KEY - REACTIONS

EVOLUTION AND SYNTHESIS

H - BURNING: pp-CHAIN
CNO-CYCLE

He - BURNING: $3\alpha \rightarrow {}^{12}C$
${}^{12}C(\alpha,\gamma){}^{16}O$

C - BURNING: ${}^{12}C + {}^{12}C$ — $\alpha + {}^{20}Ne$
— $p + {}^{23}Na$

LUNA = UNDERGROUND LABORATORY

WILLY FOWLER'S DREAM =

... MEASURING THE IMPOSSIBLE:

FUSION REACTIONS AT/NEAR GAMOW PEAK

THE CASES: $^{3}He(^{3}He,2p)^{4}He$

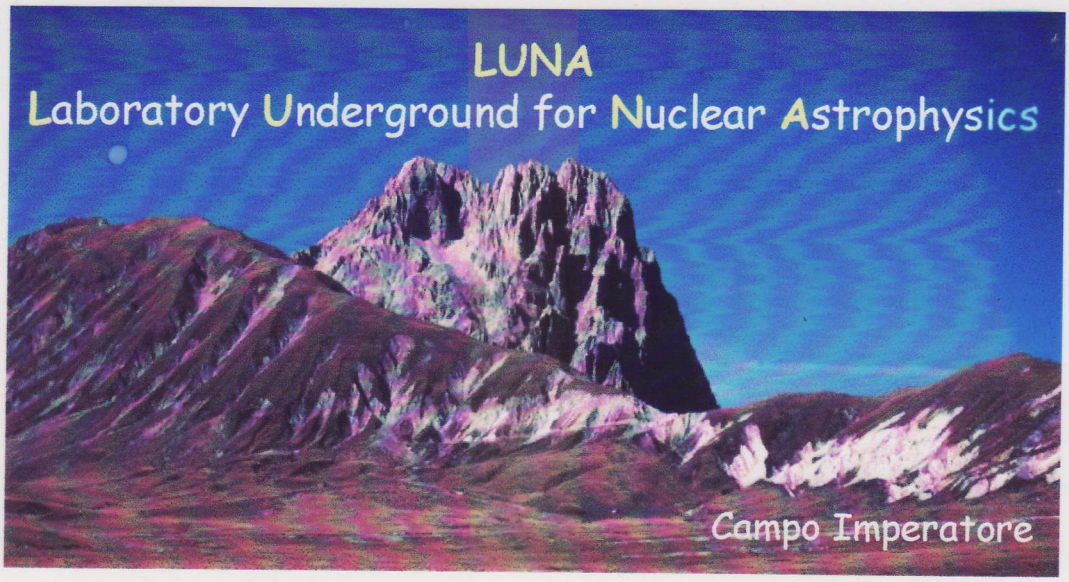
$D(p,\gamma)^{3}He$

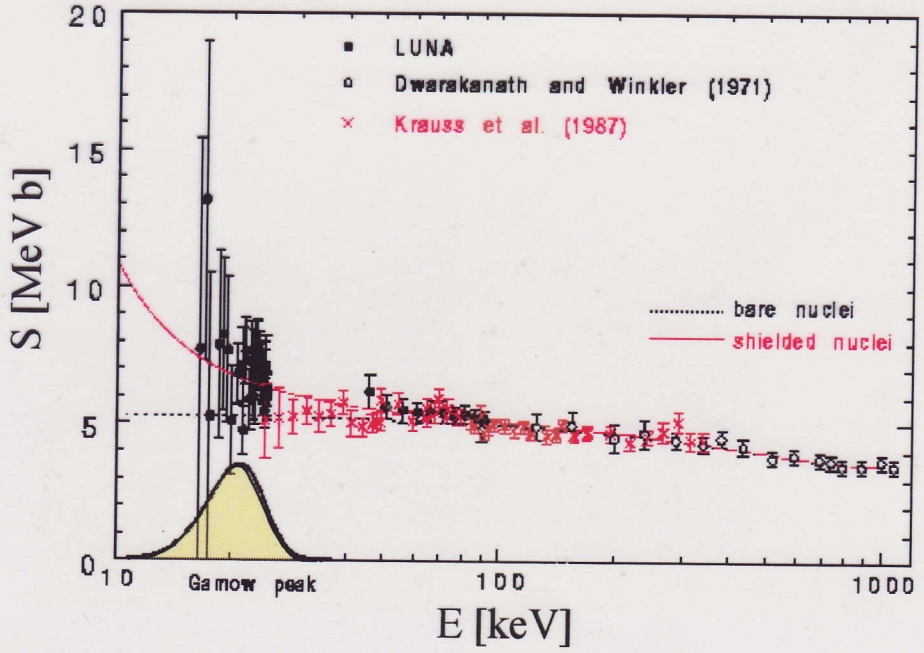
$^{14}N(p,\gamma)^{15}O$

= A QUANTUM JUMP TOWARDS THERMAL ENERGIES

THE CASE: $^3He(^3He,2p)^4He$

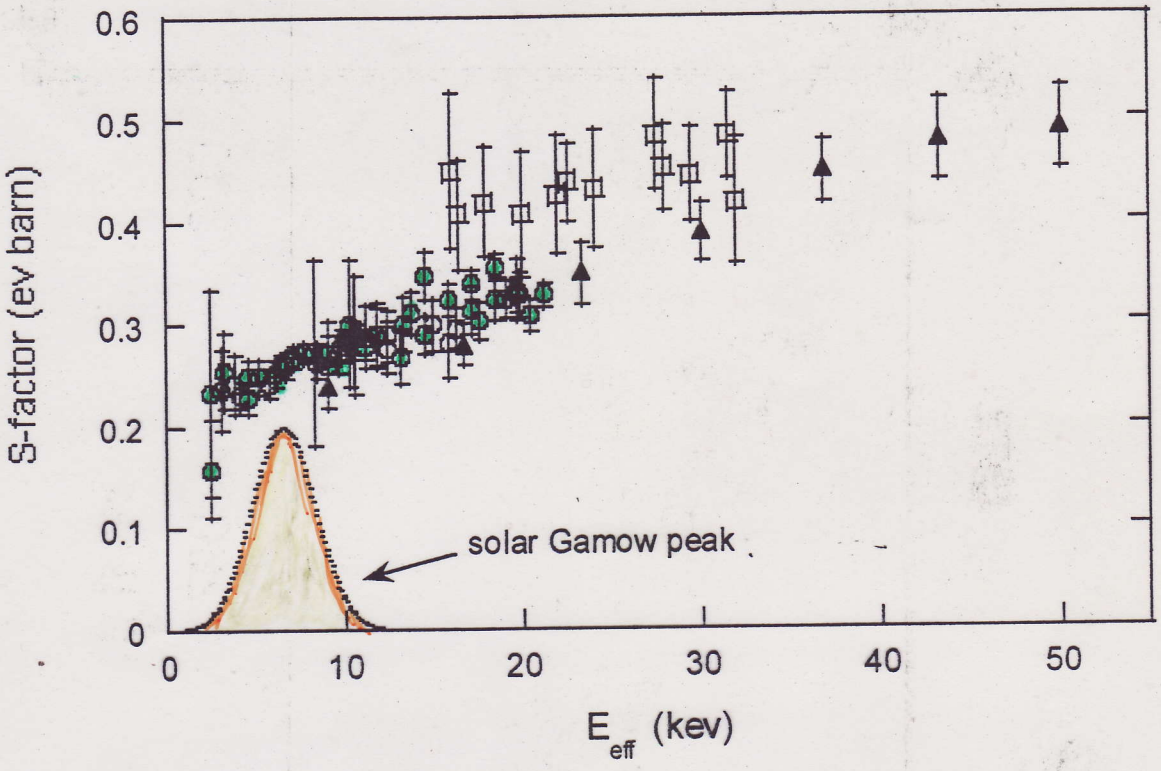
... A RESONANCE AT SOLAR ENERGIES ?





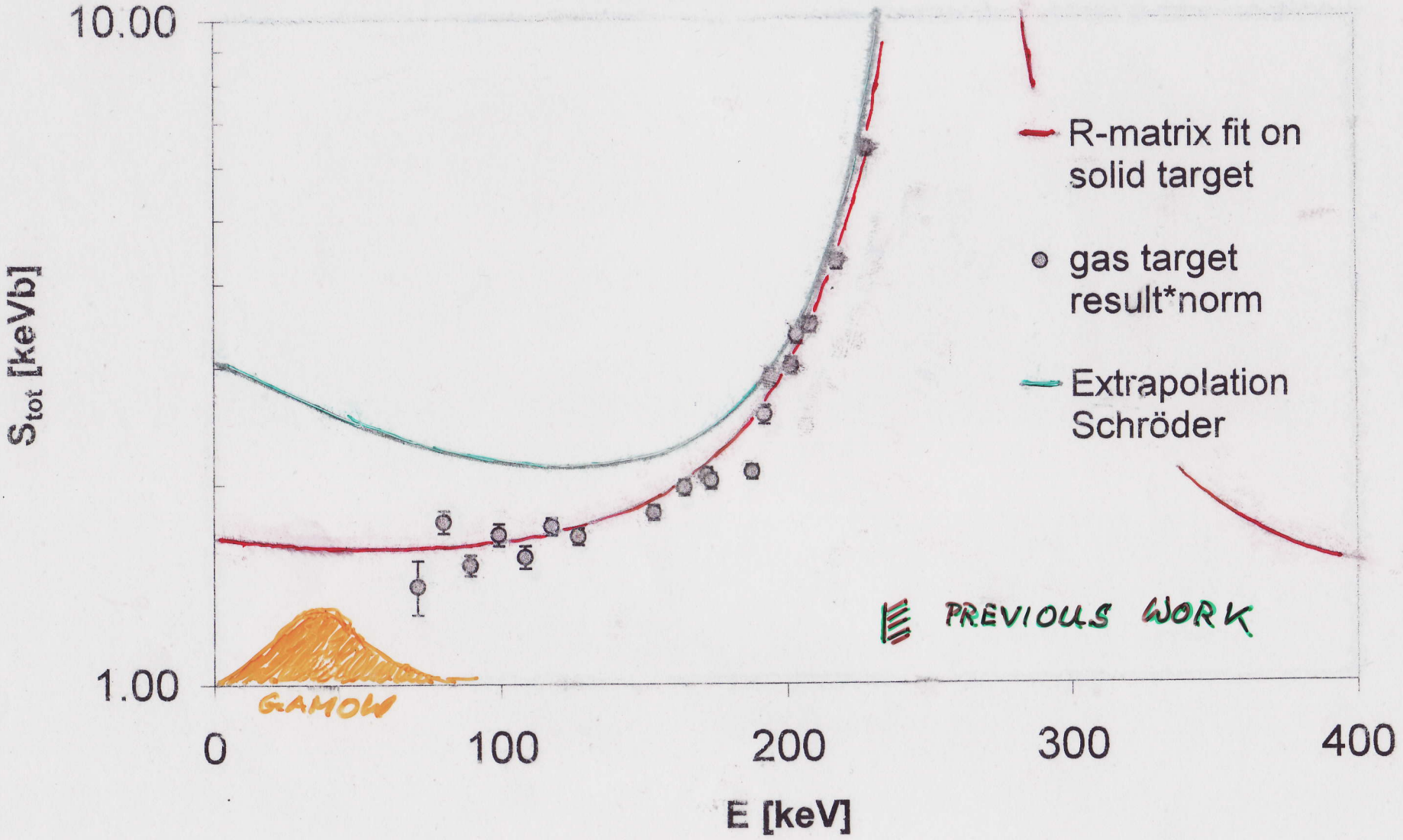
- **FIRST** MEASUREMENT WITHIN GAMOW PEAK
  ⇨ **NO** EXTRAPOLATION ANYMORE
- NO HYPOTHETICAL RESONANCE FOUND
- LOWEST ENERGY: σ = 20 FEMTO-BARN
  (1 EVENT PER MONTH)
- ELECTRON SCREENING: $U_e = 340 \pm 50$ eV
  $U_{ad} = 240$ eV } ?

THE CASE: $d(p,\gamma)^3He$



- LUNA: GAS-TARGET
  4π BGO CRYSTAL
- FIRST MEASUREMENT WITHIN GAMOW PEAK OF A CAPTURE REACTION
- PREVIOUS EXTRAPOLATION ≈ o.k.

THE CASE: $^{14}N(p,\gamma)^{15}O$



.... SOLAR NEUTRINOS AND AGE OF GLOBULAR CLUSTERS

DETAILS: COSTANTINI

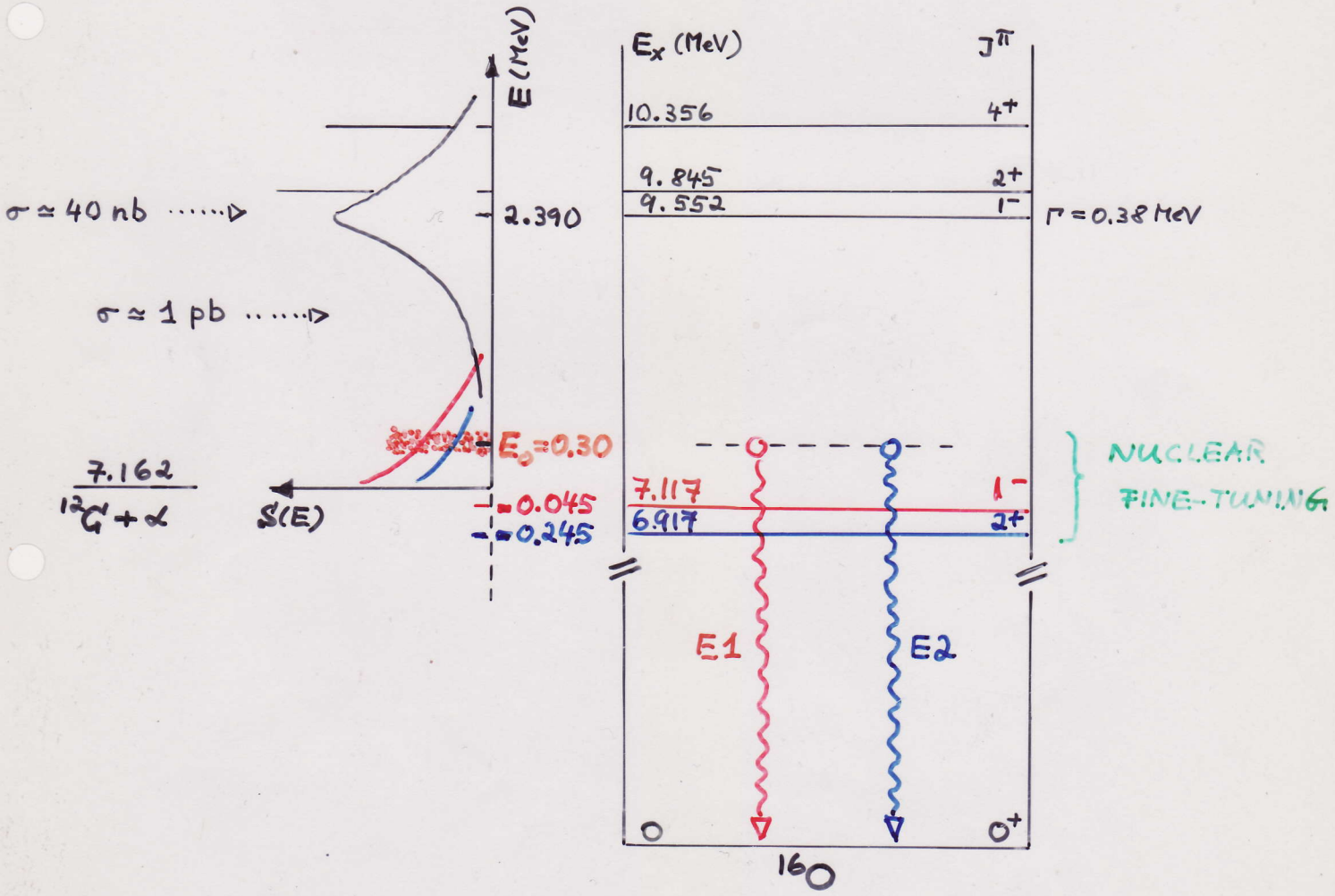
$^{12}C(\alpha,\gamma)^{16}O$ – A CHALLENGE FOR EXPERIMENT AND THEORY

$3\alpha \rightarrow {}^{12}C$
$^{12}C(\alpha,\gamma)^{16}O$

RATIO IS **KEY** FOR

- NUCLEOSYNTHESIS C .... Ni
- STRUCTURE/EVOLUTION OF STARS
- EXPLOSION-MECHANISMS
- MASS OF COMPACT REMNANTS
- ⋮

⇨ RATES NEEDED TO ±10% !



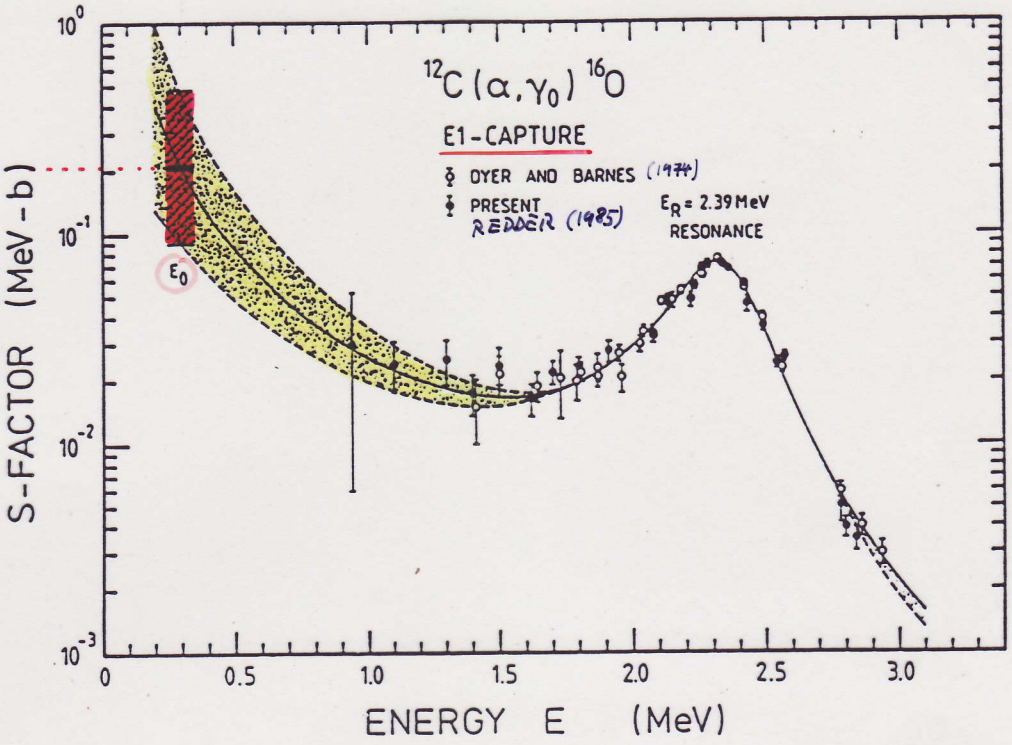
GENERAL PROBLEM: **TWO** SUBTHRESHOLD STATES DOMINATE $S(E_0)$!

EXPER. PROBLEM: $^{12}C(\alpha,\gamma)^{16}O$ ..... $\sigma_\gamma \simeq$ pb... nb
$^{13}C(\alpha,n)^{16}O$ ..... $\sigma_n \simeq$ mb... b

THEOR. PROBLEM: HOW TO EXTRAPOLATE DATA TO E_0 ?

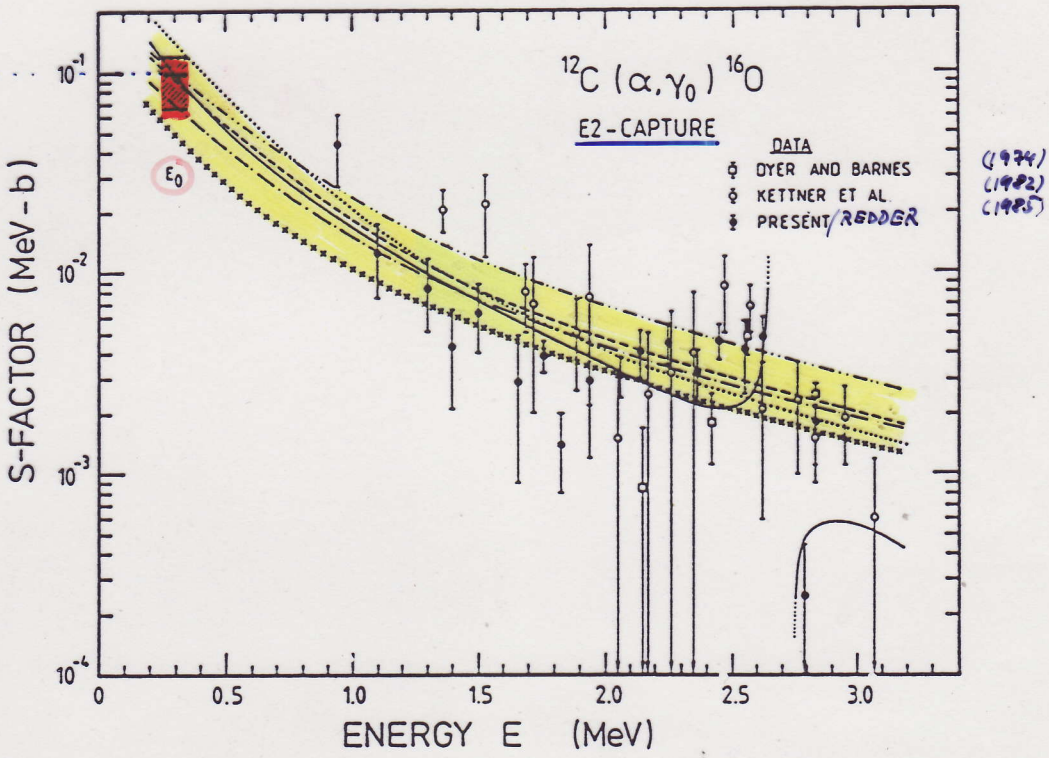
$S_{E1}(E_0)$ .....

$\simeq 0.21$ MeV-b



$S_{E2}(E_0)$ .....

$\simeq 0.10$ MeV-b



R-MATRIX FORMALISM : $S_{E1+E2}(E_0) \simeq 0.31$ MeV-b ($\pm 30\%$)

OTHER FORMALISMS : SOMEWHAT DIFFERENT VALUES

⇩

ADDITIONAL EFFORTS NEEDED

(EXPER. / THEORY)

ERNA = RECOIL MASS SEPARATOR

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

.... A **KEY** REACTION

.... UNSOLVED PROBLEM
SINCE ≈ 40 YEARS

= DIRECT OBSERVATION OF
^{16}O RECOILS

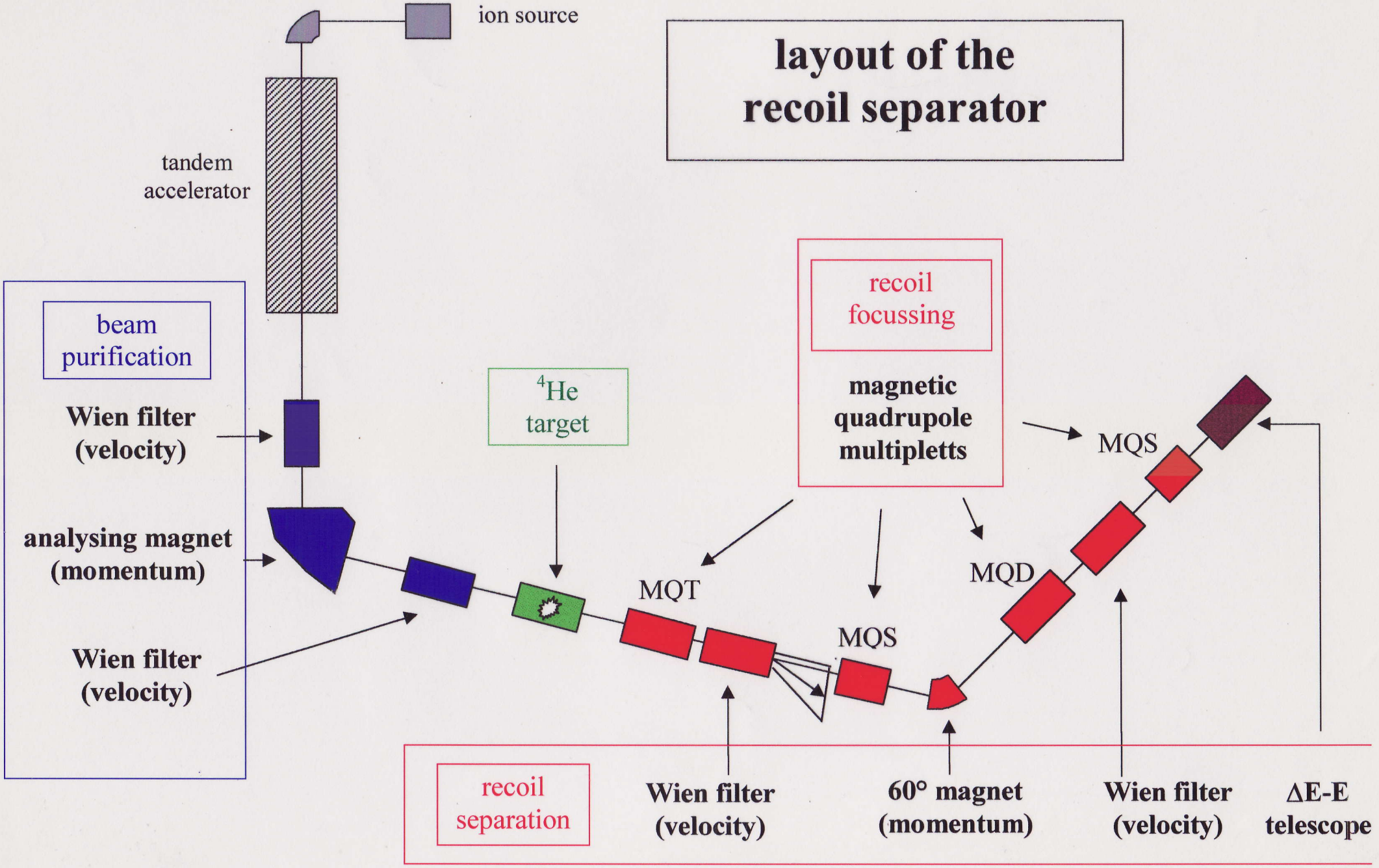
→ $\sigma_{tot}(E)$ "$\gamma_0 + \gamma\gamma$ + MONOPOLE"

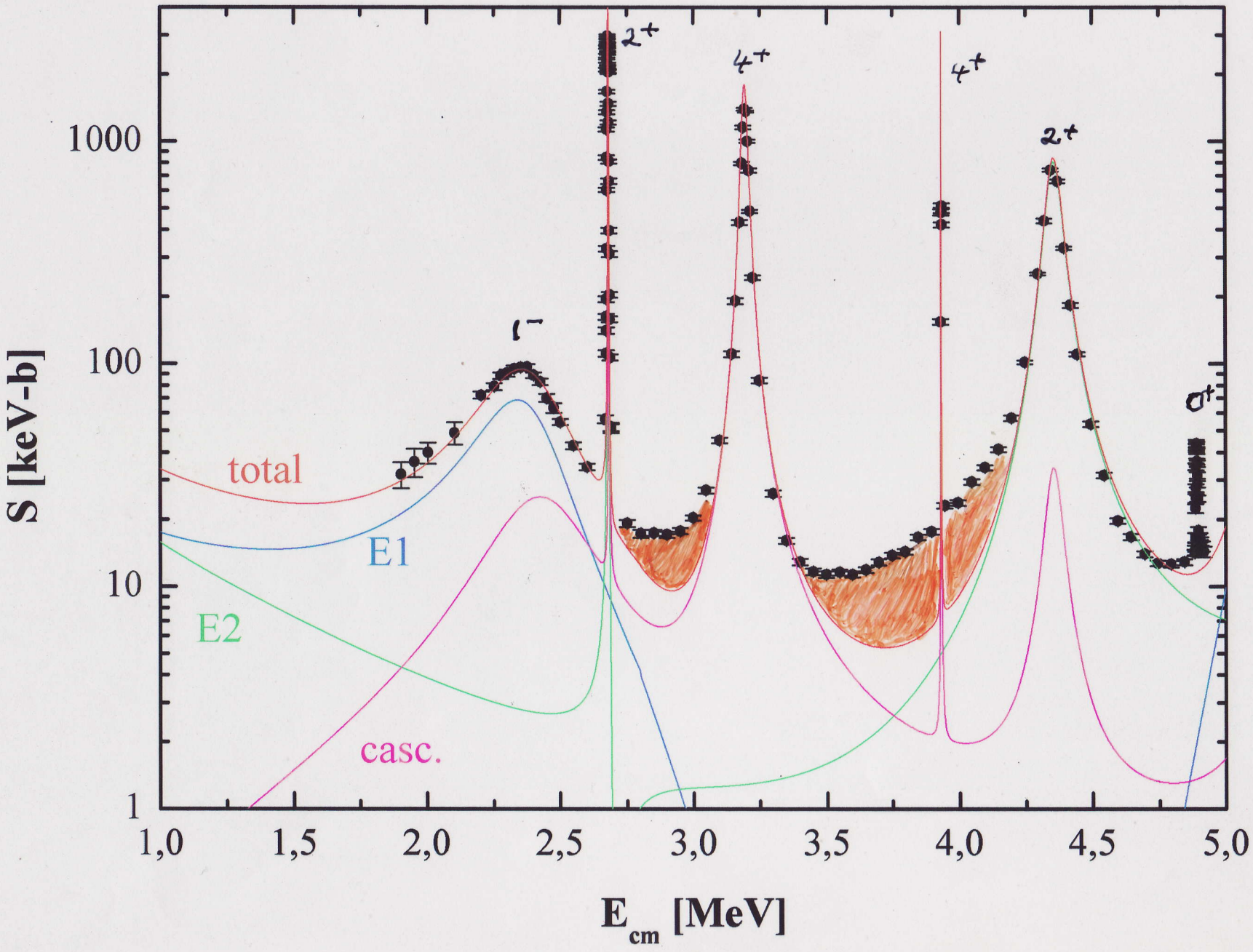
BUT: MANY EXP. OBSTACLES

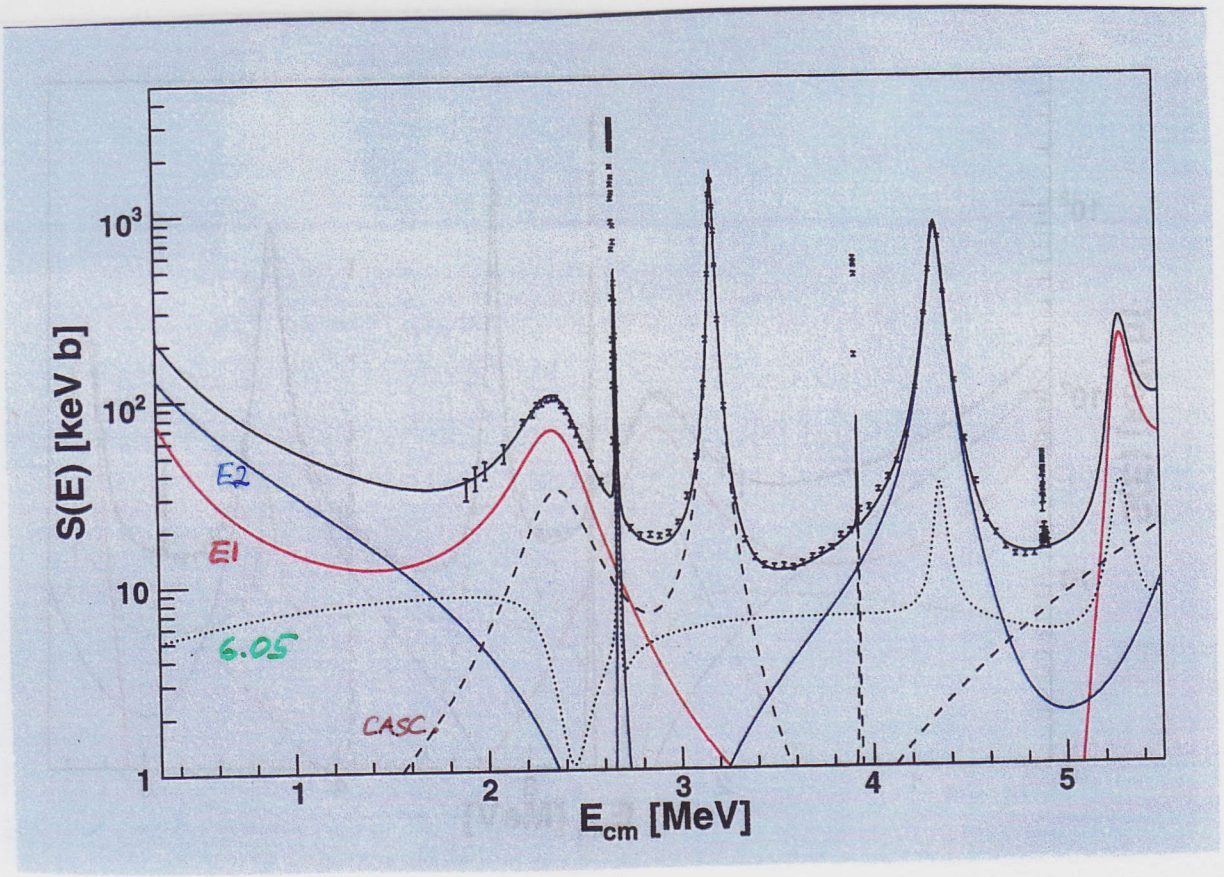
↓ 4 YEARS OF WORK

FIRST RESULTS
AT $E = 2.0 \sim 5.0$ MeV

DETAILS: SCHÜRMANN


layout of the recoil separator
ion source
tandem accelerator
beam purification
Wien filter (velocity)
analysing magnet (momentum)
Wien filter (velocity)
4He target
recoil focussing
magnetic quadrupole multipletts
MQS
MQT
MQD
MQS
recoil separation
Wien filter (velocity)
60° magnet (momentum)
Wien filter (velocity)
ΔE-E telescope


S [keV-b]
1000
100
10
1
1,0
1,5
2,0
2,5
3,0
3,5
4,0
4,5
5,0
E_cm [MeV]
total
E1
E2
casc.
1⁻
2⁺
4⁺
4⁺
2⁺
0⁺



- CAPTURE INTO 6.05 MeV STATE
  EXPLAINS MISSING YIELDS

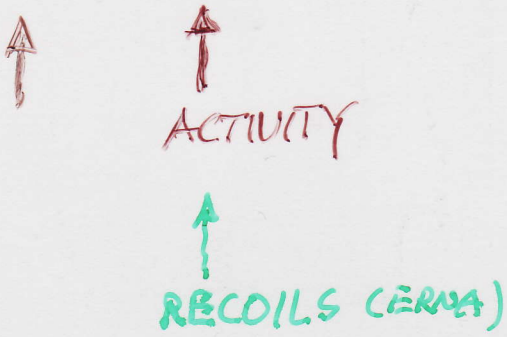
- **NO** MONOPOLE CAPTURE

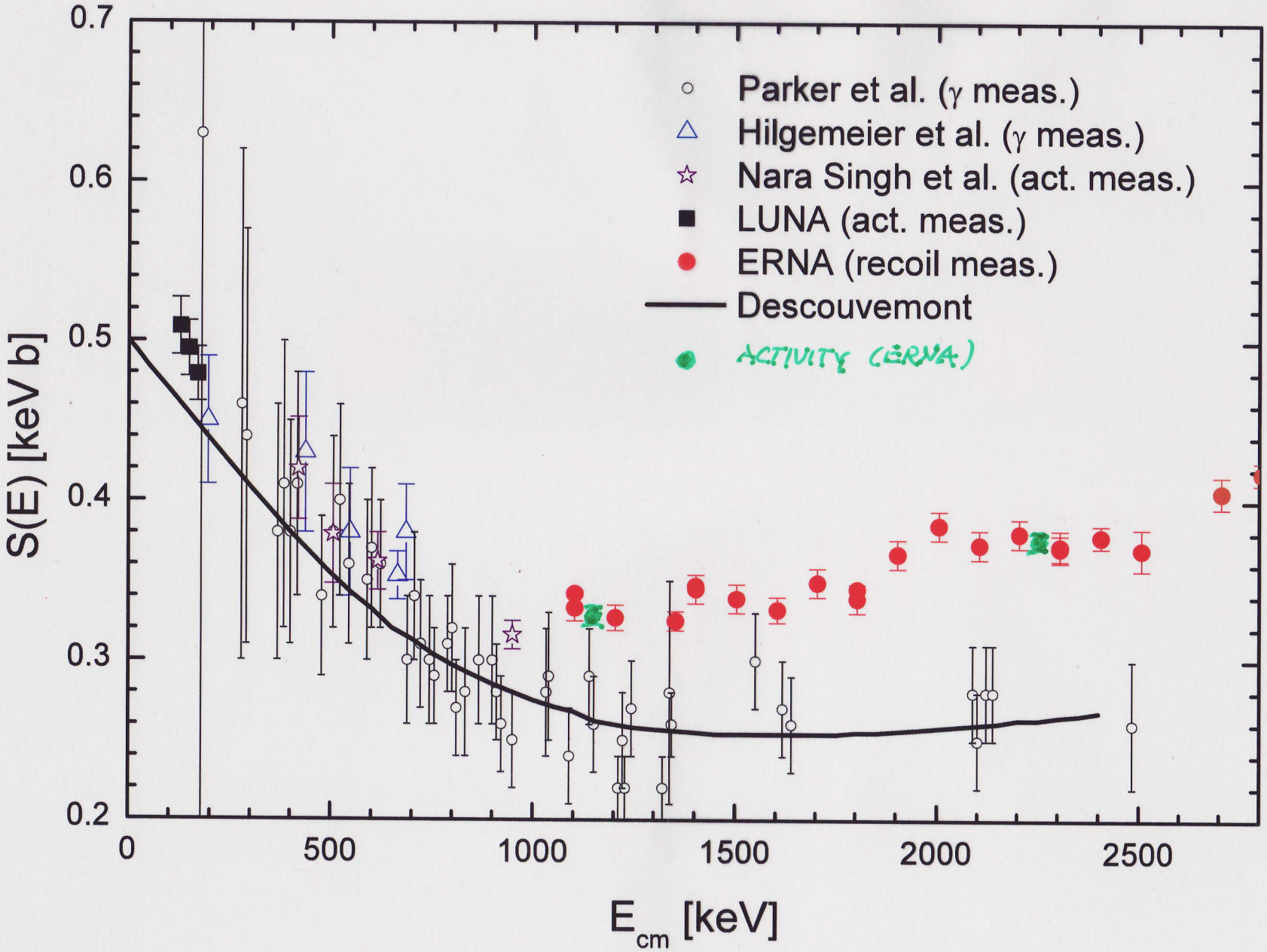
- $S(E_0) = 210$ keV-b
  (FCZ80 = 74 keV-b, ONLY E1)

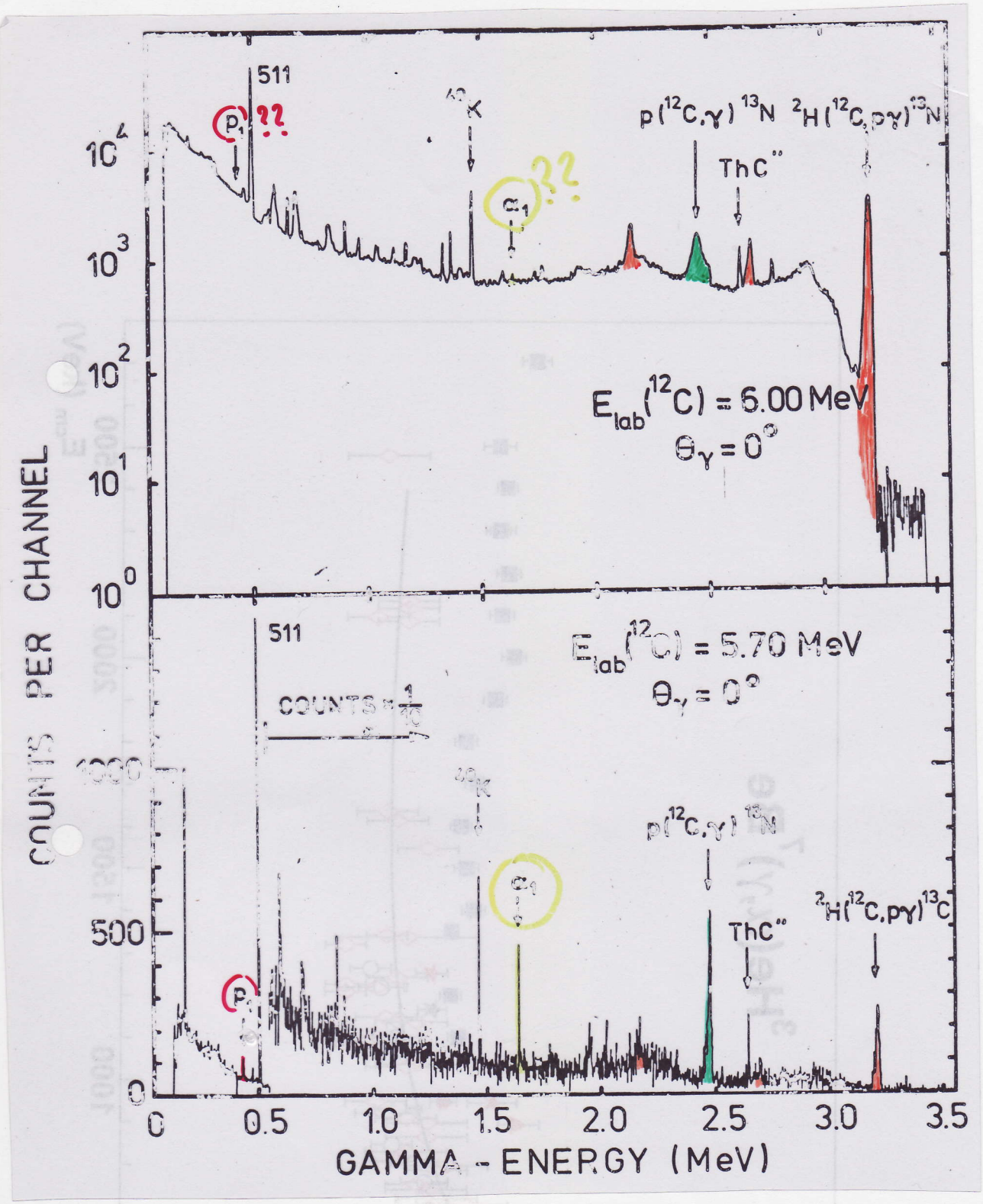
- ERNA : TOWARDS $E = 0.7$ MeV
  DETAILS OF CAPTURE MECHANISMS

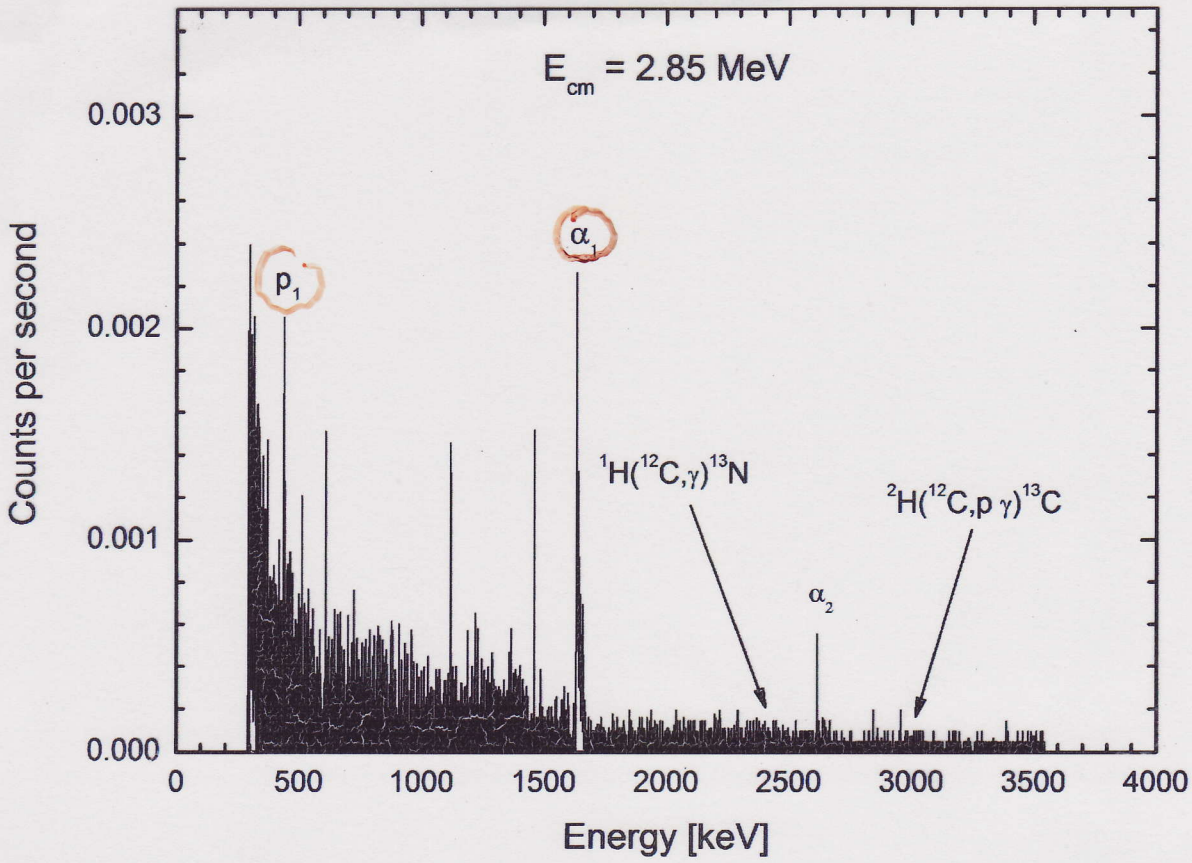
THE CASE:

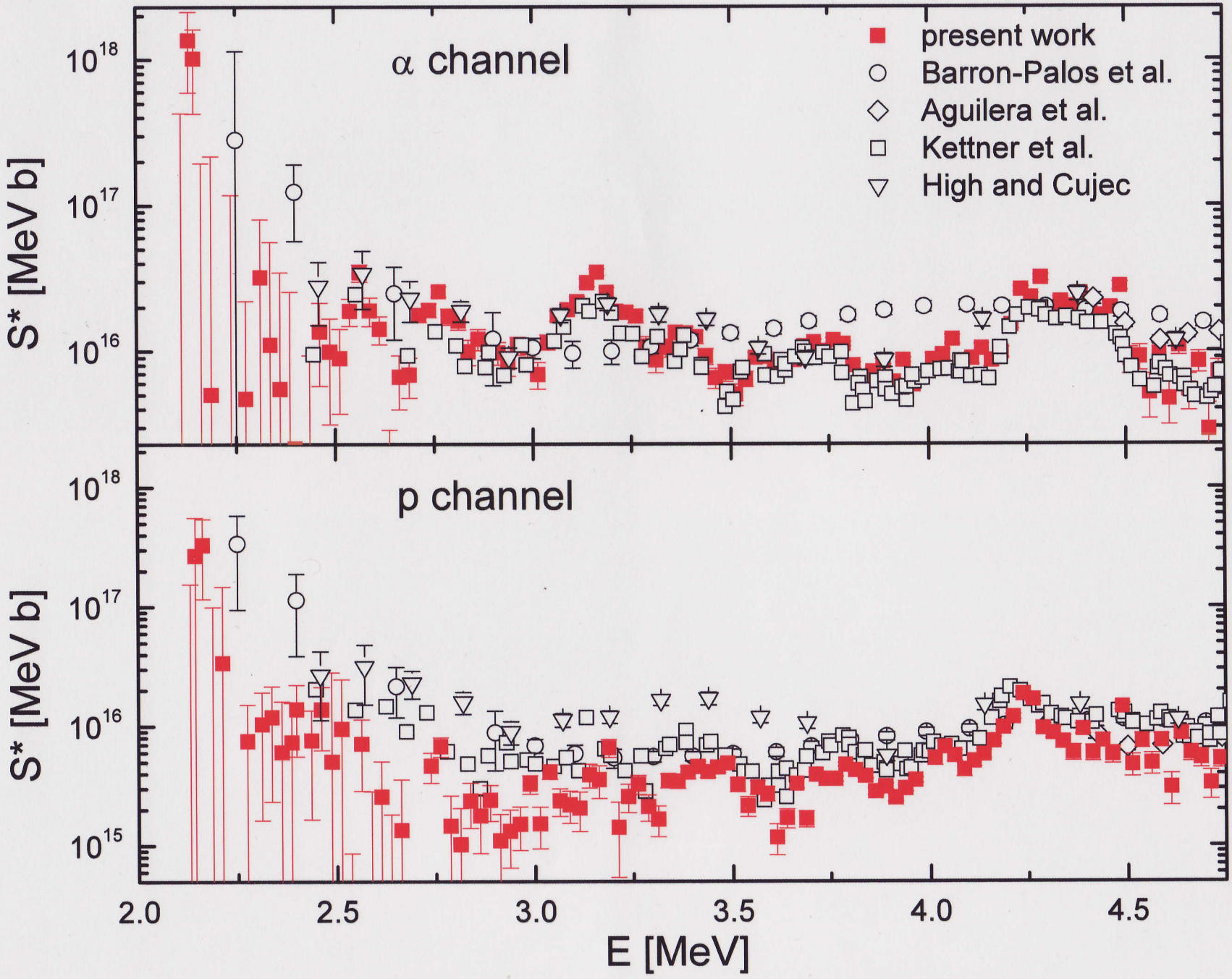
$$^{3}He(\alpha,\gamma)^{7}Be$$




0.7
0.6
0.5
0.4
0.3
0.2
S(E) [keV b]
0
500
1000
1500
2000
2500
E_cm [keV]
Parker et al. (γ meas.)
Hilgemeier et al. (γ meas.)
Nara Singh et al. (act. meas.)
LUNA (act. meas.)
ERNA (recoil meas.)
Descouvemont
ACTIVITY (ERNA)


511
p_1
??
^{40}K
c_1
??
$p(^{12}C,\gamma)^{13}N$ $^2H(^{12}C,p\gamma)^{13}N$
ThC''
$E_{lab}(^{12}C) = 6.00$ MeV
$\Theta_\gamma = 0°$
511
$E_{lab}(^{12}C) = 5.70$ MeV
$\Theta_\gamma = 0°$
COUNTS = 1/10
^{40}K
$p(^{12}C,\gamma)^{13}N$
c_1
ThC''
$^2H(^{12}C,p\gamma)^{13}C$
p_1
COUNTS PER CHANNEL
10^4
10^3
10^2
10^1
10^0
1000
500
0
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
GAMMA - ENERGY (MeV)


E_cm = 2.85 MeV
Counts per second
0.003
0.002
0.001
0.000
p1
α1
α2
1H(12C,γ)13N
2H(12C,p γ)13C
0
500
1000
1500
2000
2500
3000
3500
4000
Energy [keV]


α channel
present work
Barron-Palos et al.
Aguilera et al.
Kettner et al.
High and Cujec
p channel
S* [MeV b]
S* [MeV b]
10^18
10^17
10^16
10^15
2.0
2.5
3.0
3.5
4.0
4.5
E [MeV]