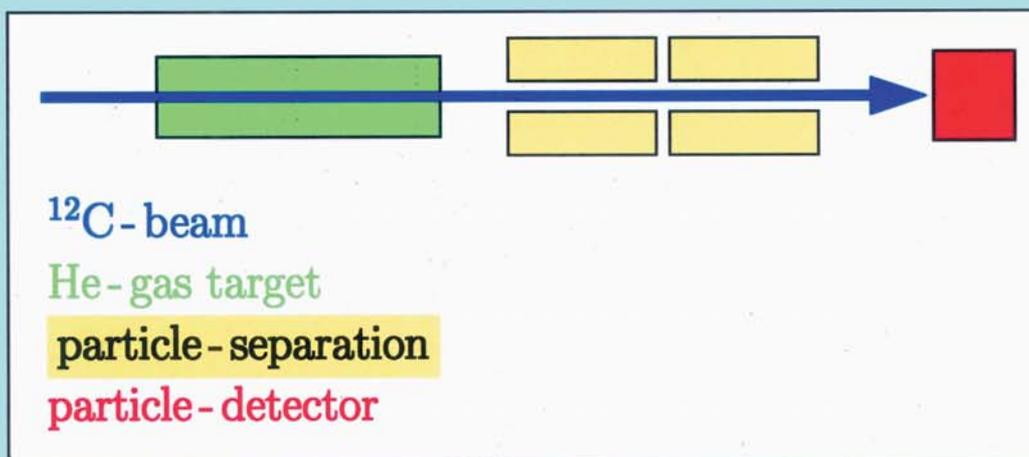
1) regular cinematics

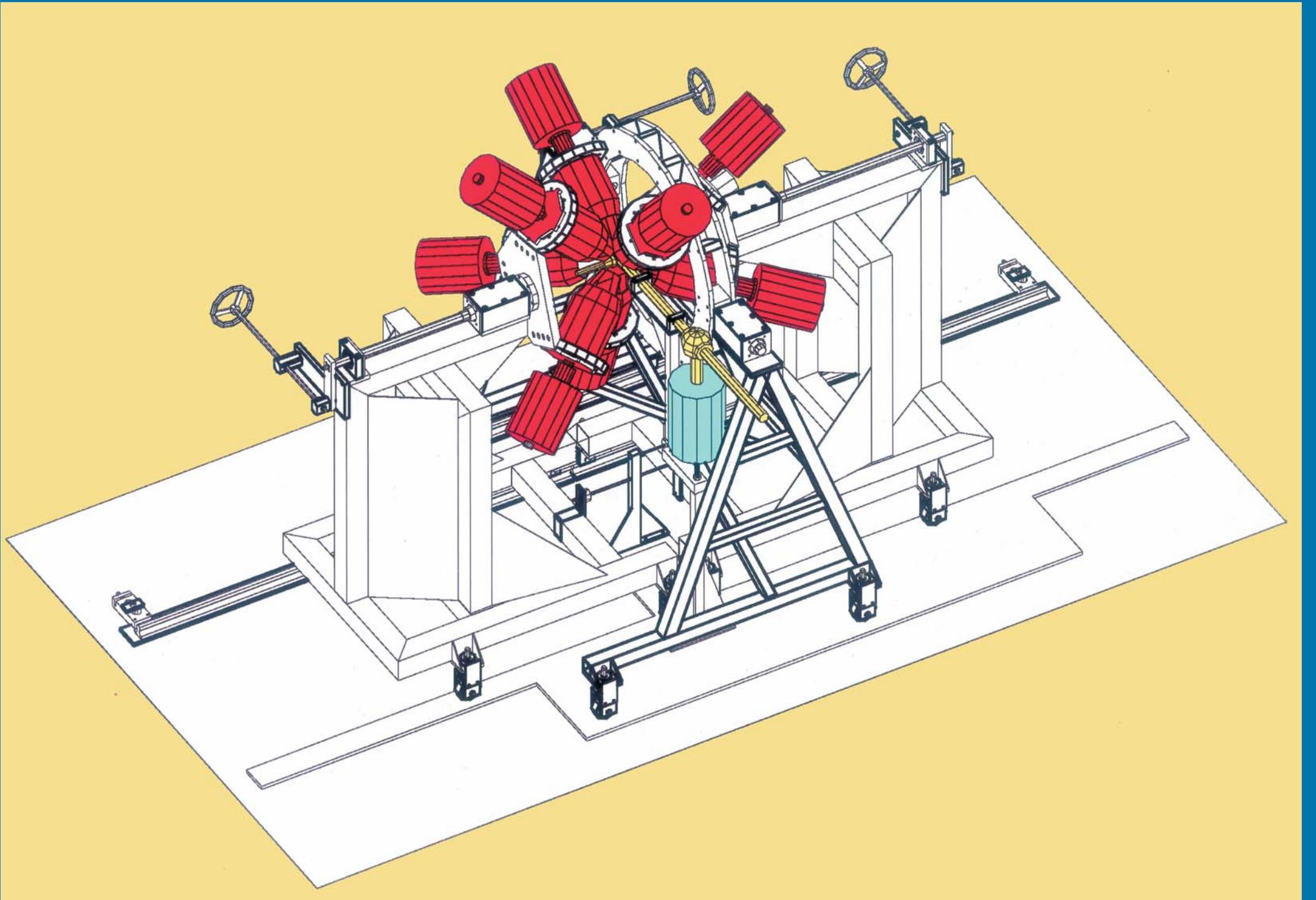


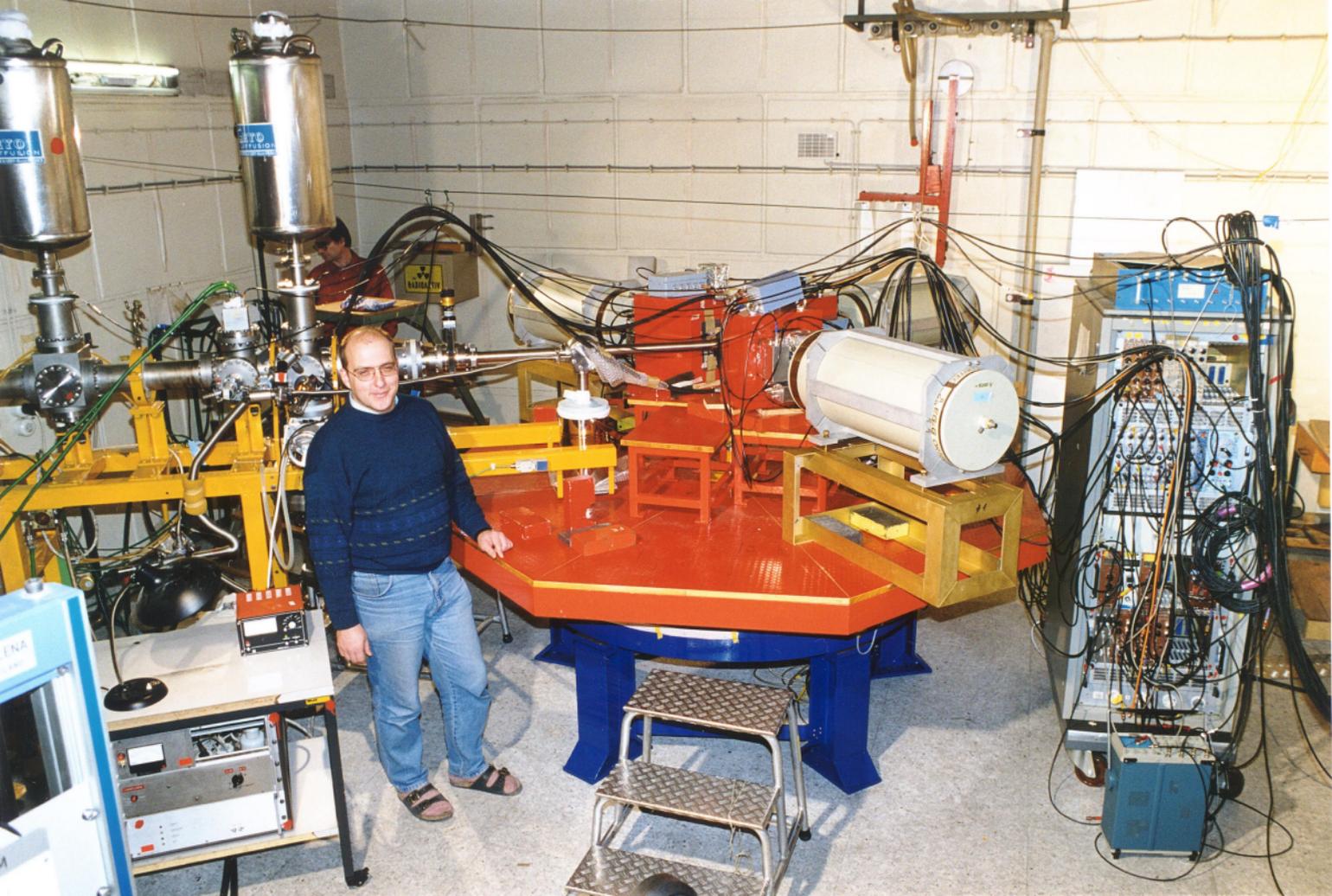
2) inverse cinematics



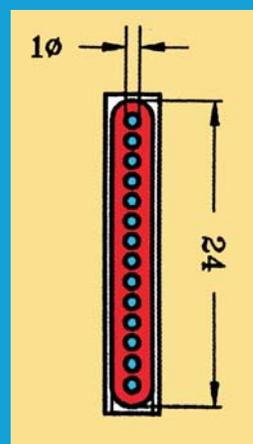
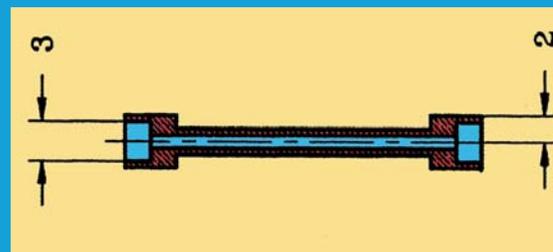
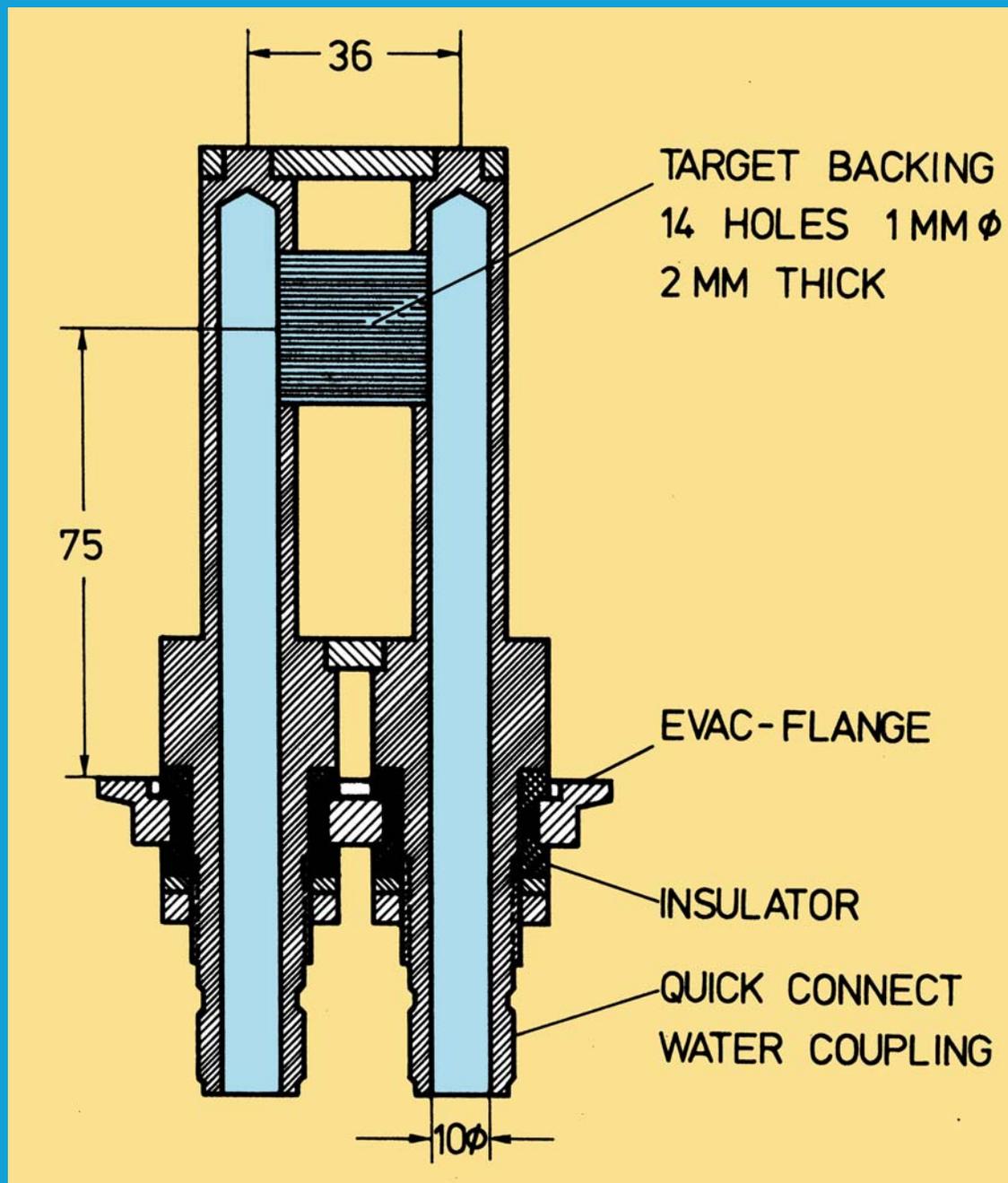
3) ^{16}O - recoil



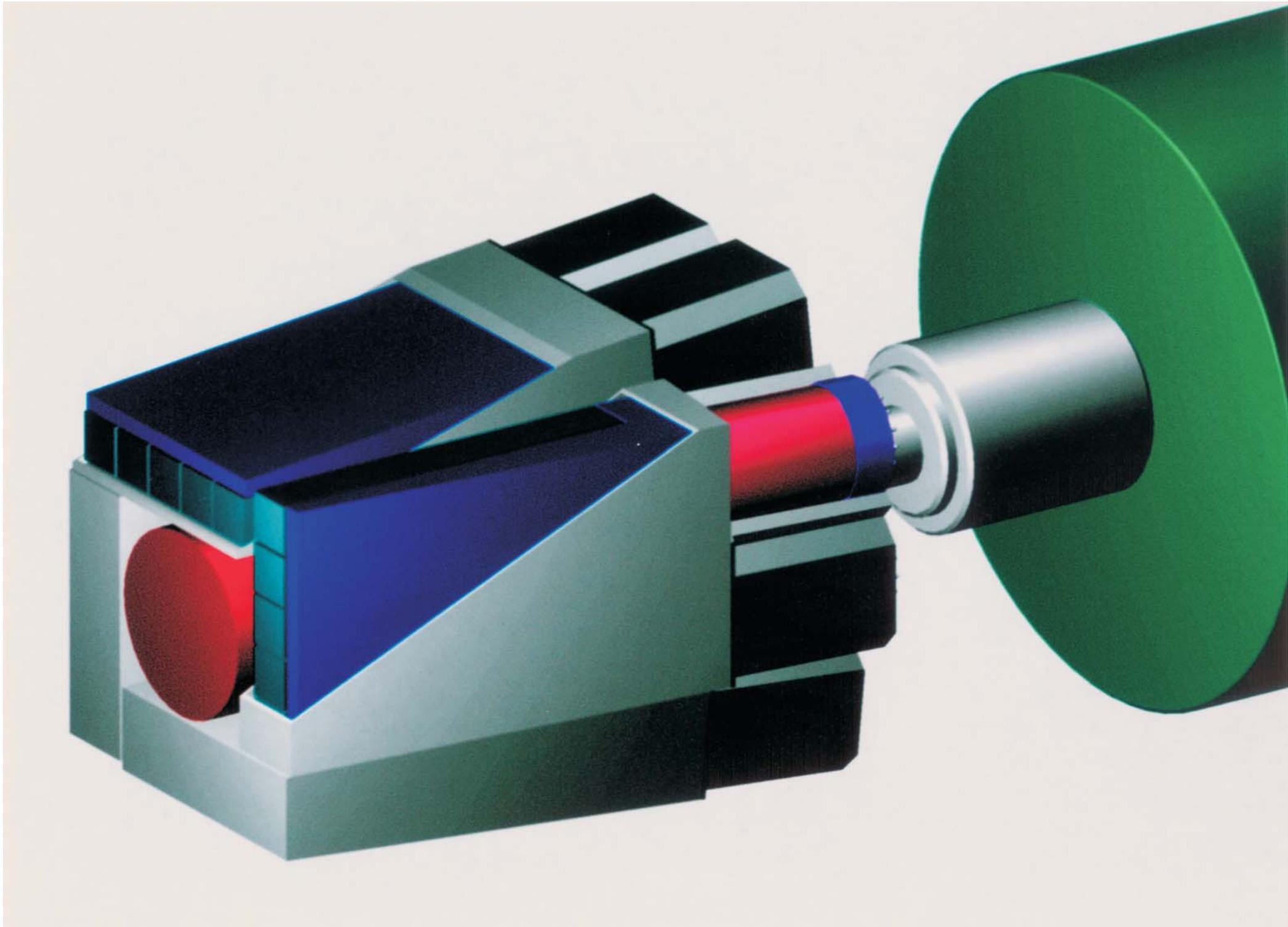




TARGET for high beam power of $10\text{kW}/\text{cm}^2$

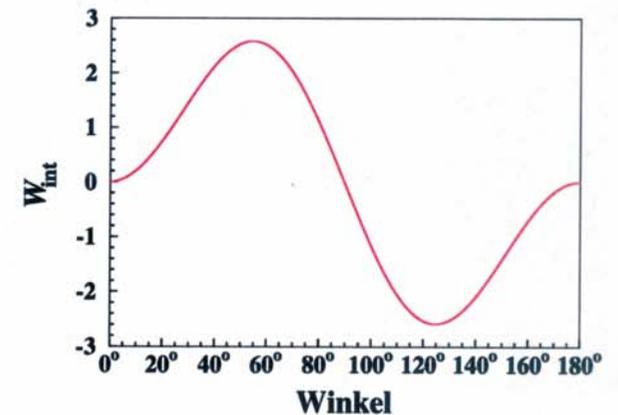
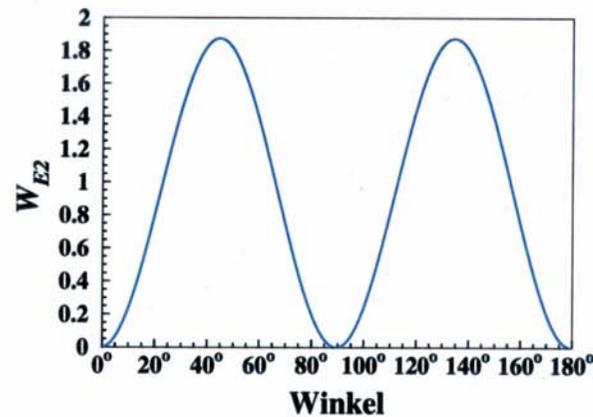
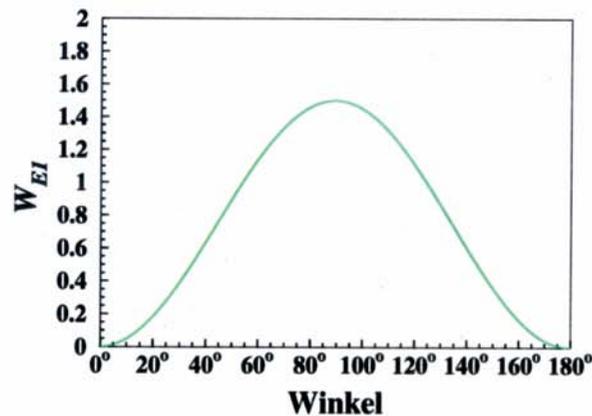


Ref.: J.W. Hammer and W. Niessner,
Kerntechnik 17 (1975) 477



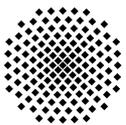
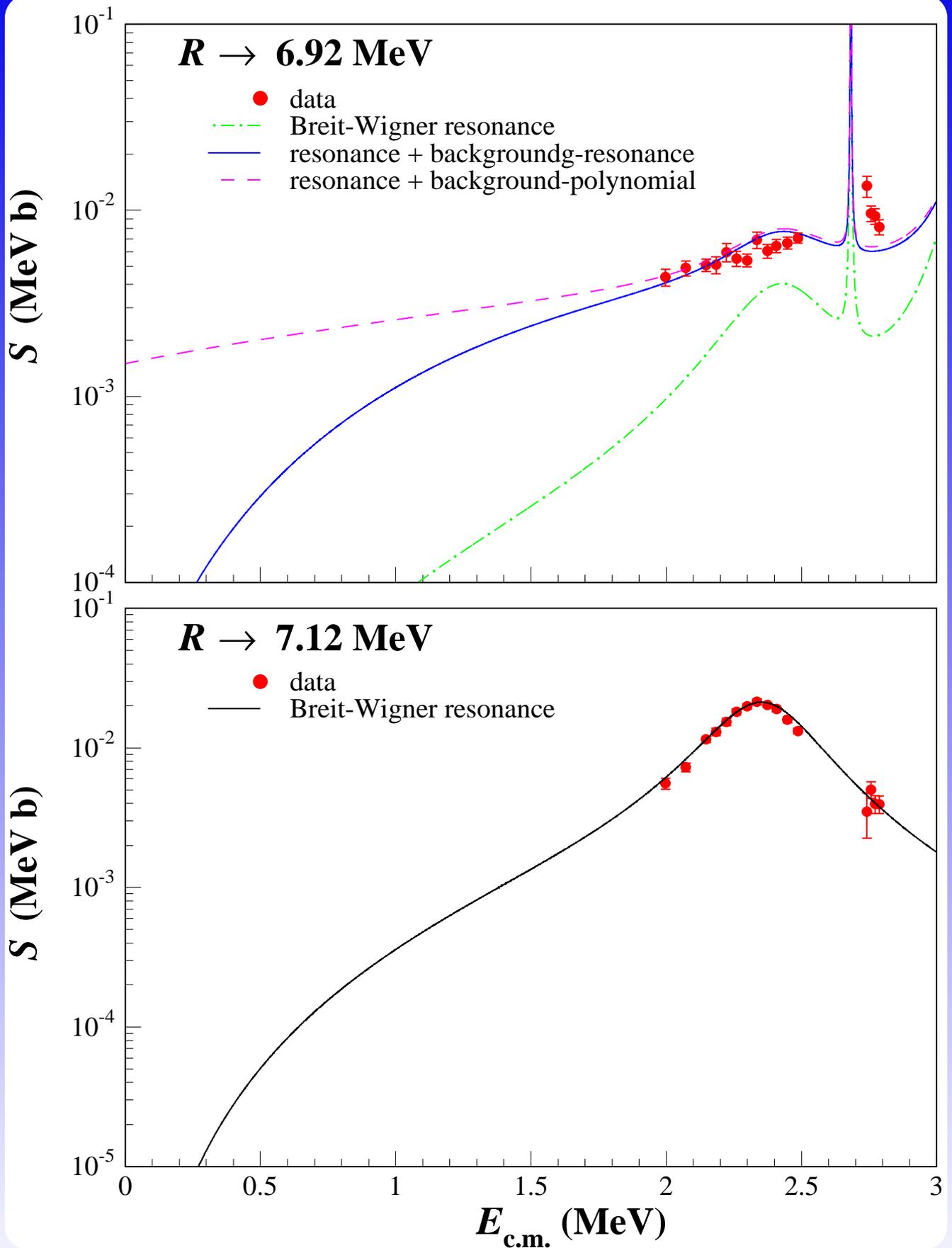
ANGULAR DISTRIBUTION ANALYSIS

$$\frac{d\sigma}{d\Omega} = \frac{\sigma_{E1}}{4\pi} W(\cos \vartheta) = \frac{\sigma_{E1}}{4\pi} \cdot \left(\underbrace{W_{E1}(\cos \vartheta)}_{\text{green}} + \frac{\sigma_{E2}}{\sigma_{E1}} \cdot \underbrace{W_{E2}(\cos \vartheta)}_{\text{blue}} + \sqrt{\frac{\sigma_{E2}}{\sigma_{E1}}} \cdot \cos \phi_{12} \cdot \underbrace{W_{\text{int}}(\cos \vartheta)}_{\text{red}} \right)$$



$$\phi_{12} = \delta_2 - \delta_1 + \arctan \frac{\eta}{2}$$

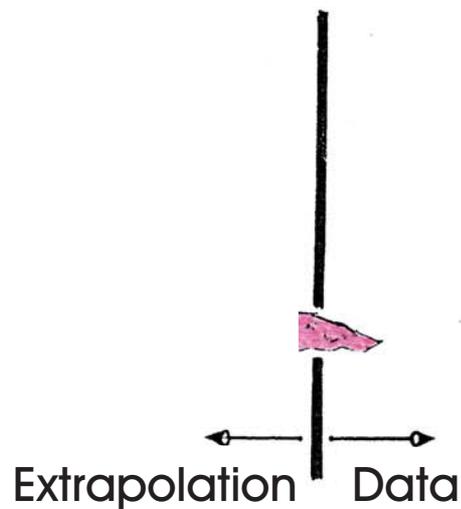
Cascade transitions



The case of subthreshold resonances:

Is it ?

detective
work



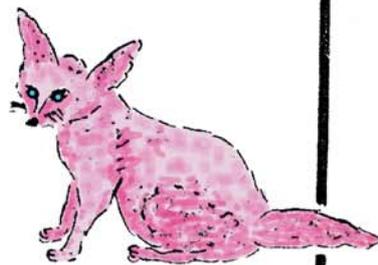
Or is it?



The case of subthreshold resonances:

Is it ?

detective
work



← Extrapolation → Data

Or is it?

