

Workshop in Honor of the 85th Birthday of Charlie Barnes

Recent Radiative Capture Measurement for $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$

Wolfgang Hammer
University of Notre Dame, Indiana
formerly University of Stuttgart, Germany

Dec. 15th 2006, Kellogg Radiation Laboratory @ Caltech Pasadena, CA

Influence on :



Carbon / Oxygen Ratio



Nucleosynthesis of Heavier Elements



Composition of White Dwarfs



Mechanism of Supernovae



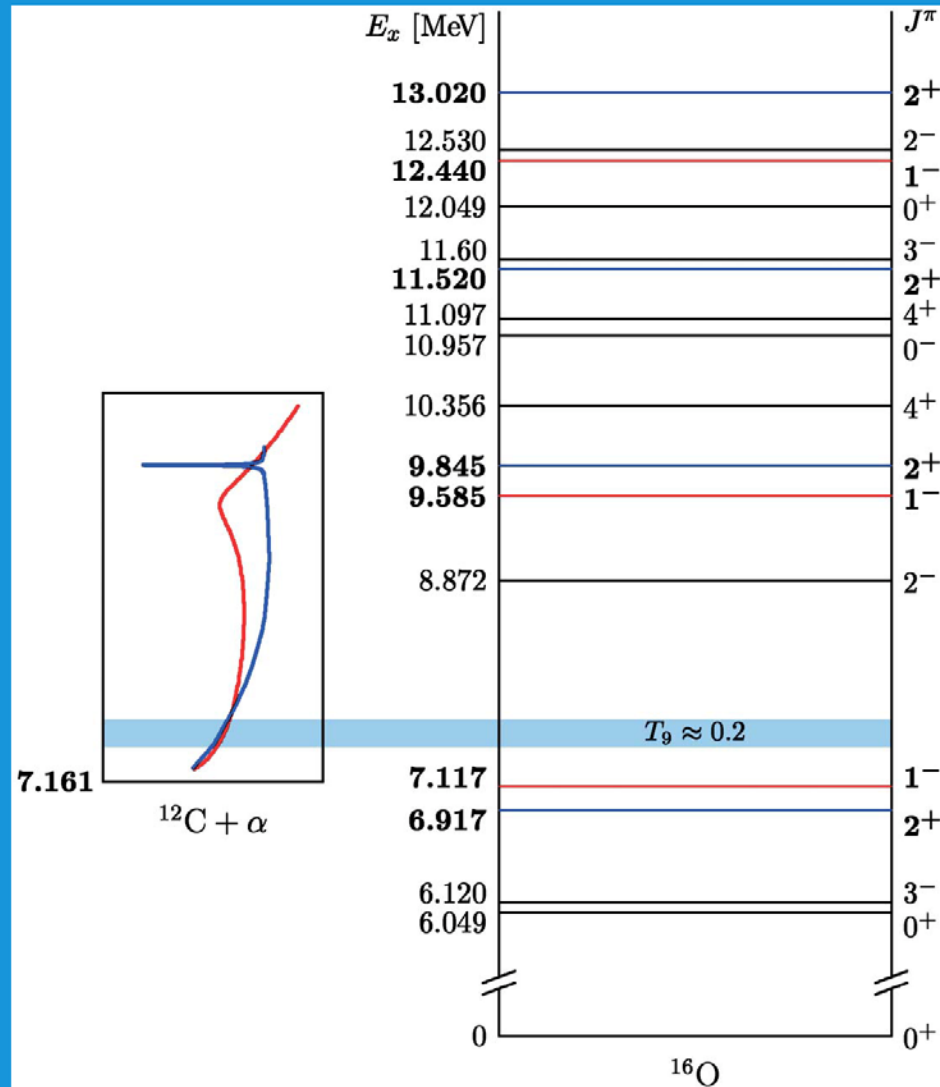
Formation of Black Holes in Massive Stars

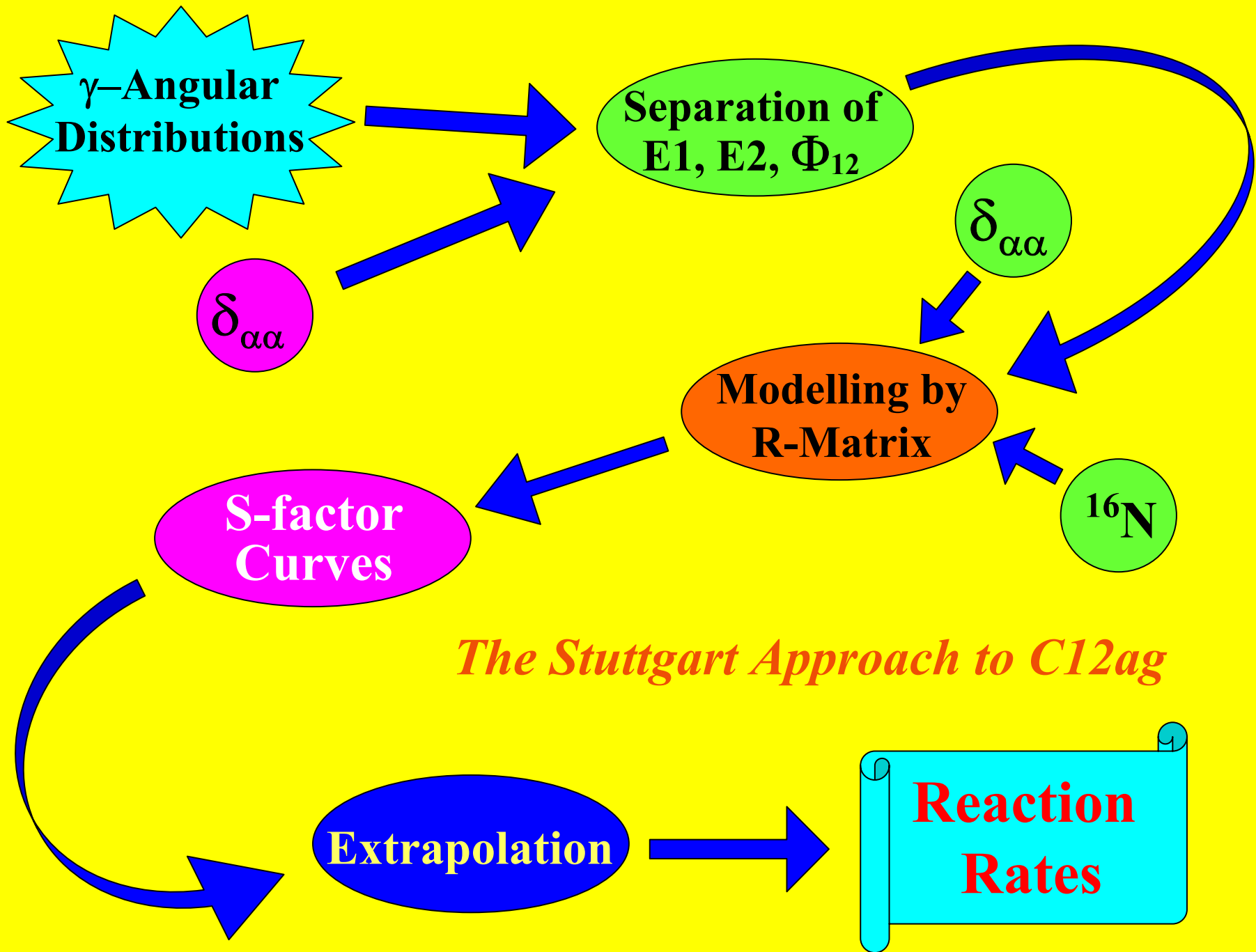
Why > 30 years of research ?

$$\sigma_{300\text{keV}} \sim 10^{-17} \text{ b}$$

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

^{16}O level scheme





Experimental Ingredients

Ion beam :

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

Targets :

- Isotope separation
- Purity
- Homogeneity
- Standing time

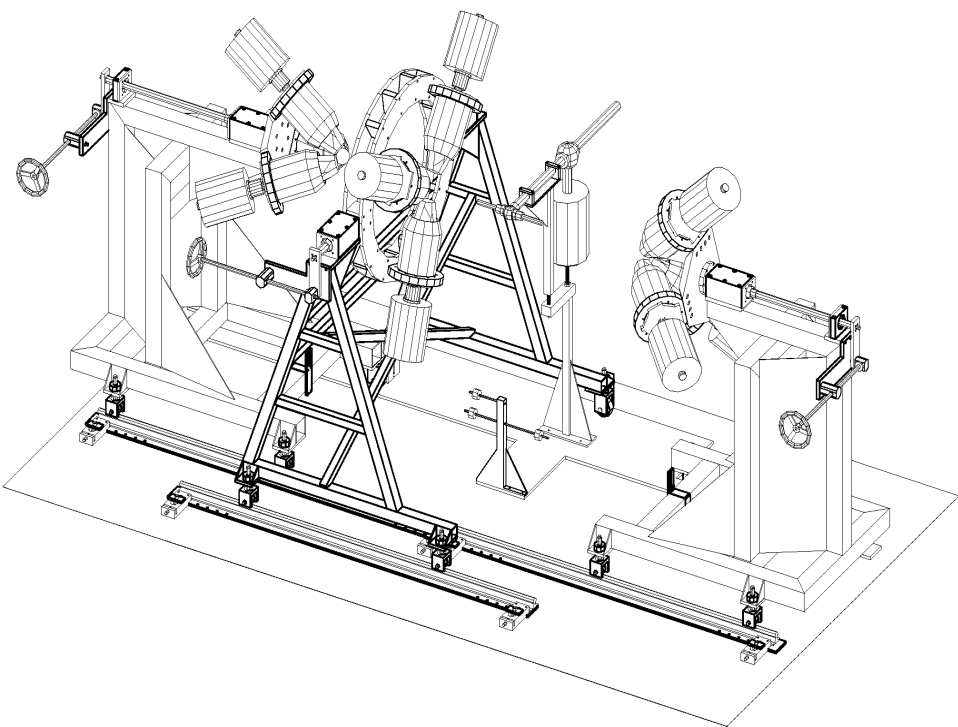
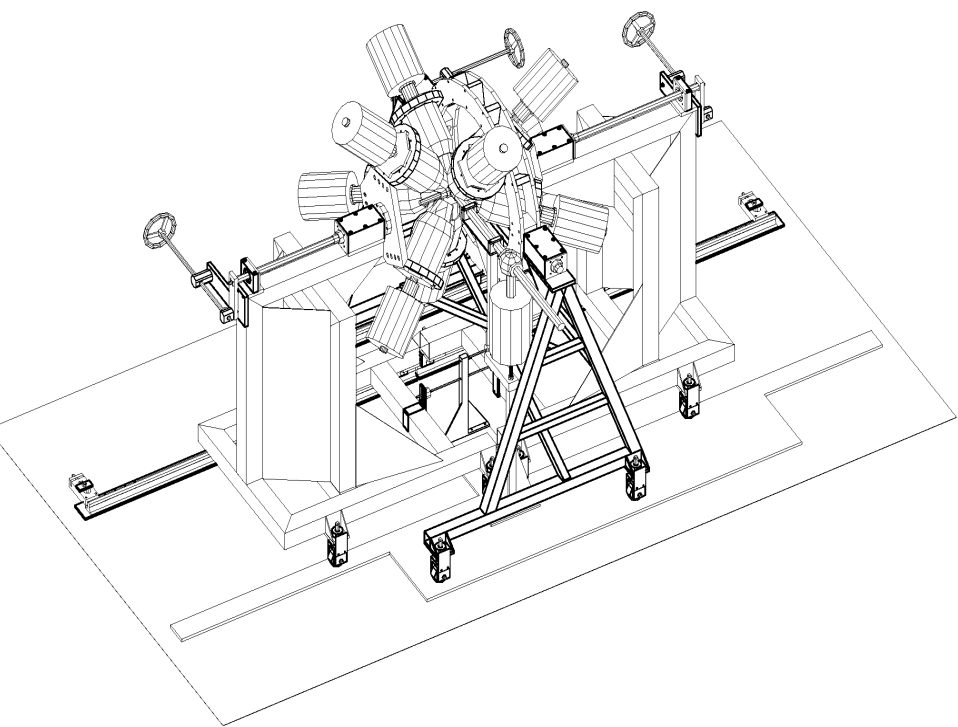
Detectors :

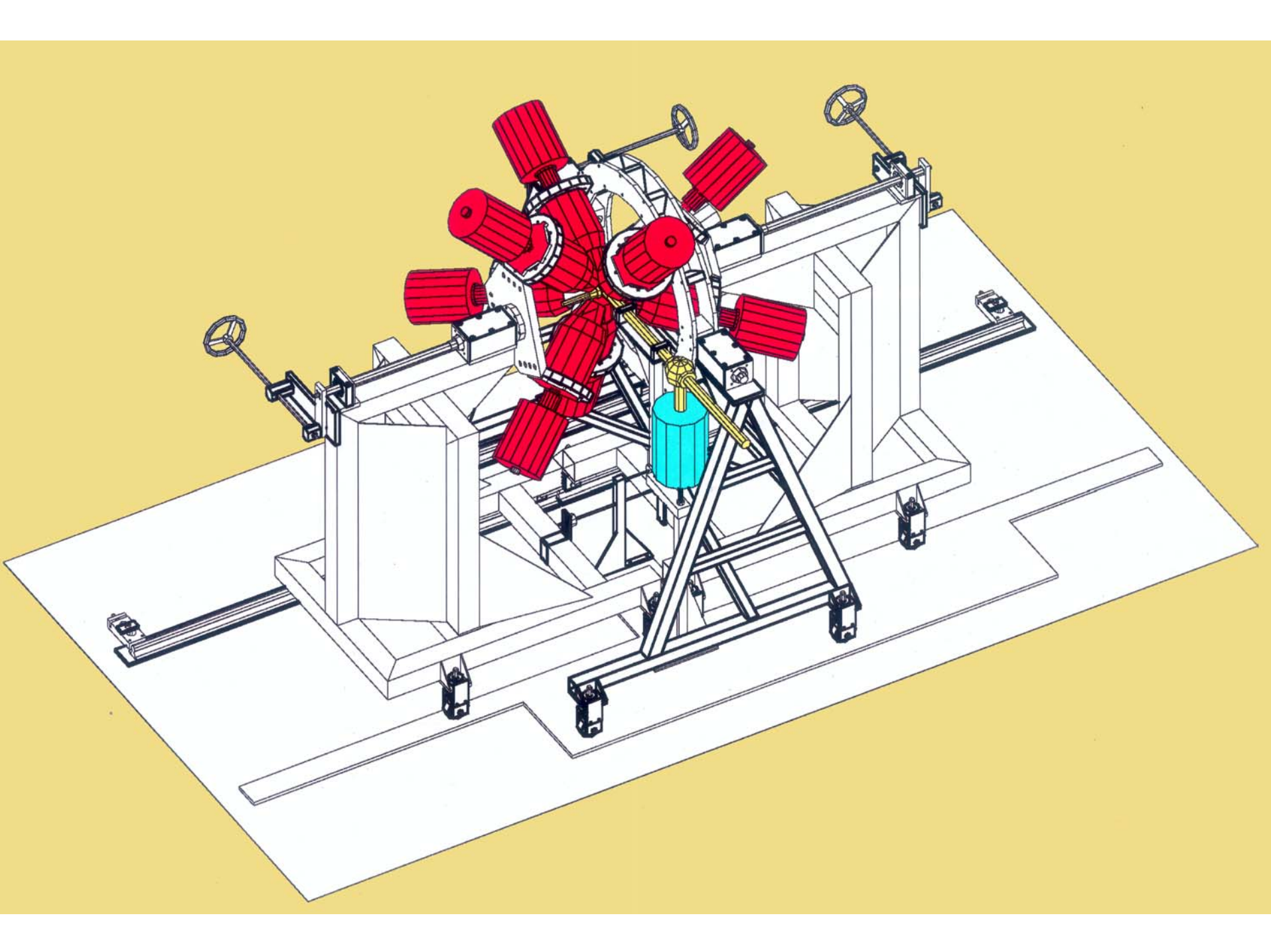
- Efficiency
- Background suppression
- Granularity



Measuring time !!!

EUROGAM Detector Array



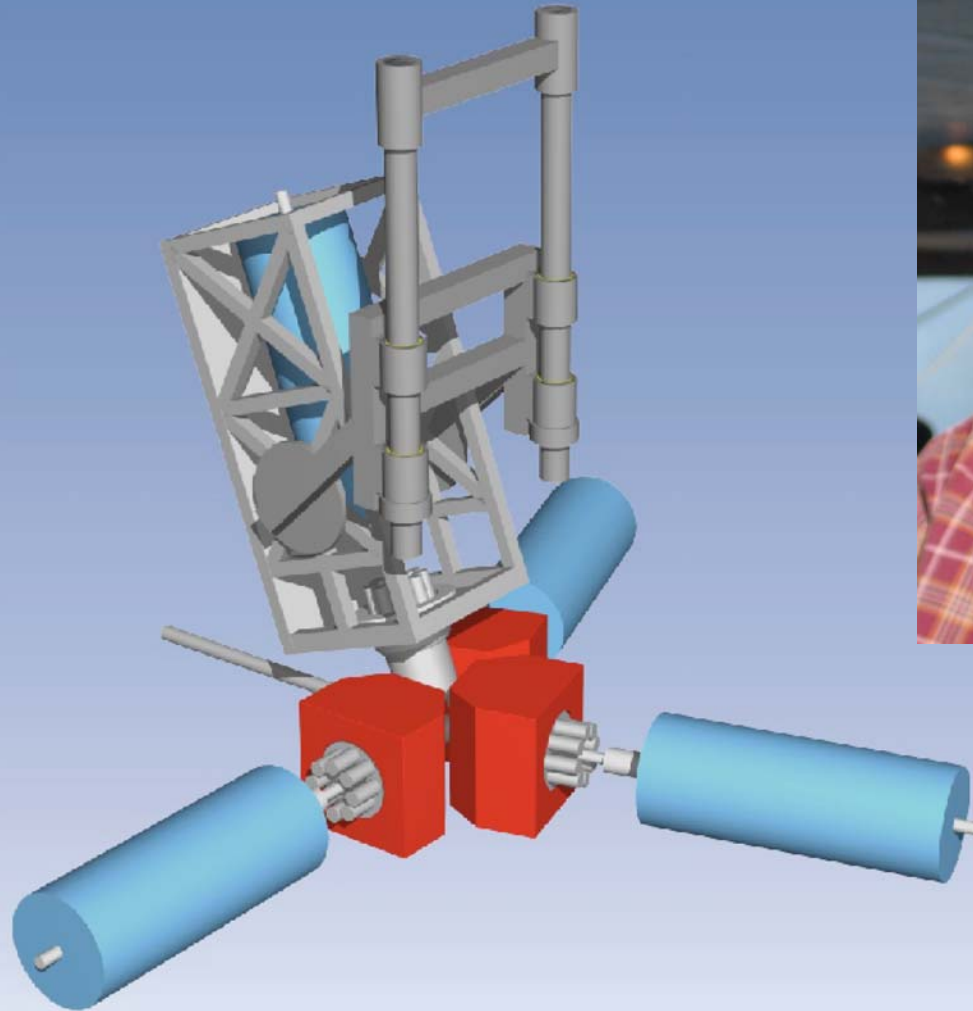




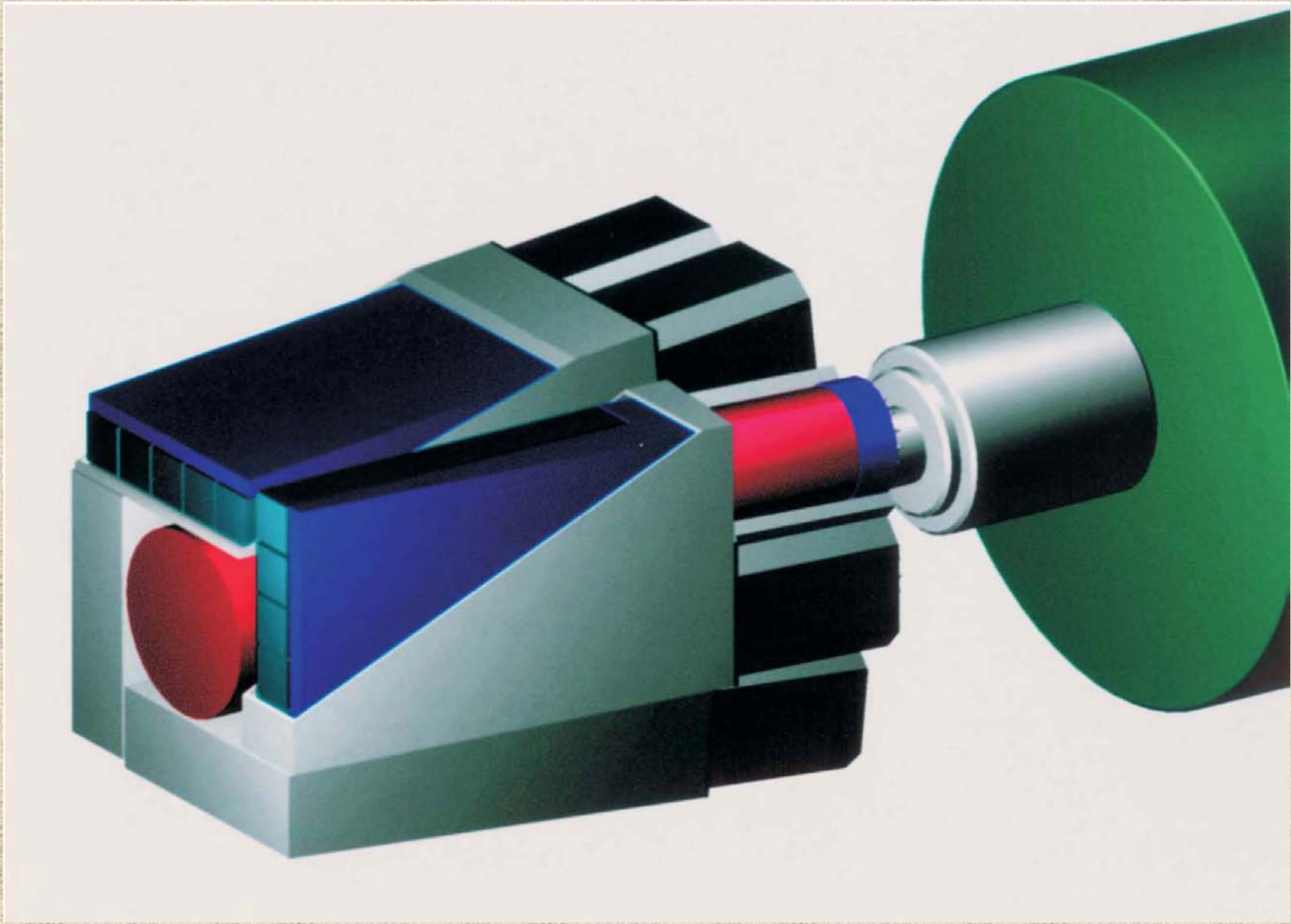
E_{cm} [MeV]	E_{α} [MeV]	σ_{tot} [nb]	count rate* for $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$	background rate	
				cosm.ind.	beam ind.
2.40	3.20	48	500 cts/h	0.2 cts/h	2 cts/h
2.06	2.75	10	100 cts/h	0.2 cts/h	1.2 cts/h
1.60	2.13	1	200 cts/d	5 cts/d	15 cts/d
1.20	1.60	0.13	25 cts/d	5 cts/d	8 cts/d
1.00	1.33	0.03	7 cts/d	5 cts/d	5 cts/d
0.80	1.06	0.005	1 cts/d	5 cts/d	3 cts/d
0.70	0.93	0.0014	0.3 cts/d	5 cts/d	-

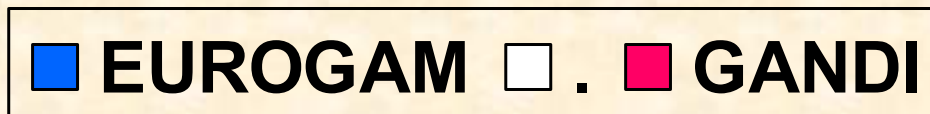
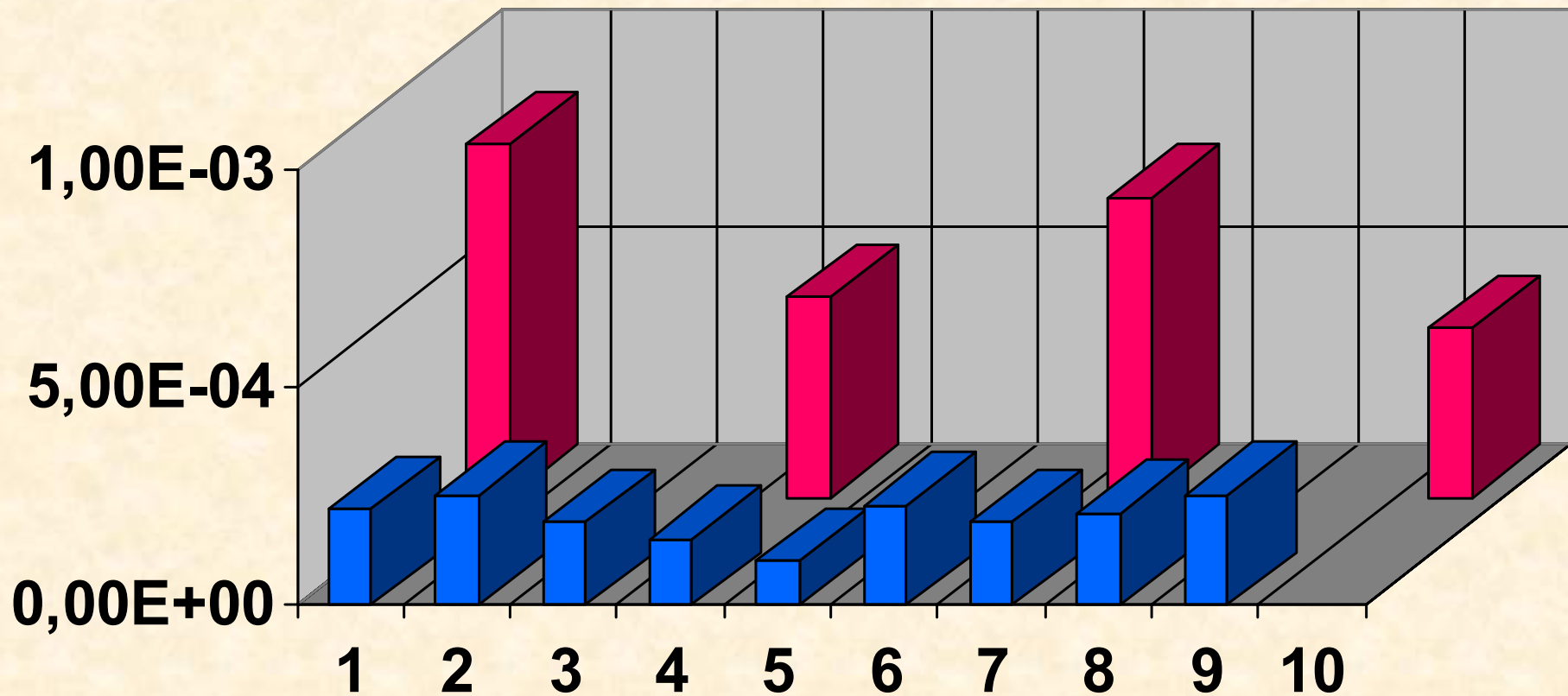
* for one Eurogam-Ge-detector at $E_{\gamma} = 9$ MeV ; distance to target 14cm ;
 $\varepsilon_{\text{rel}} = 75\%$; α -beam current 0.5 mA ; target aerial density $2 \times 10^{18} \text{ cm}^{-2}$

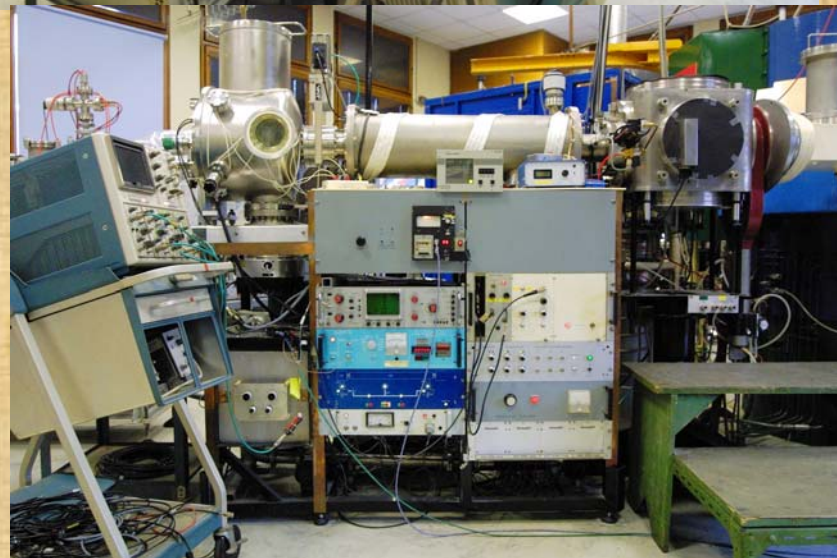
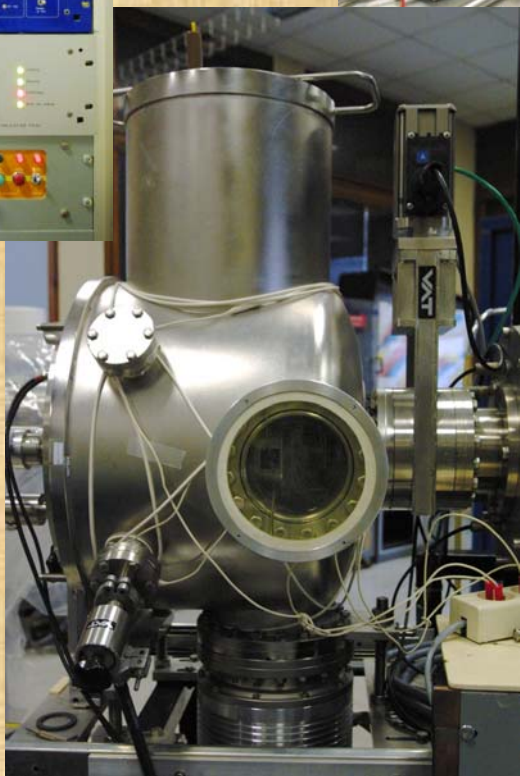
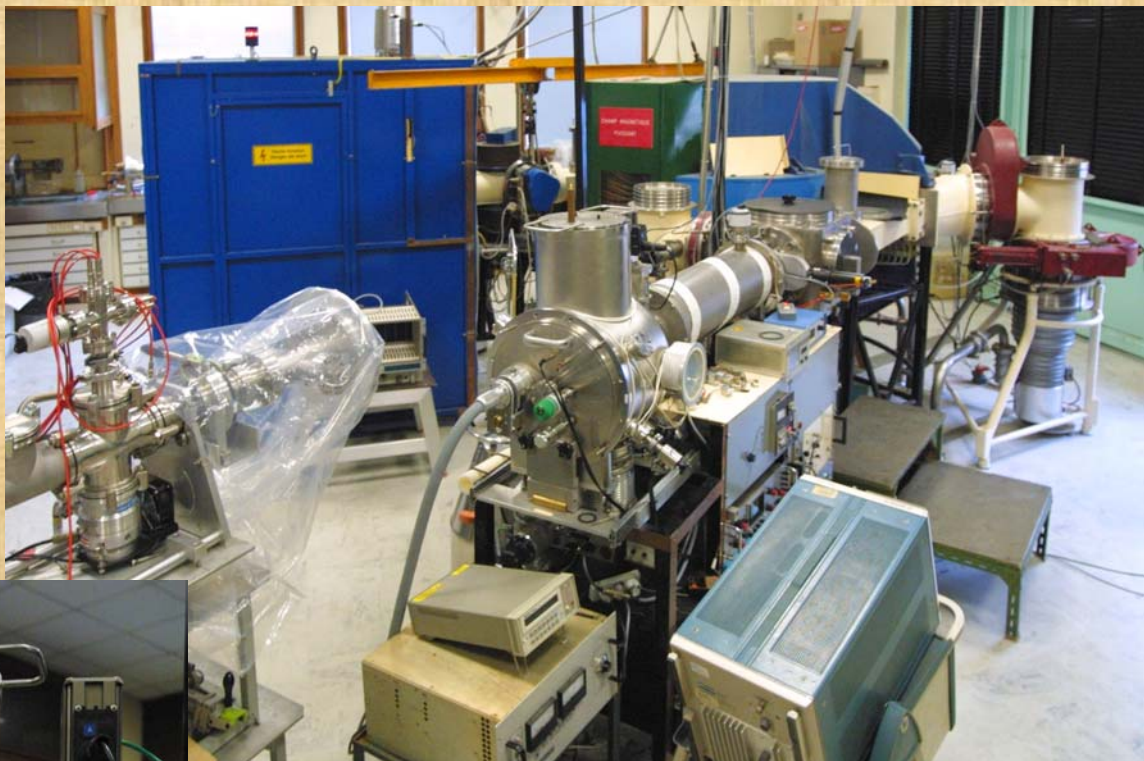
The Stuttgart GANDI Array





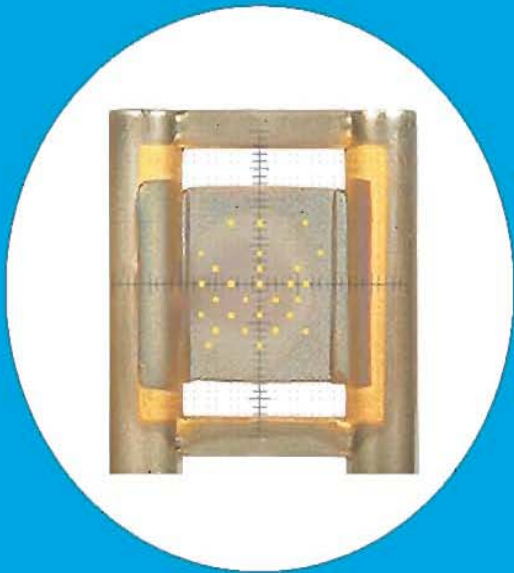




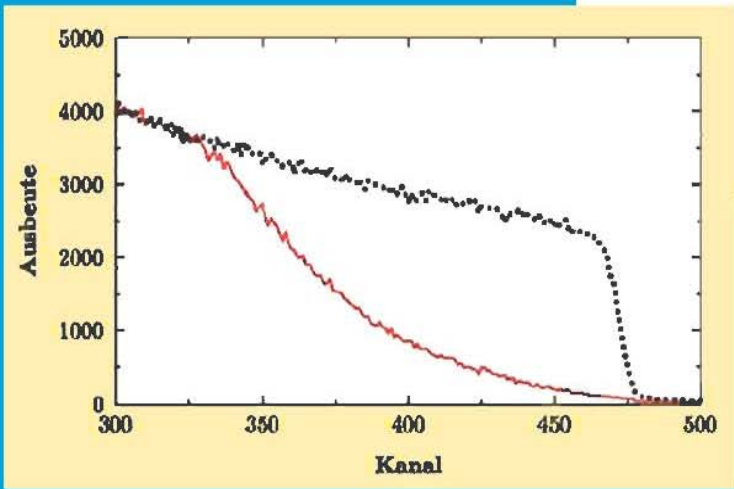
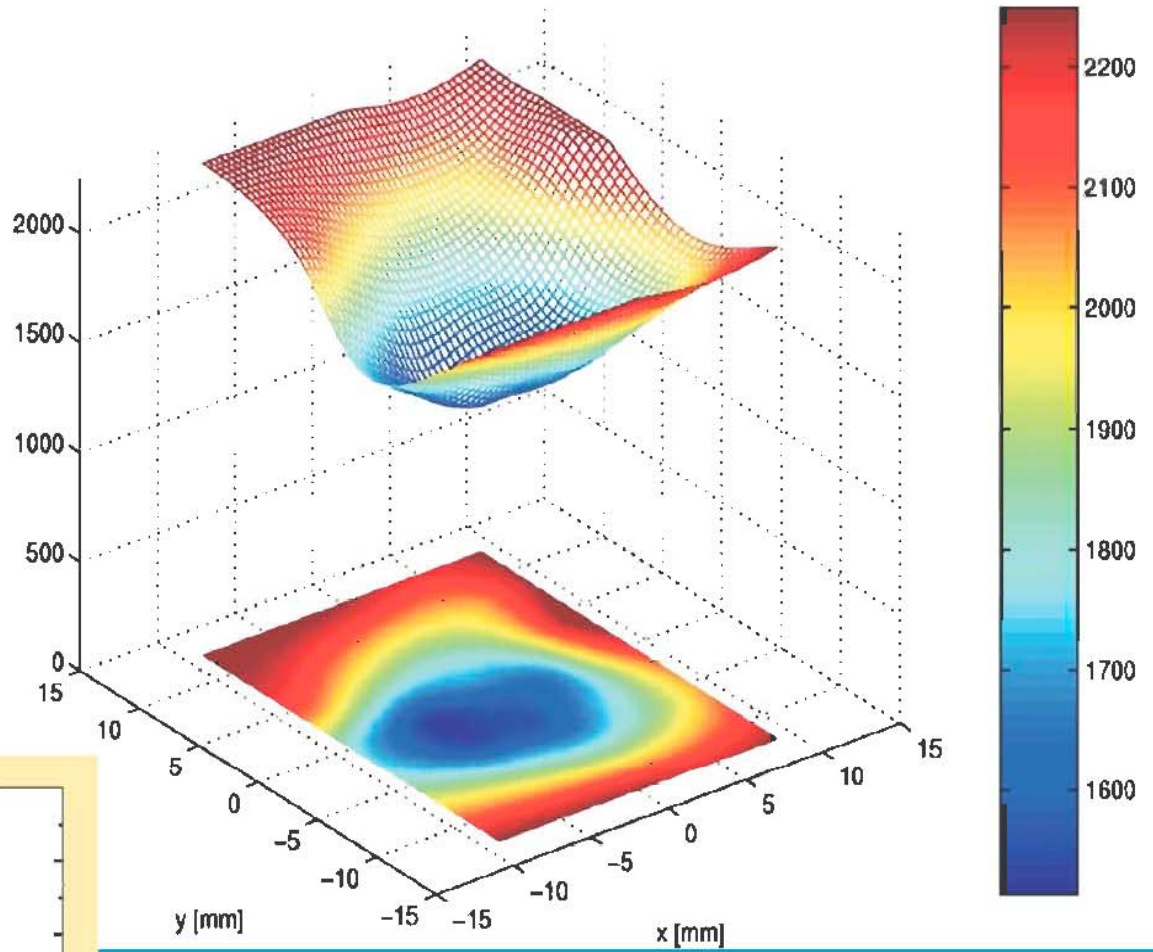


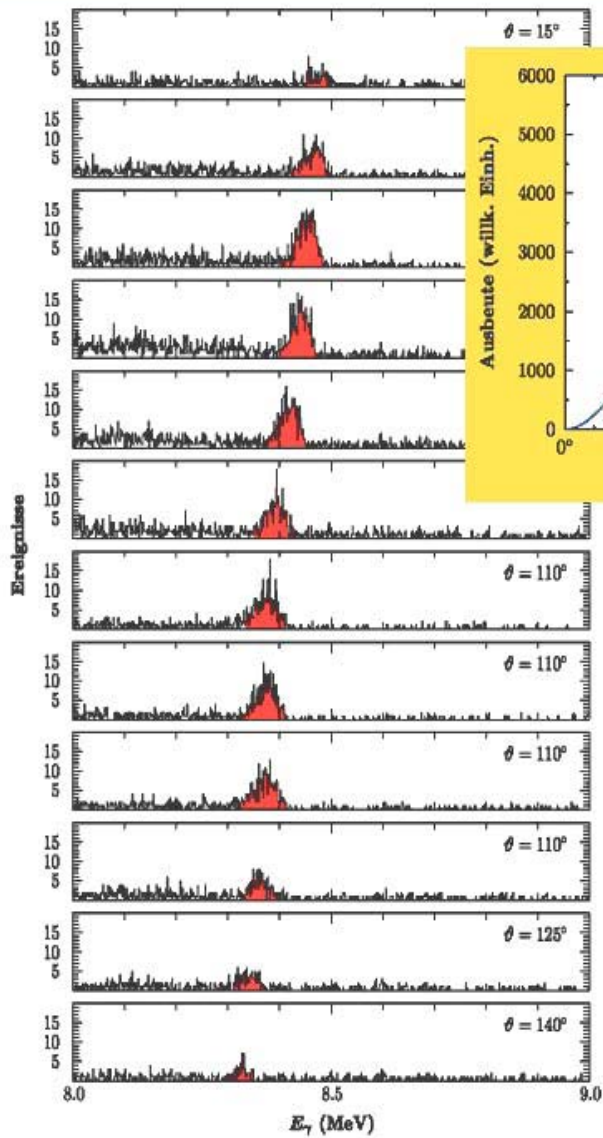
SIDONIE

Orsay

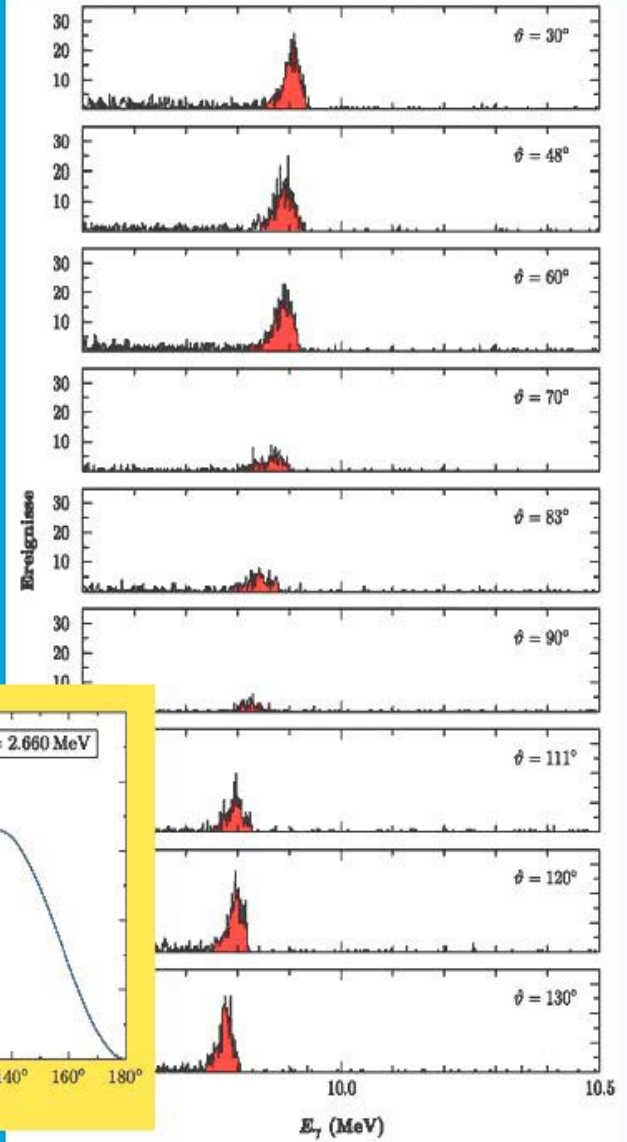
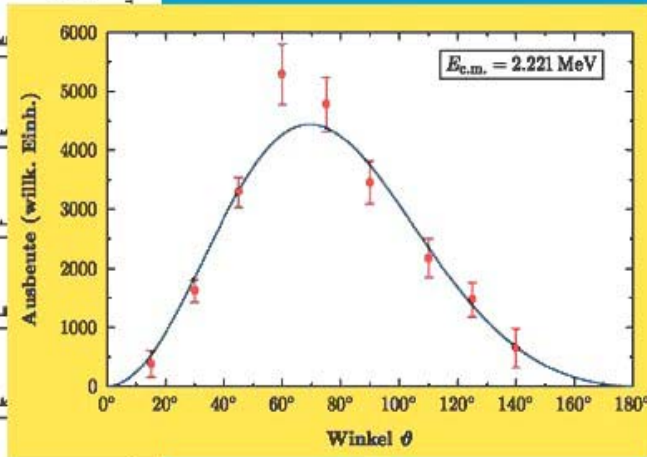


^{12}C Flächenbelegung [10^{15} Atome cm^{-2}]

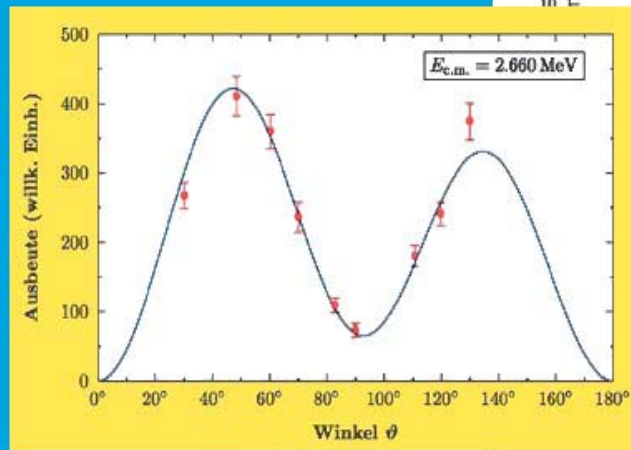


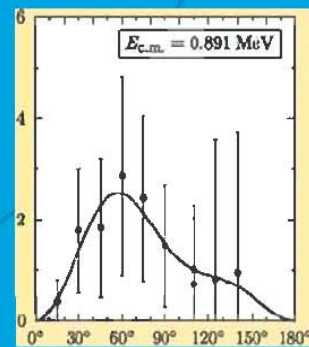
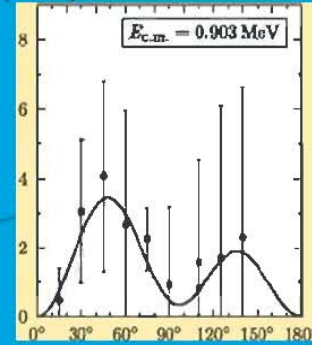
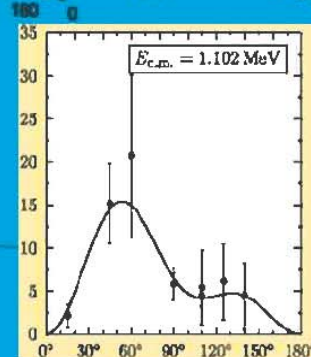
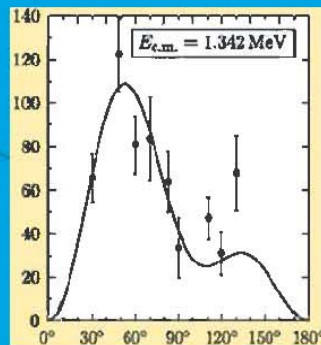
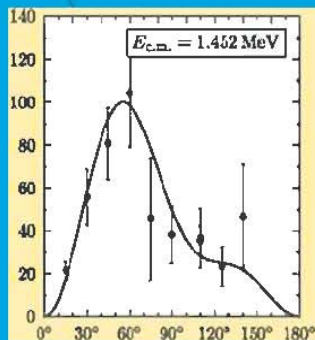
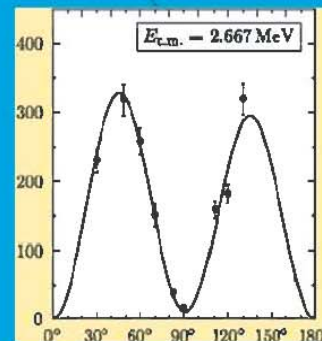
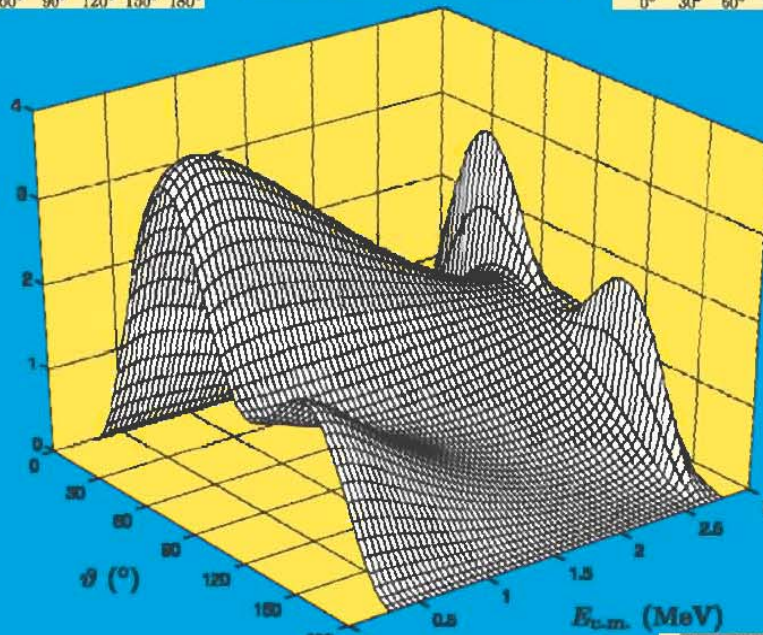
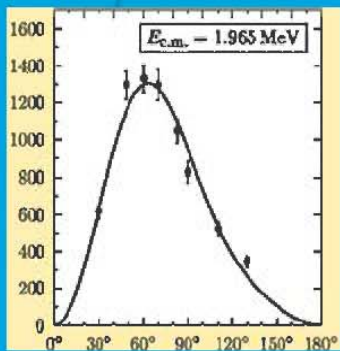
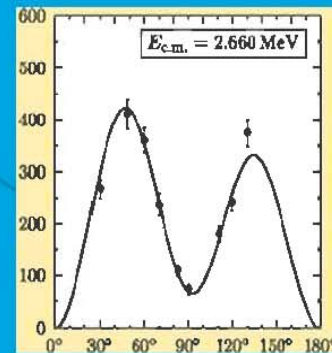
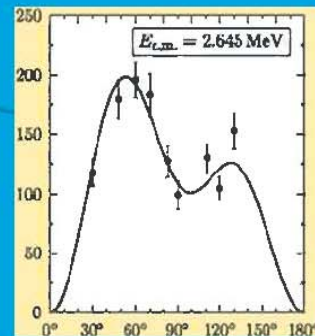
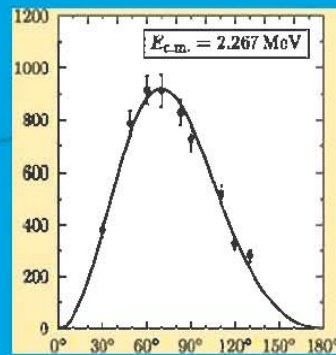
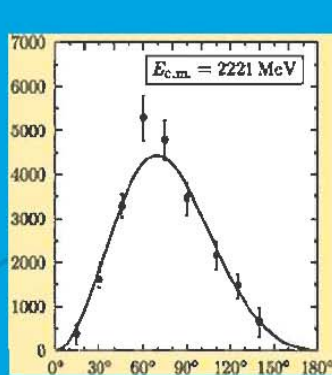
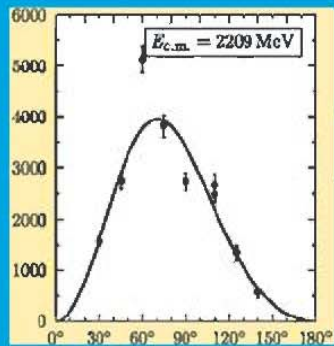


γ -Spektren bei $E_{c.m.} = 2.221$ MeV.



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





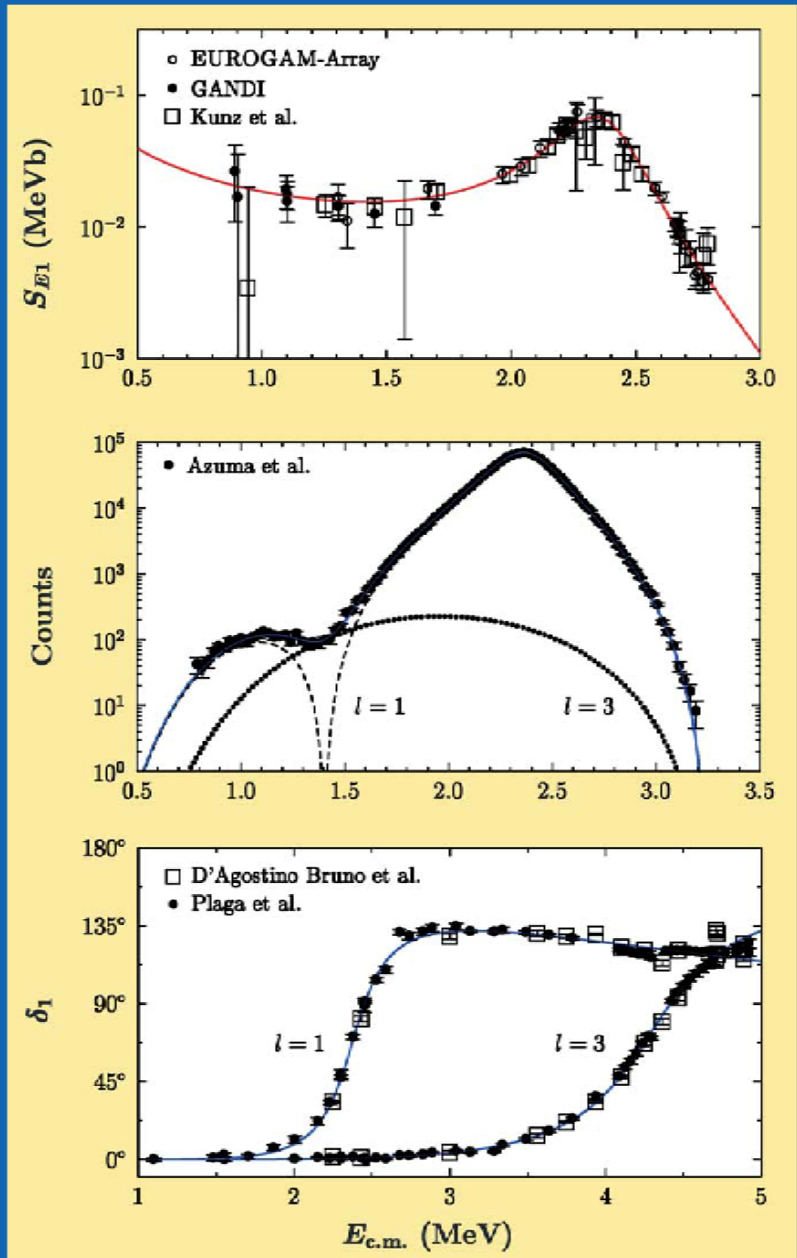
R - Matrix Fits E1

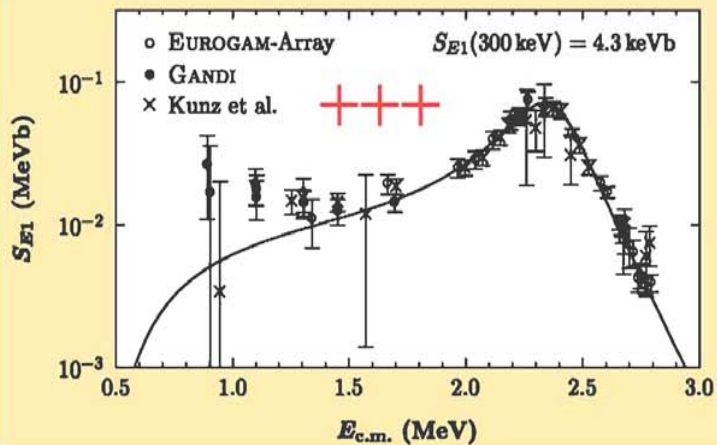
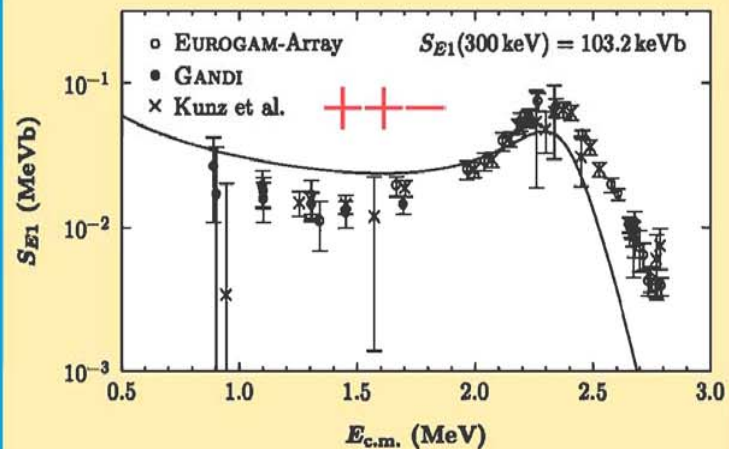
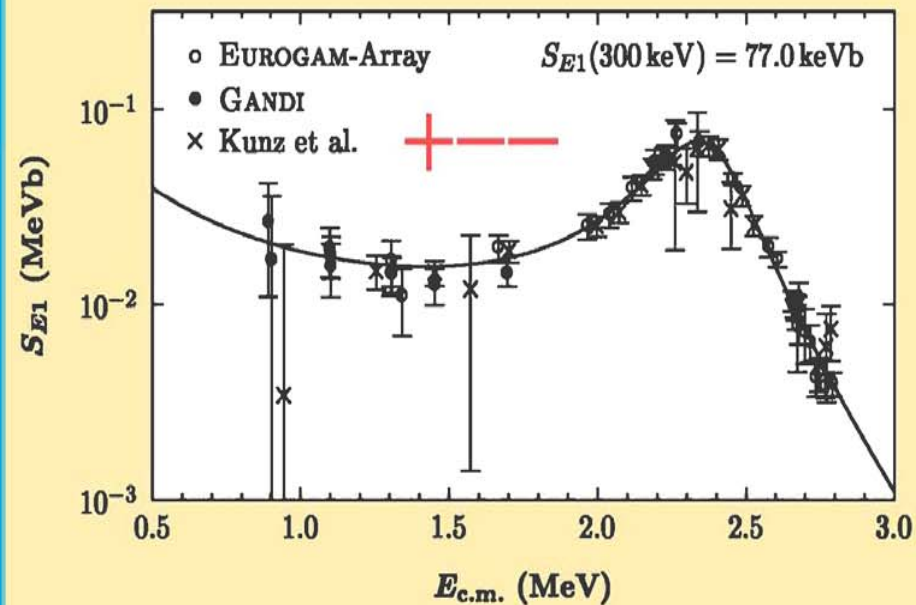
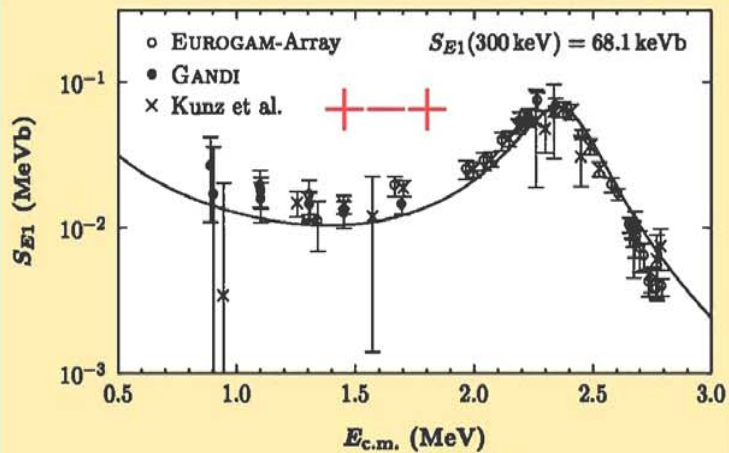
Fit of ...

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

3-level-fit

- ▶ 4 interference-combinations





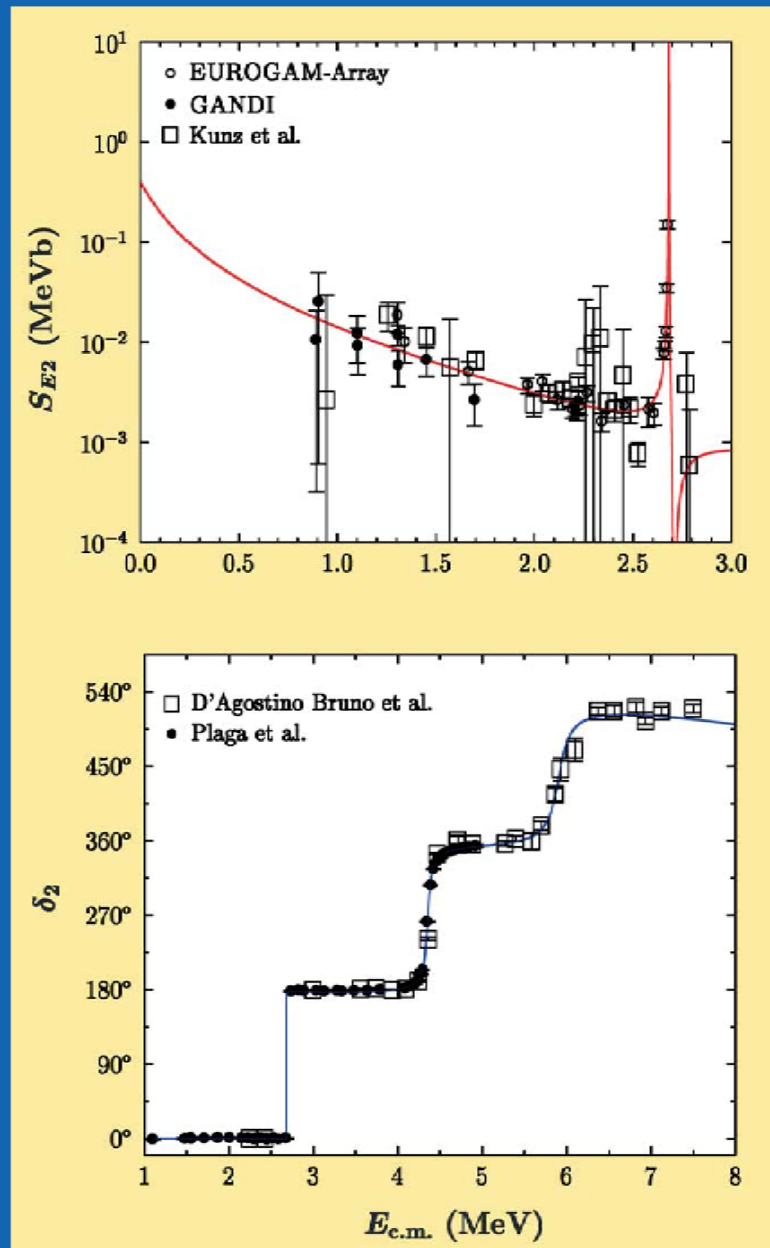
R - Matrix Fits E2

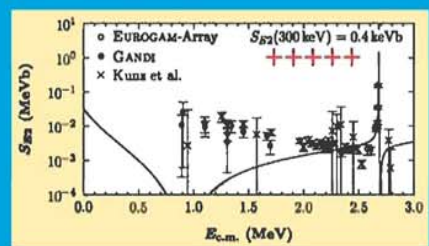
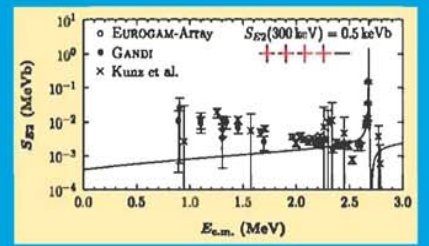
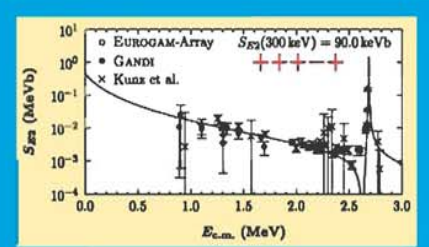
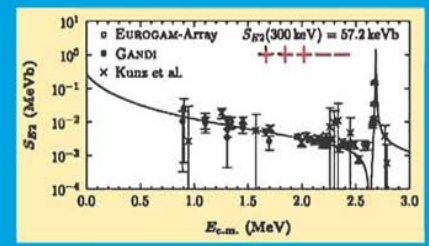
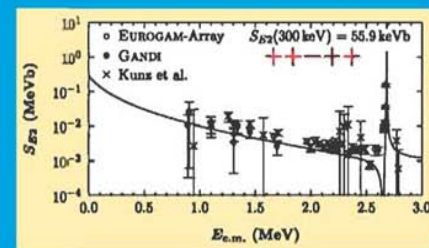
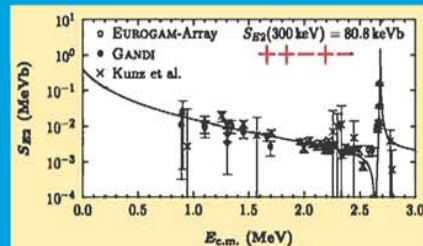
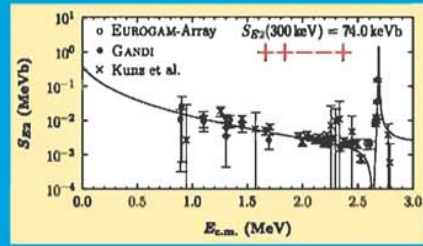
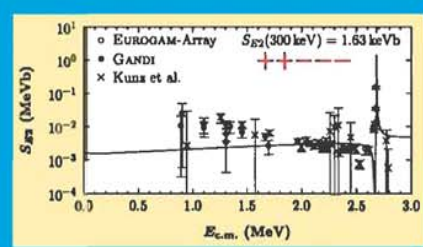
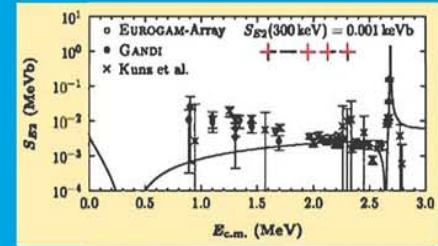
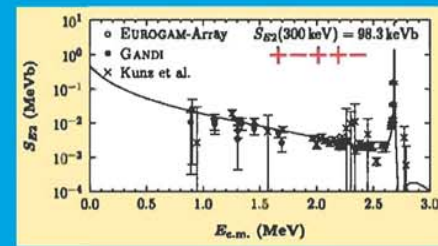
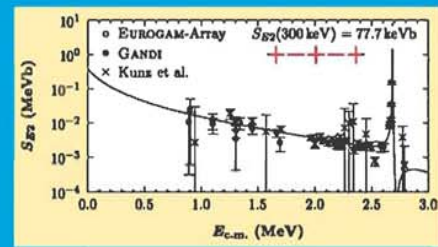
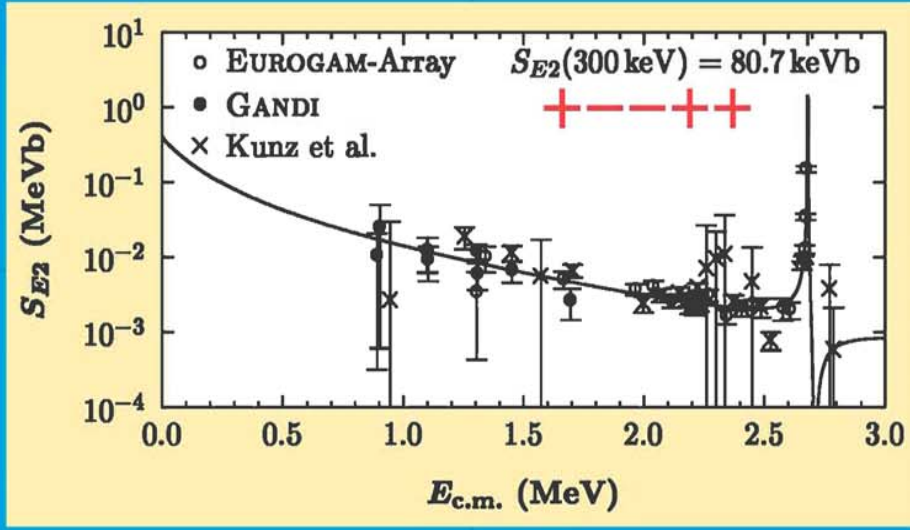
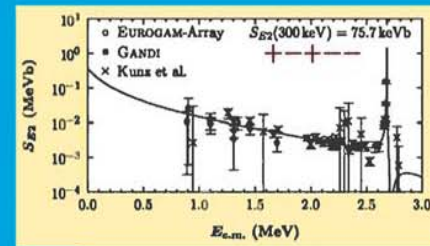
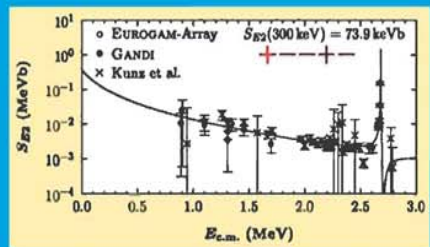
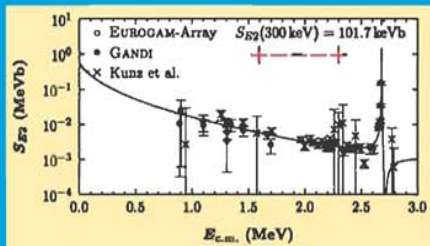
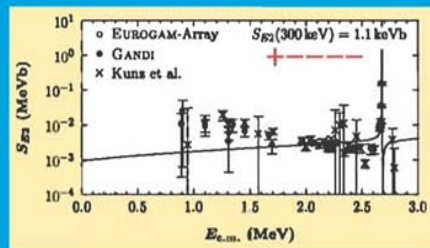
Fit of ...

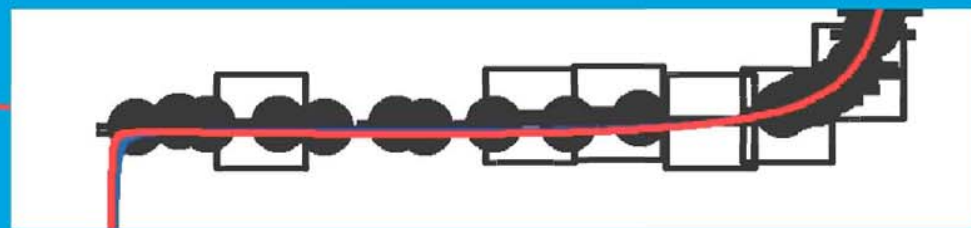
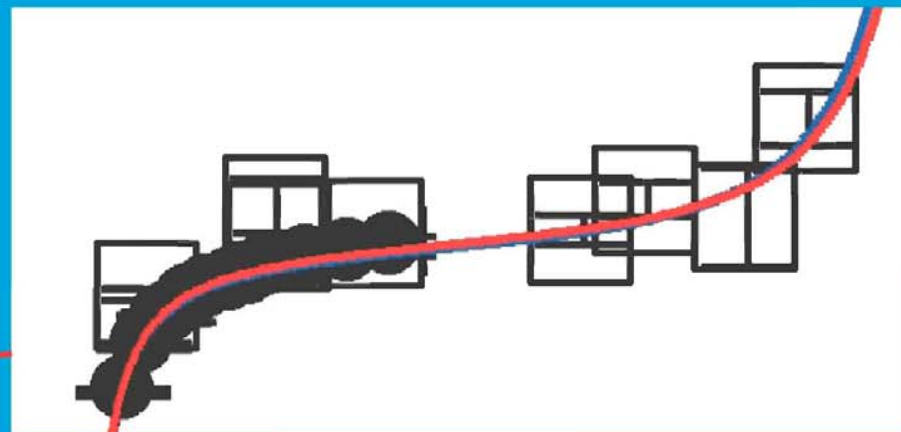
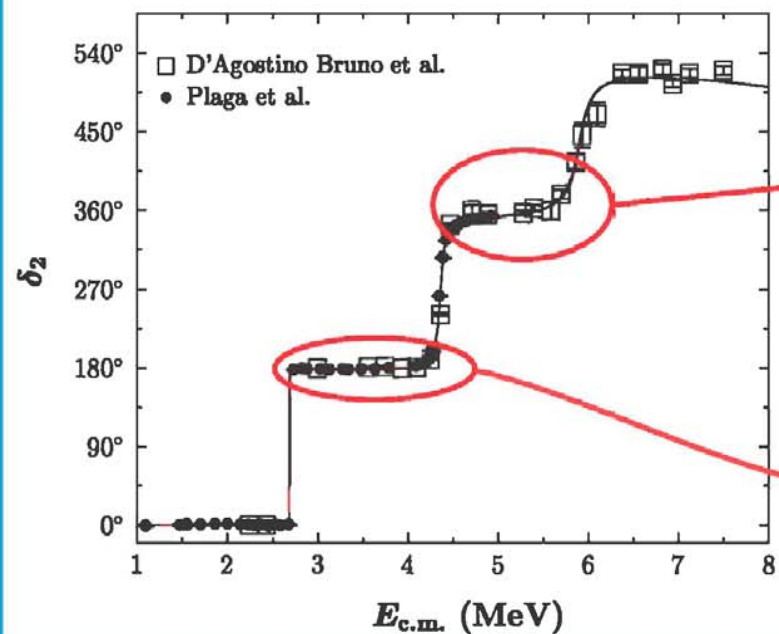
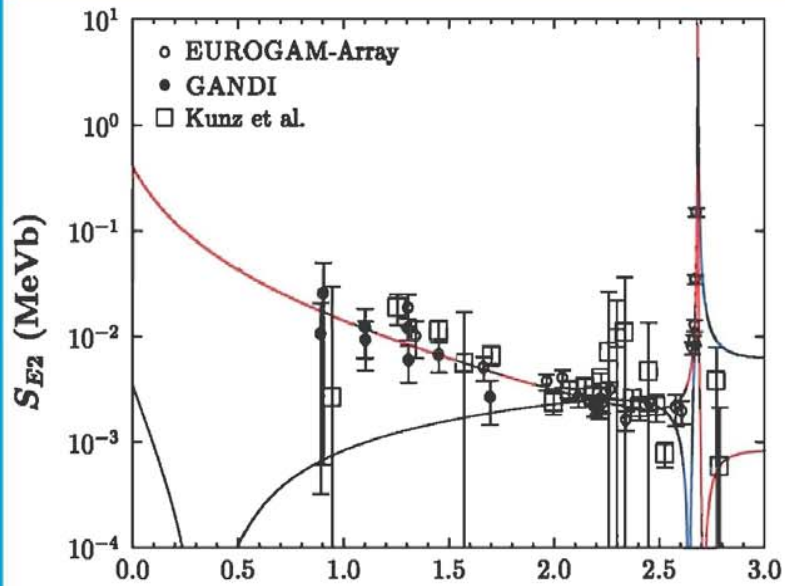
- ▶ Capture data
- ▶ α -scattering data

5-level-fit

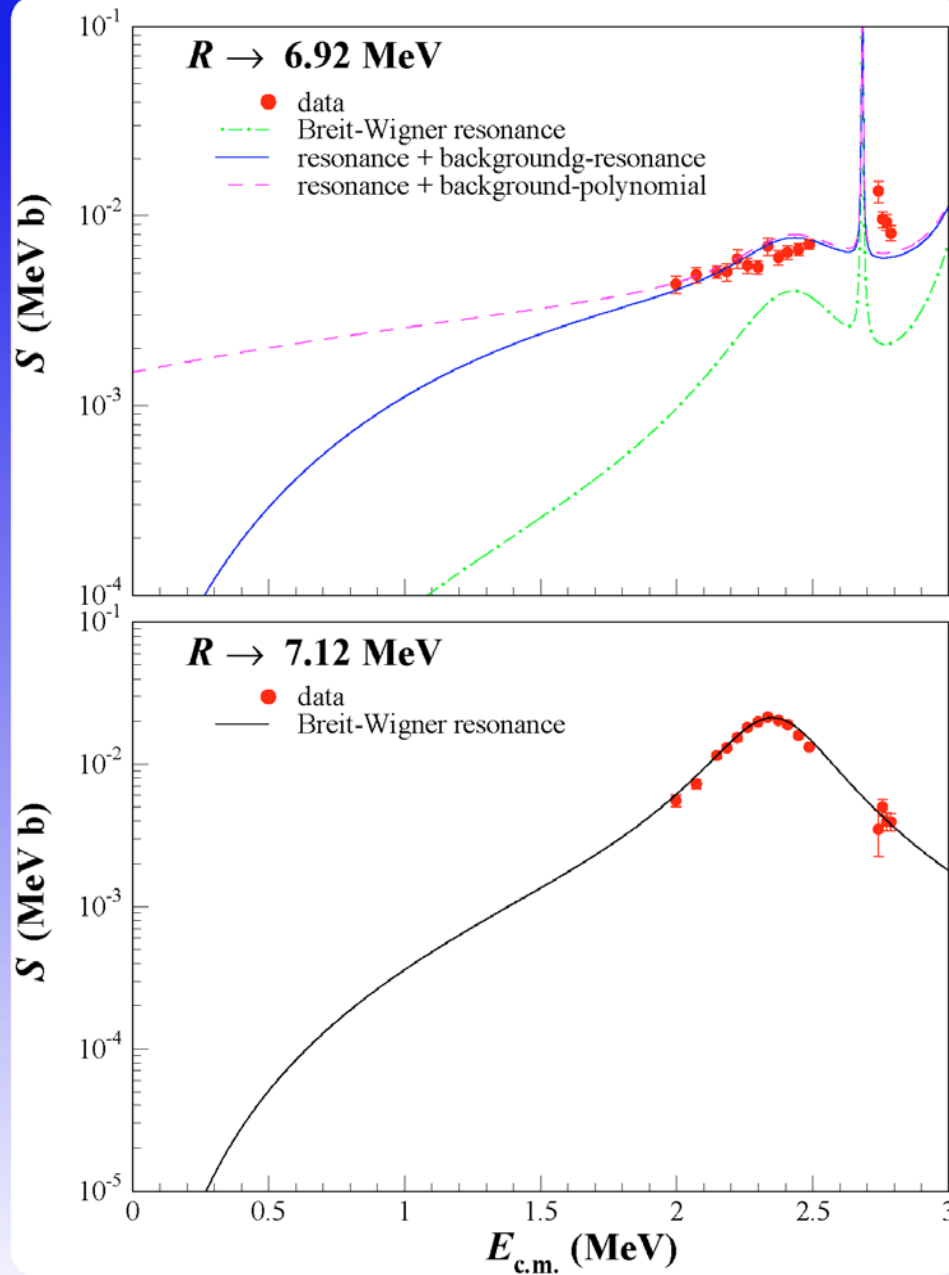
- ▶ 16 interference-combinations



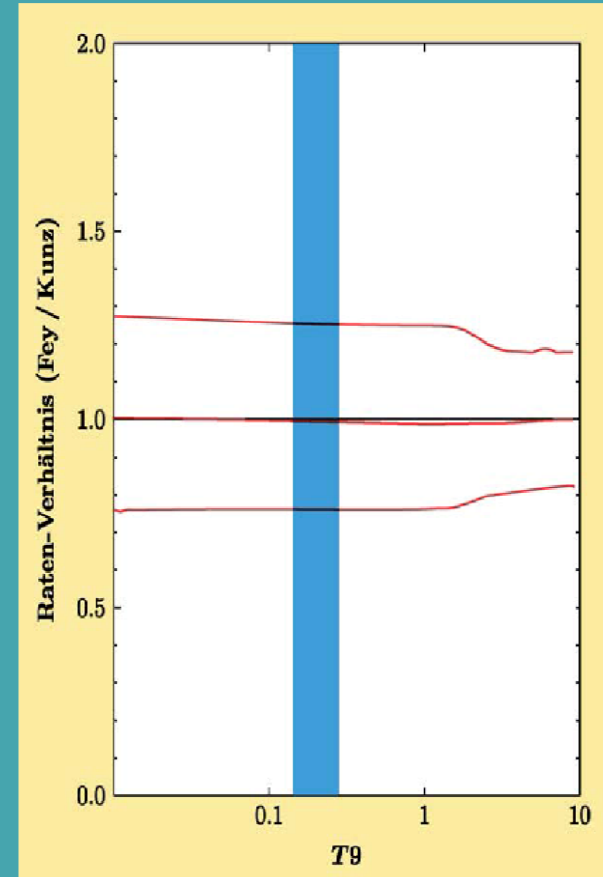
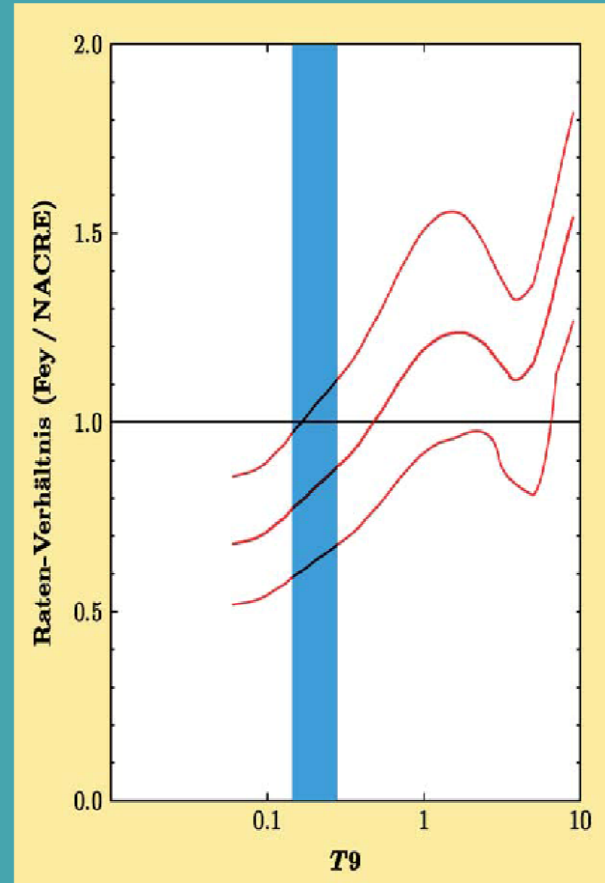
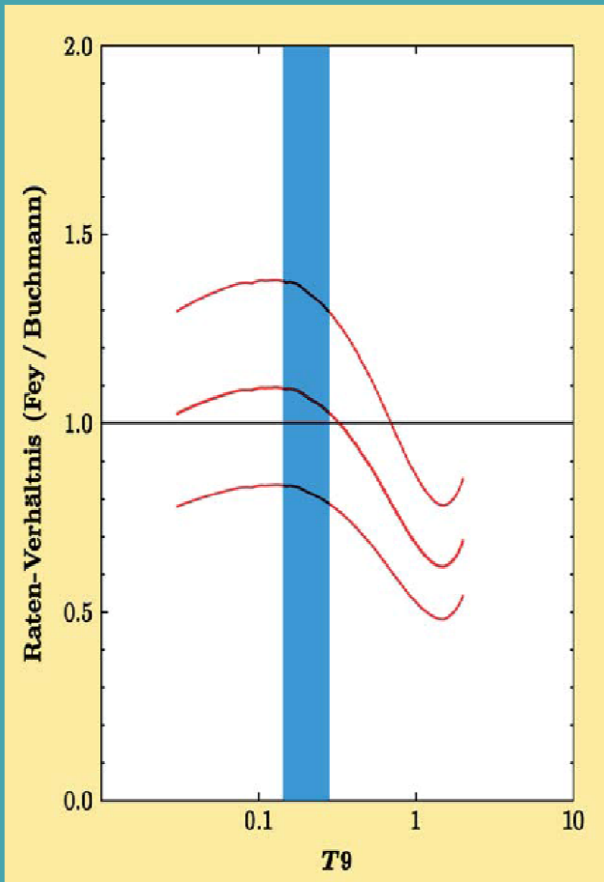




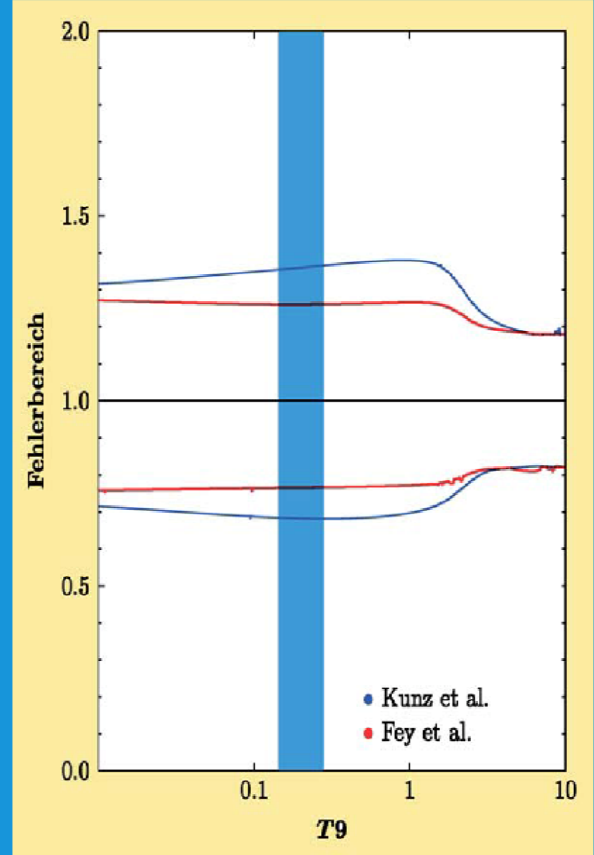
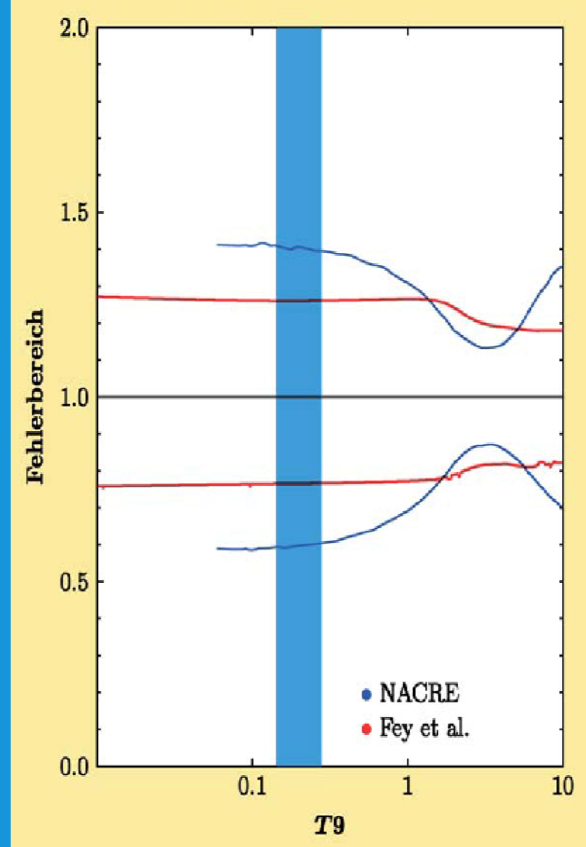
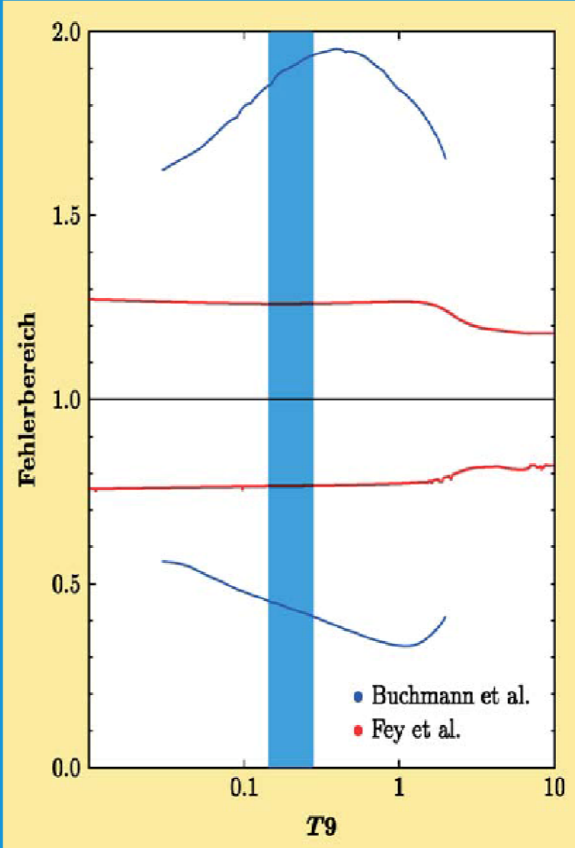
Cascade transitions

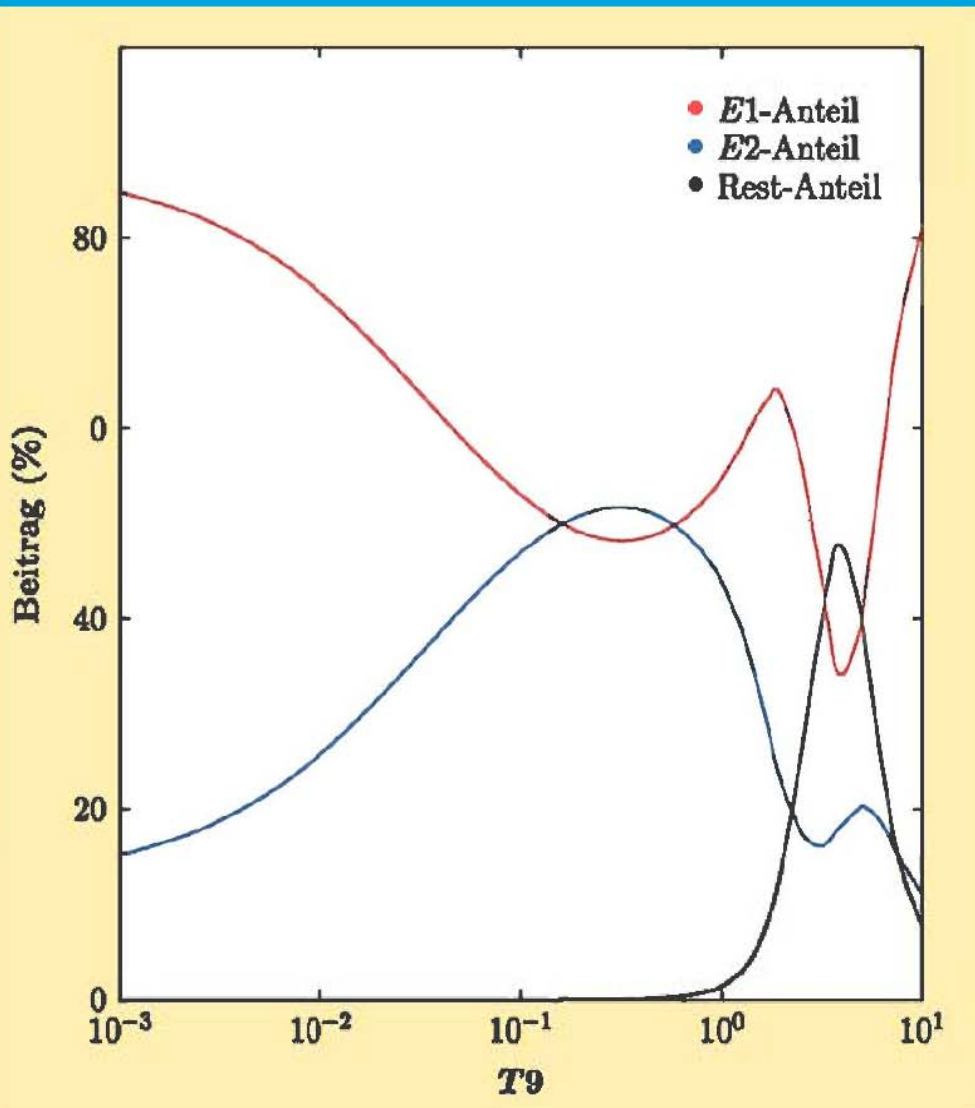
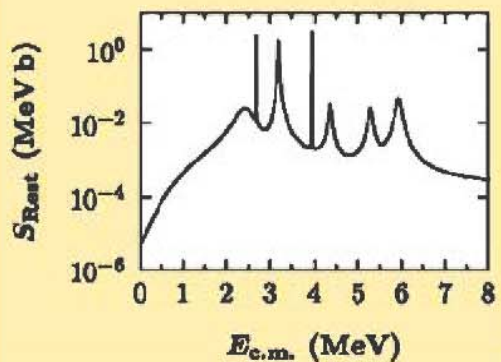
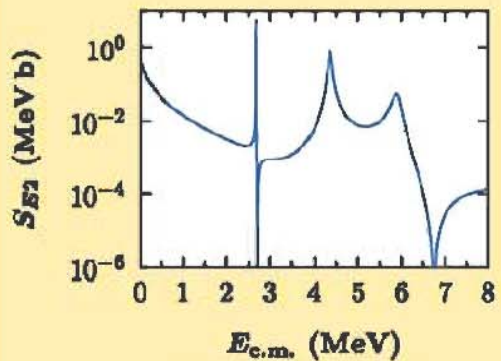
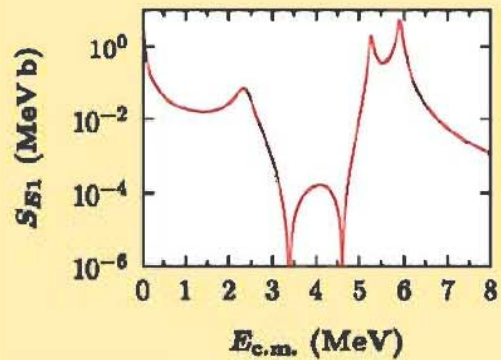


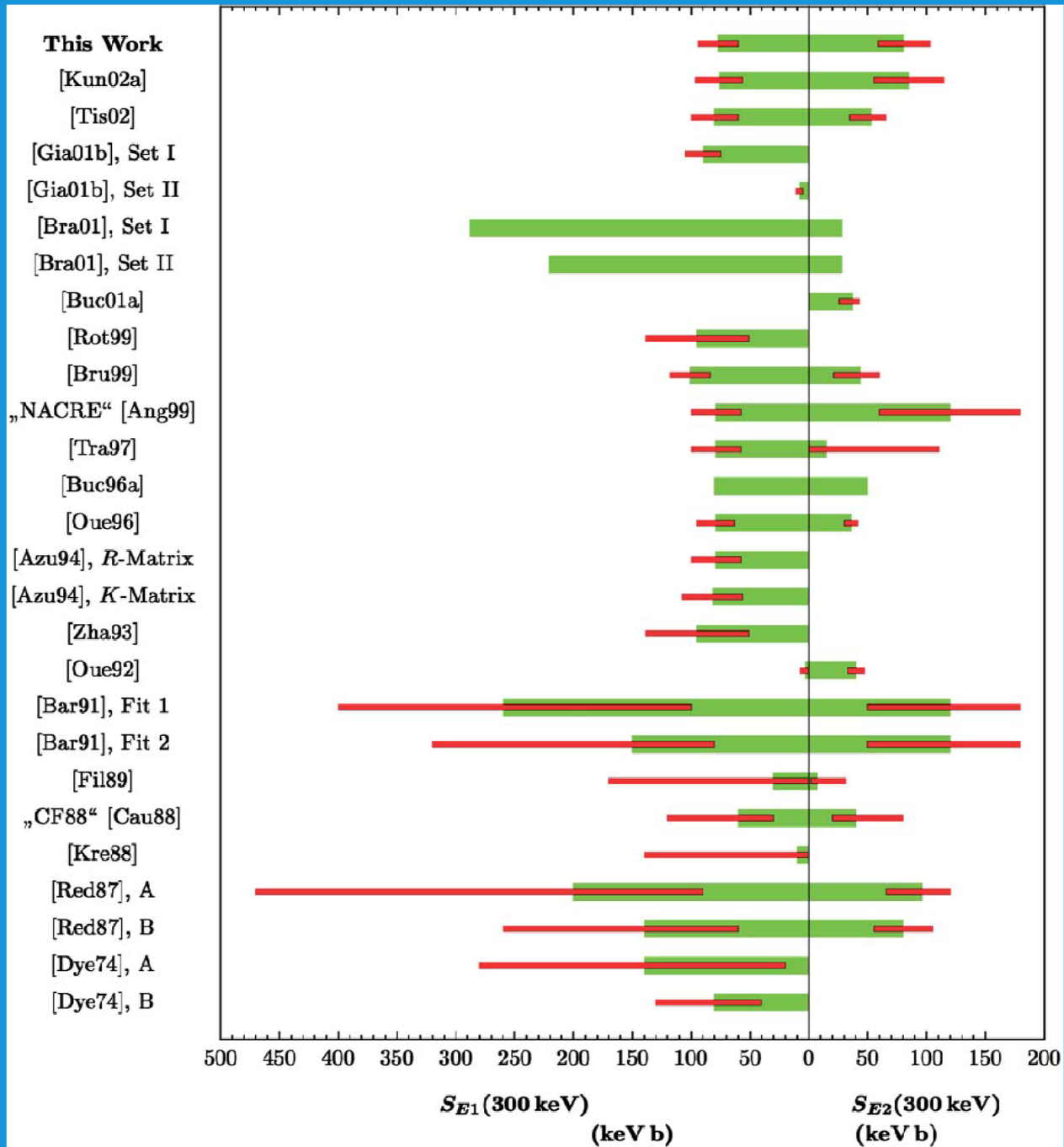
Comparison of the ratio of reaction rates : Fey : Buchmann / NACRE / Kunz



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]
E UROGAM	81 (20)	80 (27)
G ANDI	77 (19)	78 (26)
K unz 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 for $^{12}\text{C}(\alpha\gamma)^{16}\text{O}$

- 2 experiments: $E_{\text{cm}} = 0.89 - 2.8$ MeV
- Separation of E1 and E2
- Interference combinations excluded
- Reaction Rate with $\pm 25\%$ uncertainty
- Table + 2 analytical expressions
- Lowest measured energy up to now
- Most precise reaction rate

Extrapolation Values at
 $E_{\text{cm}} = 300$ keV :

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

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

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

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

Efforts for the two C12ag - experiments :

Target production

70 days

Target development

41 days

3.300 spectra

C12ag - reaction

121 days

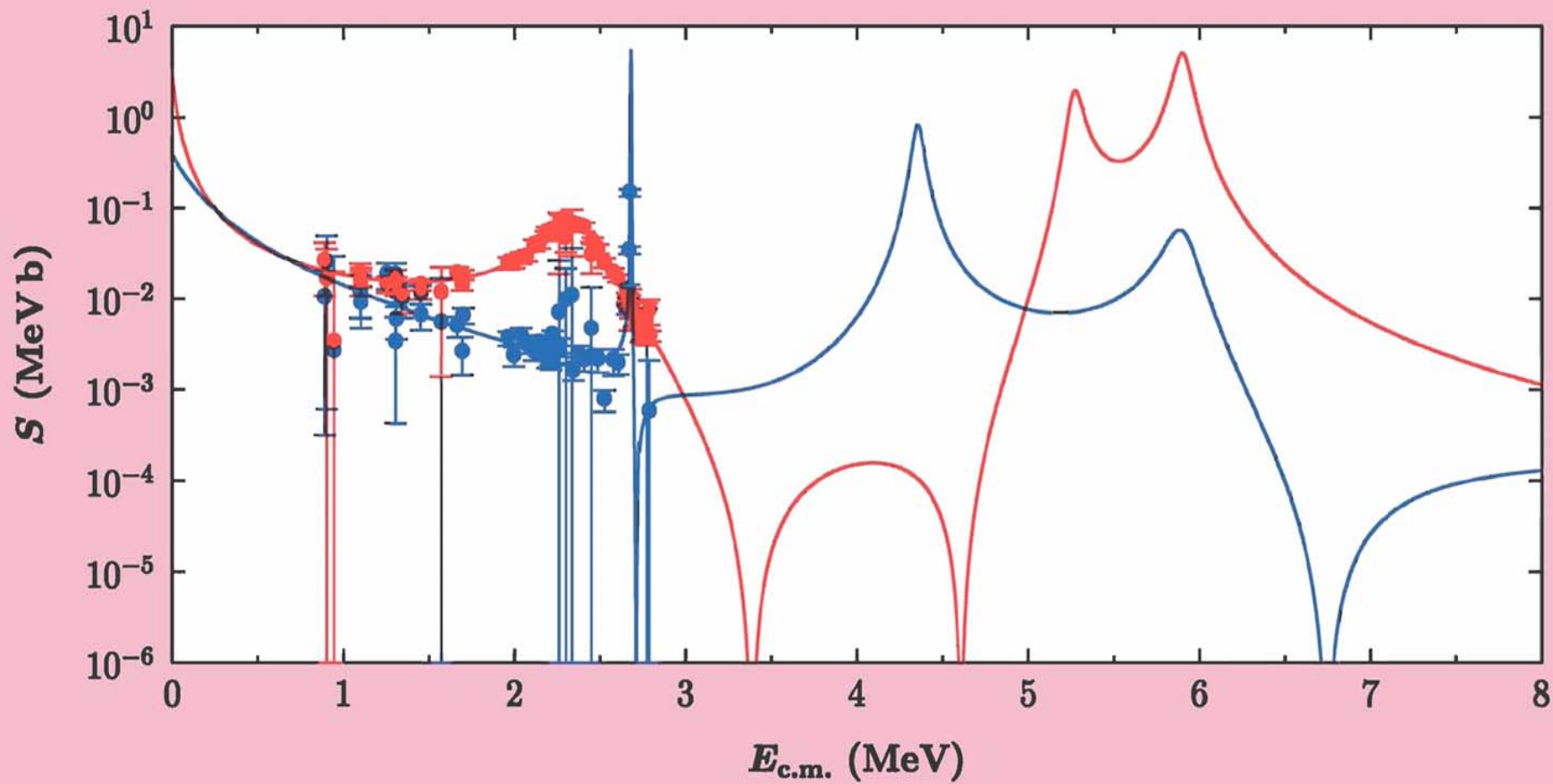
32.000 spectra

RBS-target-analysis

30 days

800 spectra





- ▶ Daniel Schürmann
- ▶ Inverse kinematic studies of $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ with ERNA at the DTL-Bochum
- ▶ Excitation function in the range $E_{\text{cm}} = 1.8 - 4.9 \text{ MeV}$
- ▶ Comparison with Stuttgart results

COLLABORATION

*CSNSM, IN2P3-CNRS and
Universite Paris-Sud, Orsay,
France*

*M. Assuncao,
A. Lefebvre-Schuhl,
J. Kjiener,
V. Tatischeff,
A. Korichi,
C. Boukari-Pelissie,
A. Coc,
J.J. Correia,
C. Grama,
F. Hannachi,
D. LeDu,
A. Lopez-Martens,
R. Meunier
J.P. Thibaud*

*Institut fuer Strahlenphysik (IfS),
Universitaet Stuttgart, Germany*

*M. Fey,
R. Kunz,
E. Krmpotic,
D. Malcherek,
J.W. H.*

*Institute of Nuclear Physics
(N.C.S.R.)*

*Demokritos Athens, Greece
S. Harissopoulos
E. Galanopoulos
Th. Paradellis*

*Institut de Recherches Subatomiques
(IReS), Strasbourg, France*

*F. Haas
P. Papka
C. Beck
S. Courtin,
M. Rousseau,
N. Rowley
S. Szilner*

*Institute of Isotopes,
Budapest, Hungary*

*and
Dept. of Physics,
University of Kentucky,
Lexington, USA
J.L. Weil*

*Gesellschaft fuer Schwer-
ionenforschung mbH (GSI),
Darmstadt, Germany*

F. Hammache

*Kernfysisch Versneller Instituut
(KVI), University of Groningen,
Netherlands*

F. Fleurot

*Physikalisches Institut,
Universitaet Tuebingen,
Germany*

G. Staudt

$^{12}\text{C} (\alpha, \gamma) ^{16}\text{O} :$

technical means by far not exhausted :

- *γ -efficiency factor 10*
- *α -current factor 2-5*
- *time factor 5*

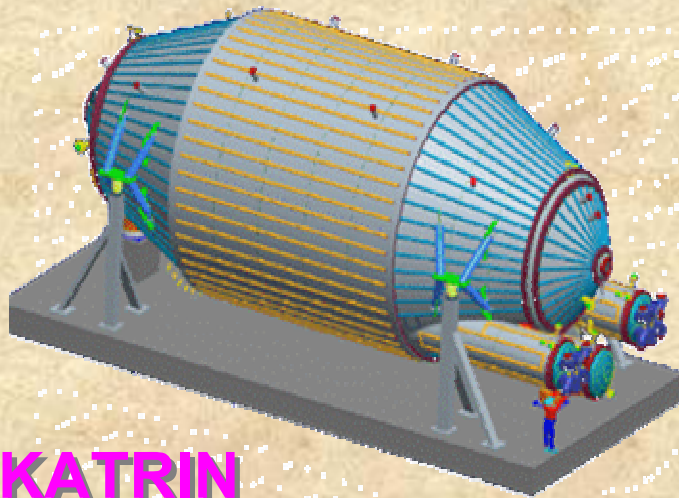
....like listening to a nightingale

whilst the
home team
scores a
goal !

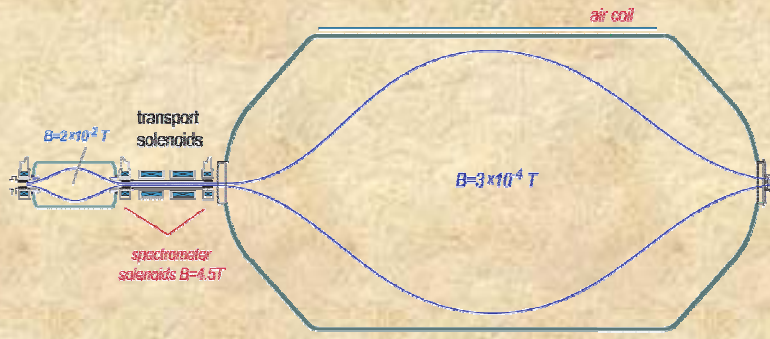




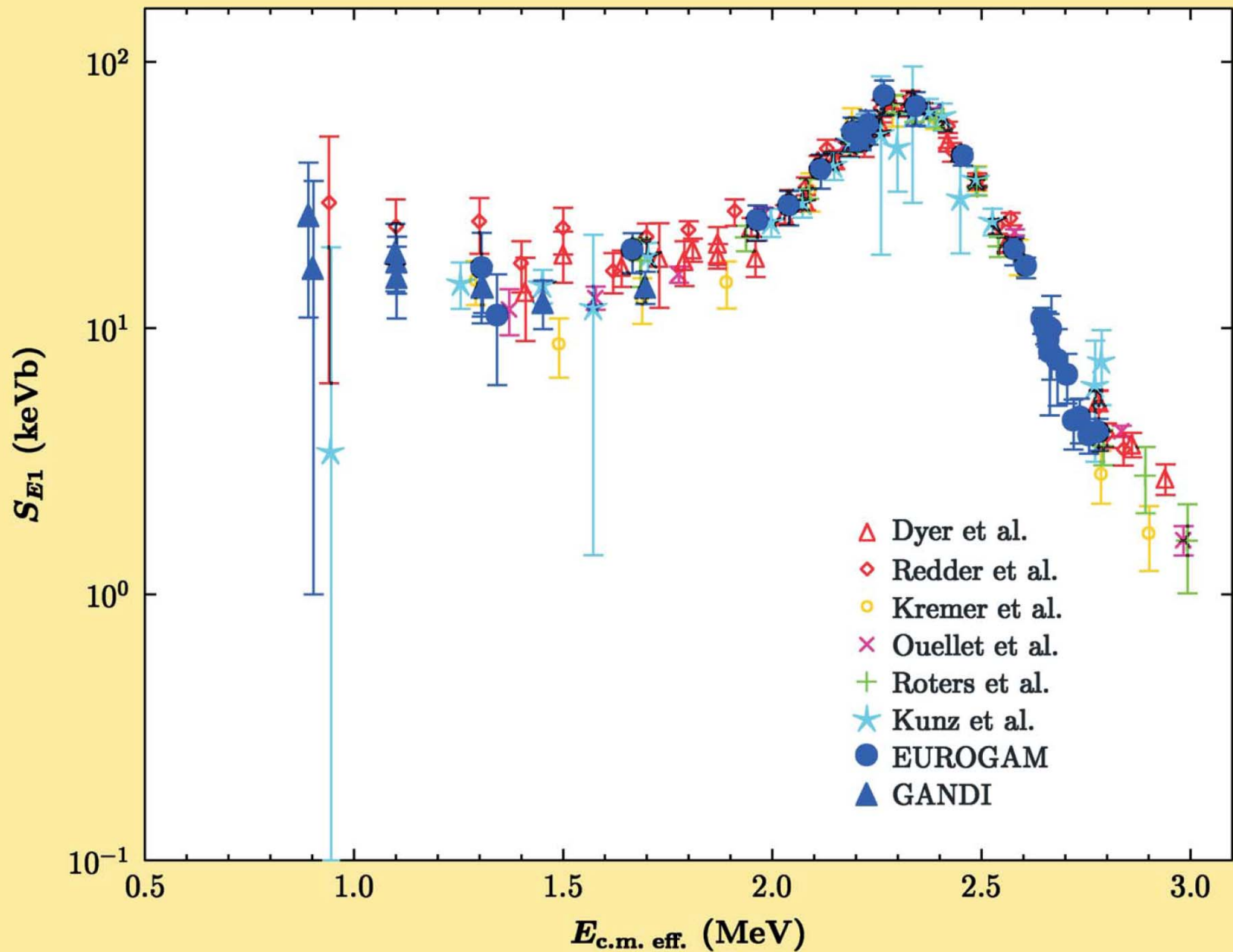
Saint-Gobin : ball-detector

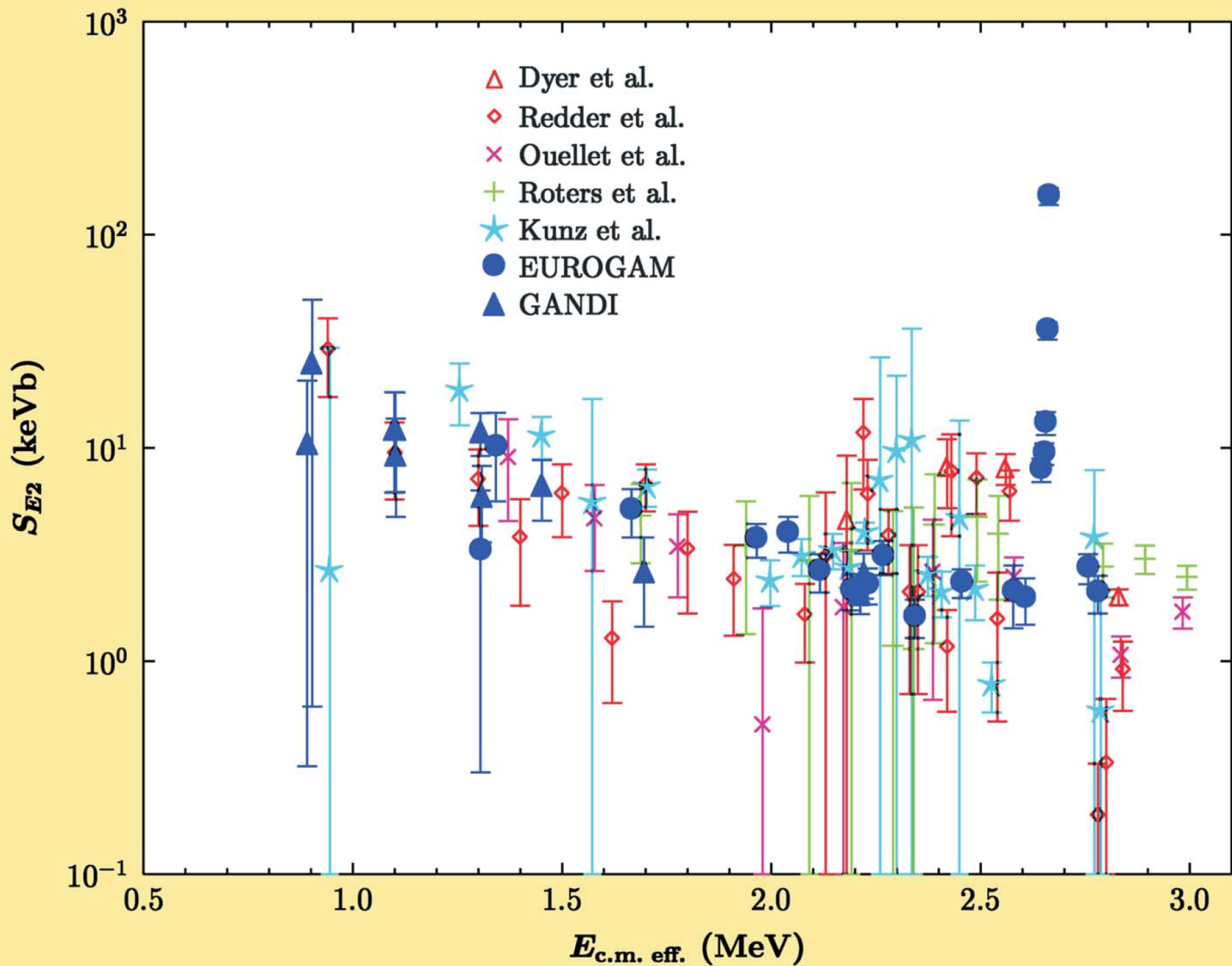


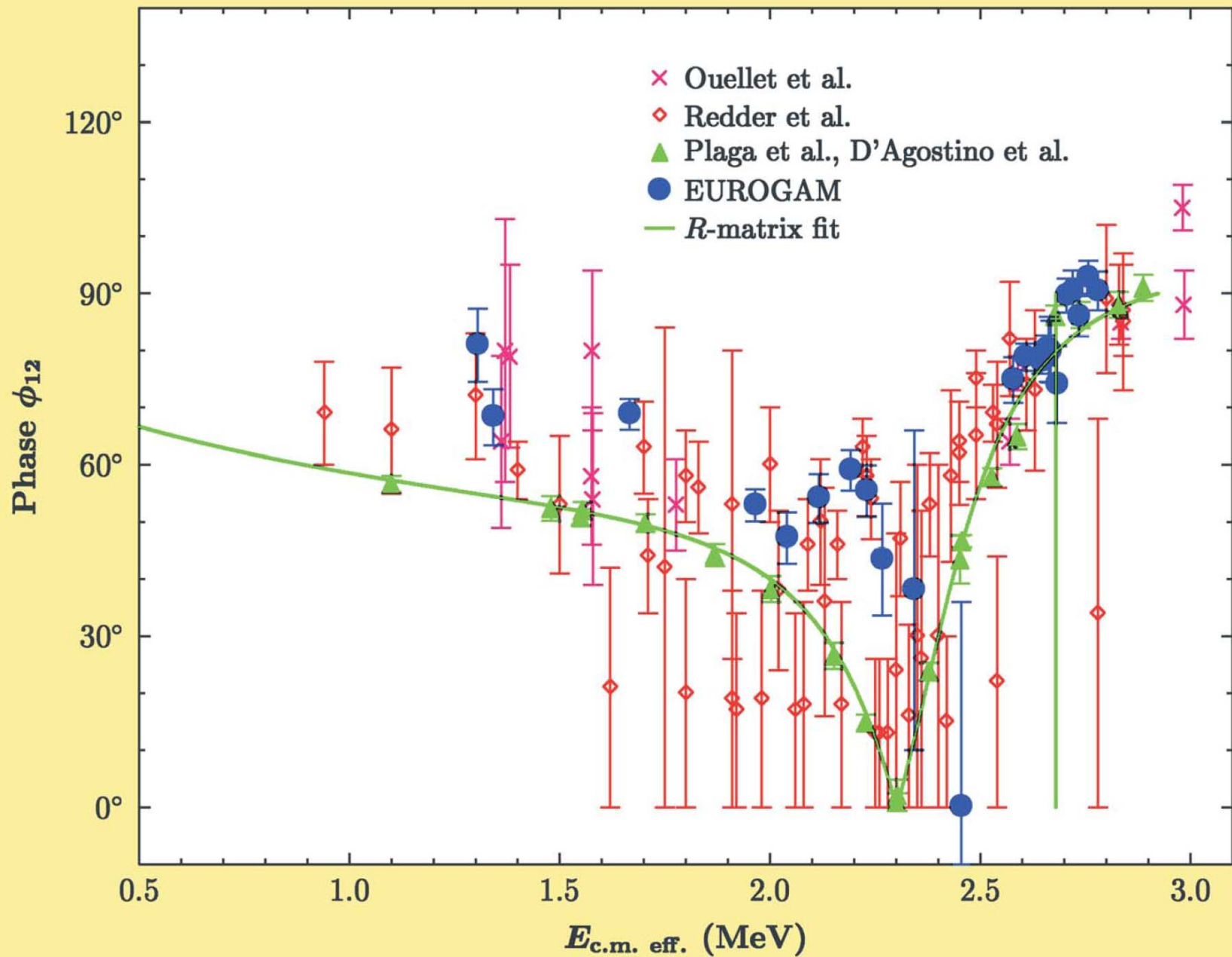
KATRIN

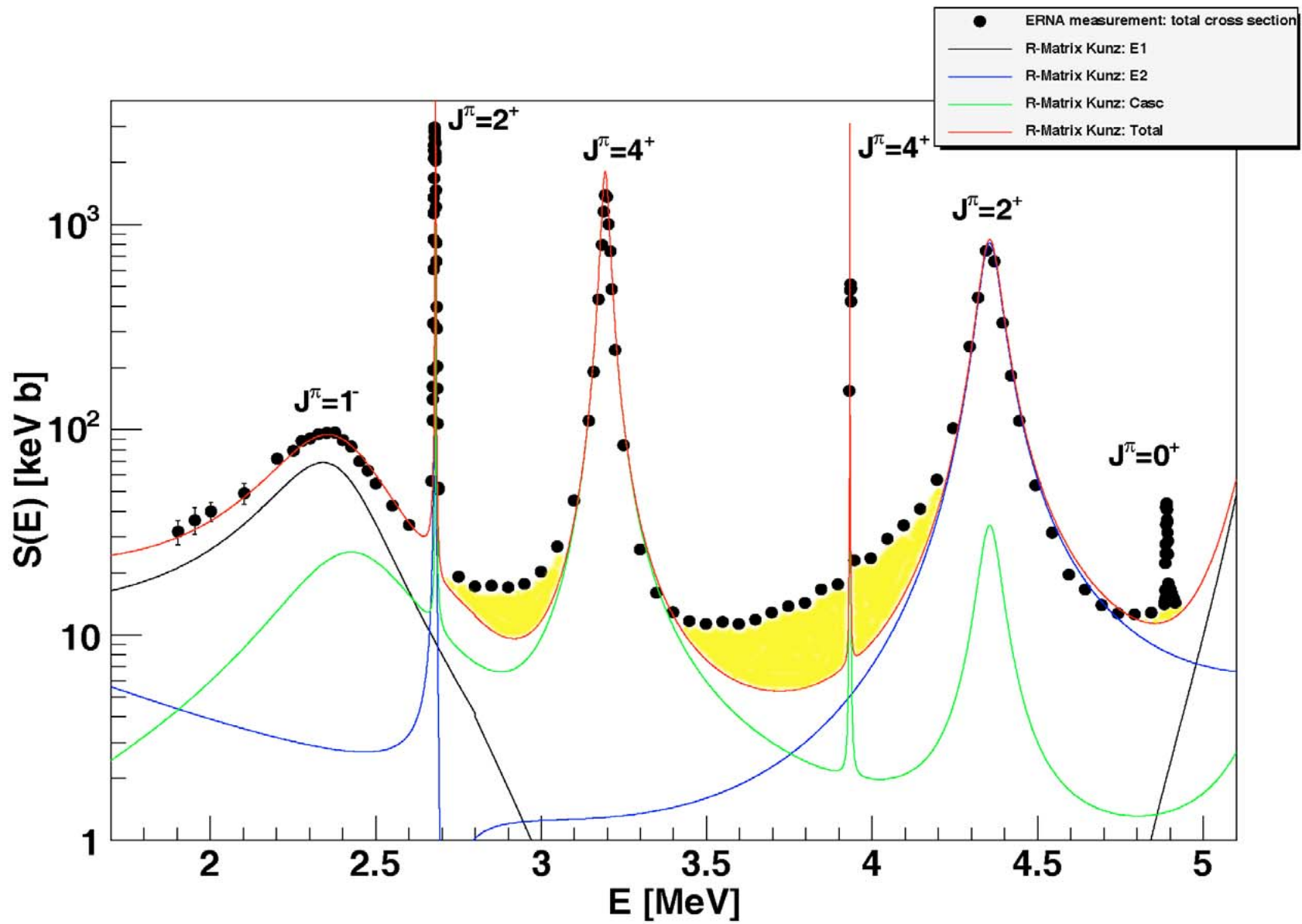


Appendix

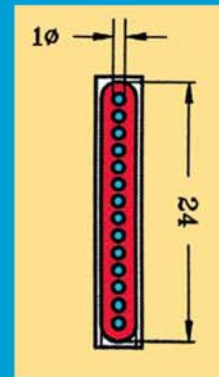
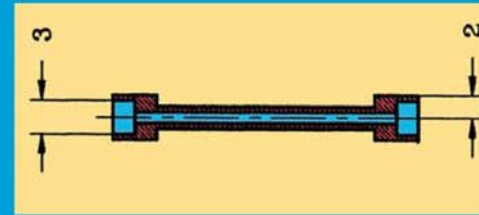
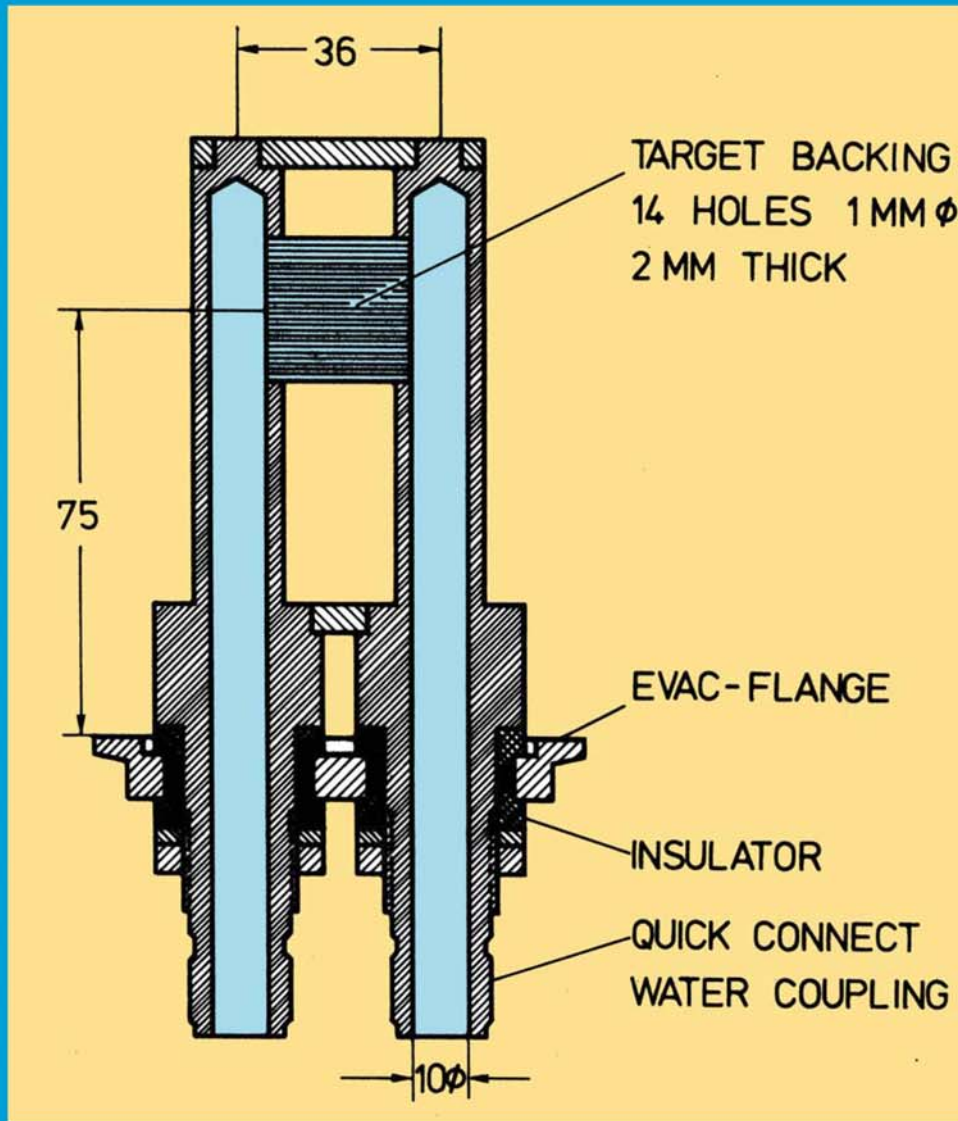




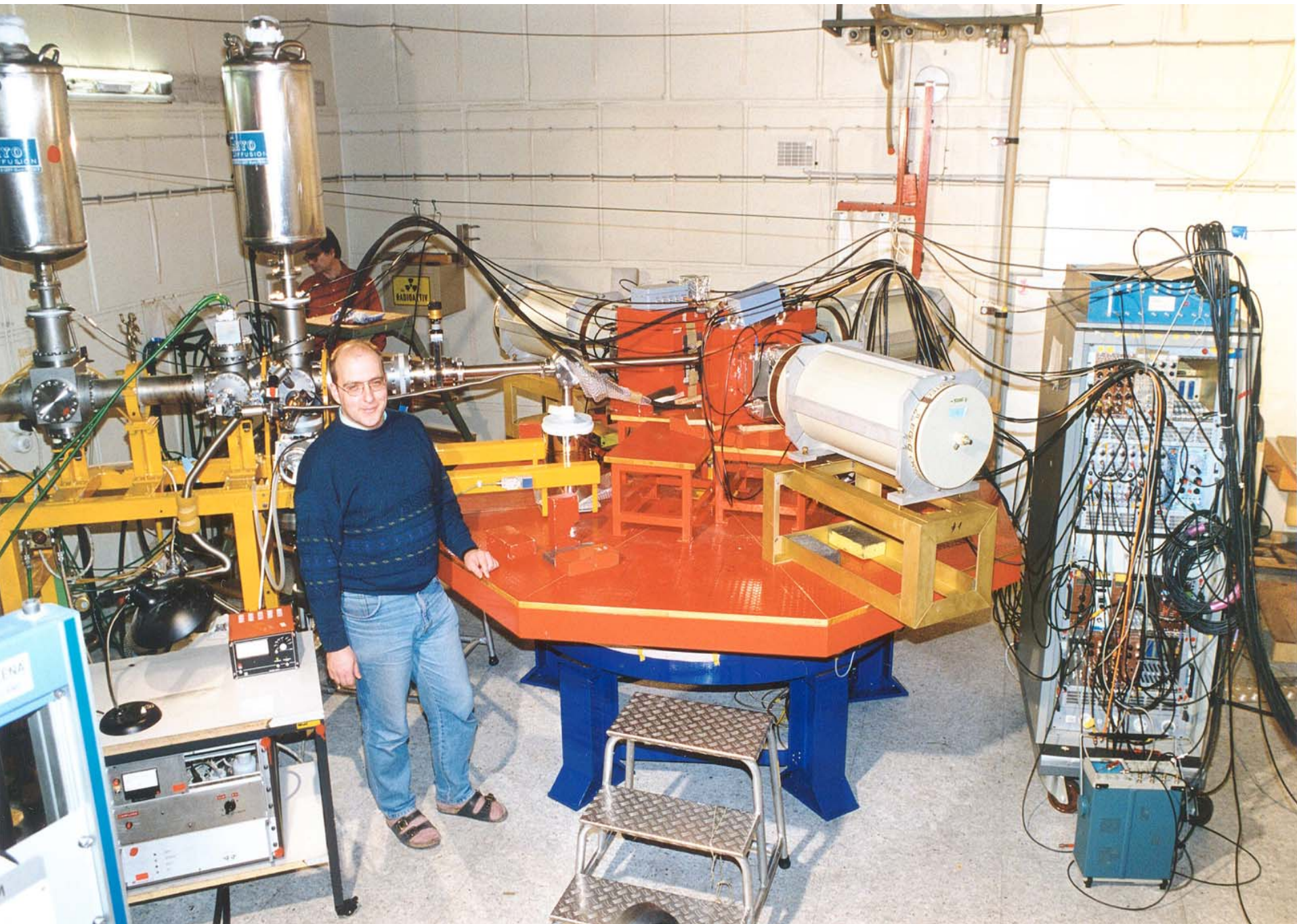


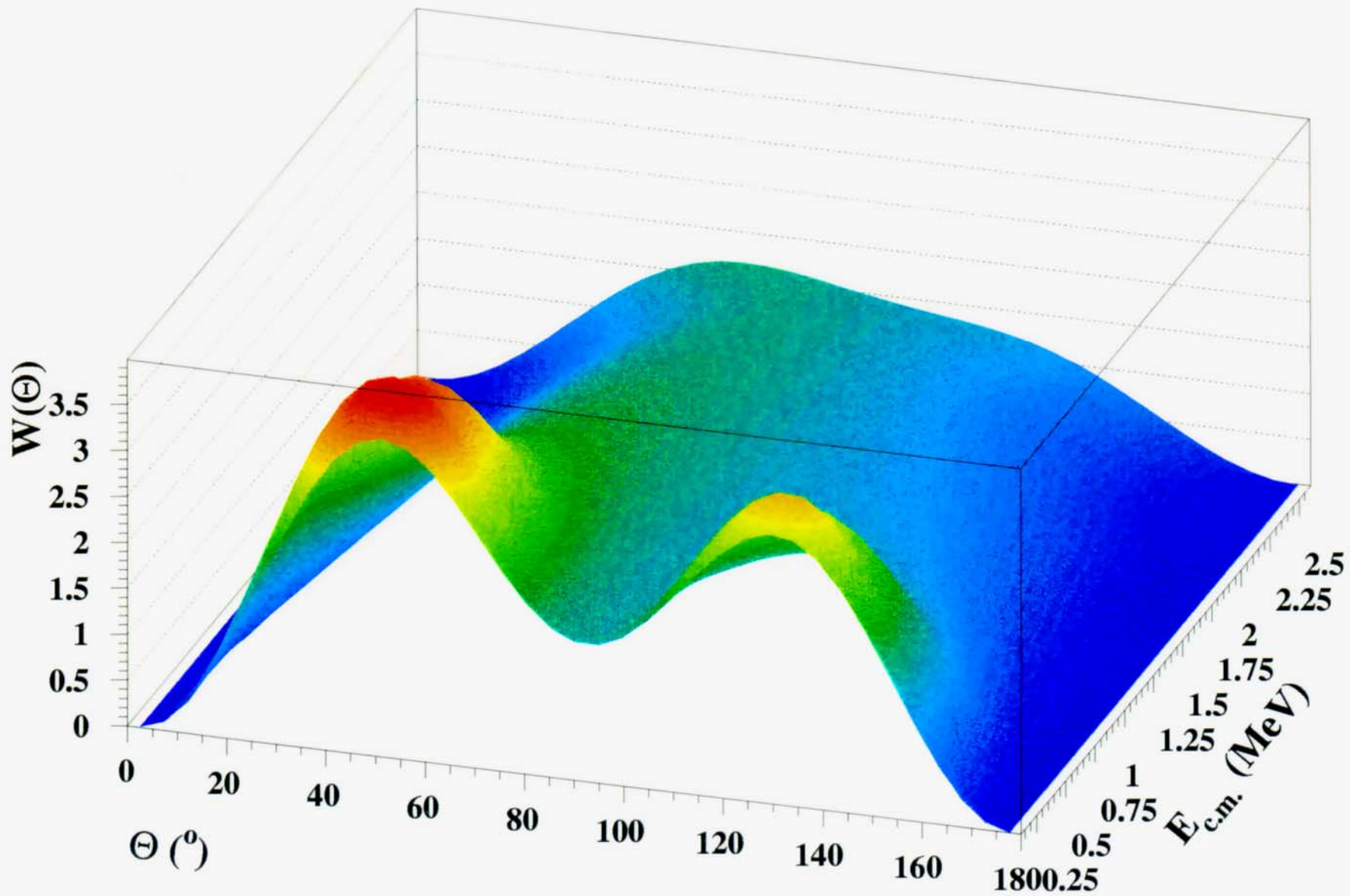


TARGET for high beam power of $10\text{kW}/\text{cm}^2$

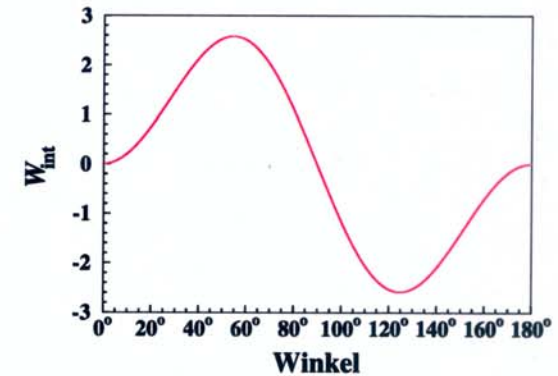
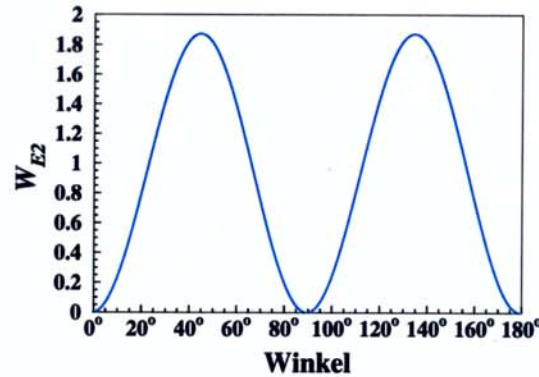
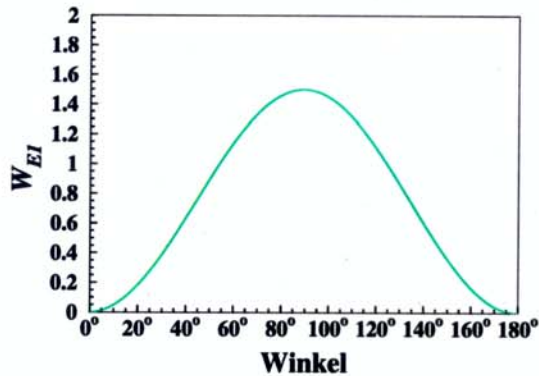


Ref.: J.W. Hammer and W. Niessner,
Kerntechnik 17 (1975) 477





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



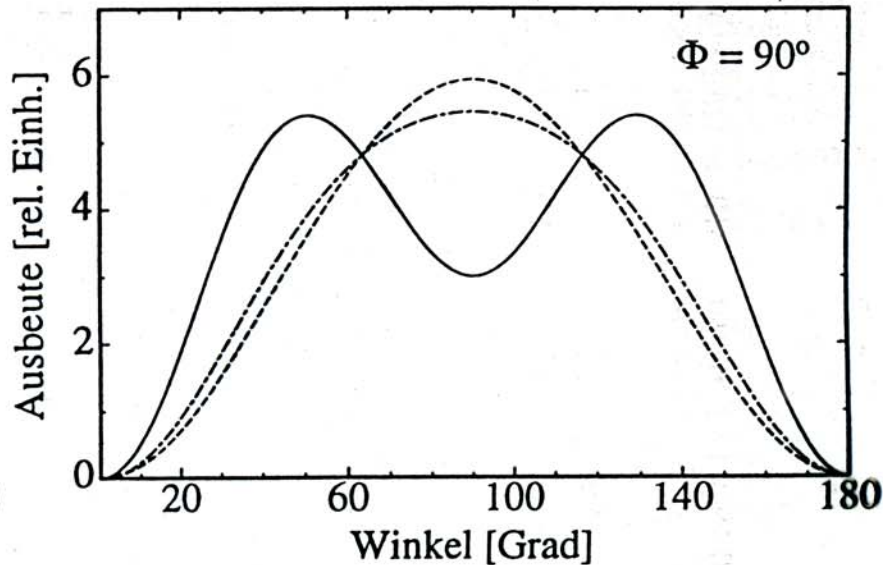
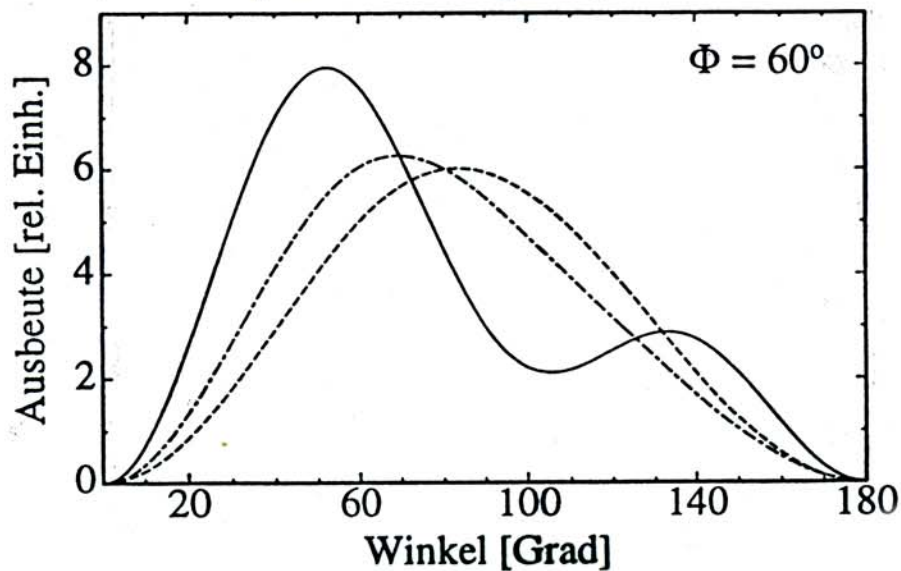
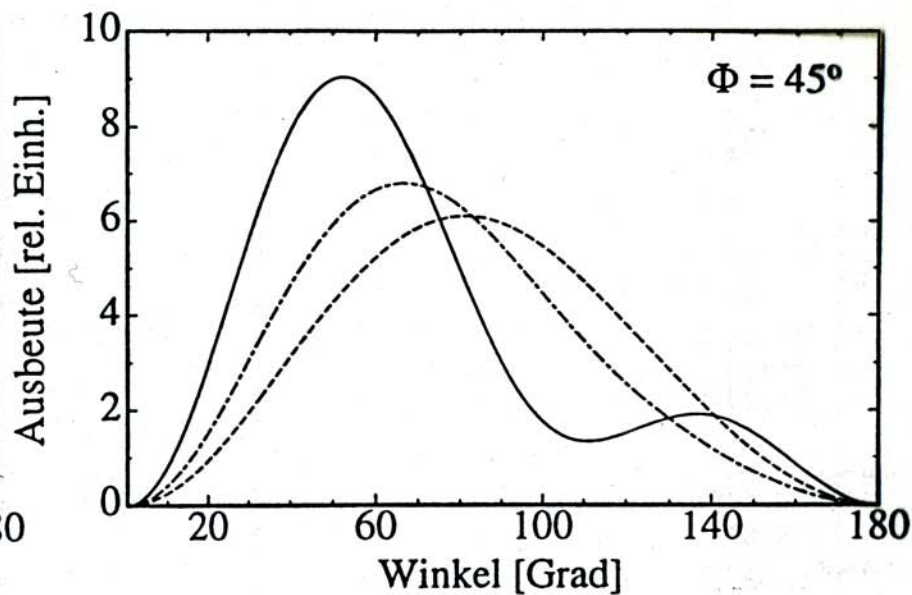
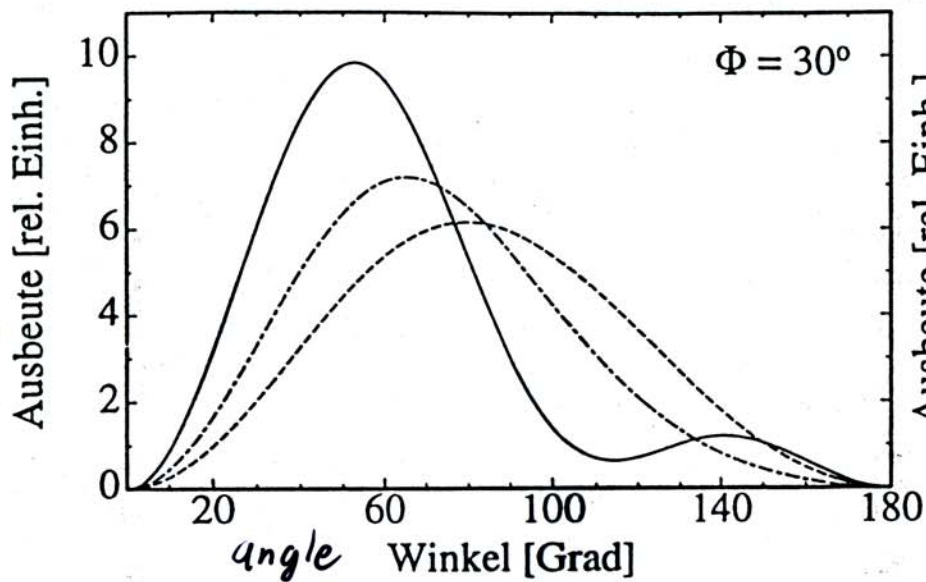
$$\phi_{12} = \delta_2 - \delta_1 + \arctan \frac{\eta}{2}$$

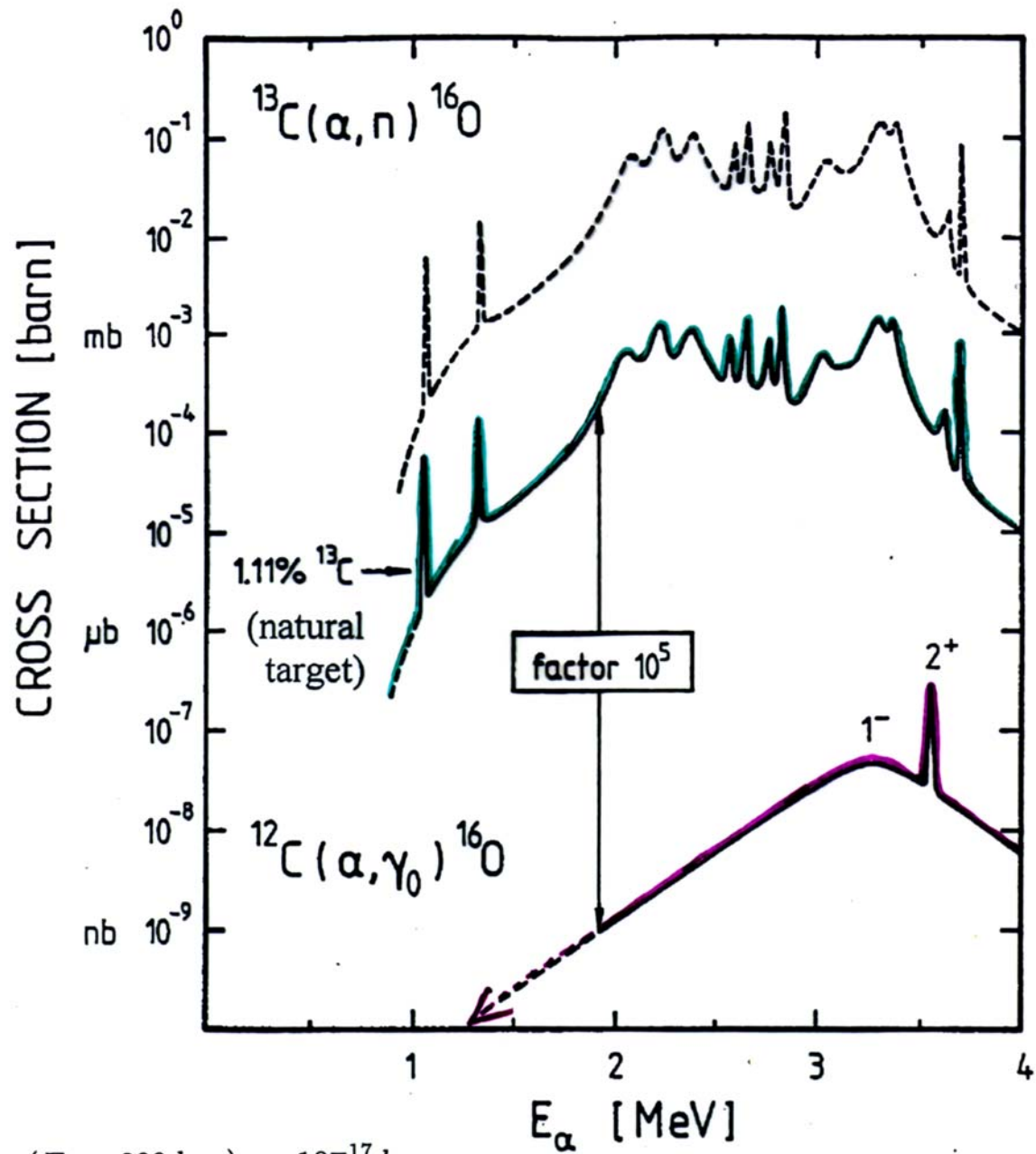
$$\frac{E_2}{E_1} = 1 \text{ —}$$

$$\frac{E_2}{E_1} = 0.1 \text{ - - - -}$$

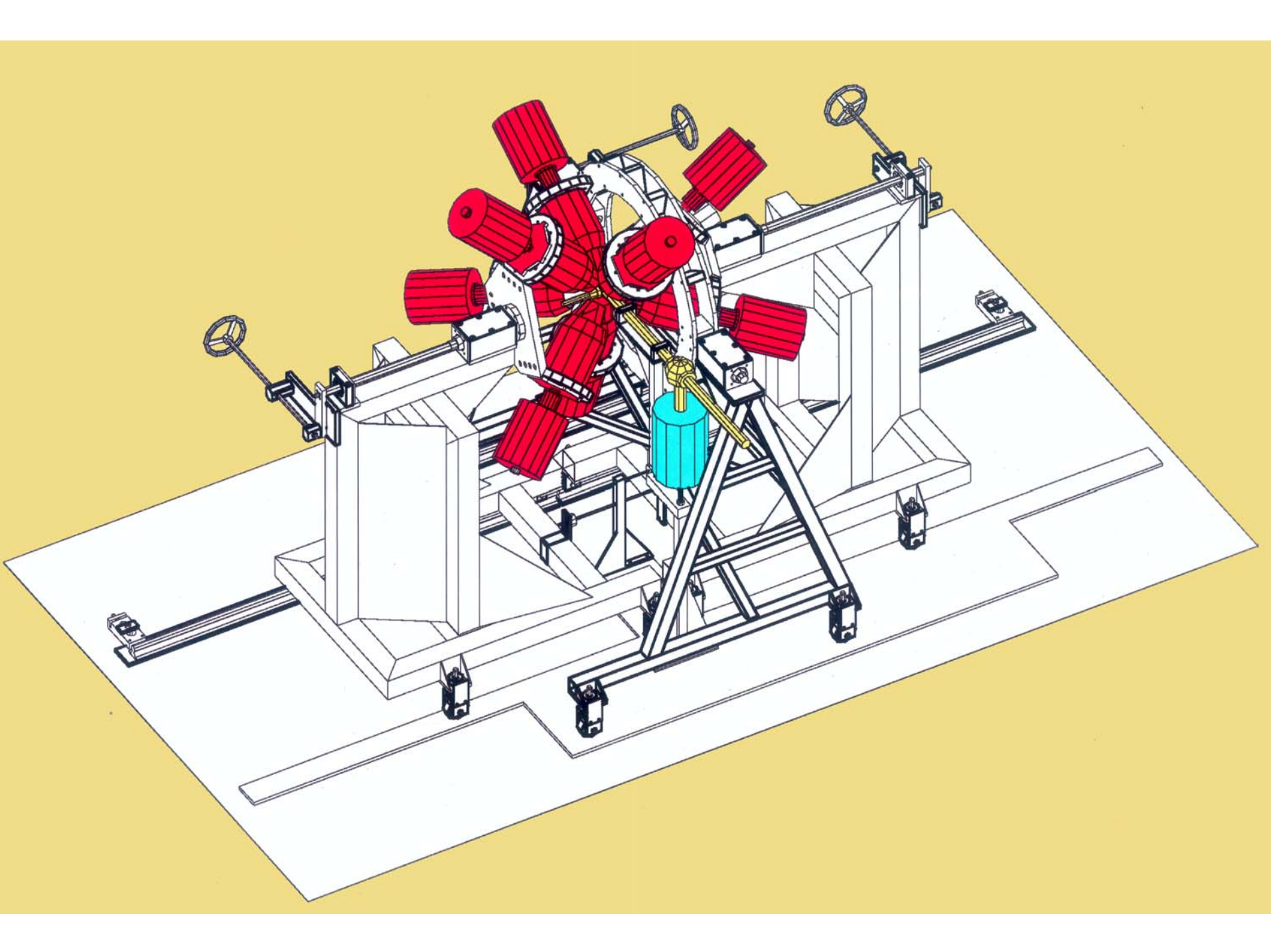
$$\frac{E_2}{E_1} = 0.01 \text{ - - - - -}$$

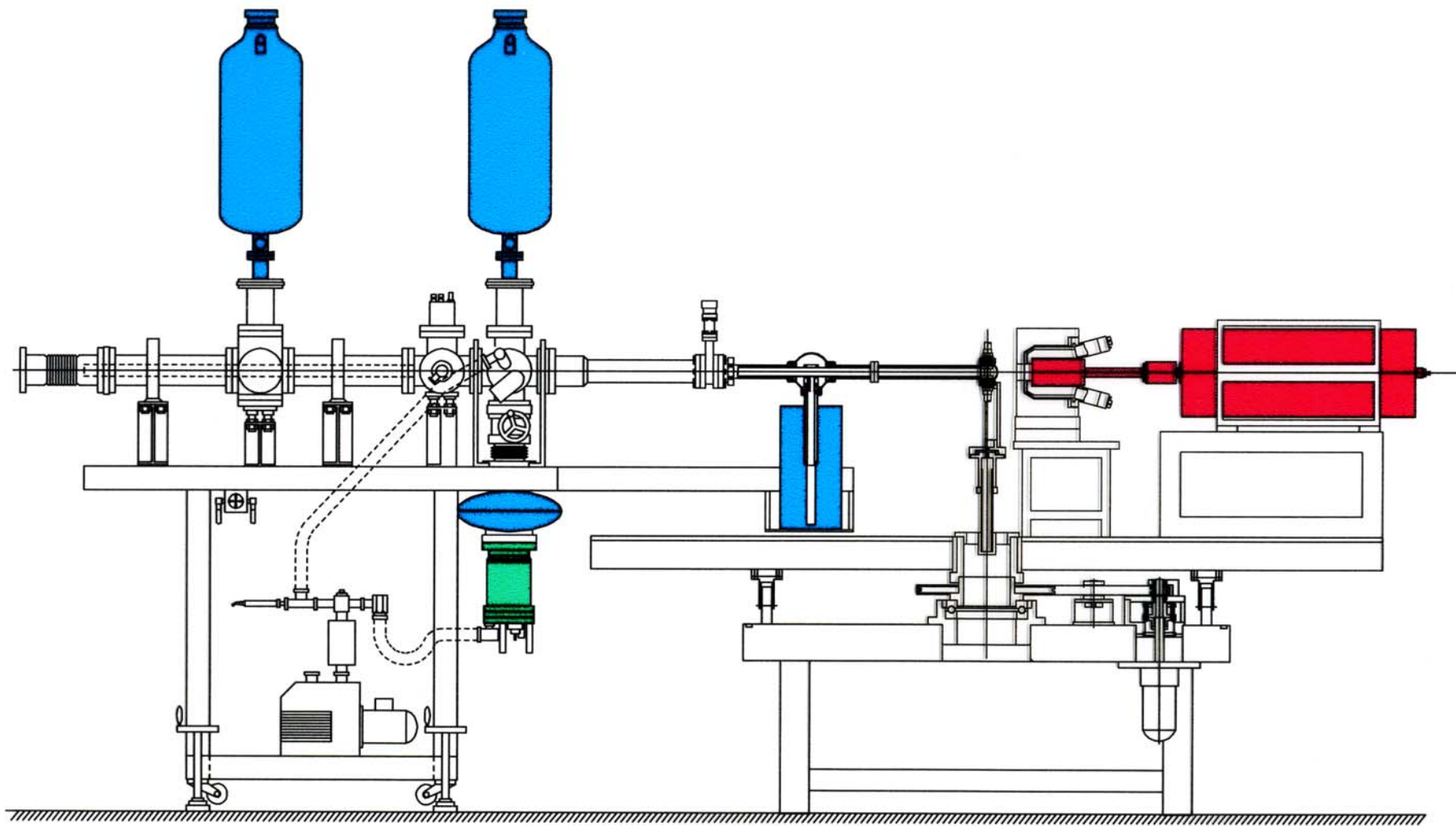
Yield

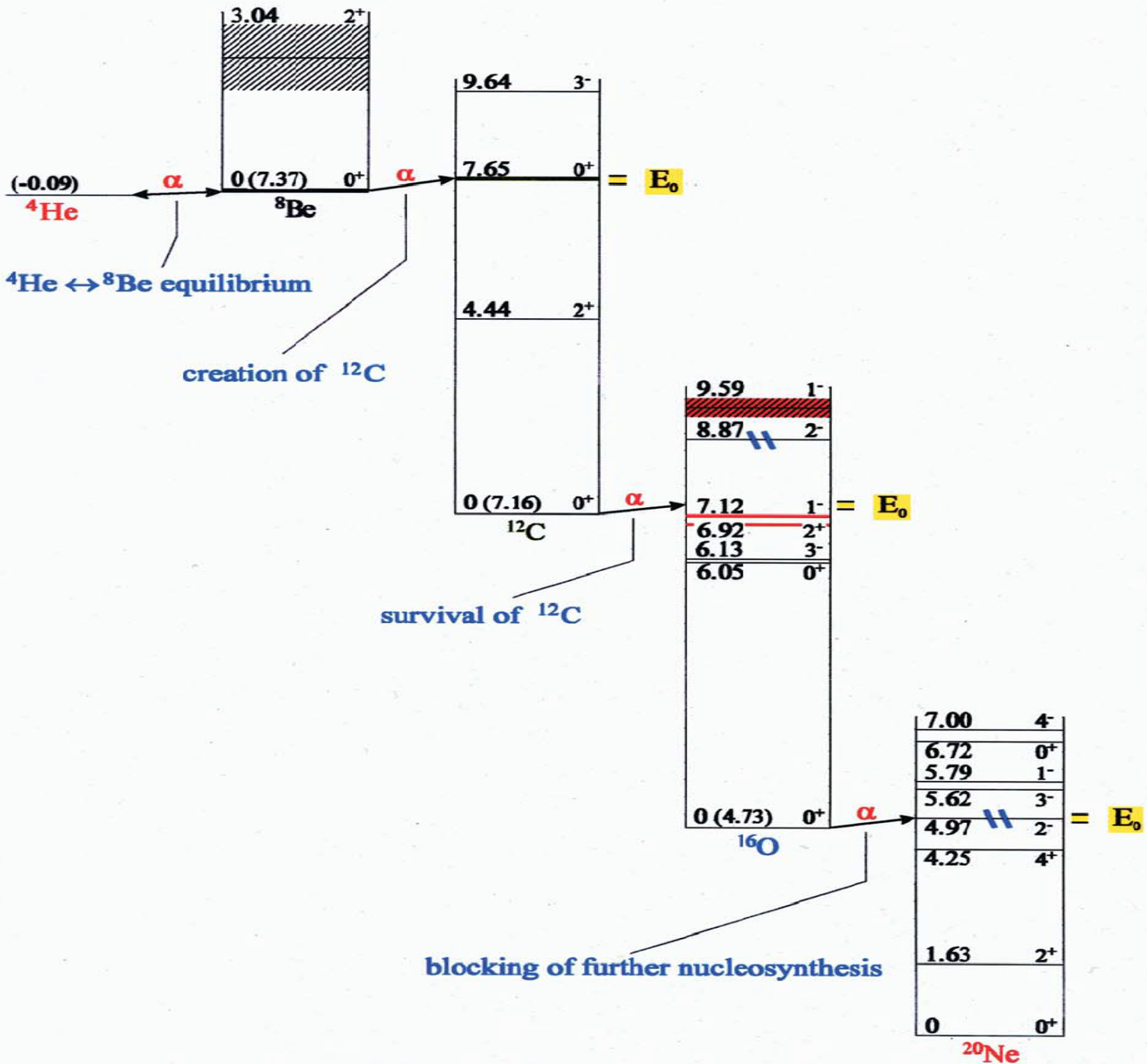


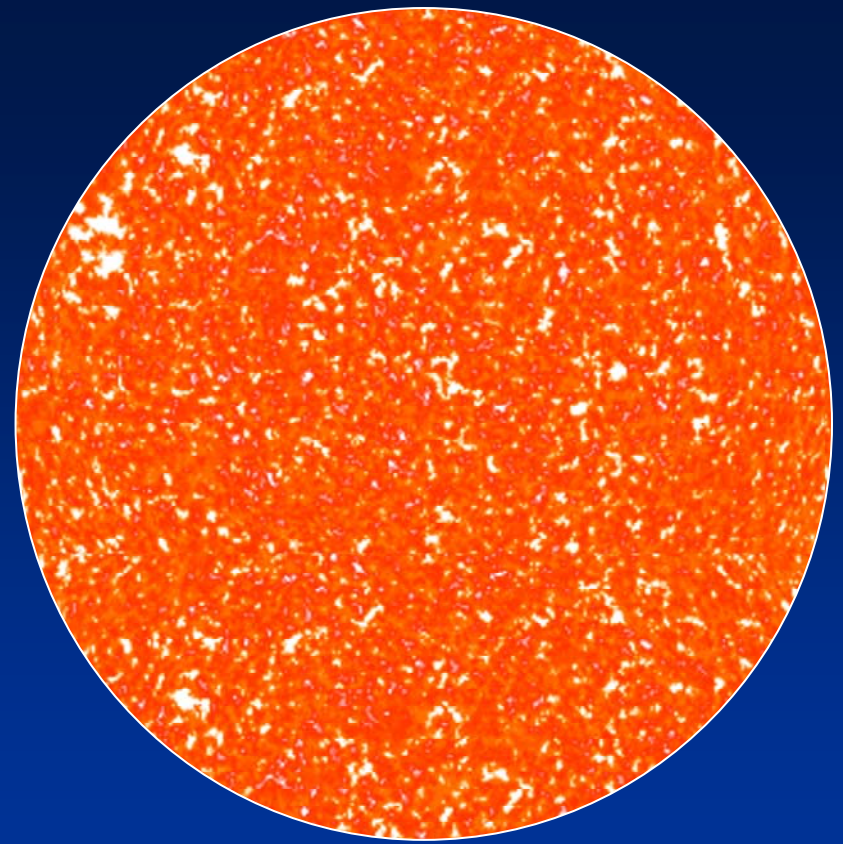


$\sigma(E_0 = 300 \text{ keV}) \approx 10^{-17} \text{ barn}$









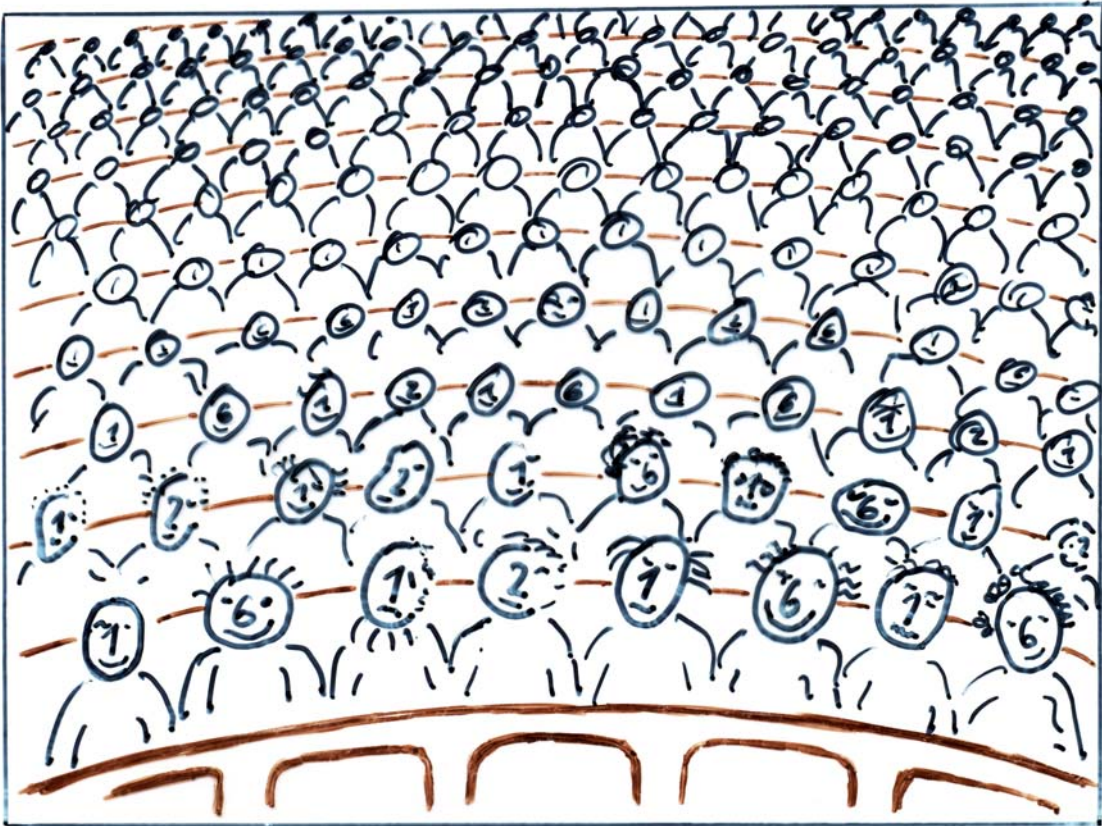
the key reaction in stellar nucleosynthesis





Man :

65% O
18% C
rest H





*technical means for direct
measurement exhausted
(except underground)*



by far

not

- *γ -efficiency factor 10*
- *α -current factor 2-5*
- *time factor 5*

The Stuttgart team

M. Fey

R. Kunz

M. Jaeger

A. Mayer

J.W.H.

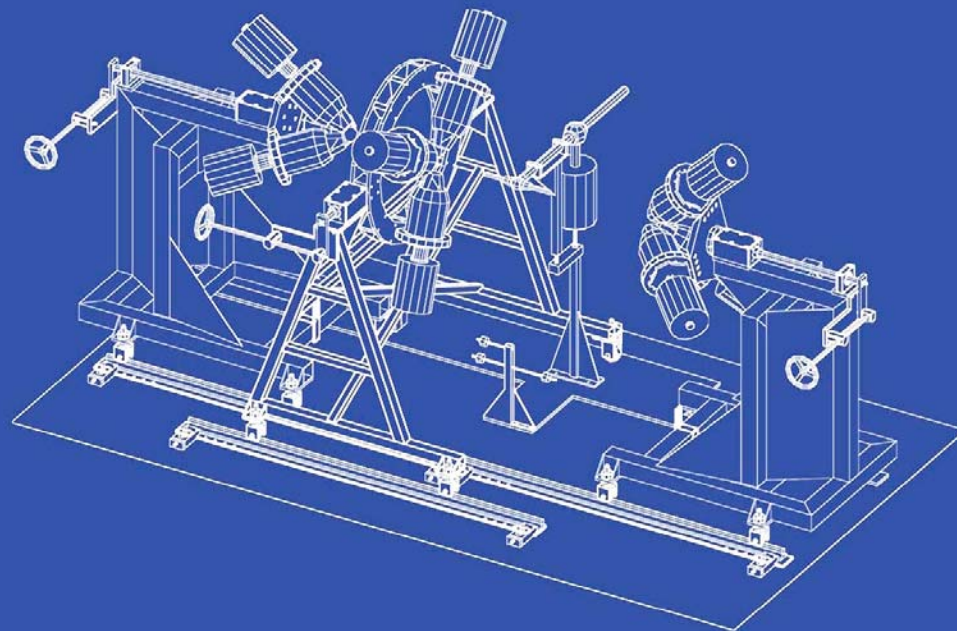
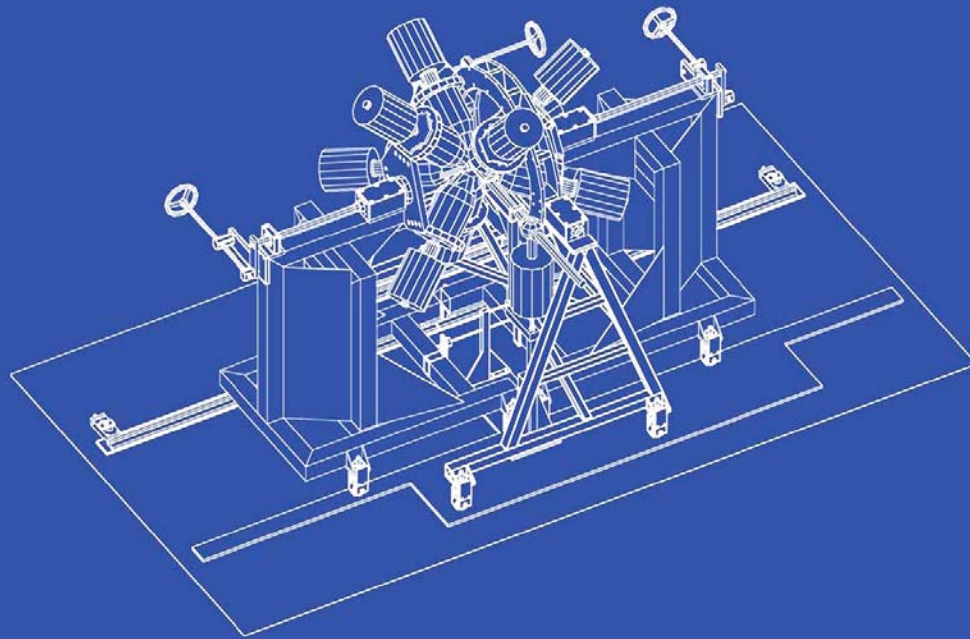
In collaboration with

K.L. Kratz, Mainz

B. Pfeiffer, Mainz

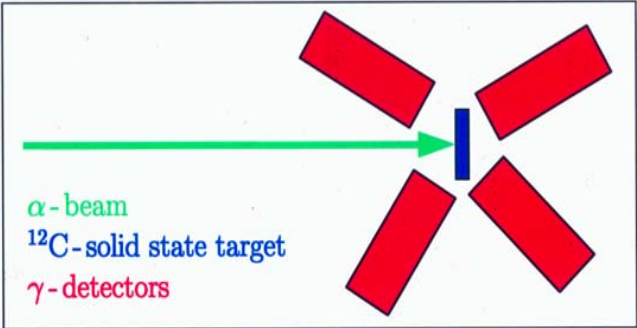
G. Staudt, Tuebingen

all in Germany

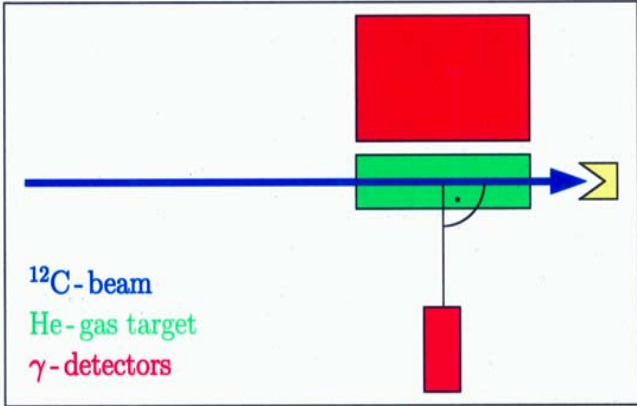


$^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ – direct methods

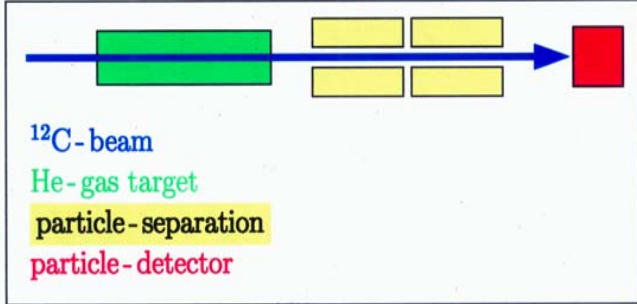
1) regular cinematics



2) inverse cinematics

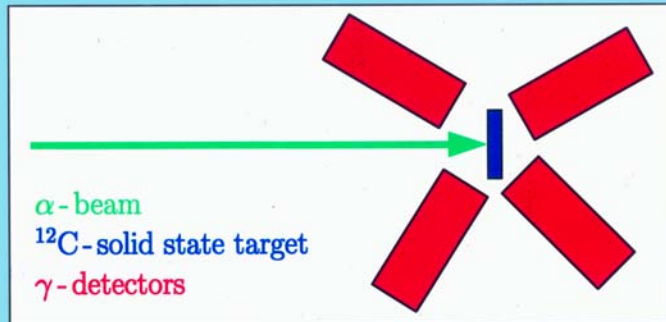


3) ^{16}O - recoil

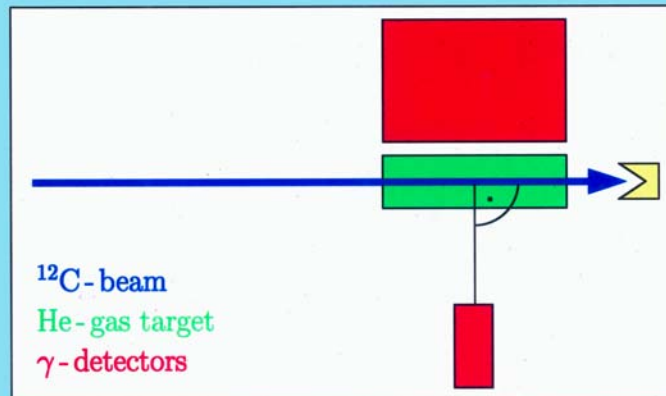


$^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ – direct methods

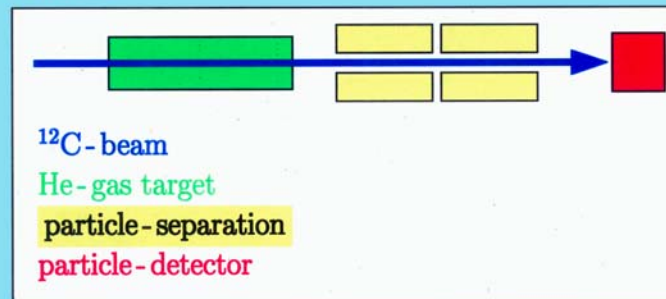
1) regular cinematics



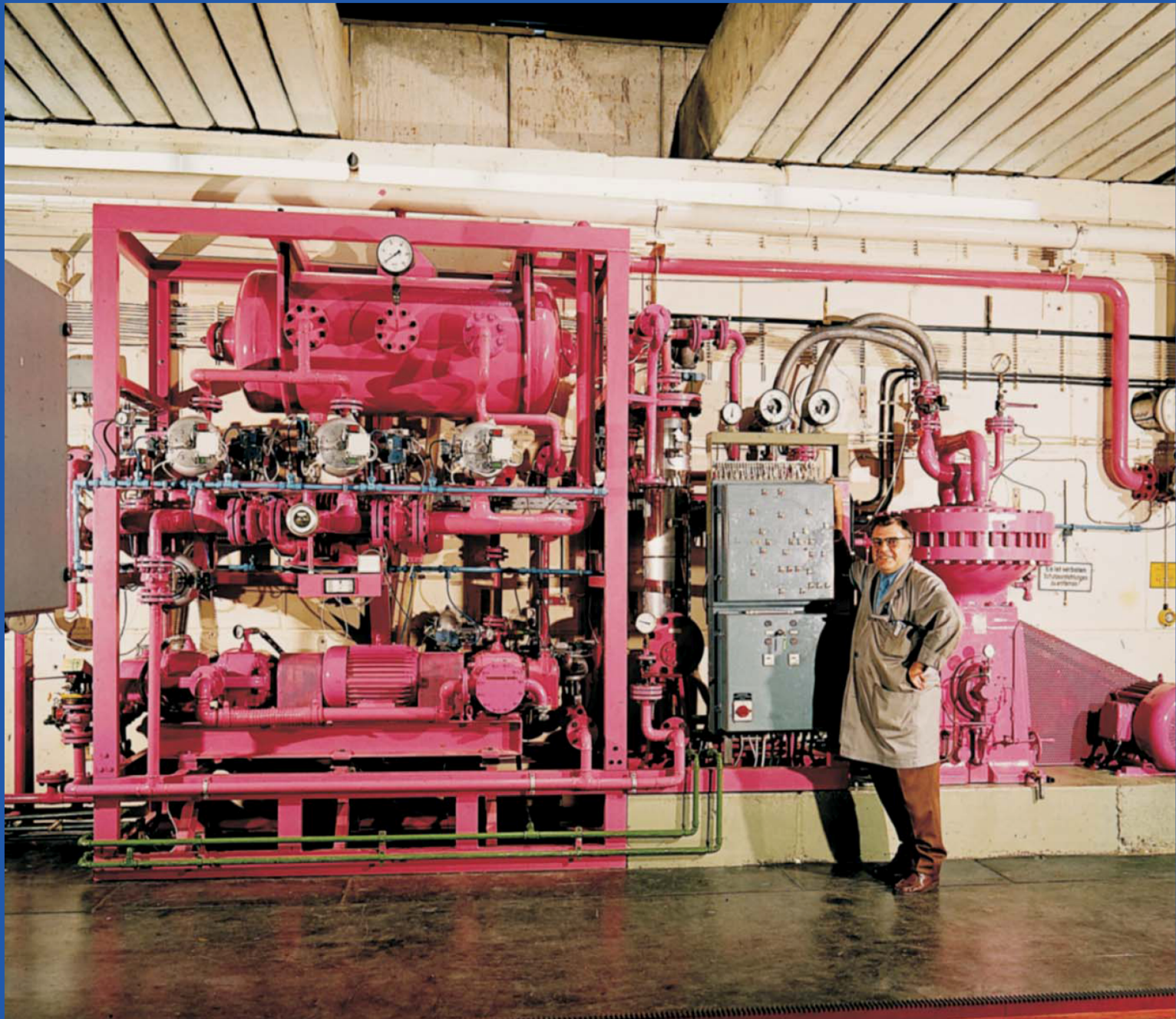
2) inverse cinematics

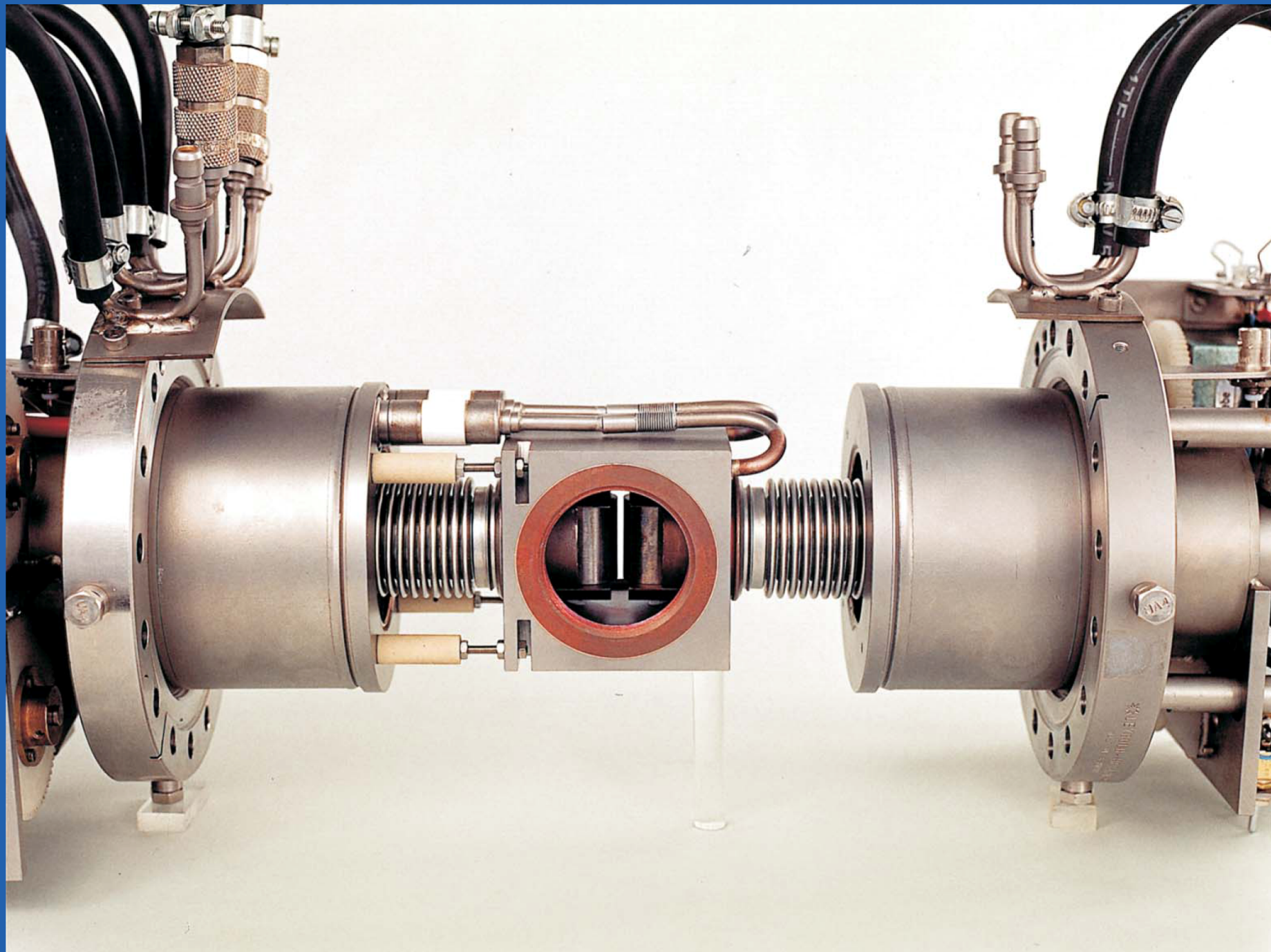


3) ^{16}O -recoil











*I saw a wolf licking a yellow
star until his tongue began to
bleed*

Heinrich Heine



*I saw a wolf licking a yellow
star until his tongue began to
bleed*

Heinrich Heine



Workshop in Honor of the 85th Birthday of Charlie Barnes

December 15, 2006

**Recent radiative capture measurement
for $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$**

Wolfgang Hammer

**University of Notre Dame, Indiana,
formerly University of Stuttgart, Germany**

Kellogg Radiation Laboratory @ Caltech, Pasadena, CA

