# PRESENTATIONS

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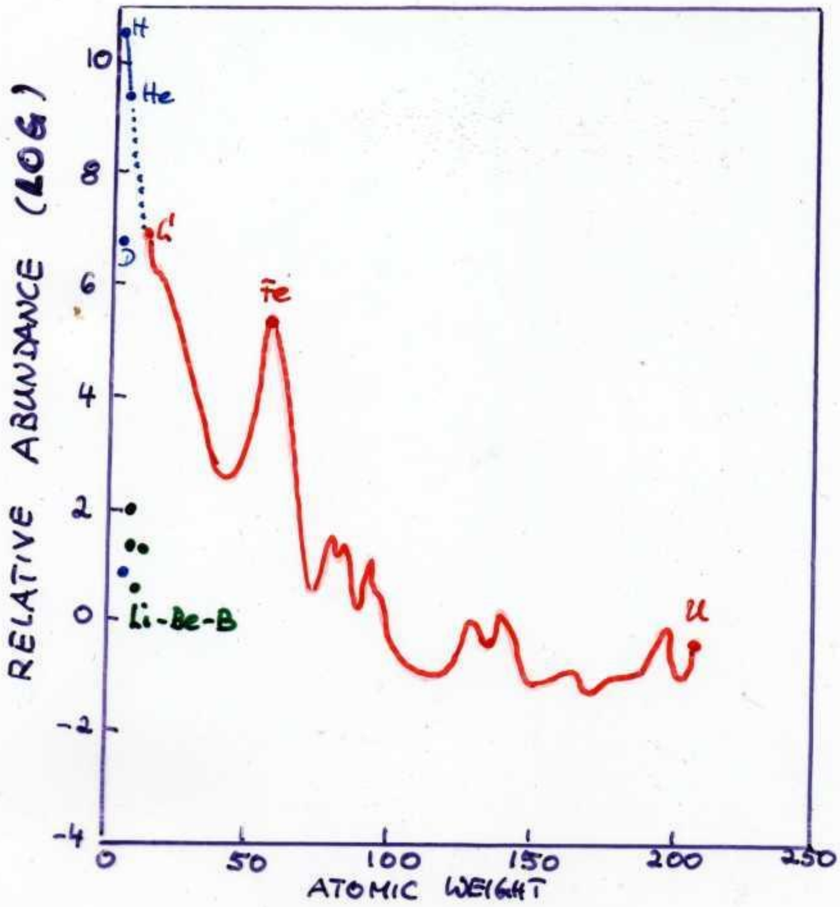
RUHR-UNIVERSITY BOCHUM

DUBNA, 7. – 10. Aug. 2007

# LECTURE 1

# ORIGIN OF THE ELEMENTS

SUESS / UREY ... : EARTH, METEORITES, MOON, STELLAR SPECTRA, ....




H ≃ 75 %

He ≃ 23 %

C .... U ≃ 2%

QUESTIONS: WHERE / WHEN / HOW / WHY / ⋮ } MADE ?

.... KEY: NUCLEAR PHYSICS

TODAY: (i) BIG BANG

$^{1}H$, $^{4}He$ + D, $^{3}He$, $^{7}Li$

(ii) STARS

C .... U : THE "METALS"

(iii) INTERSTELLAR SPACE (SPALLATION)

$^{6}Li$, $^{9}Be$, $^{10}B$, $^{11}B$

} NUCLEAR ASTROPHYSICS

GAMOW
BETHE
VON WEIZSÄCKER
HOYLE
FOWLER
⋮

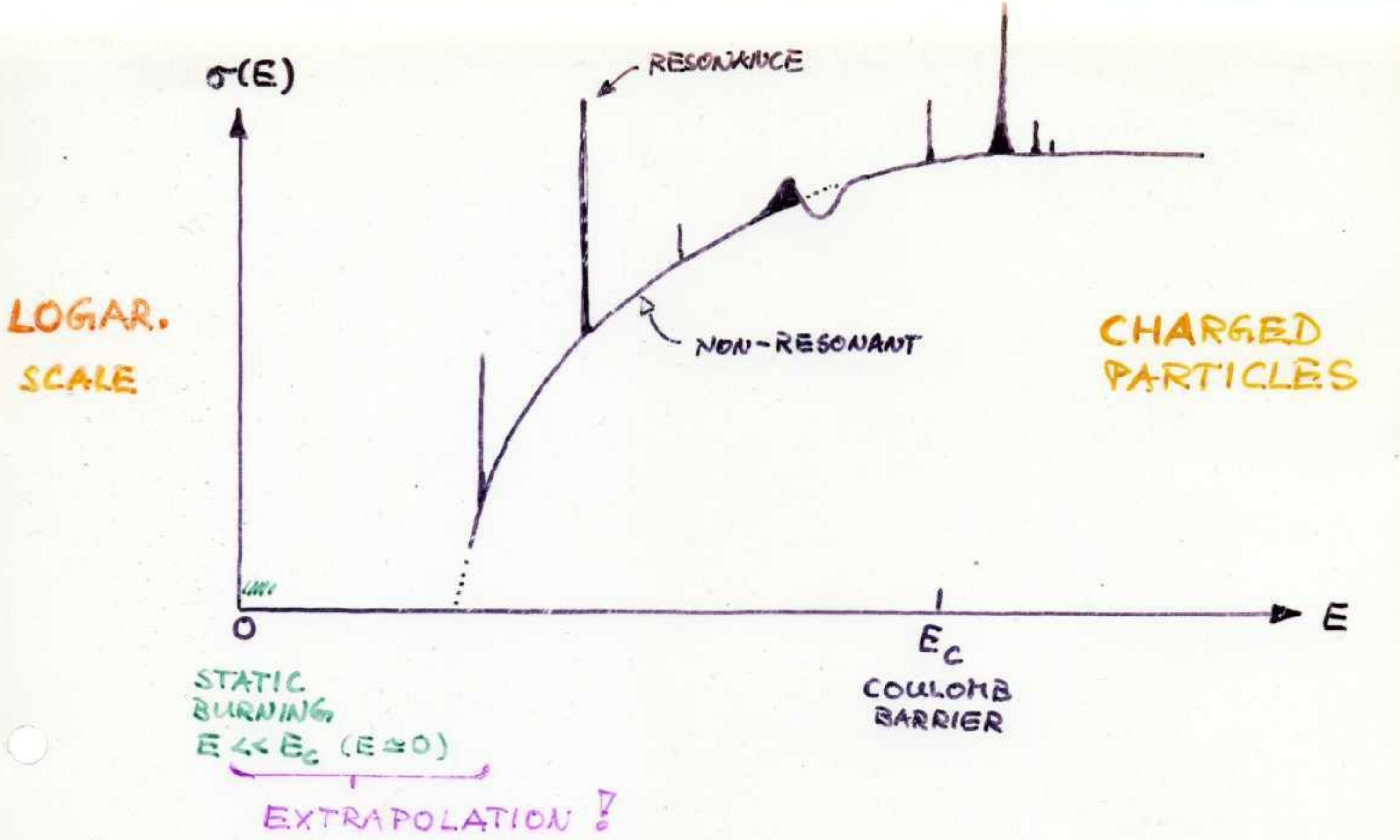
# KEY - REACTIONS

## EVOLUTION AND SYNTHESIS

**H** - BURNING: pp - CHAIN
CNO - CYCLE

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

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

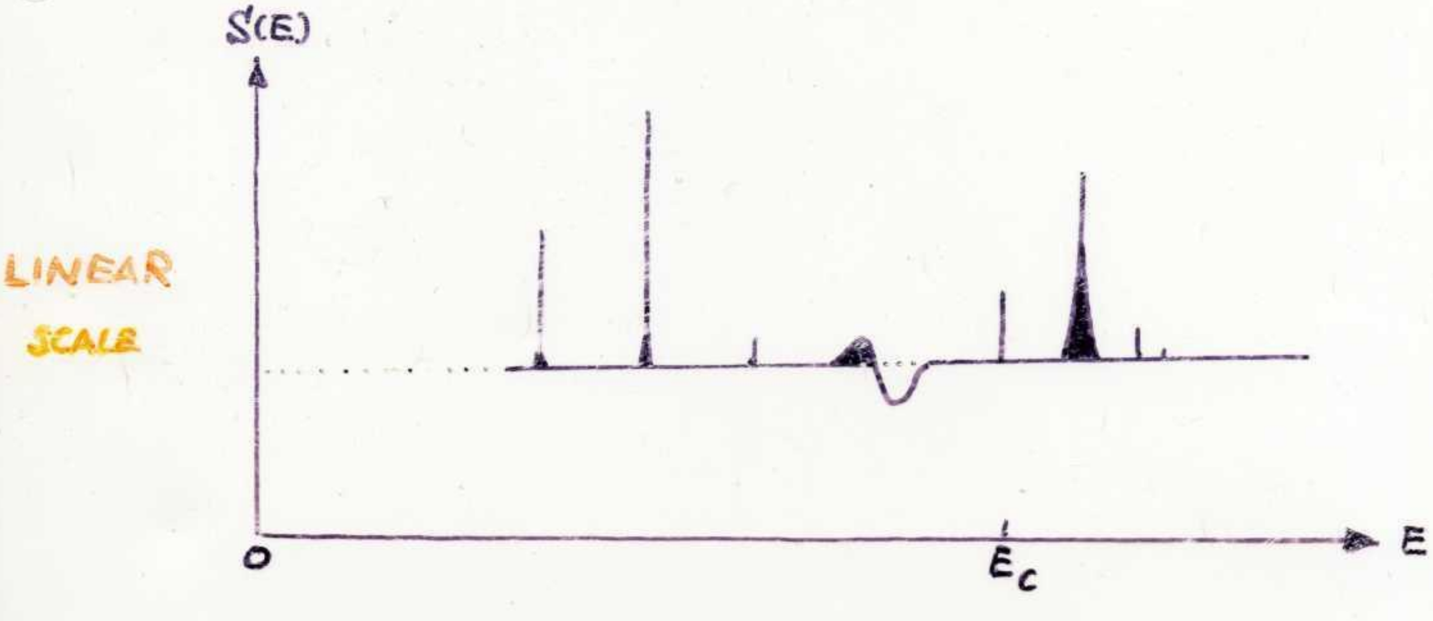


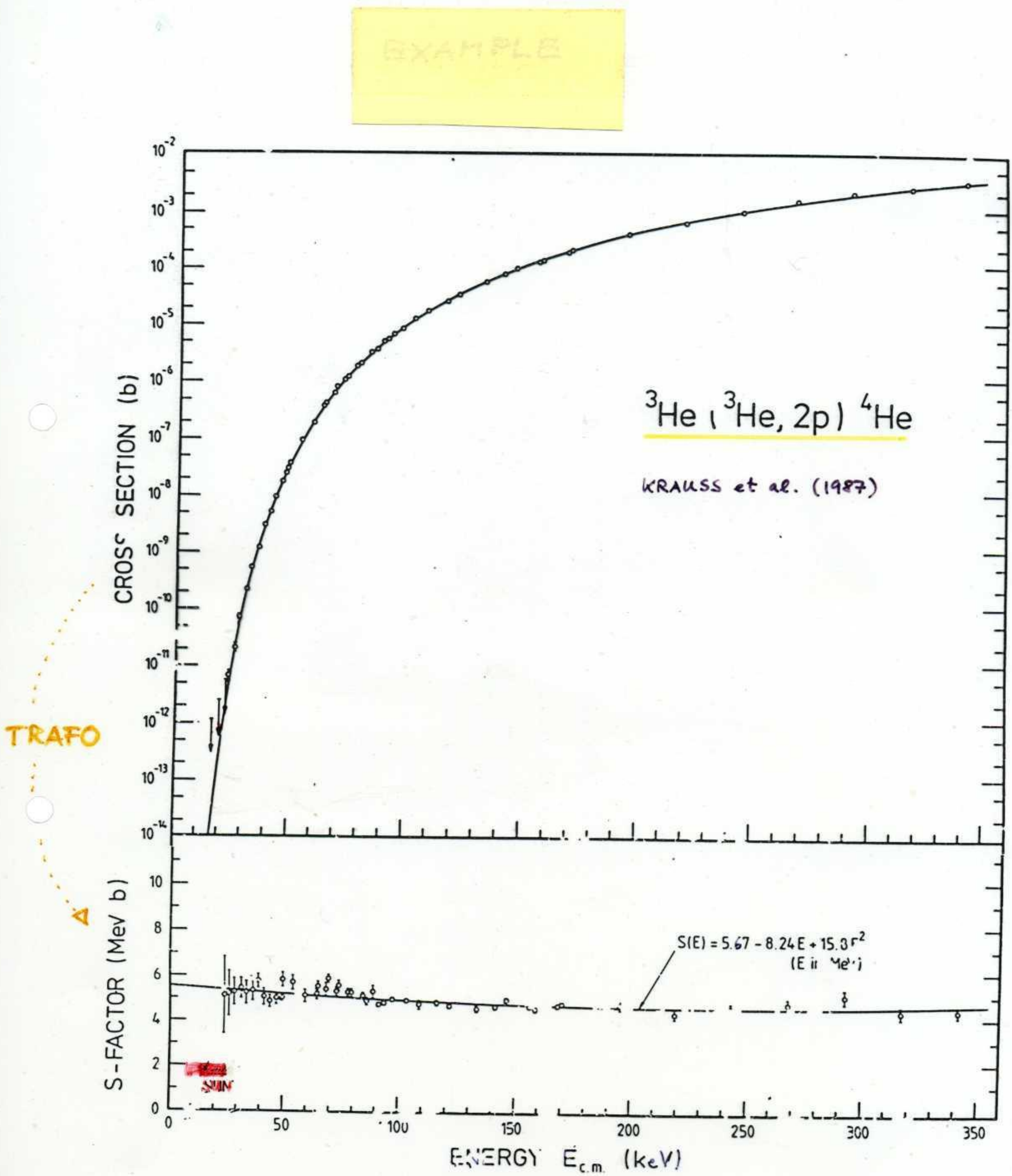

$$\sigma(E) = S(E)\,\frac{1}{E}\,\exp(-2\pi\eta)$$

$2\pi\eta$ = SOMMERFELD PARAMETER

COULOMB BARRIER (FOR S-WAVES)

NUCLEAR/ASTROPH. S-FACTOR "eV-b"

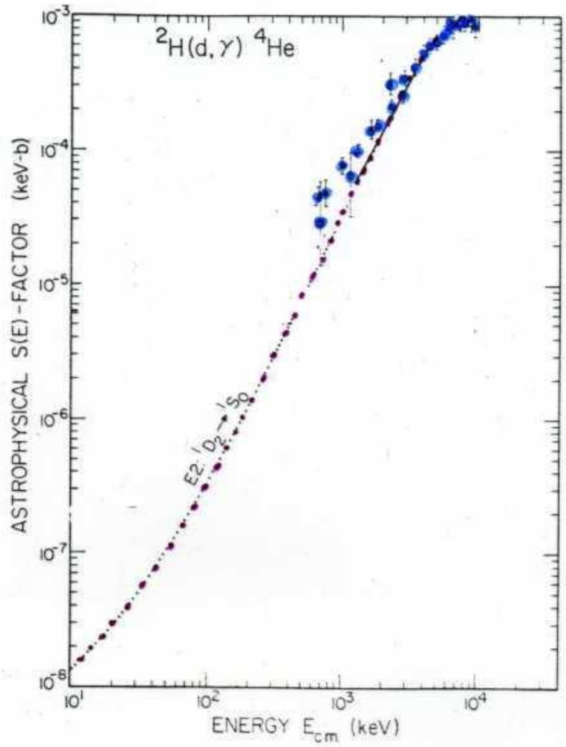



EXAMPLE
CROSS SECTION (b)
$^3He(^3He, 2p)^4He$
KRAUSS et al. (1987)
TRAFO
S-FACTOR (MeV b)
S(E) = 5.67 - 8.24E + 15.3E²
(E in MeV)
SUN
ENERGY $E_{c.m.}$ (keV)

# DANGER OF EXTRAPOLATIONS

## $D(d,\gamma)^4He$

— AN EXAMPLE —

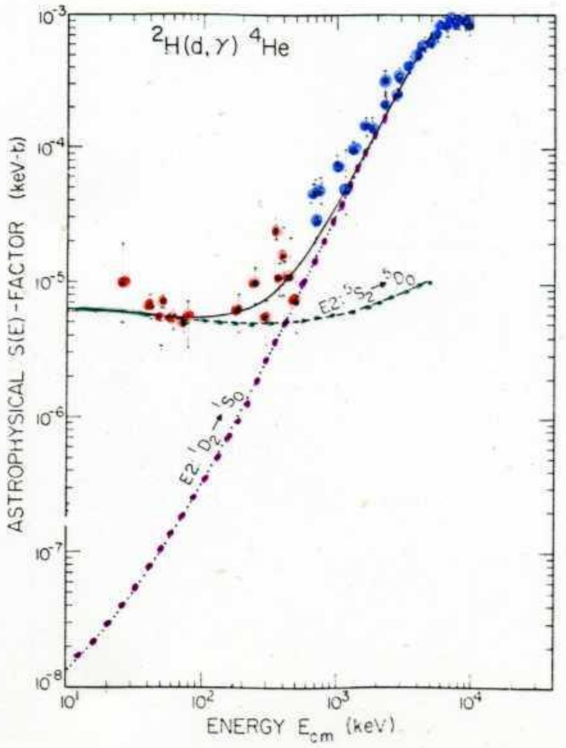



PREVIOUS WORK : $E_{c.m.} \geq 600$ keV

$E2\ (^1D_2 \rightarrow {}^1S_0)$

CENTRIF. BARRIER

SPHERICAL $^4He$




RECENT WORK : $E_{c.m.} \geq 20$ keV

$E2\ (^5S_2 \rightarrow {}^5D_0)$

NO CENTRIF. BARRIER

FEW % D-ADMIXTURE ≡ DEFORMATION

⋮

NUCLEAR FINE-TUNING

**LUNA** = UNDERGROUND LABORATORY

**WILLY** FOWLER'S DREAM =

... MEASURING THE **IMPOSSIBLE**:

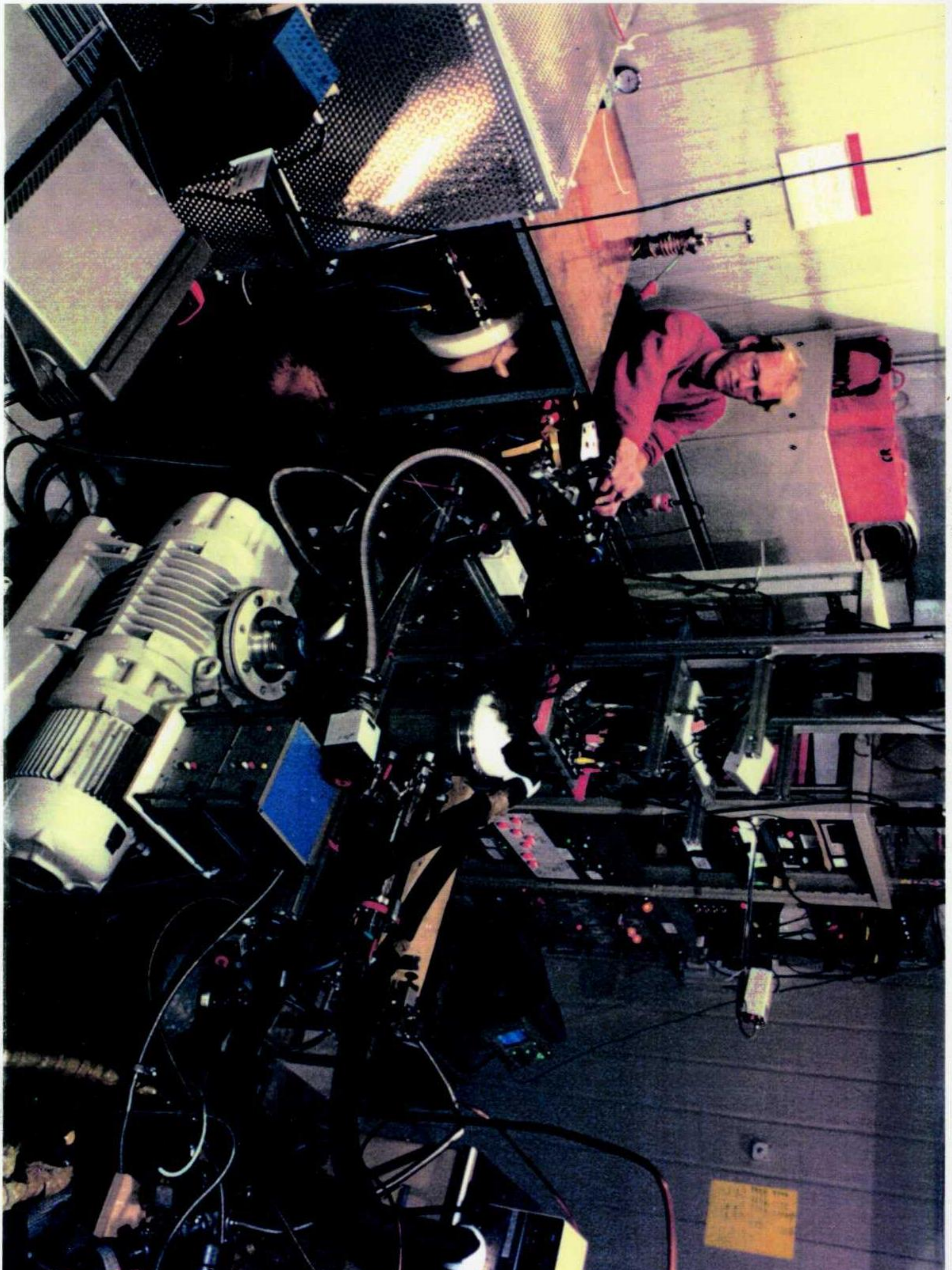
FUSION REACTIONS AT/NEAR GAMOW PEAK

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

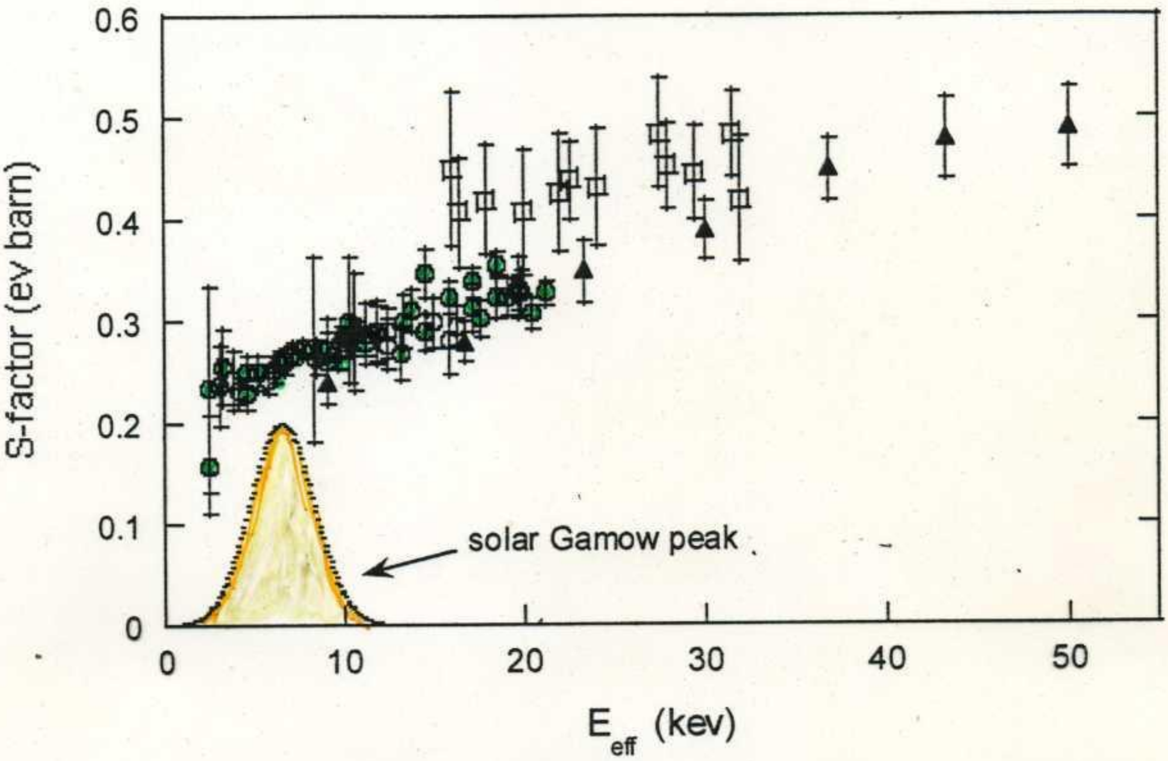
$D(p,\gamma)^3He$

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

= A **QUANTUM** JUMP TOWARDS THERMAL ENERGIES

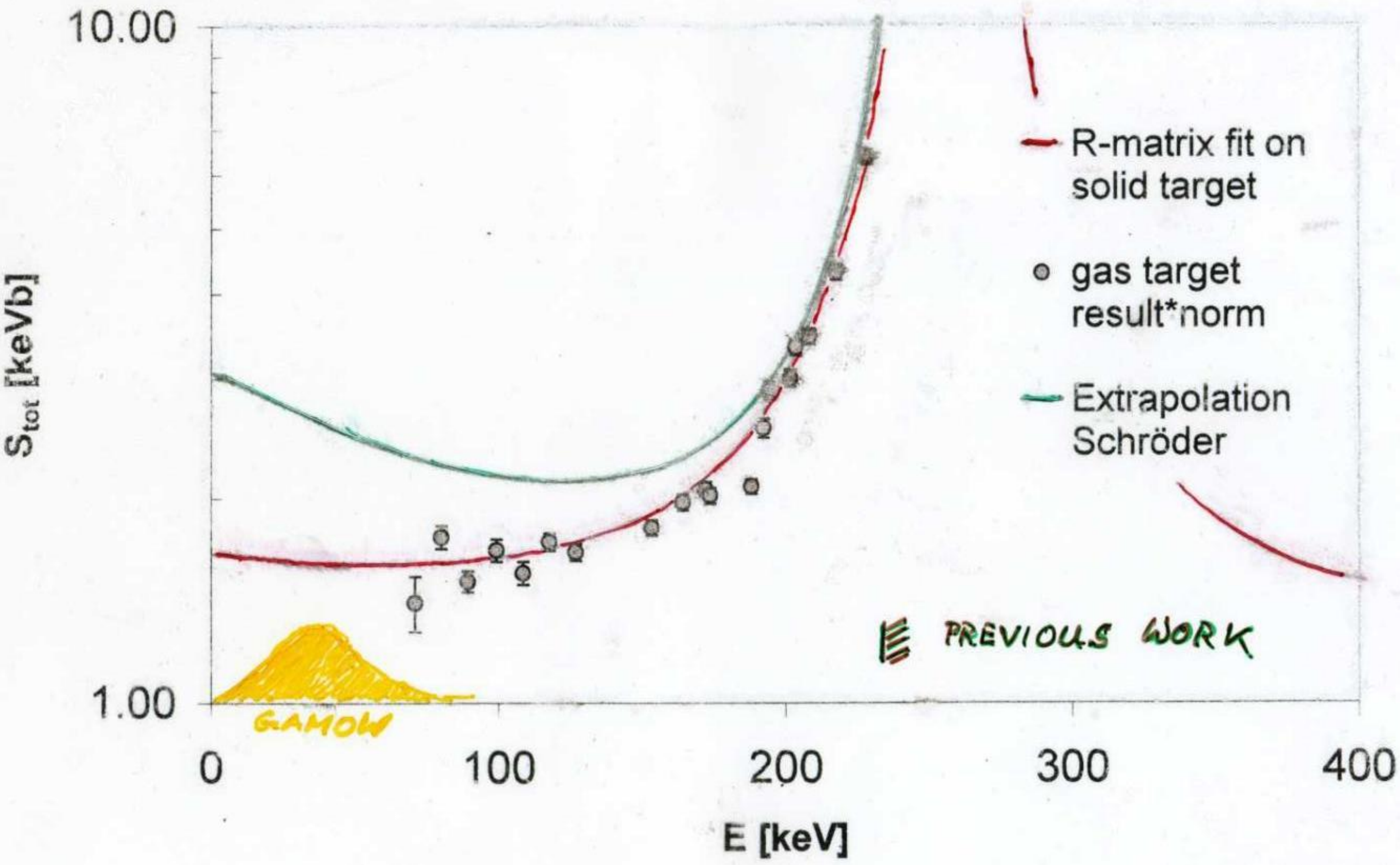


# THE CASE: $d(p,\gamma)^3He$




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

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

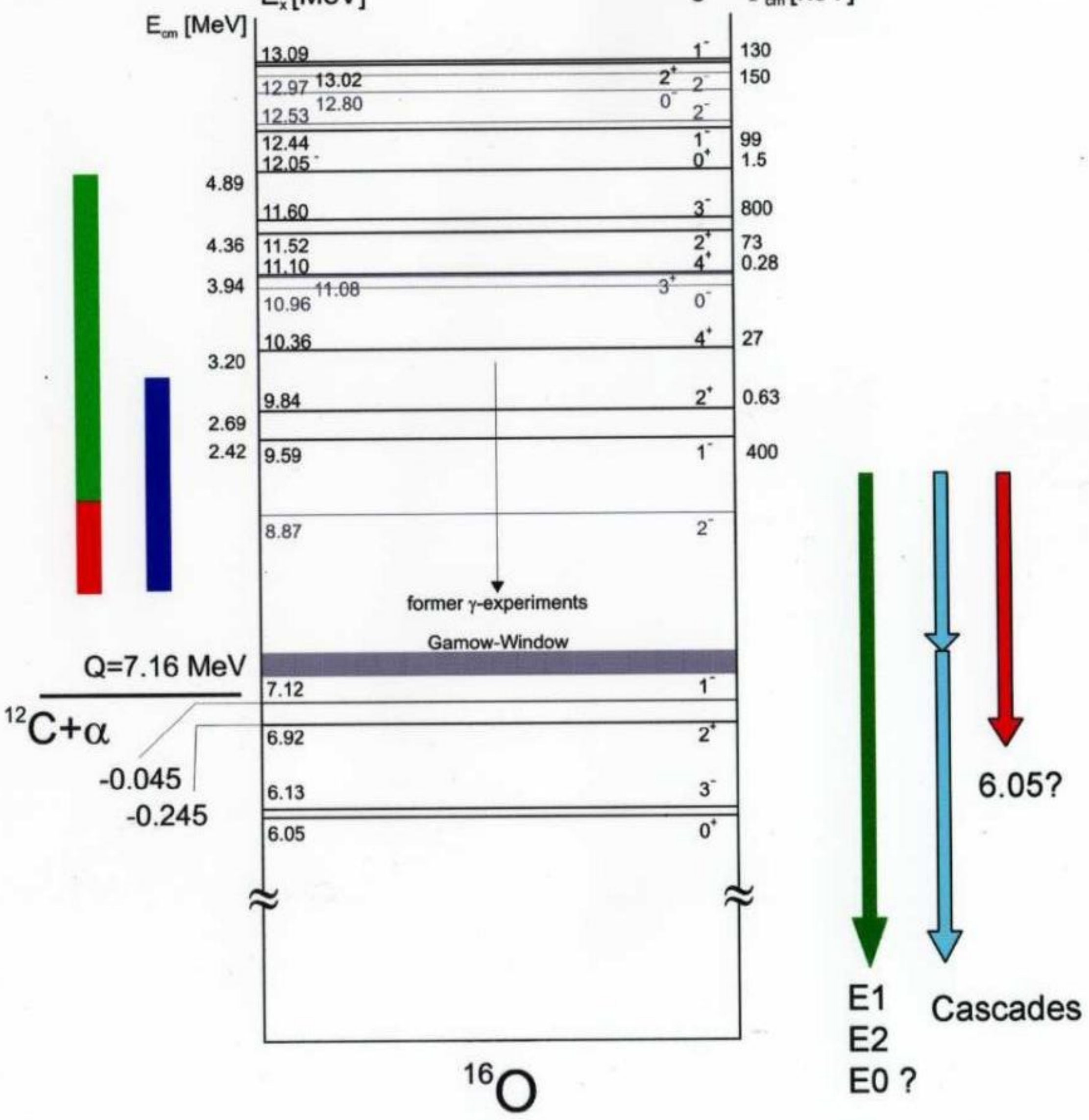



... SOLAR NEUTRINOS AND AGE OF GLOBULAR CLUSTERS

DETAILS: COSTANTINI

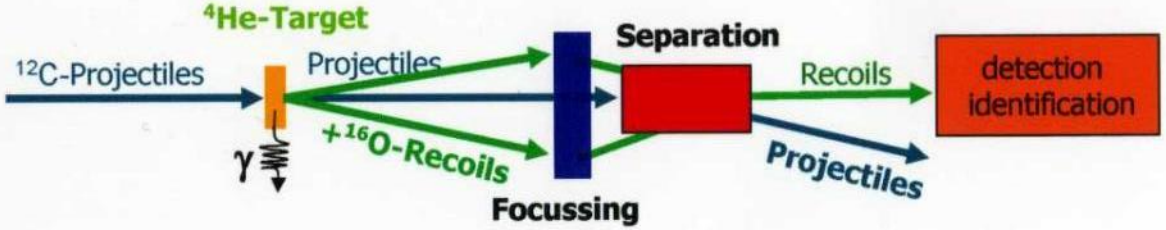
# $^{12}C(\alpha,\gamma)^{16}O$

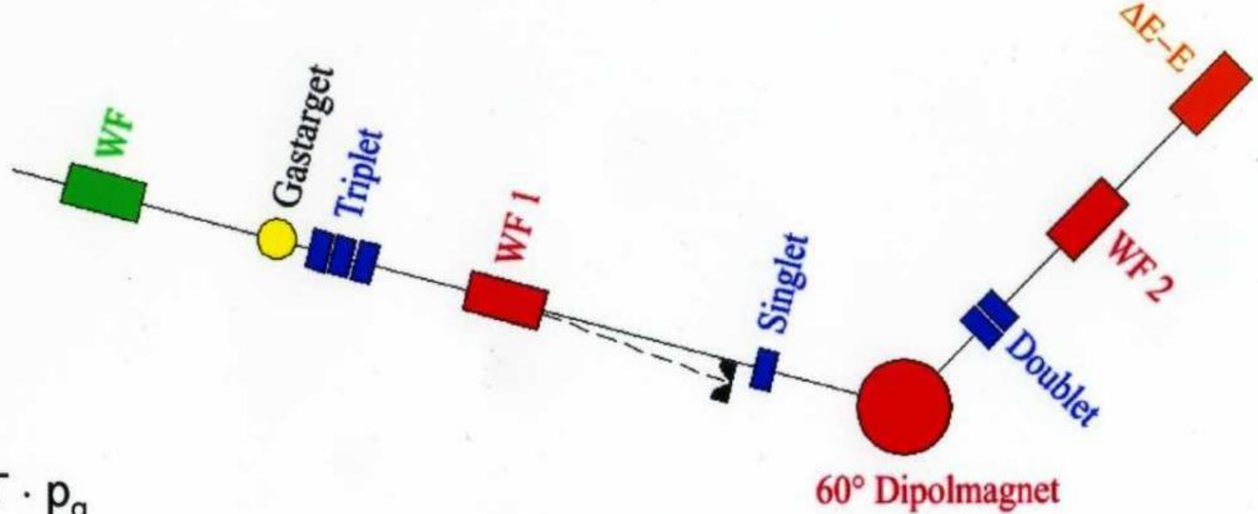
## „The holy grail of nuclear astrophysics“ (W. Fowler)



# Method: Recoil-Separator

## inverse kinematics: $^{4}He(^{12}C,\gamma)^{16}O$

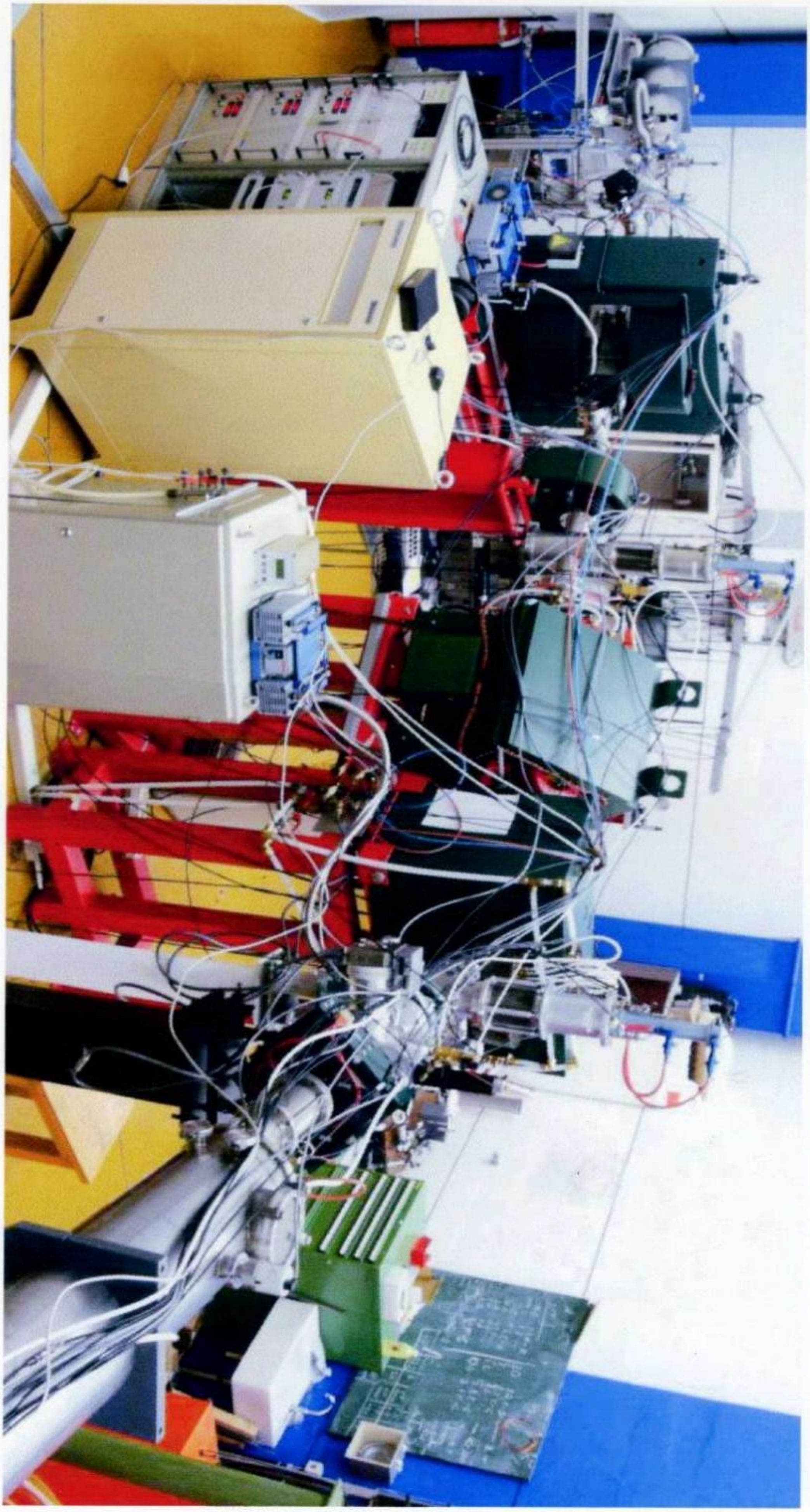


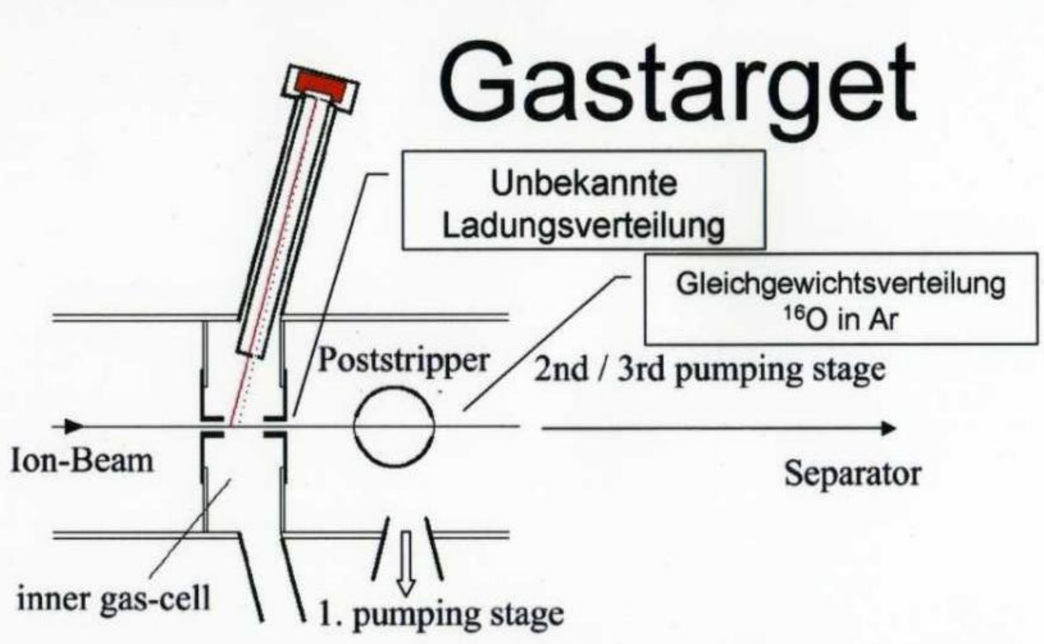

detected $^{16}O$ Events

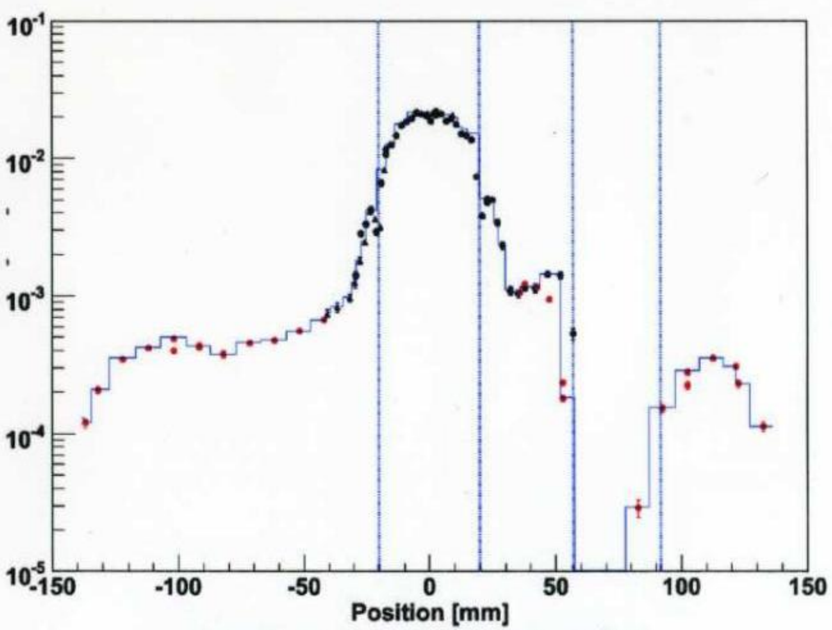
$N = N_{Projektile} \cdot n \cdot \sigma \cdot T \cdot p_q$

n = number density
T = Transmission
$p_q$ = charge state probabilty

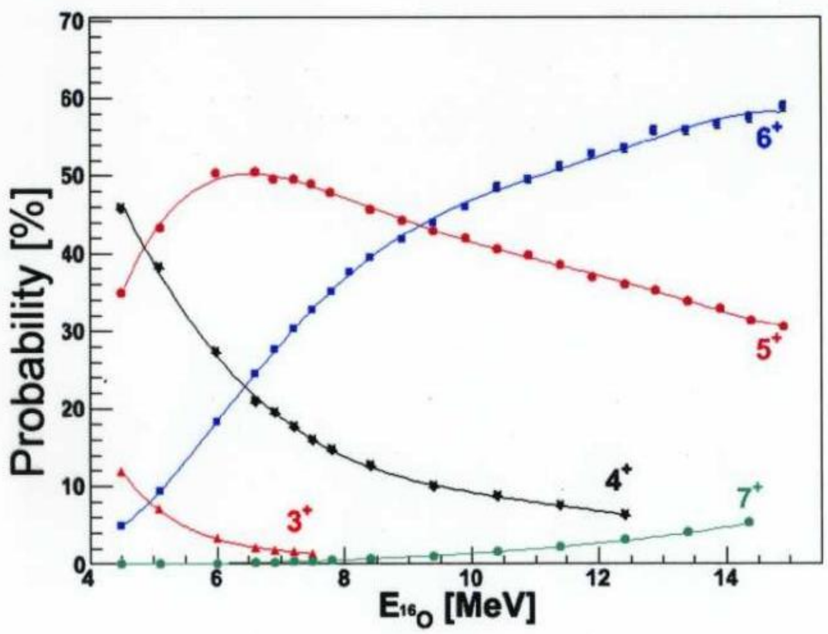


# Gastarget

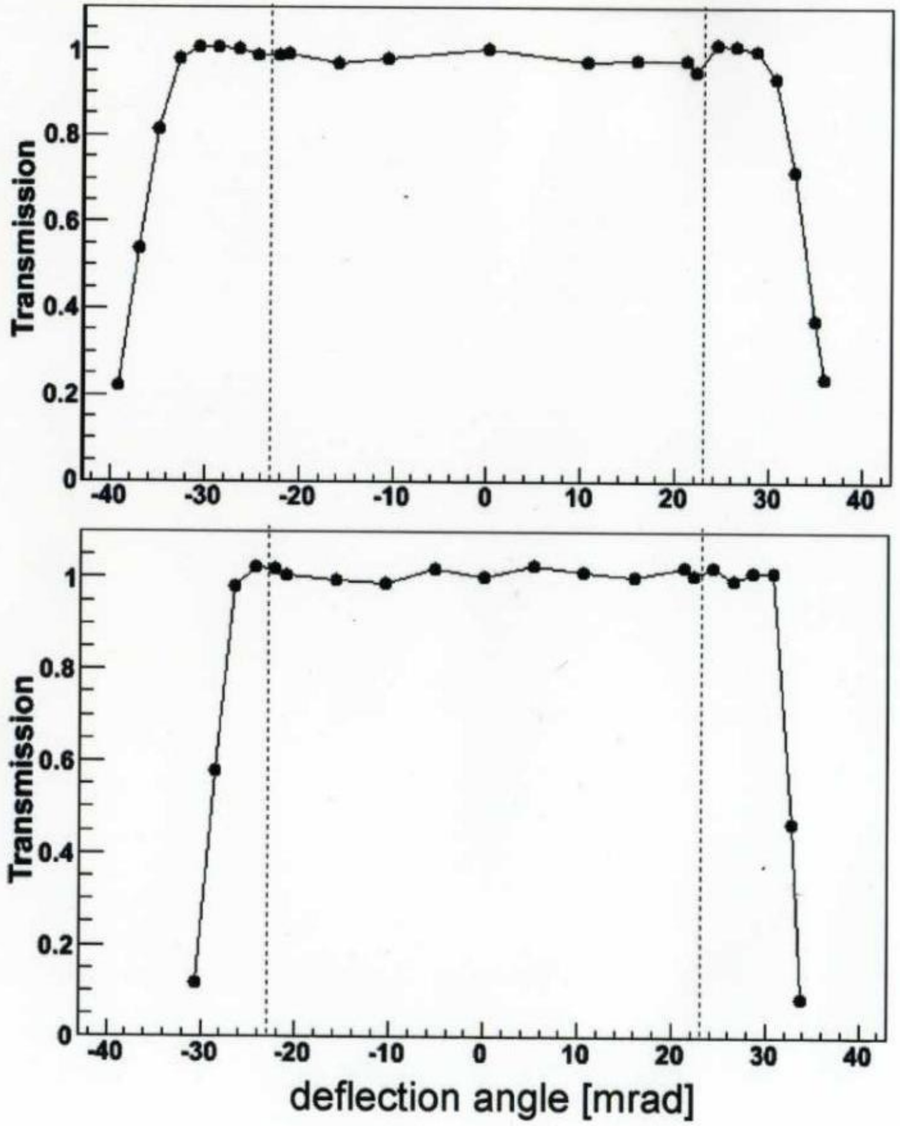



detection of γ-radiation from $^{7}Li^{*}$



# Transmission



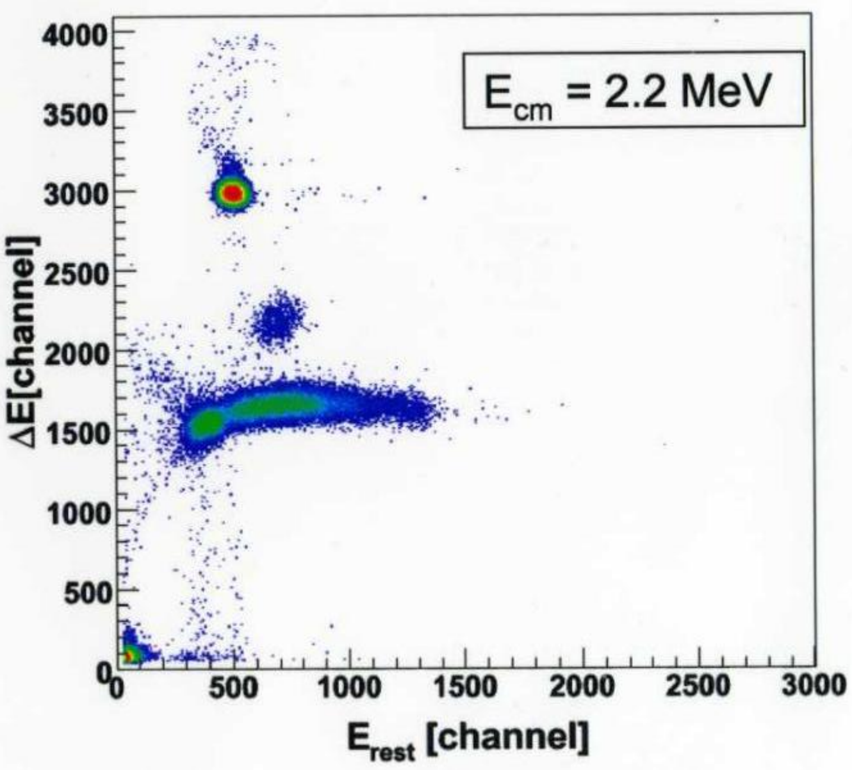

horizontal

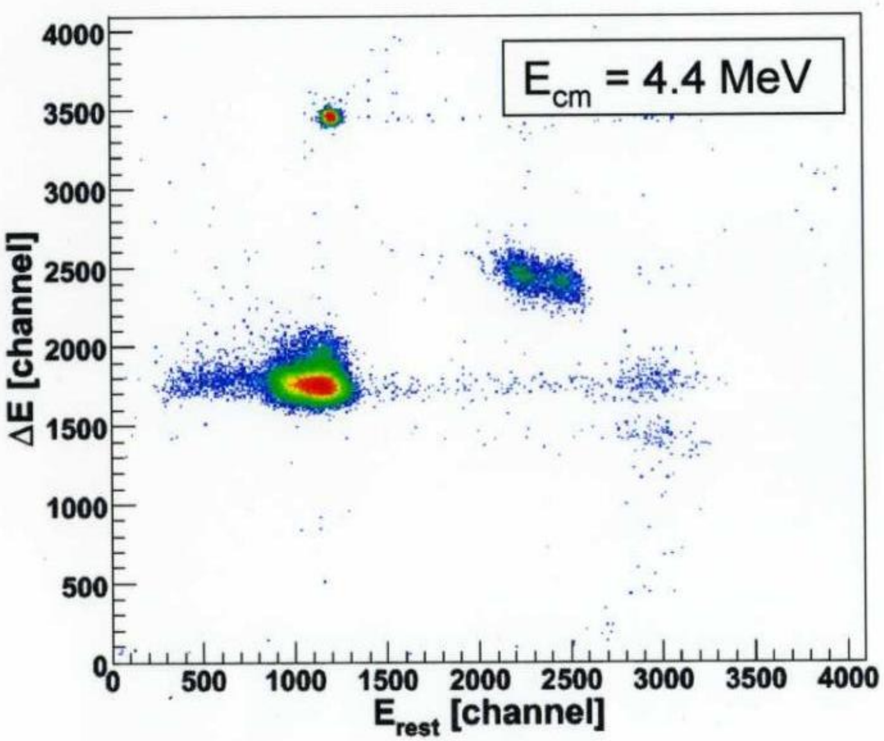
angular acceptance
$E_{cm}$ = 2.7 MeV

vertikal

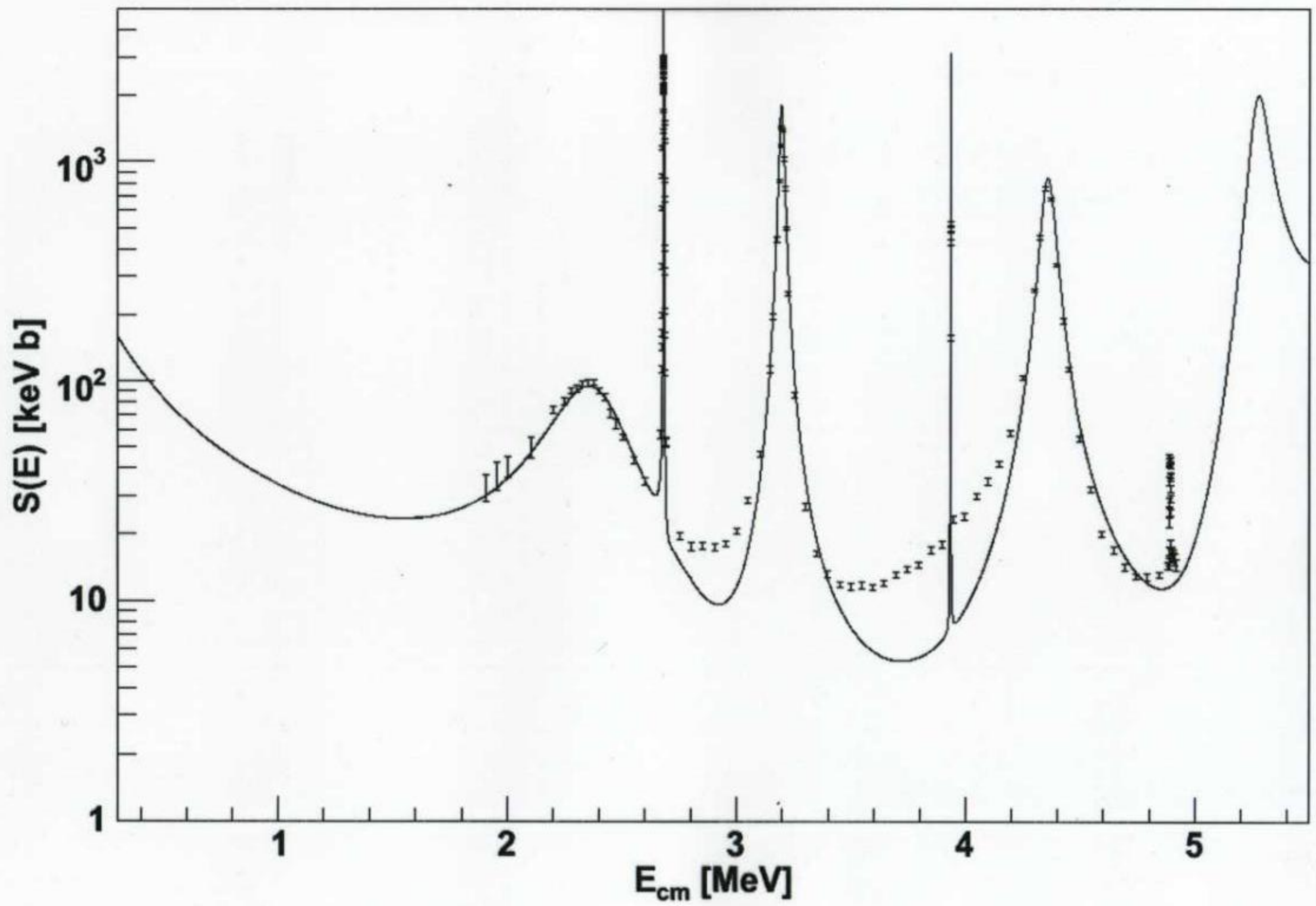
T=1 in whole energy region

# ΔE-E matrices



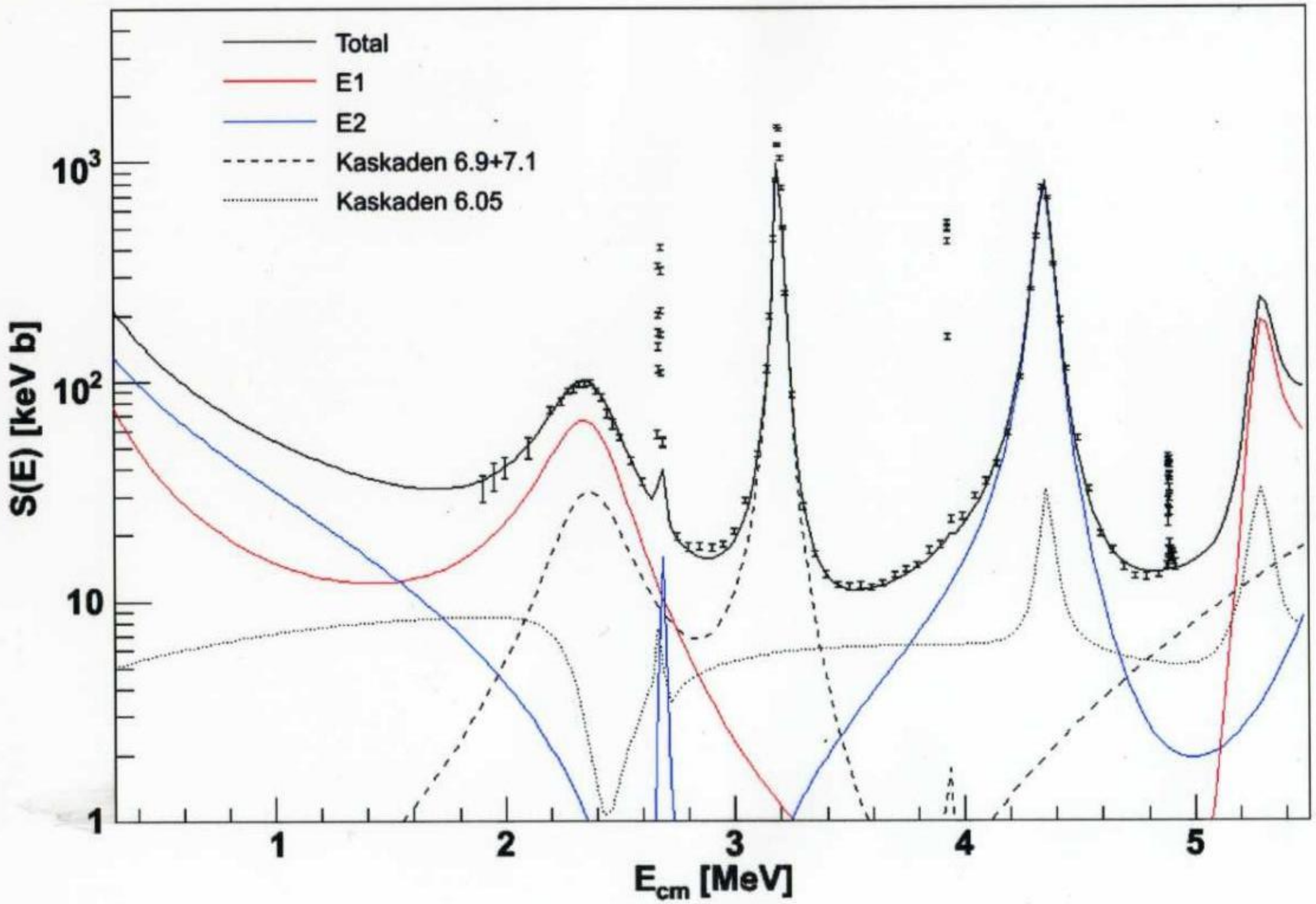



# Results




R-Matrix calculation from Kunz et al., APJ 567, 643-650 (2002)

# Results

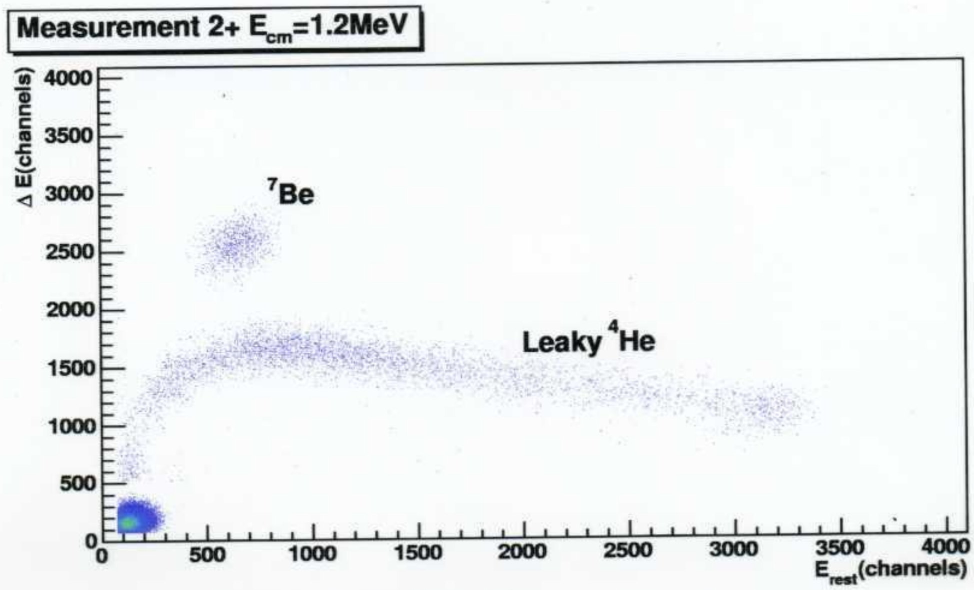

Total
E1
E2
Kaskaden 6.9+7.1
Kaskaden 6.05
S(E) [keV b]
$10^3$
$10^2$
10
1
1
2
3
4
5
$E_{cm}$ [MeV]

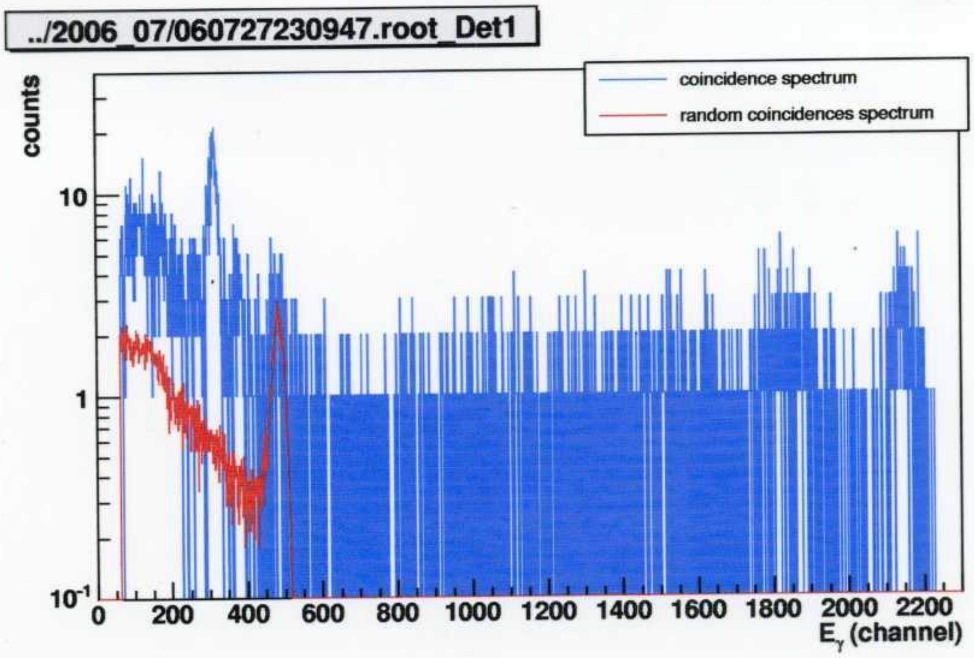
THE CASE:

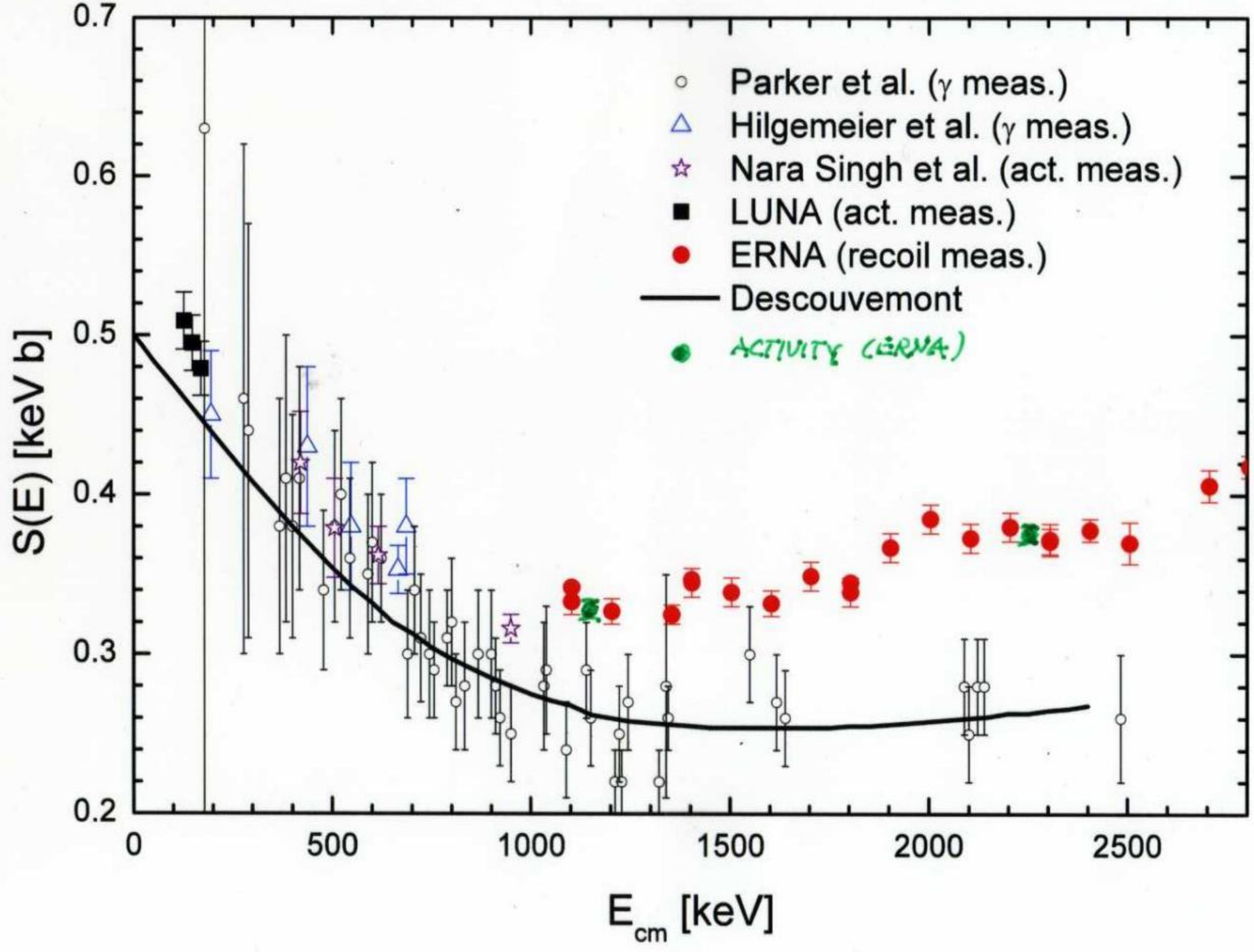
$$^{3}He(\alpha,\gamma)^{7}Be$$

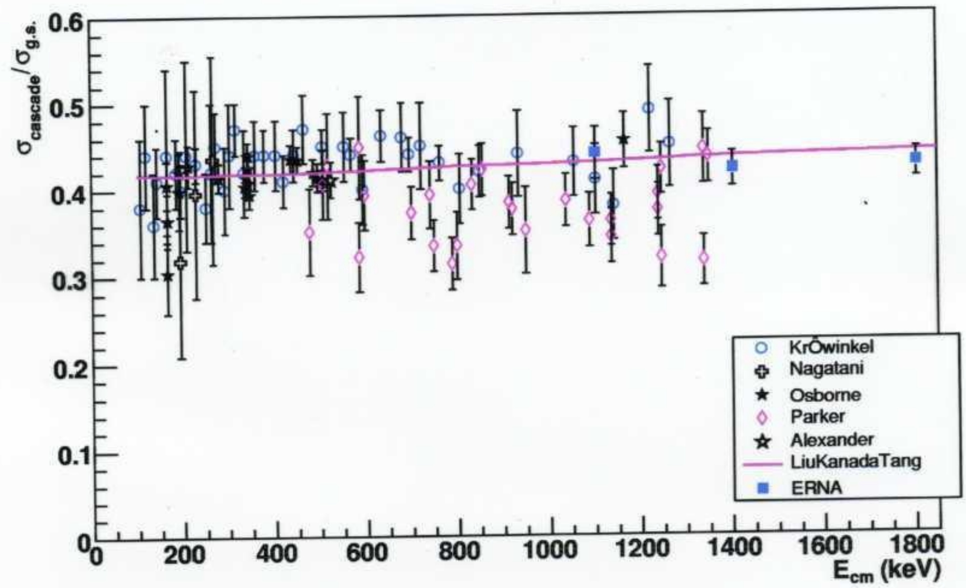
ACTIVITY

RECOILS (ERNA)

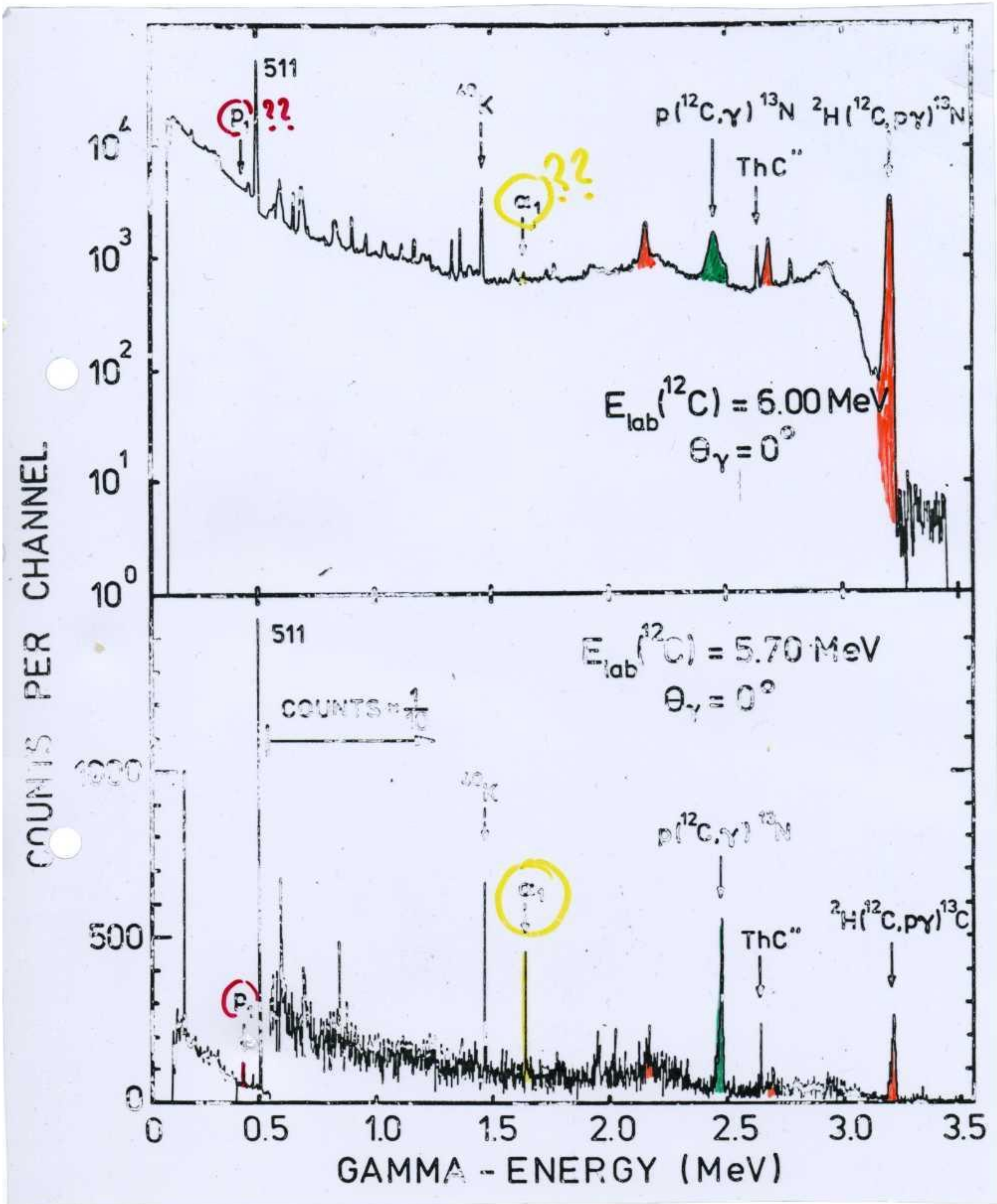

Measurement 2+ $E_{cm}$=1.2MeV
Δ E(channels)
$^7$Be
Leaky $^4$He
$E_{rest}$(channels)
0
500
1000
1500
2000
2500
3000
3500
4000


../2006_07/060727230947.root_Det1
coincidence spectrum
random coincidences spectrum
counts
10
1
$10^{-1}$
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
$E_\gamma$ (channel)

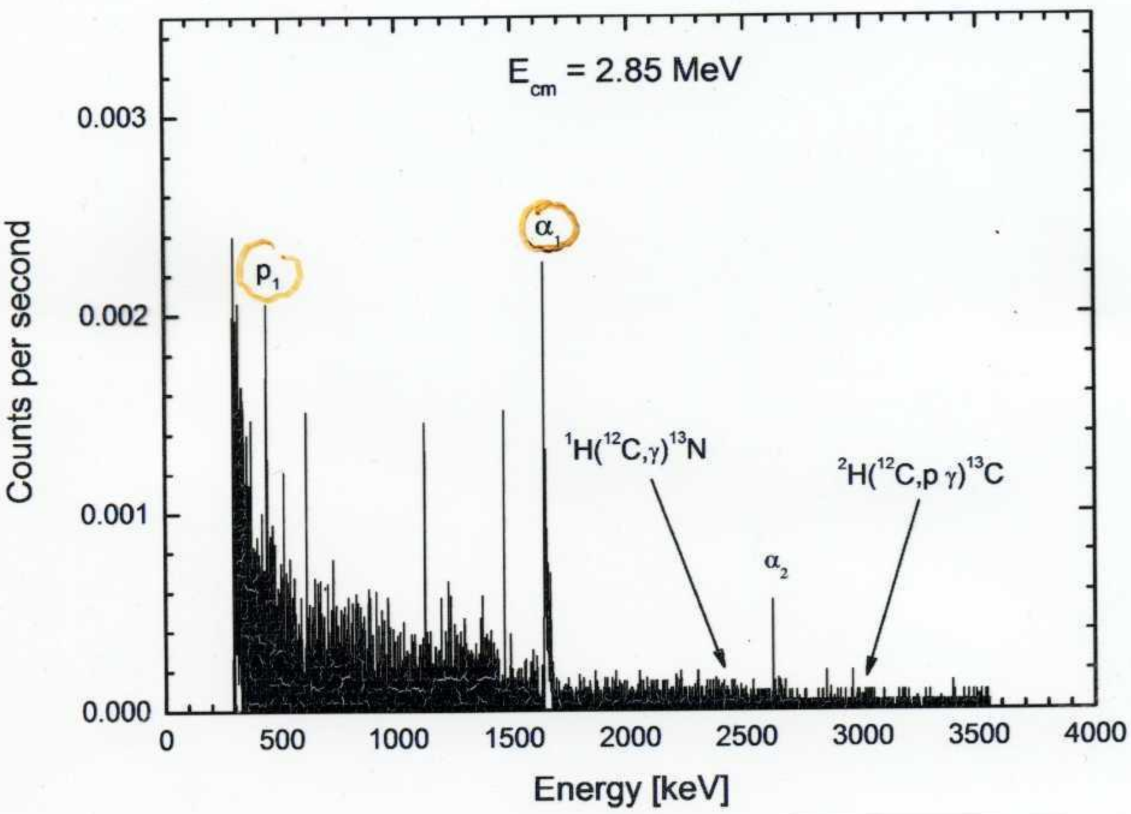

Parker et al. (γ meas.)
Hilgemeier et al. (γ meas.)
Nara Singh et al. (act. meas.)
LUNA (act. meas.)
ERNA (recoil meas.)
Descouvemont
ACTIVITY (ERNA)
S(E) [keV b]
0.2
0.3
0.4
0.5
0.6
0.7
0
500
1000
1500
2000
2500
E_cm [keV]



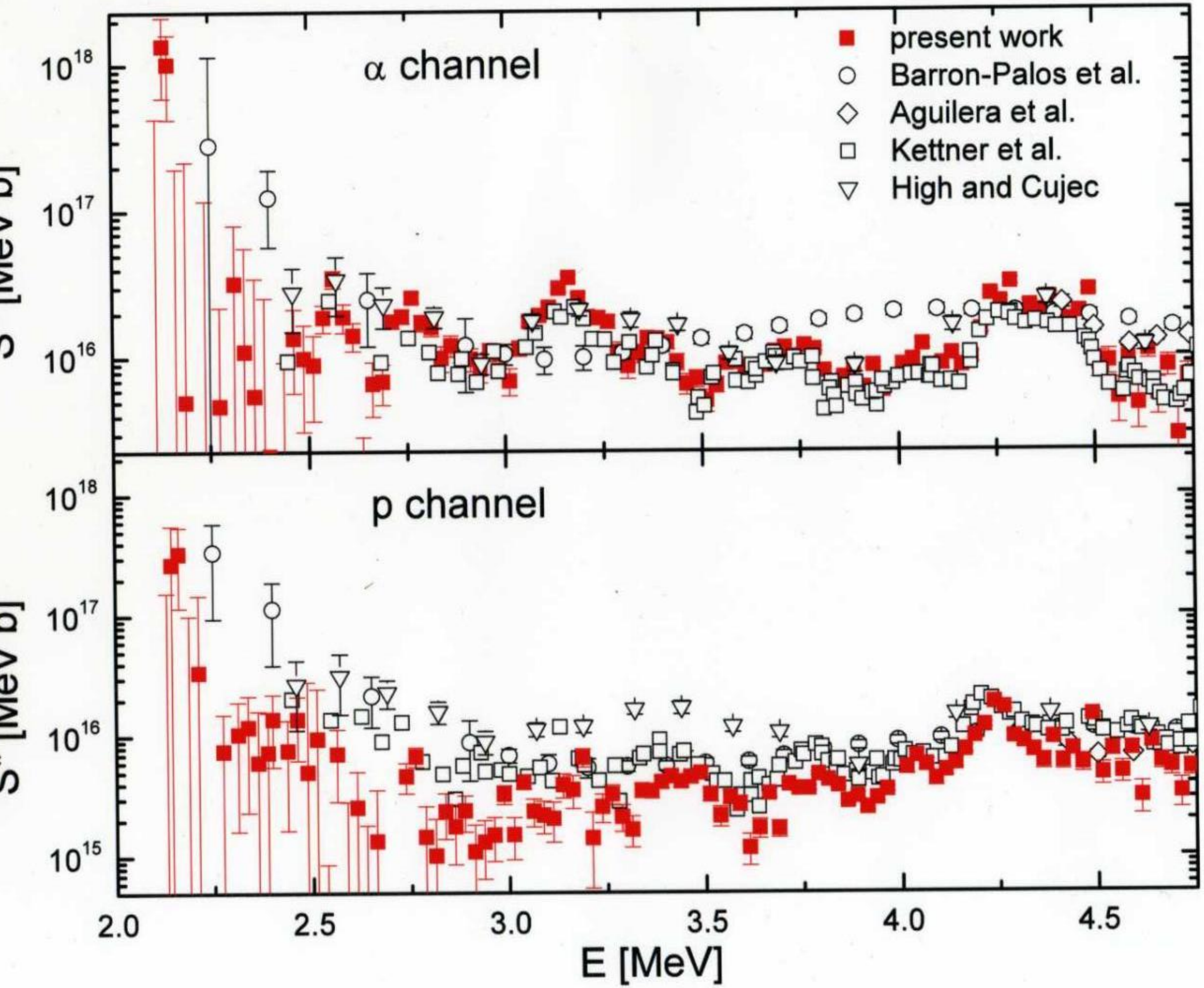
0.6
0.5
0.4
0.3
0.2
0.1
0
$\sigma_{cascade}/\sigma_{g.s.}$
0
200
400
600
800
1000
1200
1400
1600
1800
$E_{cm}$ (keV)
KrÔwinkel
Nagatani
Osborne
Parker
Alexander
LiuKanadaTang
ERNA



COUNTS PER CHANNEL
511
p1 ??
40K
α1 ??
p(12C,γ)13N
2H(12C,pγ)13N
ThC''
E_lab(12C) = 6.00 MeV
Θγ = 0°
511
E_lab(12C) = 5.70 MeV
Θγ = 0°
COUNTS × 1/10
40K
p(12C,γ)13N
α1
2H(12C,pγ)13C
ThC''
p1
GAMMA - ENERGY (MeV)

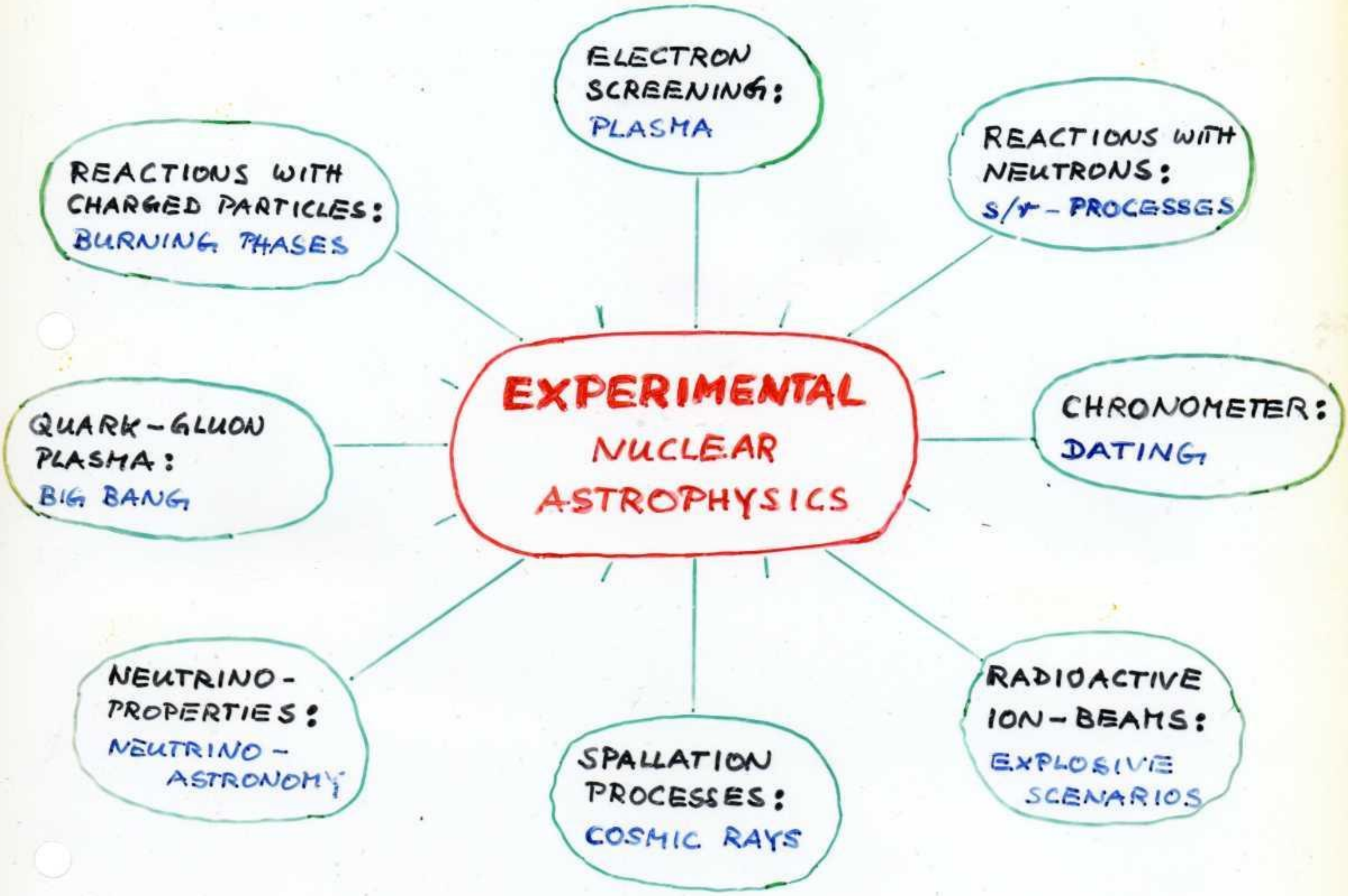


E_cm = 2.85 MeV
Counts per second
0.003
0.002
0.001
0.000
p1
α1
α2
1H(12C,γ)13N
2H(12C,p γ)13C
0
500
1000
1500
2000
2500
3000
3500
4000
Energy [keV]



α channel
p channel
present work
Barron-Palos et al.
Aguilera et al.
Kettner et al.
High and Cujec
S* [MeV b]
E [MeV]

# DATA NEEDS



EXPERIMENTAL
NUCLEAR
ASTROPHYSICS
ELECTRON
SCREENING:
PLASMA
REACTIONS WITH
NEUTRONS:
s/r - PROCESSES
CHRONOMETER:
DATING
RADIOACTIVE
ION-BEAMS:
EXPLOSIVE
SCENARIOS
SPALLATION
PROCESSES:
COSMIC RAYS
NEUTRINO-
PROPERTIES:
NEUTRINO-
ASTRONOMY
QUARK-GLUON
PLASMA:
BIG BANG
REACTIONS WITH
CHARGED PARTICLES:
BURNING PHASES

# EXPERIMENTAL NUCLEAR ASTROPHYSICS

= SOURCE OF NEW PHYSICS

= UNFINISHED FIELD

= BRIGHT FUTURE

# PRESENTATIONS

C. ROLFS

RUHR-UNIVERSITY BOCHUM

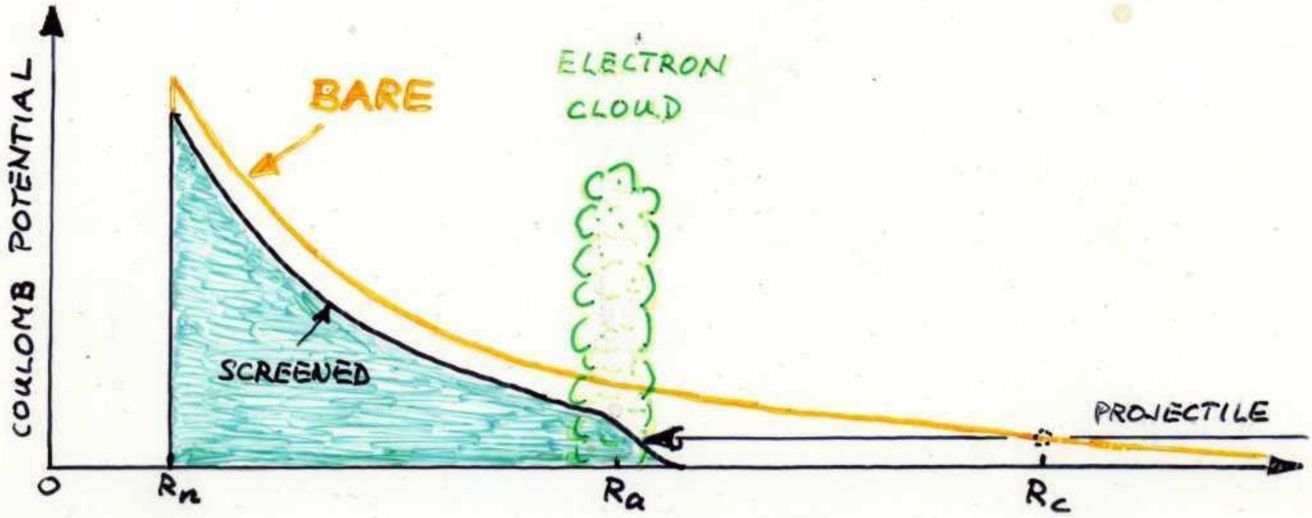
DUBNA, 7. – 10. Aug. 2007

# LECTURE 2

# ELECTRON SCREENING

$$\sigma(E) = S(E)\,\frac{1}{E}\,\underbrace{\exp(-2\pi\eta)}_{\text{BARE NUCLIDES}}$$

## LABORATORY:

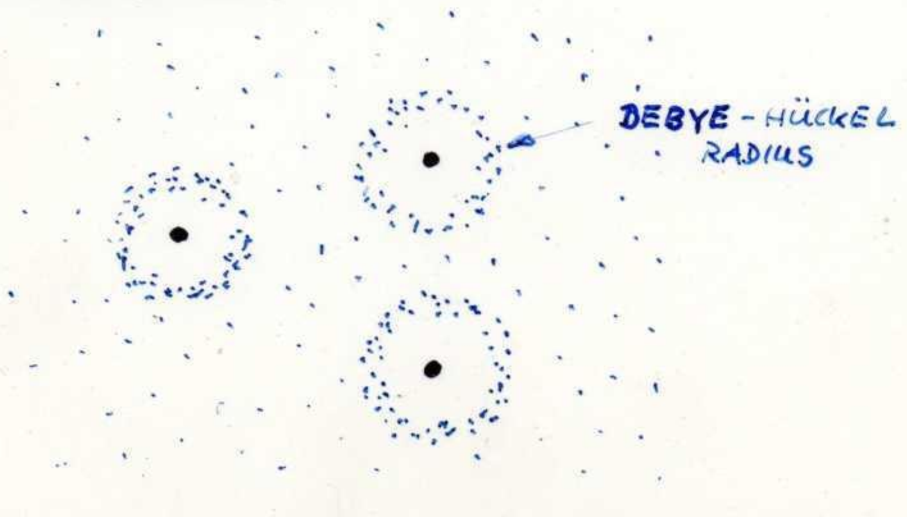



$$\sigma_{LAB}(E) = f_{LAB}(E)\ \sigma_{BARE}(E)$$

$$f_{LAB}(E) = \exp\left(\pi\eta\frac{U_e}{E}\right) \geq 1$$

$U_e$ = ELECTRON – POTENTIAL – ENERGY
= FIT – PARAMETER

## STELLAR PLASMA:

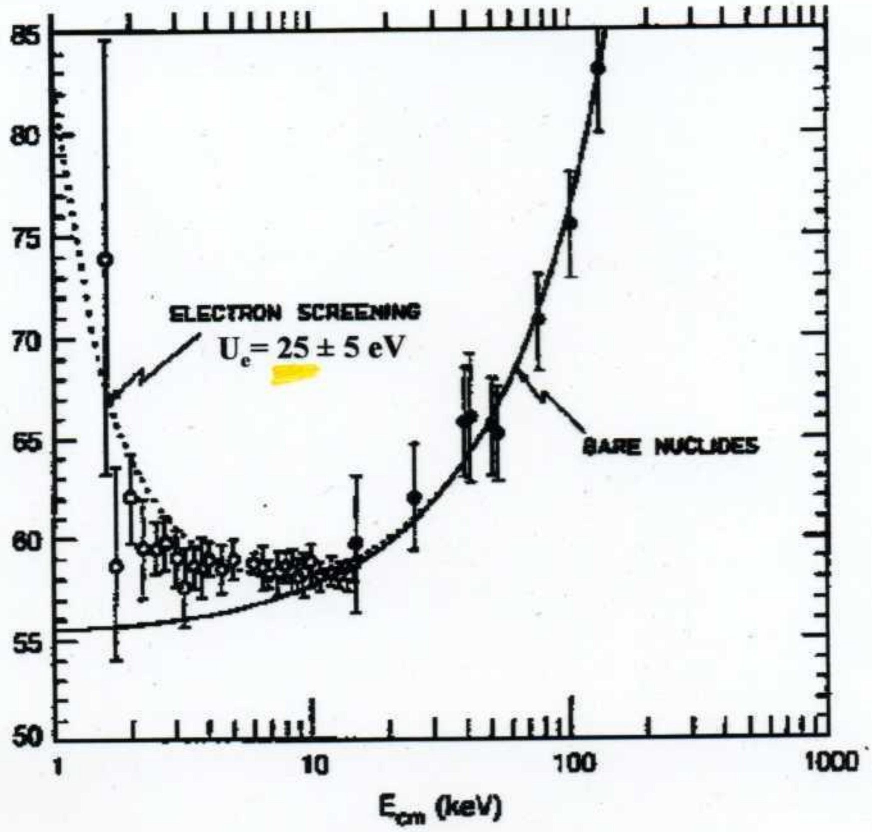



$$\sigma_{PLASMA}(E) = f_{PLASMA}(E)\ \sigma_{BARE}(E)$$

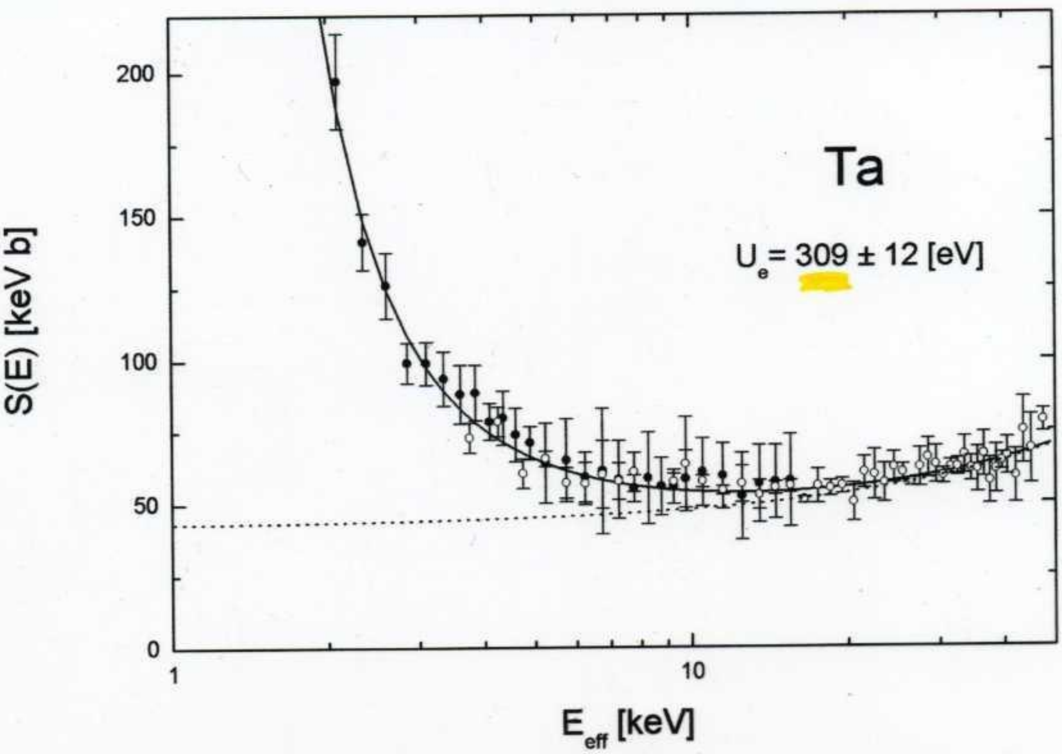
ENERGY PRODUCTION
NEUTRINO FLUXES

# THE CASE: d(d, p)t

D₂ – GASTARGET




DEUTERATED METAL (Ta)




UFF!

## .: SETUP:

DETECTORS IN CLOSE GEOMETRY
ULTRA-HIGH VACUUM
VARIABLE TEMPERATURE *

## .: PROCEDURES:

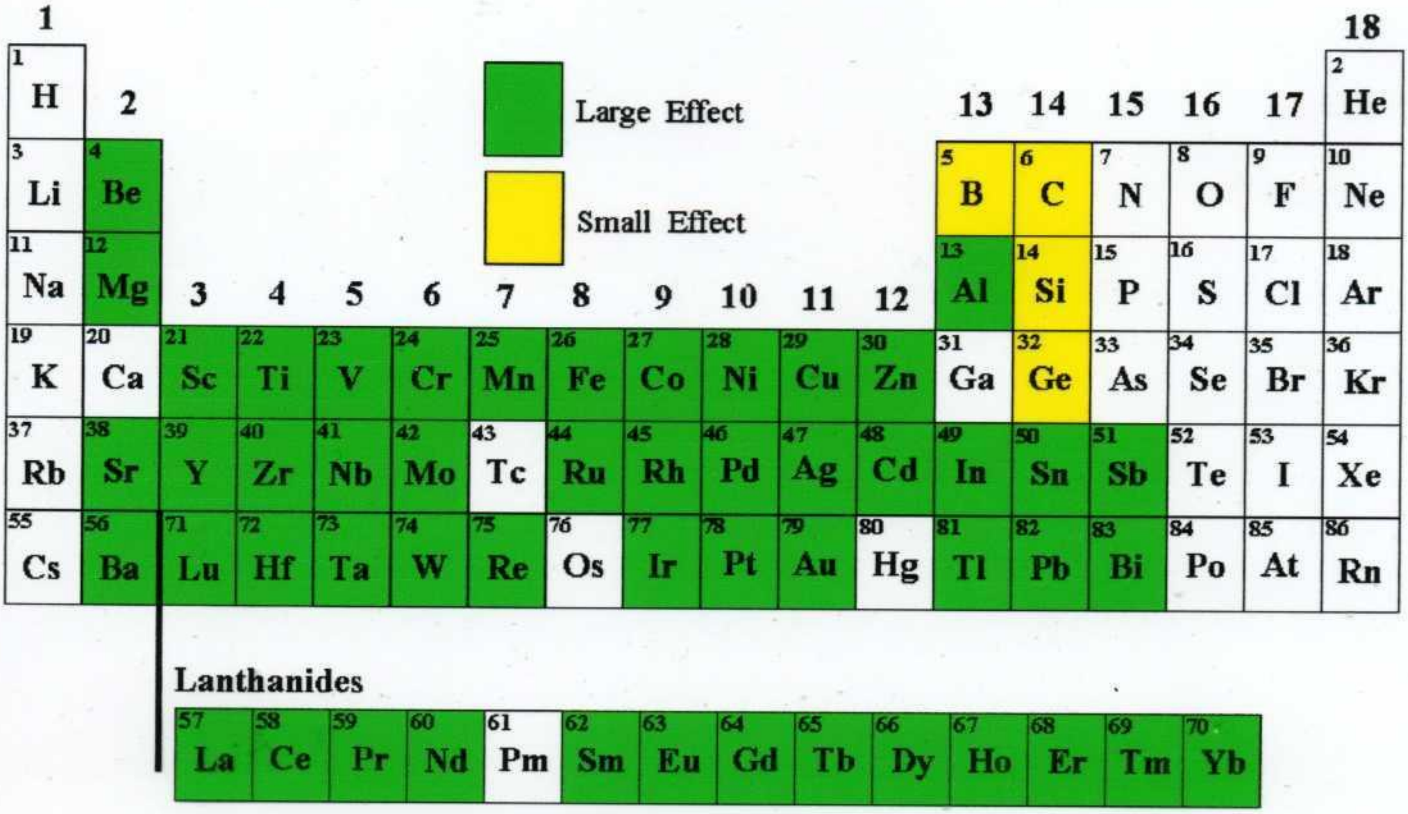
SURFACE CLEANING BY SPUTTERING
D-IMPLANTATION TO SATURATION
EXCITATION FUNCTION
ANALYSIS
- ABSOLUTE YIELD ➡ H-SOLUBILITY
- ENERGY DEPENDENCE ➡ $U_e$-VALUE

## .: SAMPLES:

METALS
INSULATORS
SEMICONDUCTORS

} = 58

# PERIODIC TABLE




METALS : LARGE EFFECT

INSULATORS : SMALL EFFECT

WHAT IS ACCELERATION ?

**METALS** = HIGH ELECTRIC / HEAT CONDUCTIVITY

⇩

**DRUDE:** QUASI-FREE ELECTRONS

⇩

ROLFS: THEY REPRESENT A **PLASMA**

⇩

DEBYE: $R_D \approx \left( \frac{\varepsilon_0 kT}{n_e \rho e^2} \right)^{1/2}$

$U_D \approx \frac{e^2}{R_D}$

e.g. **Ta** $U_e \approx 309 \pm 12$ eV

⇩

$n_e \approx 0.9 \pm 0.2$

$n_{HALL} \approx 1.0 \pm 0.2$

} o.k.

# PREDICTIONS / TESTS

- ALL 51 METALS: $n_e = n_{HALL}$ ✓
- $U_D \sim \frac{1}{\sqrt{T}}$ ✓
- $U_D \sim Z_t$ (3, 4, 13, 72) ✓
- $U_D \sim Z_i$ ✓

⇩

PLASMA - DEBYE - MODEL FOR STARS

= VERIFIED

⇩

METALS = PLASMA

OF THE POOR MAN

# PREDICTIONS / TESTS

- ALL 51 METALS: $n_e = n_{HALL}$ ✓
- $U_D \sim \frac{1}{\sqrt{T}}$ ✓
- $U_D \sim Z_t$ (3, 4, 13, 72) ✓
- $U_D \sim Z_i$ ✓

⇩

PLASMA – DEBYE – MODEL FOR STARS

= VERIFIED

⇩

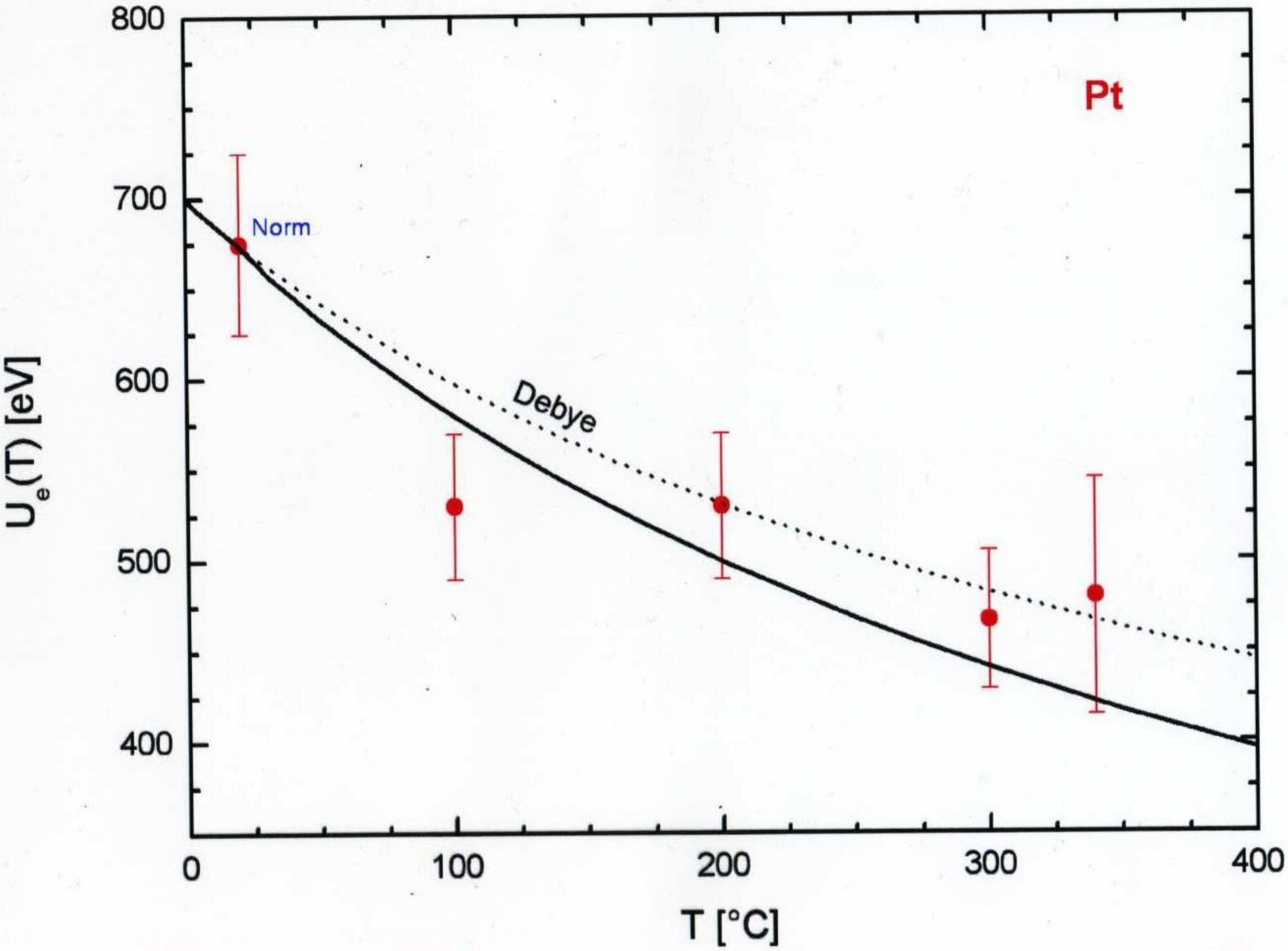
METALS = PLASMA

OF THE POOR MAN

$$U_D = Z_i \, Z_t \, U_{dtd} \sqrt{\frac{293}{T_K}}$$

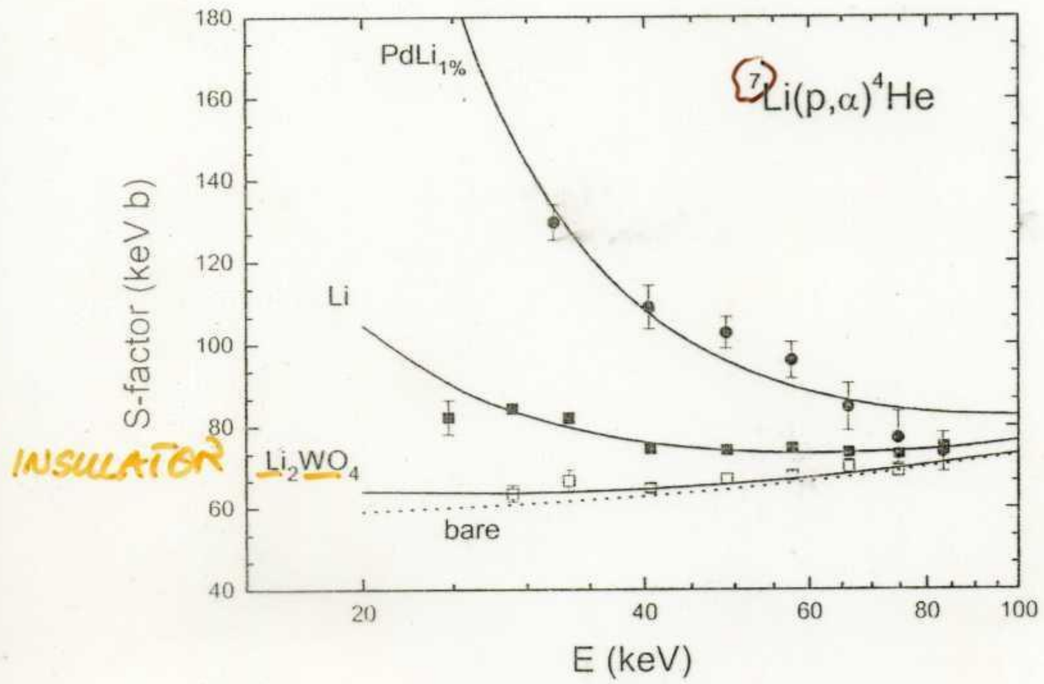
$U_{dtd}$ ≈ 300 eV

$U_D \propto \frac{1}{\sqrt{T}}$




$u_{eD} \stackrel{!}{\sim} \frac{1}{\sqrt{T}}$

# DIFFERENT ENVIRONMENTS




**INSULATOR**

$n_{eff} \equiv 0$

⇩

$U_e = 0.17$ keV

**Li-METAL:**

$n_{eff} = 1.0$

⇩

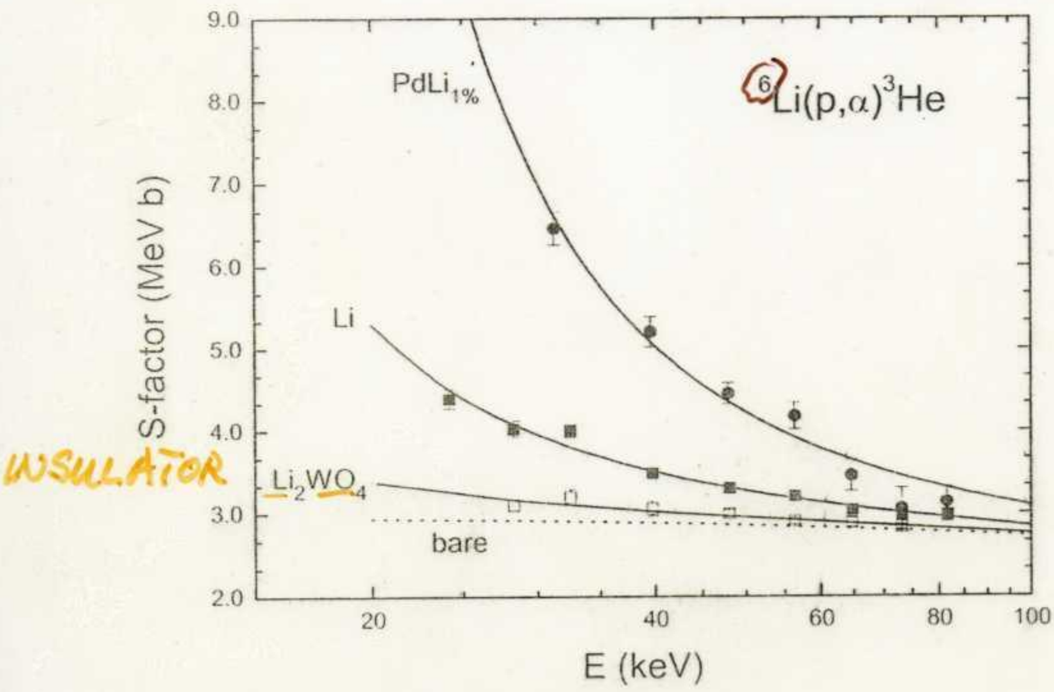
$U_e = 1.1$ keV

**PdLi$_{1\%}$-ALLOY:**

$n_{eff} = 7.0$

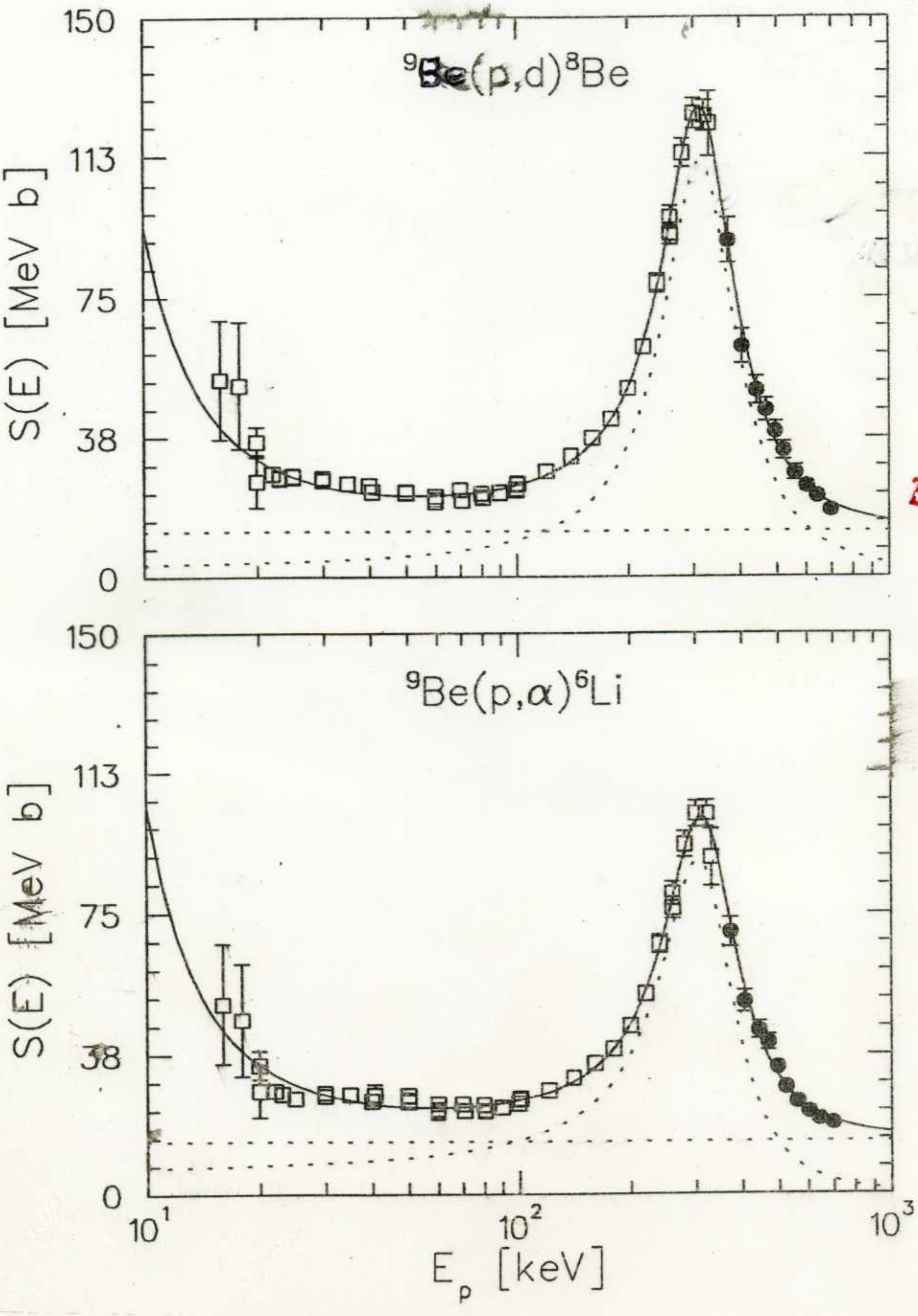
⇩

$U_e = 3.5$ keV




ISOTOPIC INDEPENDENCE

EXPERIMENT IN **1996** : $U_e = 900 \pm 50$ eV




Be-METAL:

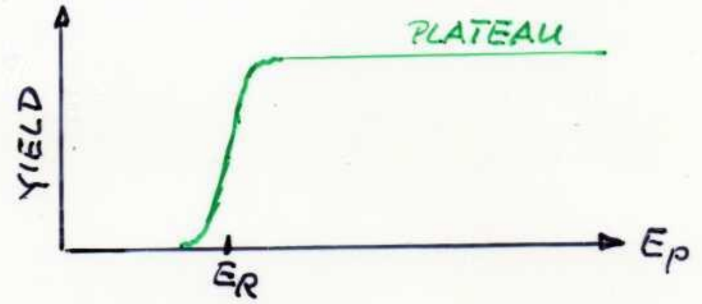
$u_{eff} = 0.2$

⇩

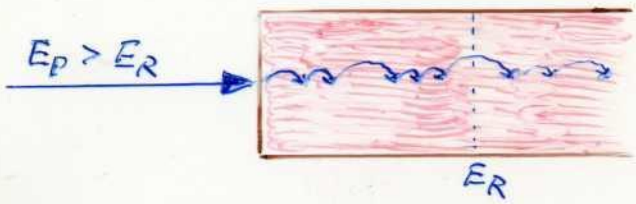
$U_e = 0.90$ keV

# LEWIS EFFECT (PEAK)

THICK - TARGET YIELD OF NARROW RESONANCE (Γ)




FOR $E_p > E_R$ , ENERGY LOSS IN TARGET



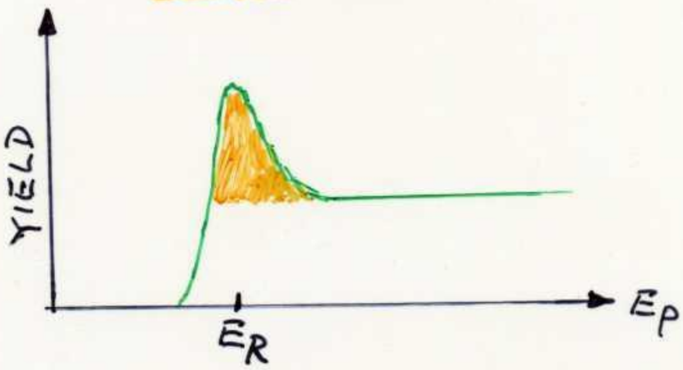

DISCRETE ENERGY LOSS $\Delta E$

$\Delta E \neq 0$ $(b=0)$

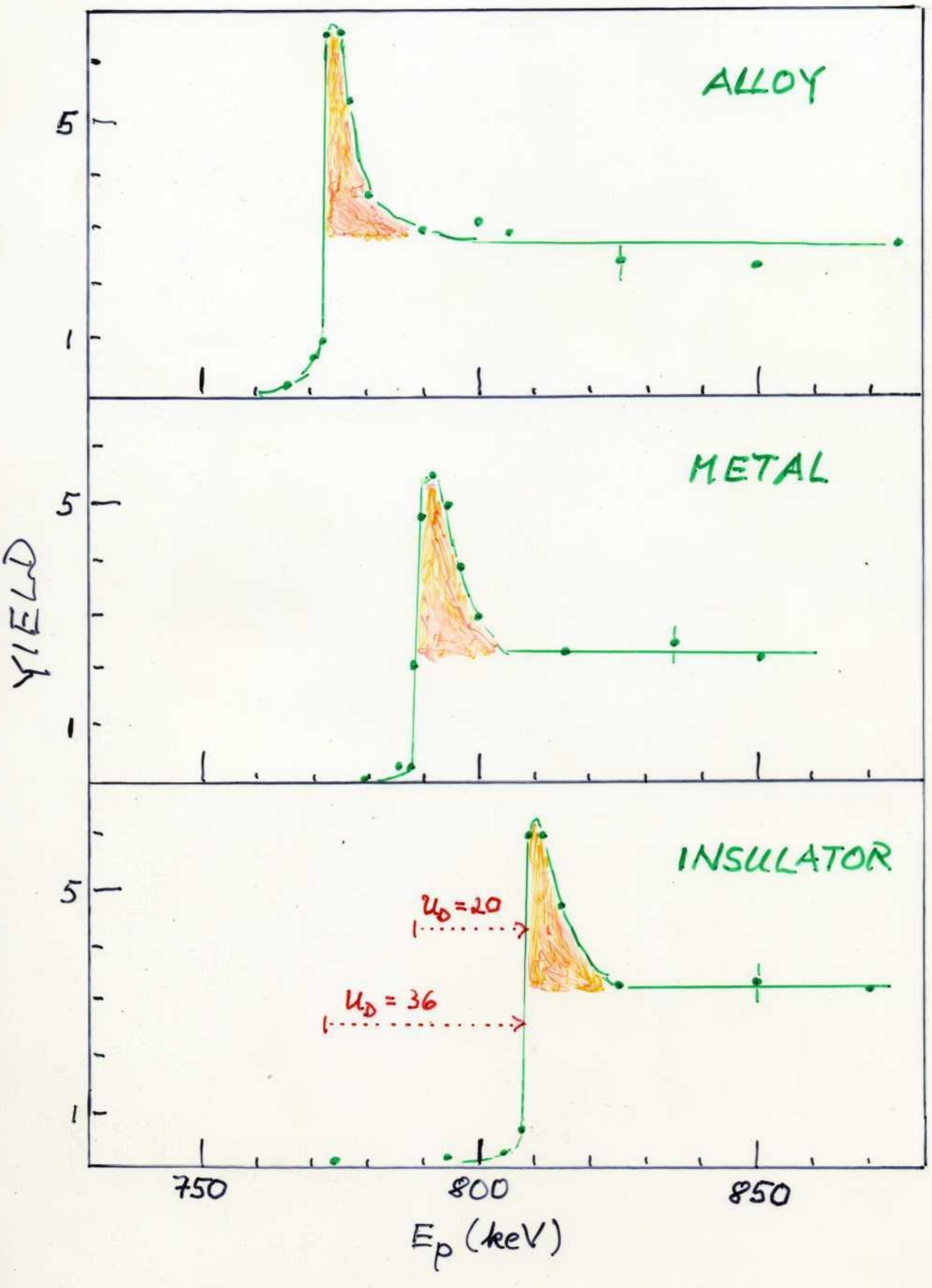
... SOME JUMP OVER RESONANCE

⇩

LEWIS PEAK



$^{176}Lu(p,n)^{176}Hf$

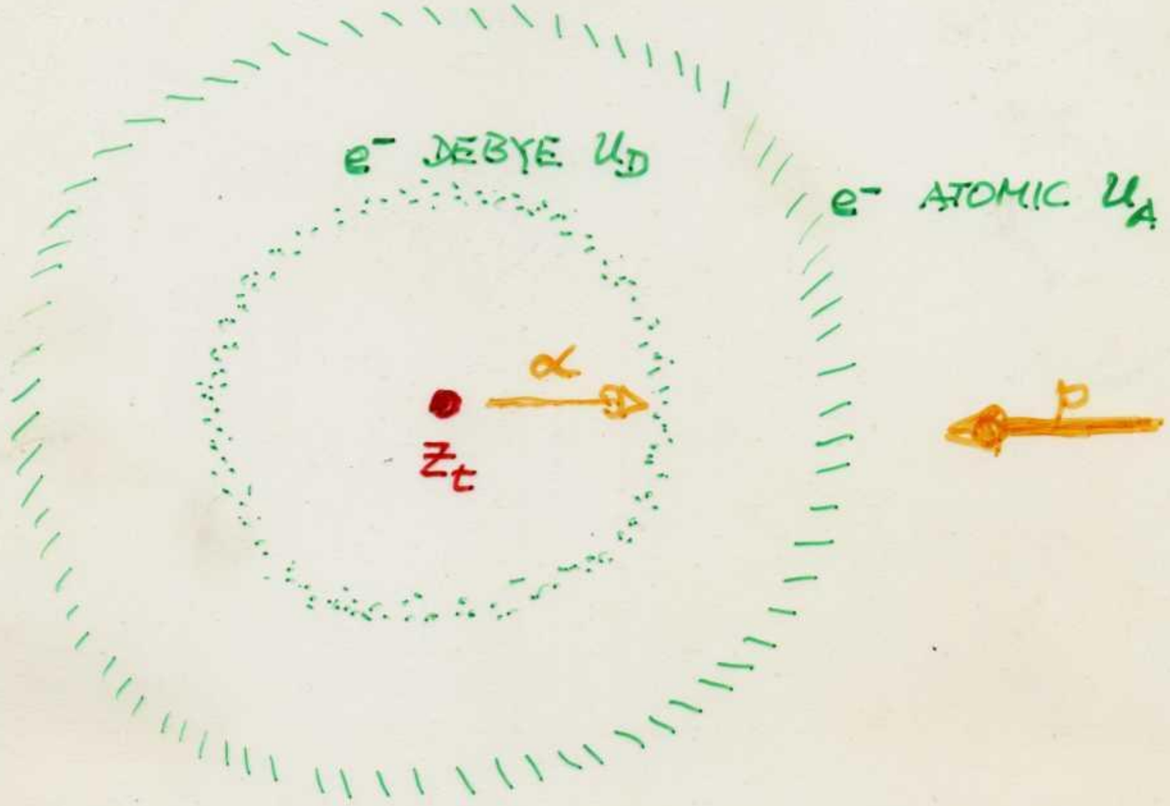


# ACCELERATIONS


METALS: $u_e = u_A + u_D \approx u_D \ (\gg u_A)$

INSULATORS: $u_e = u_A$

# ACCELERATIONS




METALS: $U_e = U_A + U_D \approx U_D \; (\gg U_A)$

INSULATORS: $U_e = U_A$

# PREDICTIONS

∴ **AC**CELERATION: IN **METALS** — $\alpha$ – DECAY, $\beta^+$ – DECAY — **SHORTER** $T_{1/2}$

∴ **DE**CELERATION: IN **METALS** — $\beta^-$ – DECAY, $e^-$ – CAPTURE — **LONGER** $T_{1/2}$

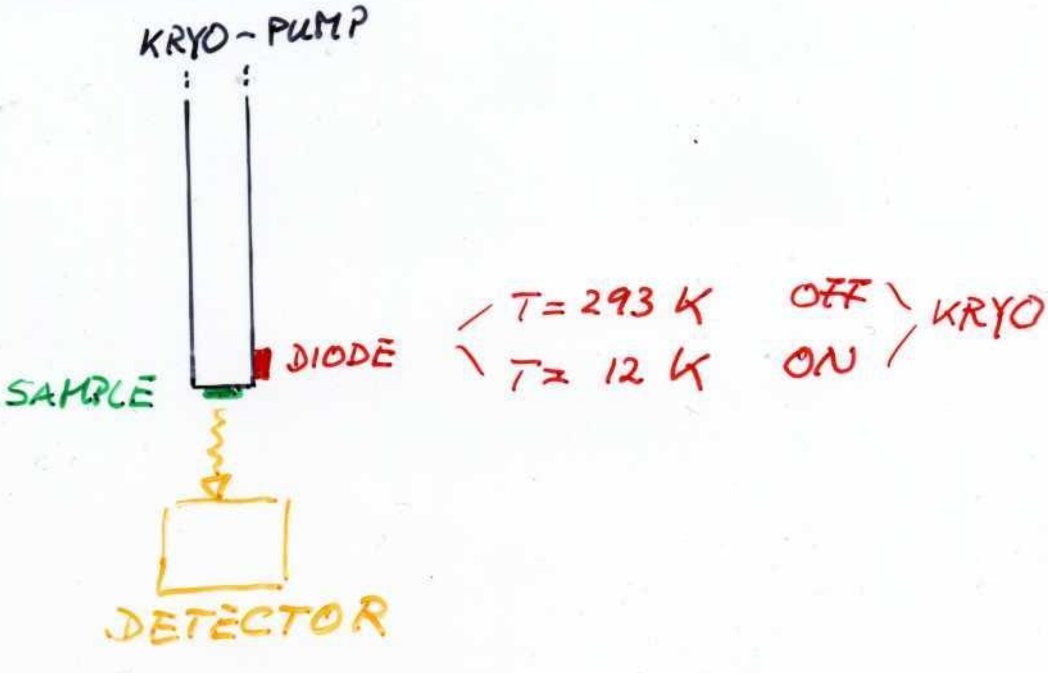
# EXPERIMENT

T- VARIATION

$$u_D \sim \frac{1}{\sqrt{T}} \Rightarrow T_{1/2}(T)$$

RELATIVE ACTIVITY $A(T) \sim \frac{1}{T_{1/2}(T)}$

# SETUP



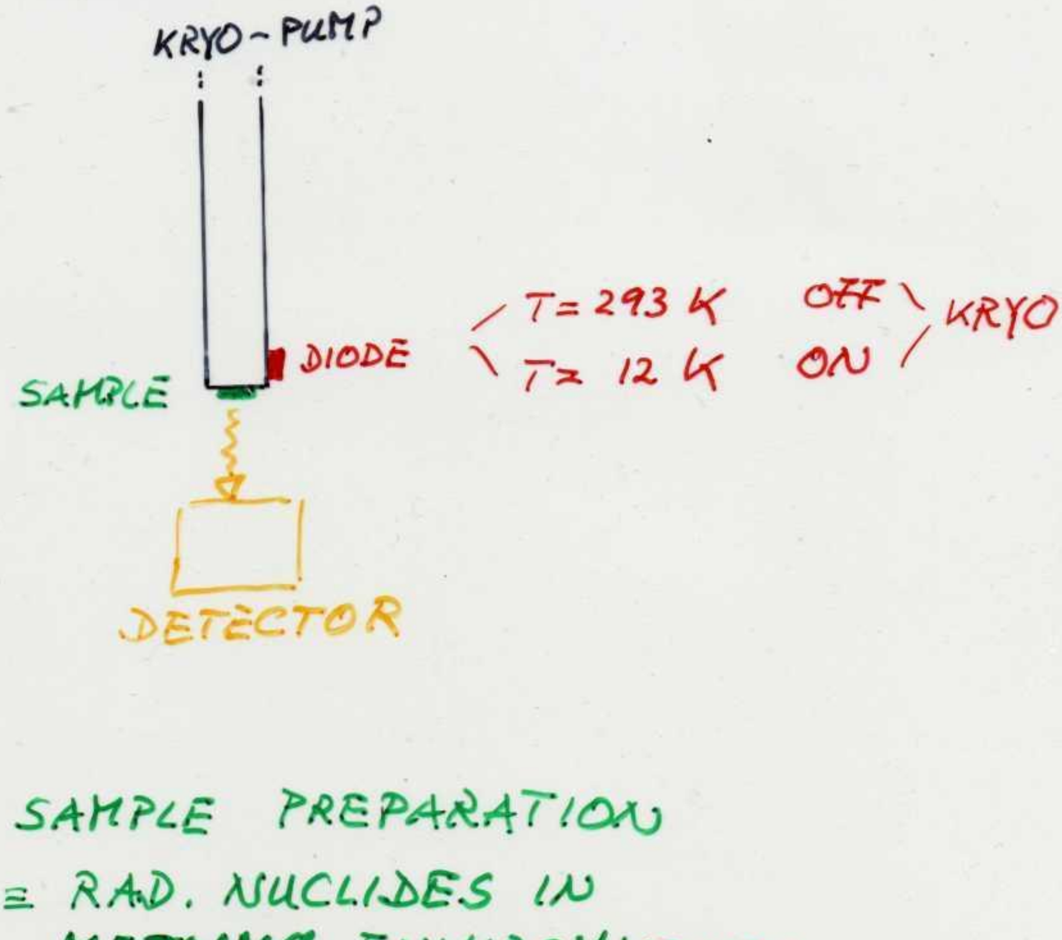

CRUX : SAMPLE PREPARATION
≡ RAD. NUCLIDES IN
METALLIC ENVIRONMENT

# EXPERIMENT

FOR **LONG** $T_{1/2}$ $\left\{ \begin{array}{l} T\text{- VARIATION} \\ U_D \sim \frac{1}{\sqrt{T}} \Rightarrow T_{1/2}(T) \\ \textbf{RELATIVE} \text{ ACTIVITY } A(T) \sim \frac{1}{T_{1/2}(T)} \end{array} \right.$

FOR **SHORT** $T_{1/2}$ : DECAY CURVE $\exp(-t/\tau)$

# SETUP




**CRUX** : SAMPLE PREPARATION

≡ RAD. NUCLIDES IN **METALLIC** ENVIRONMENT

# THE 4 CASES

LOOK FOR DECAYS WITH SMALL Q-VALUES

1. ELECTRON-CAPTURE

$$f = \left(\frac{Q - U_D}{Q}\right)^2 < 1$$

LONGER $T_{1/2}$

2. BETA - MINUS

$$f = \left(\frac{Q - U_D}{Q}\right)^5 < 1$$

LONGER $T_{1/2}$

3. BETA - PLUS

$$f = \left(\frac{Q + U_D}{Q}\right)^5 > 1$$

SHORTER $T_{1/2}$

4. ALPHA-DECAY

$$f = \exp\left(\pi \eta \frac{U_D}{Q}\right) \gg 1$$

SHORTER $T_{1/2}$

# THE 4 CASES

LOOK FOR DECAYS WITH SMALL Q-VALUES

1. ELECTRON-CAPTURE — $^{7}Be$ ✓

$$f = \left(\frac{Q-U_D}{Q}\right)^2 < 1$$

LONGER $T_{1/2}$

2. BETA - MINUS — $^{198}Au$ ✓

$$f = \left(\frac{Q-U_D}{Q}\right)^5 < 1$$

LONGER $T_{1/2}$

3. BETA - PLUS — $^{22}Na$ ✓

$$f = \left(\frac{Q+U_D}{Q}\right)^5 > 1$$

SHORTER $T_{1/2}$

4. ALPHA - DECAY — $^{210}Po$ ✓

$$f = \exp\left(\pi \eta \frac{U_D}{Q}\right) \gg 1$$

SHORTER $T_{1/2}$

# THE 4 CASES

LOOK FOR DECAYS WITH SMALL Q-VALUES

1. ELECTRON-CAPTURE — $^{7}Be$ (0.9%)

$$f = \left(\frac{Q - U_D}{Q}\right)^2 < 1$$

LONGER $T_{1/2}$

2. BETA - MINUS — $^{198}Au$ (4.0%)

$$f = \left(\frac{Q - U_D}{Q}\right)^5 < 1$$

LONGER $T_{1/2}$

3. BETA - PLUS — $^{22}Na$ (1.2%)

$$f = \left(\frac{Q + U_D}{Q}\right)^5 > 1$$

SHORTER $T_{1/2}$

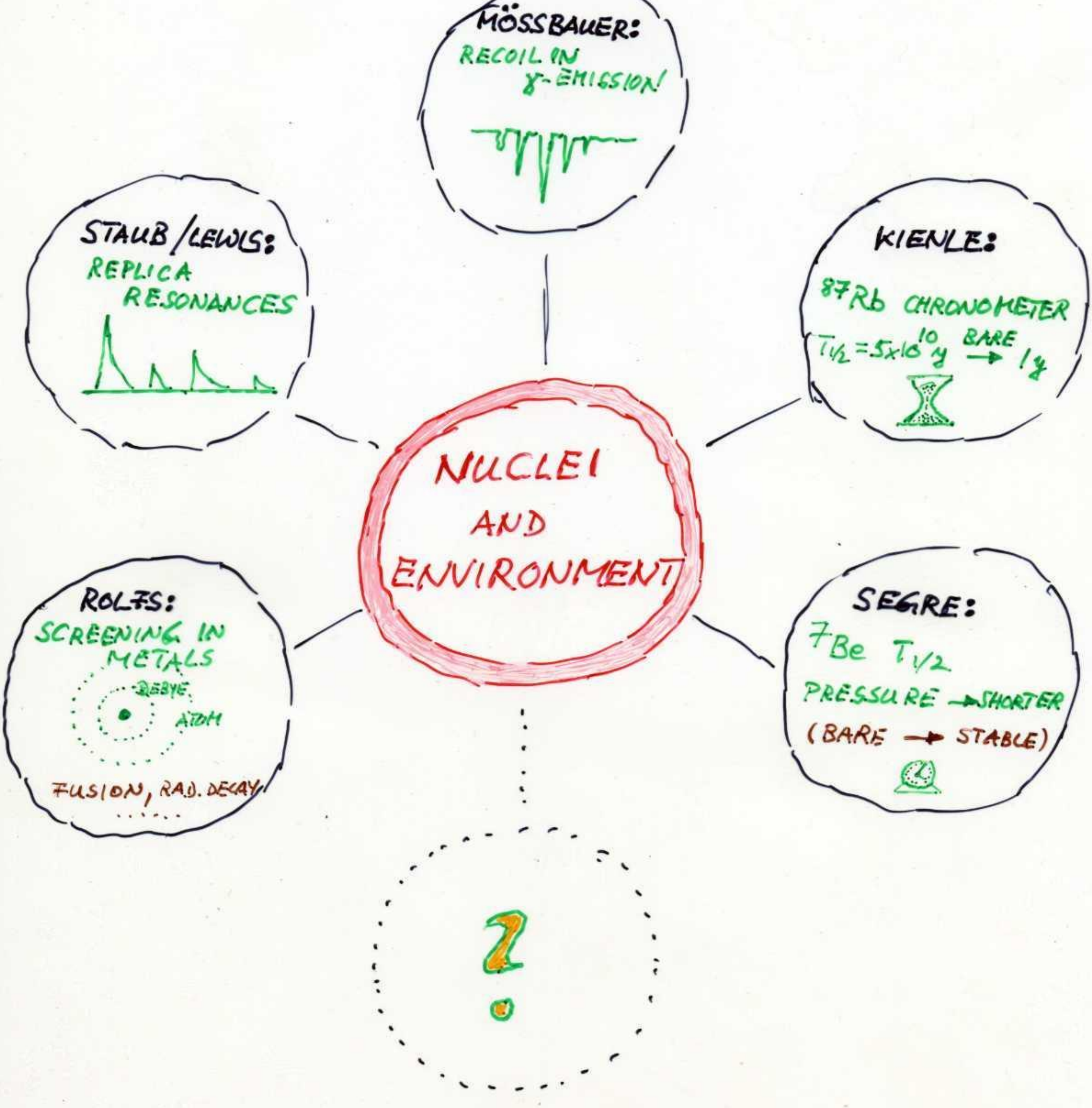
4. ALPHA-DECAY — $^{210}Po$ (25%)

$$f = \exp\left(\pi \eta \frac{U_D}{Q}\right) \gg 1$$

SHORTER $T_{1/2}$

1994: REIFENSCHWEILER — $^{3}H$ (40%)

1992: ZASTAWNY — $^{210}Po$ (300%)


MÖSSBAUER:
RECOIL IN γ-EMISSION!
STAUB / LEWIS:
REPLICA RESONANCES
KIENLE:
87Rb CHRONOMETER
T1/2 = 5x10^10 y BARE → 1 y
NUCLEI AND ENVIRONMENT
ROLFS:
SCREENING IN METALS
DEBYE
ATOM
FUSION, RAD. DECAY
SEGRE:
7Be T1/2
PRESSURE → SHORTER
(BARE → STABLE)
?