The $^{12}C+^{12}C$ key reaction for astrophysics applications

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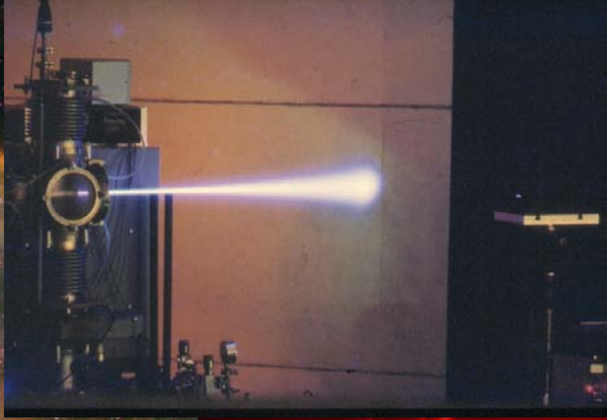
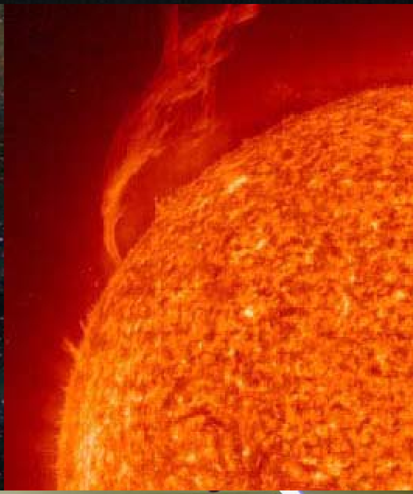




Outline of this Presentation

The $^{12}C+^{12}C$ key reaction for astrophysics applications

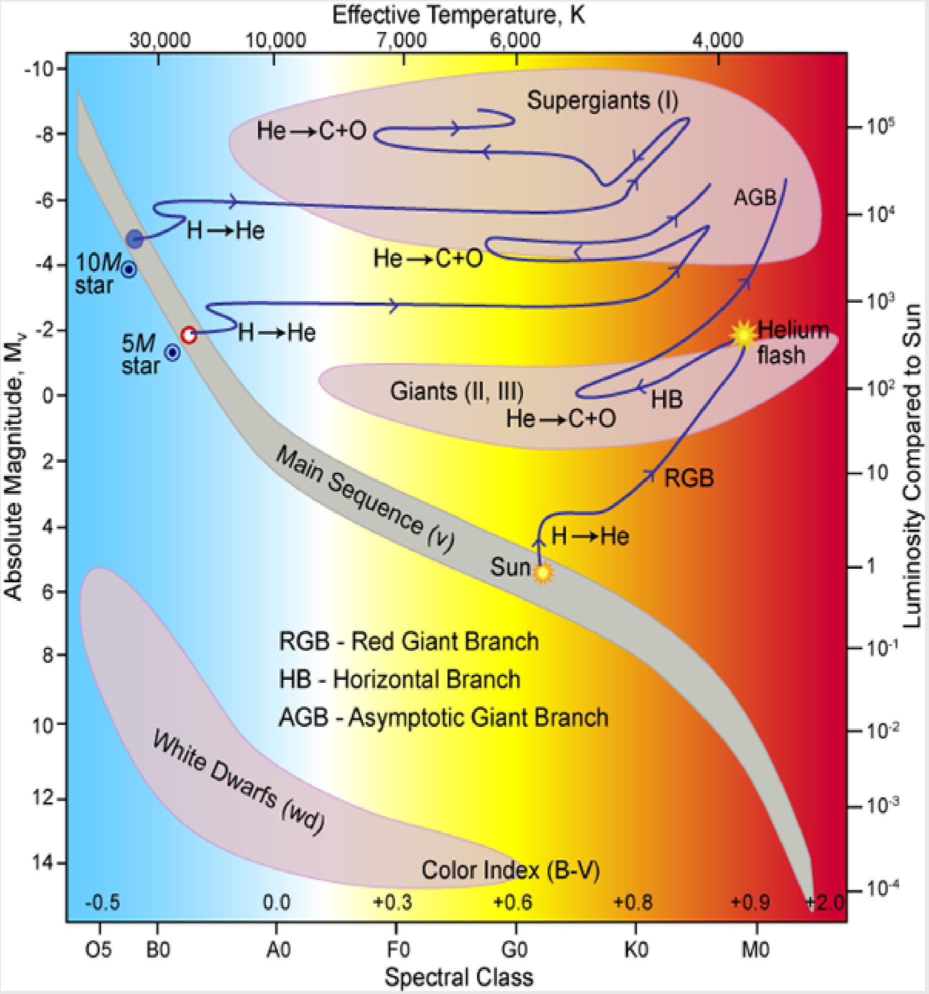
- Astrophysical Motivation – Carbon Burning

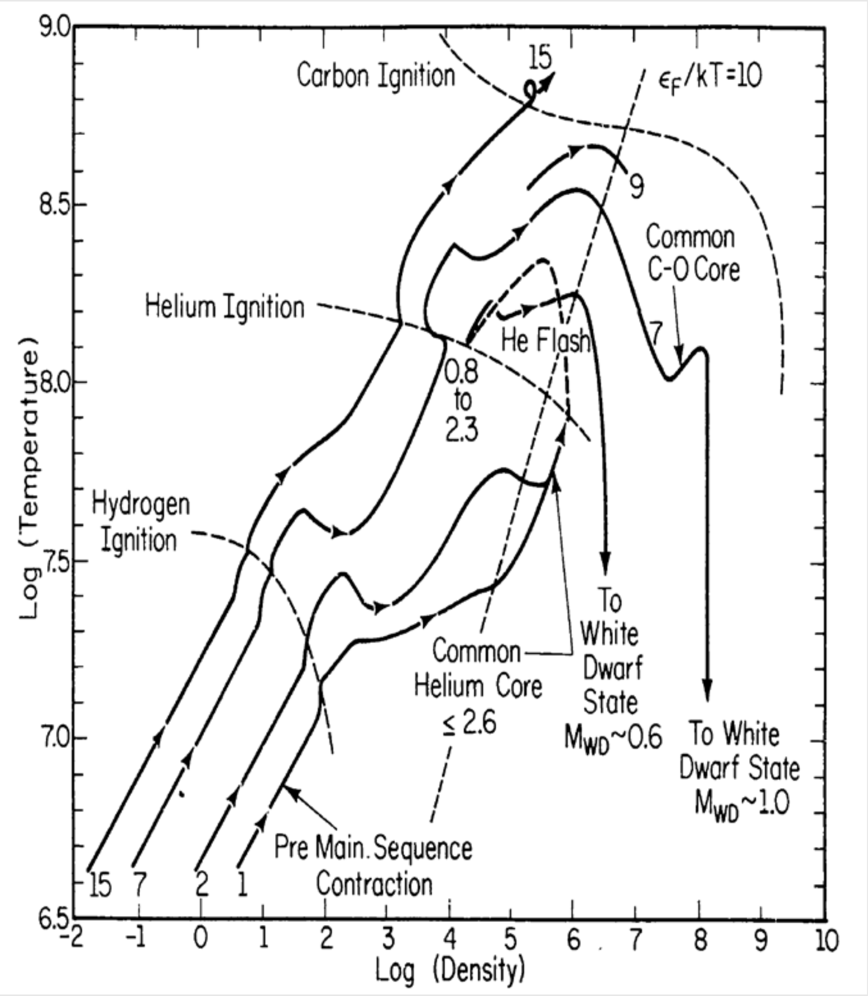
- The Carbon Fusion - ^{12}C + ^{12}C - recent experiments
  $\rightarrow$ experimental problems and difficulties
  $\rightarrow$ extrapolation
  $\rightarrow$ robustness of data

- Recommendations for future experments

Motivation

Nucleosynthesis → Stellar Evolution





Astrophysical Motivation $^{12}C + ^{12}C$ fusion

Results of current Stellar Models suggest:

$M_{up} \equiv$ minimum mass for carbon ignition

- **Stars with $M < M_{up}$ (presently $8M_{solar}$)**
  These stars shed their H-rich envelopes during He burning (AGB phase) and end as CO White Dwarfs

*→ **Impact on the Nucleosynthesis and the chemical evolution of the Universe***

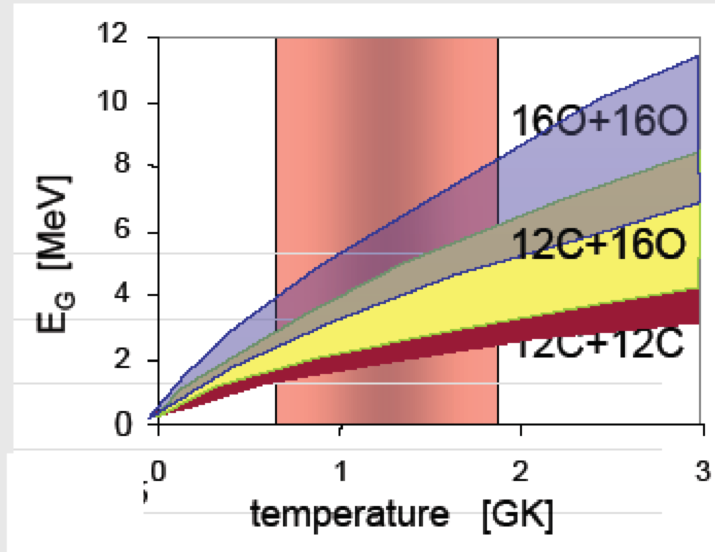
*→ **the expected observational rates for Supernovae and Novae depend on the fundamental mass limits M_{up} and M'_{up} and, thus on the $^{12}C+^{12}C$ reaction rates***

- **Stars with $M > M'_{up}$**
  Ignition of central <u>carbon burning</u> followed by Ne, O, and Si burning. The subsequent evolution proceeds in most cases to a core collapse Supernova.
  → These stars make the bulk of newly processed matter that is returned to the ISM.

Carbon Burning in Stars

Wide range of possible heavy ion reactions – at low energies most important:

$^{12}C + {}^{12}C$ (lowest Coulomb Barrier)

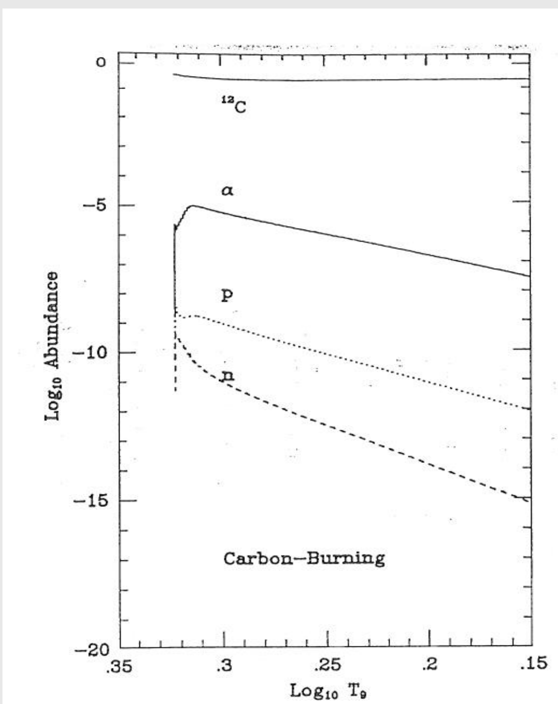


$^{12}C(^{12}C,p)^{23}Na$ Q = 2.240 MeV

$^{12}C(^{12}C,\alpha)^{20}Ne$ Q = 4.617 MeV

$^{12}C(^{12}C,n)^{23}Mg$ Q = -2.598 MeV

$E_G = 2.42\times T_9^{2/3} \pm 0.75\times T_9^{5/6}$



The $^{12}C+^{12}C$ fusion reactions produce light elements; their abundances stay relatively low and reflect the rate ratio of the reactions destroying them and of $^{12}C+^{12}C$.

Nucleosynthese in surrounding burning shell

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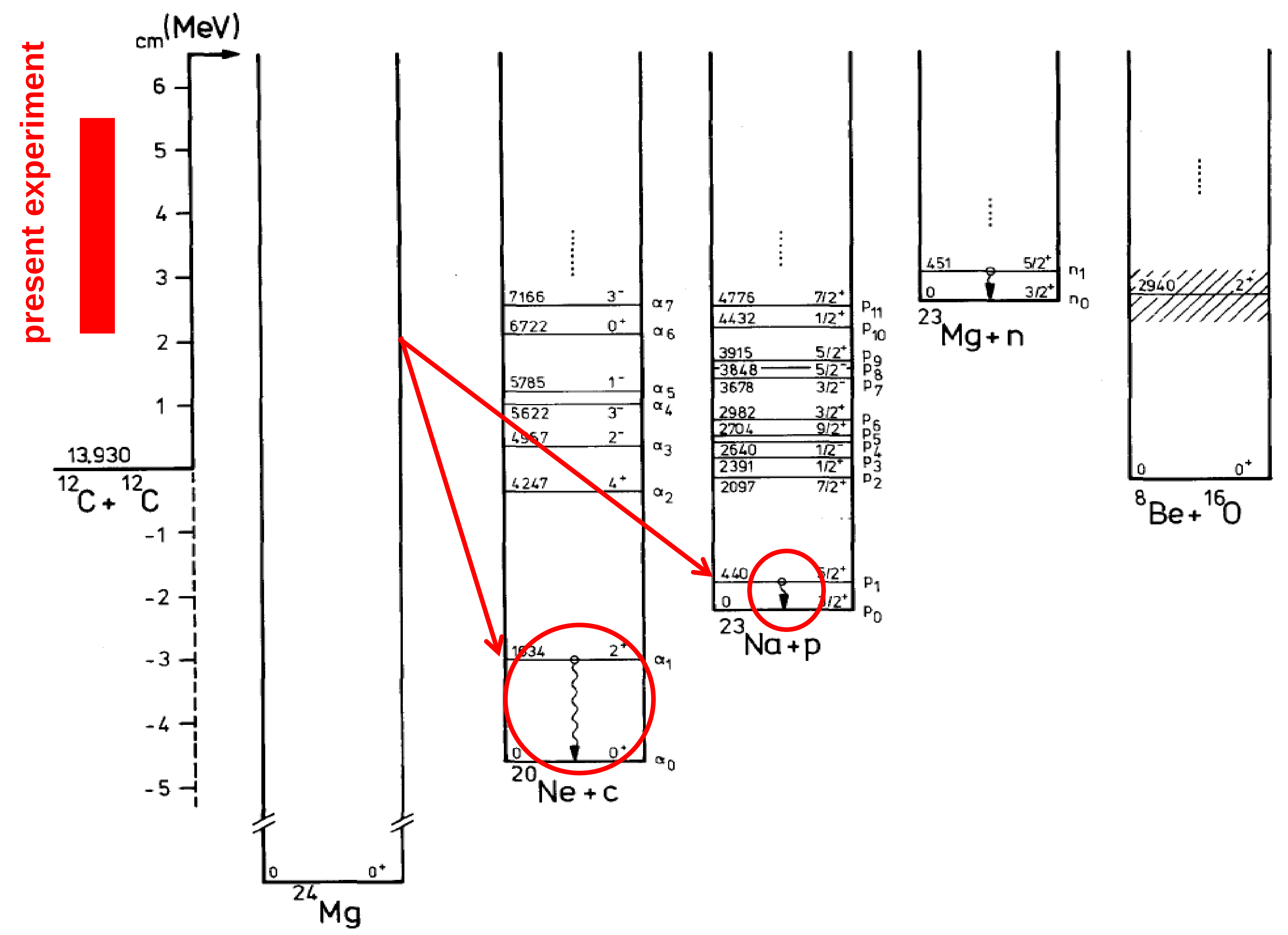
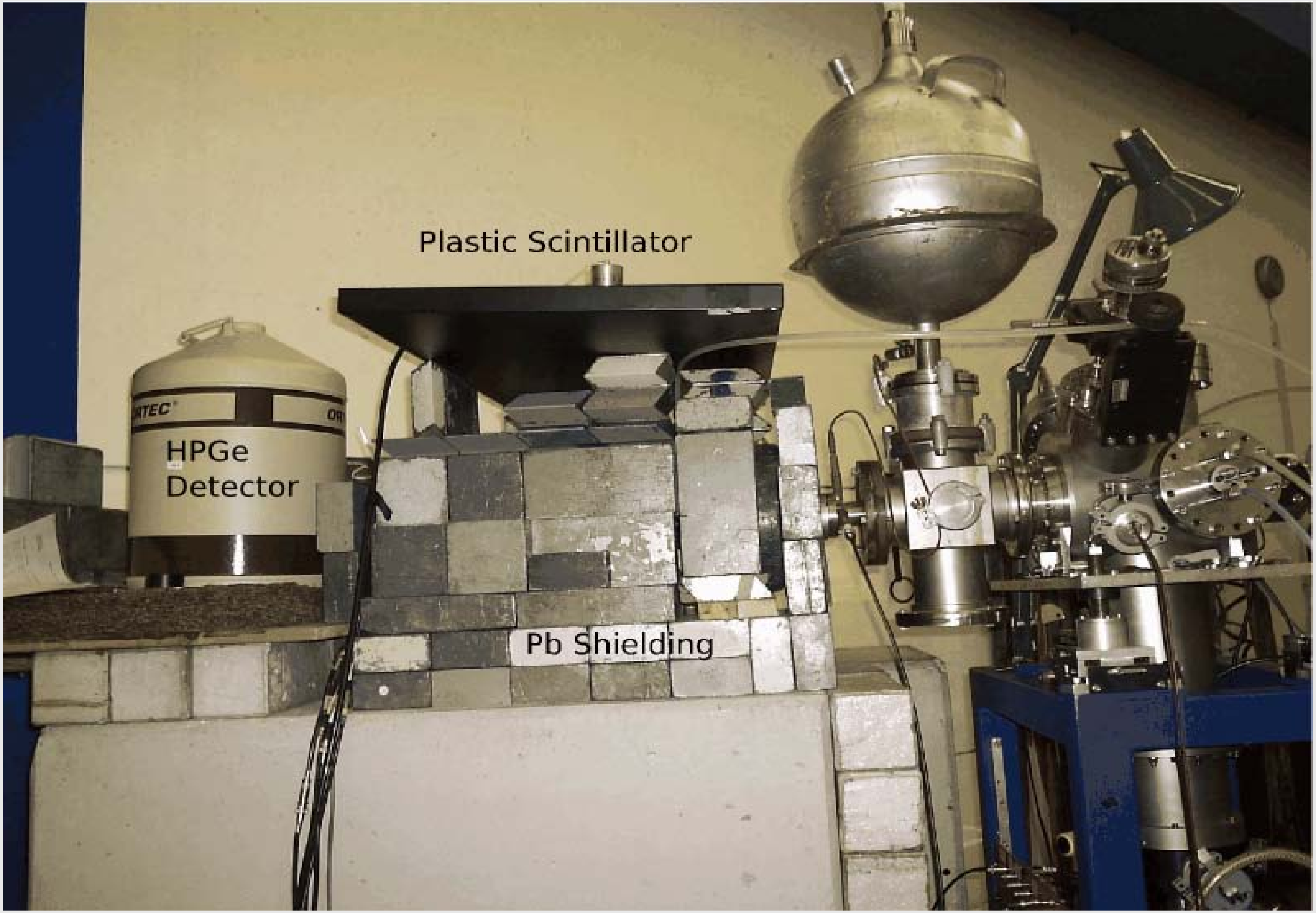
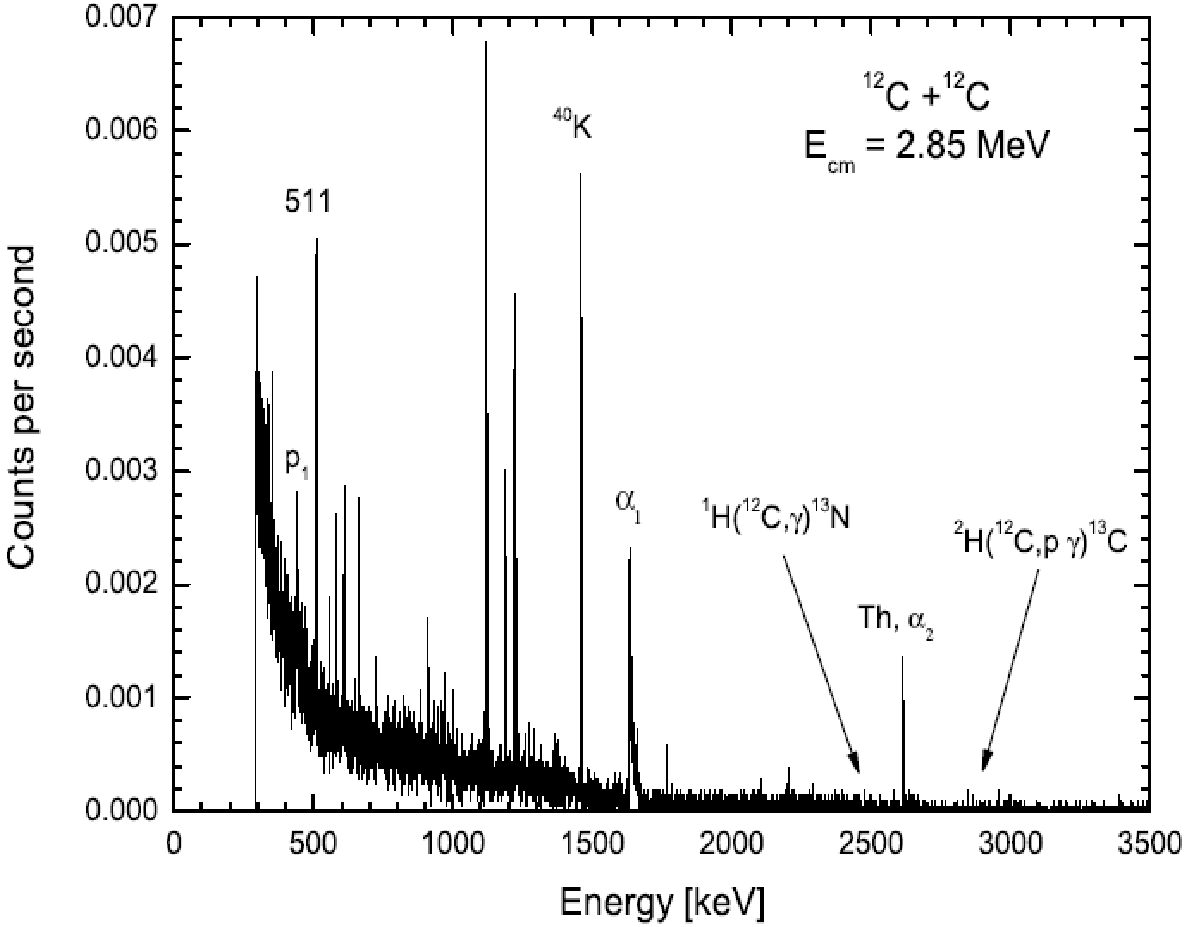
Level Scheme - γ-ray spectroscopy

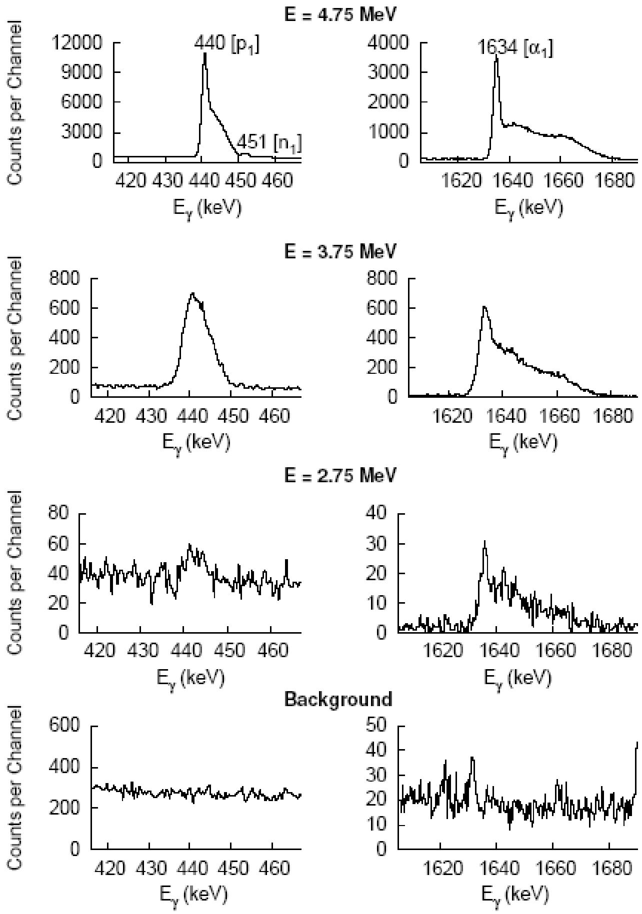


Experimental Setup - γ-ray spectroscopy



Experimental Results - γ-ray spectroscopy



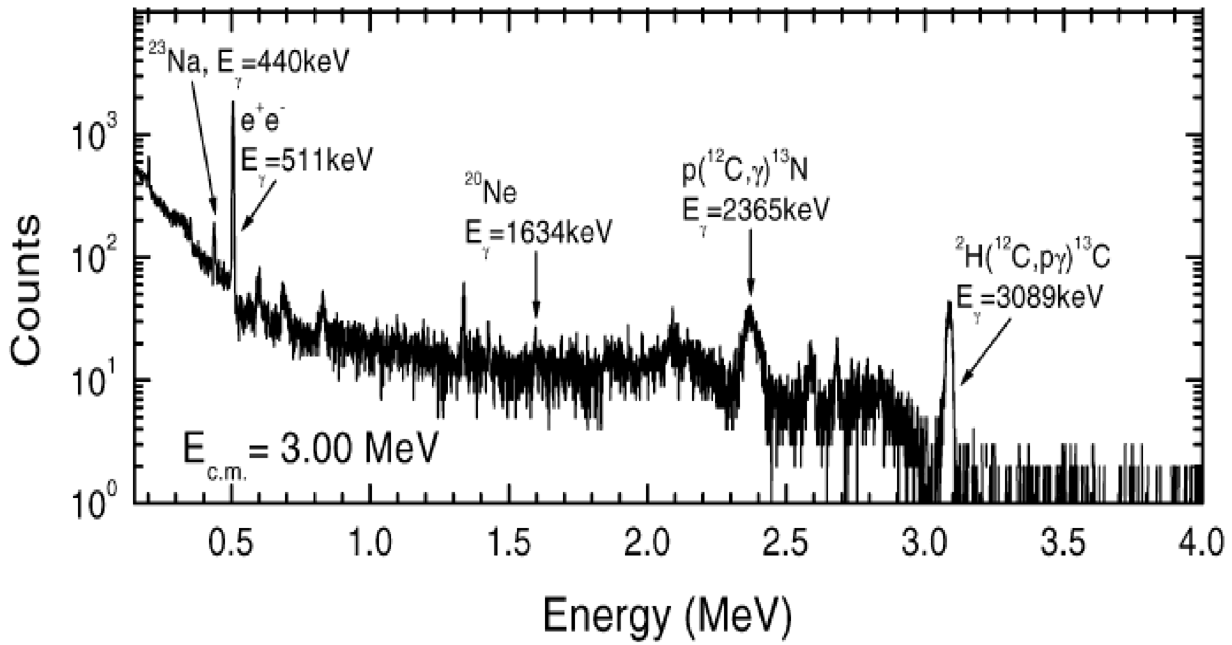


Spillane et al., PRL 98, 122501 (2007)

Experimental Results - γ-ray spectroscopy

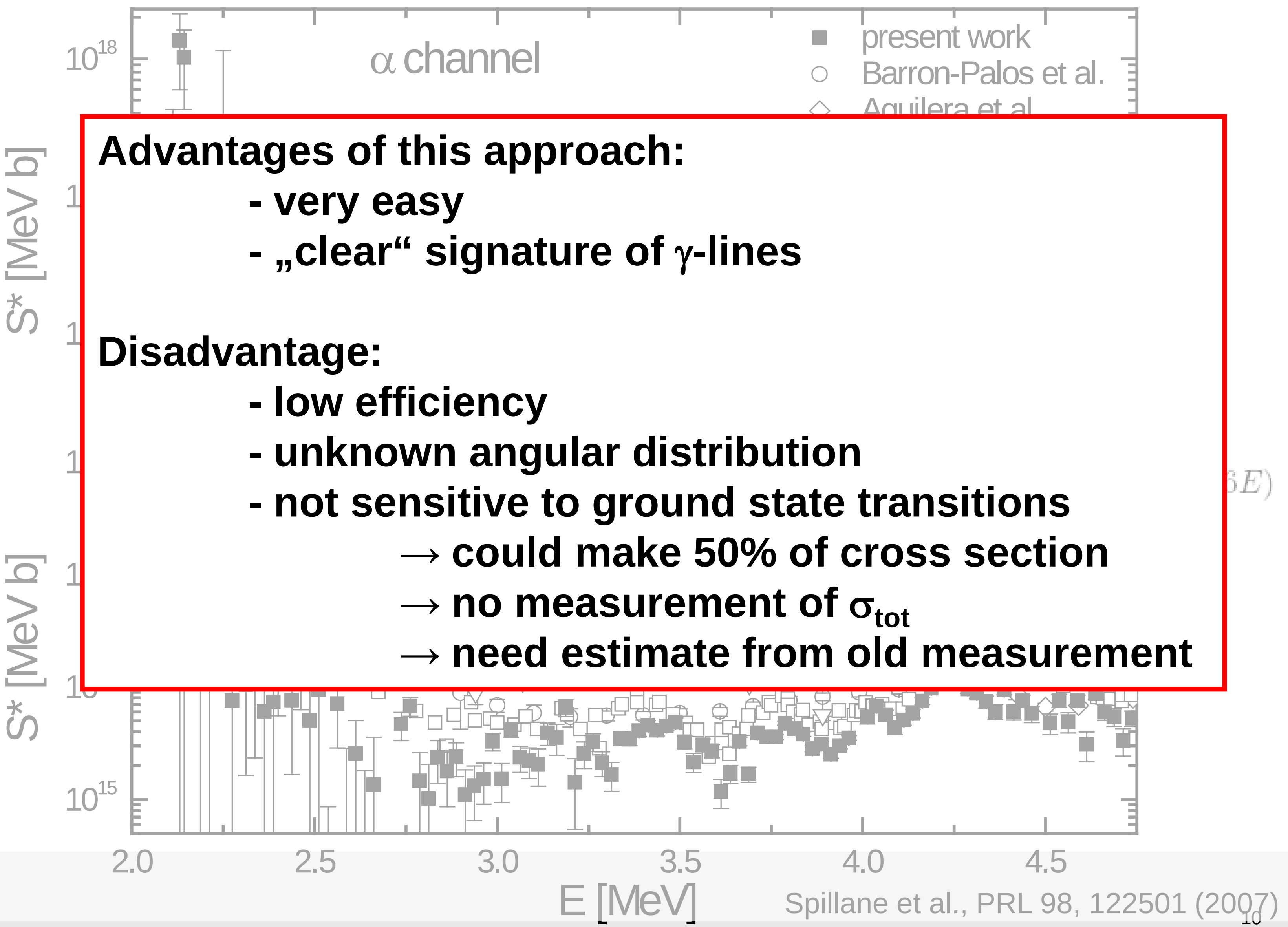
very important feature of this experiment: low hydrogen content in target

comparison of γ-ray spectra with earlier experiments



Baron-Palos et al., NPA 779 (2006) 318

Experimental Results - γ-ray spectroscopy



Advantages of this approach:

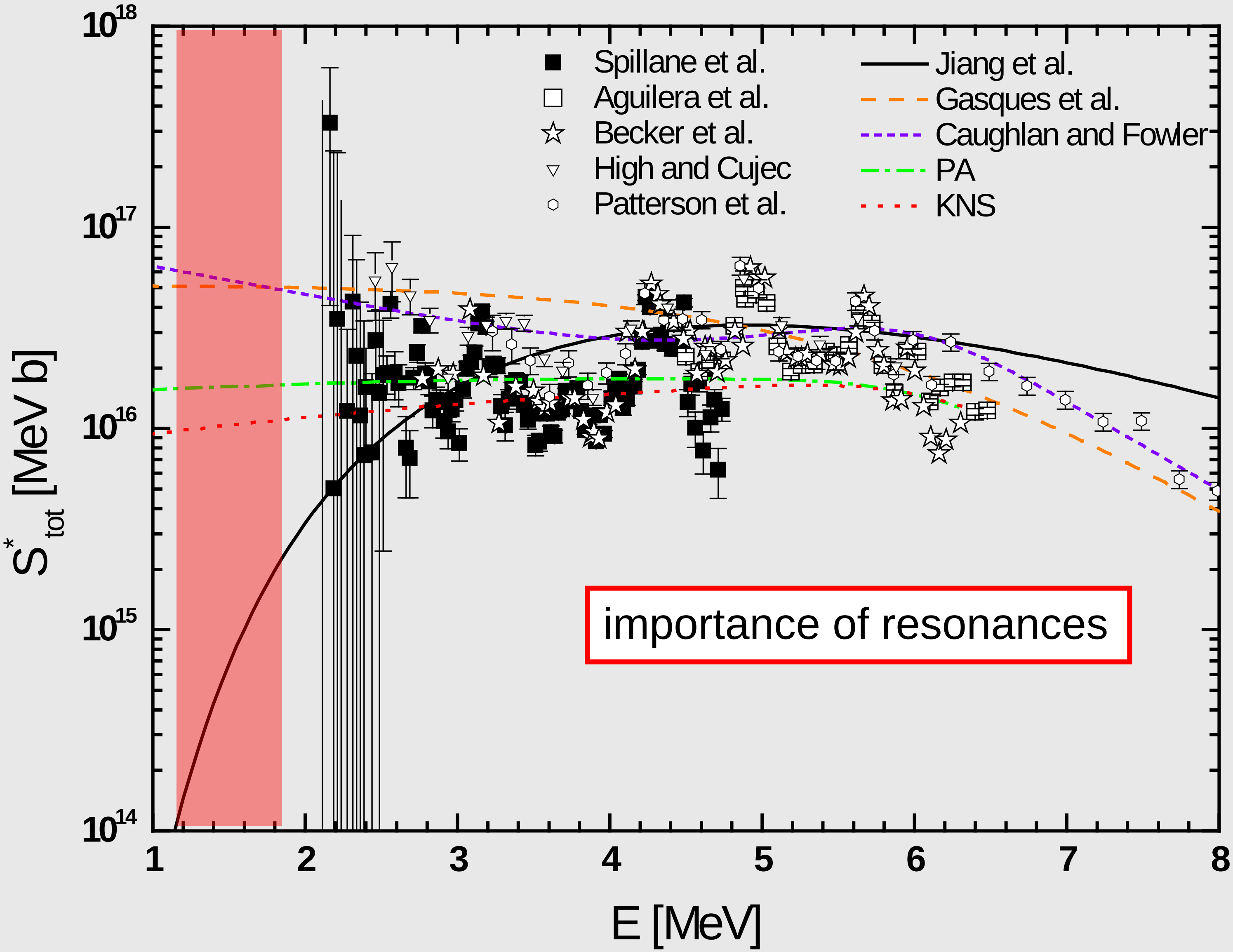
- **very easy**
- **„clear“ signature of γ-lines**

Disadvantage:

- **low efficiency**
- **unknown angular distribution**
- **not sensitive to ground state transitions**
  - **→ could make 50% of cross section**
  - **→ no measurement of σ_{tot}**
  - **→ need estimate from old measurement**

Spillane et al., PRL 98, 122501 (2007)

Experimental Results – total S-factor



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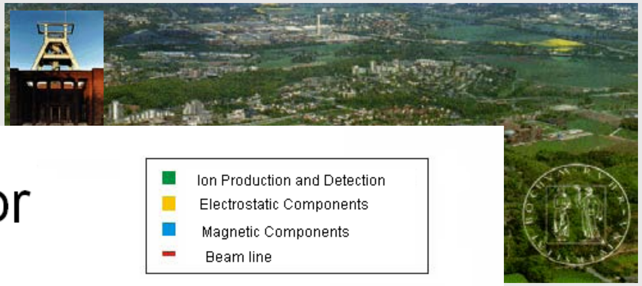
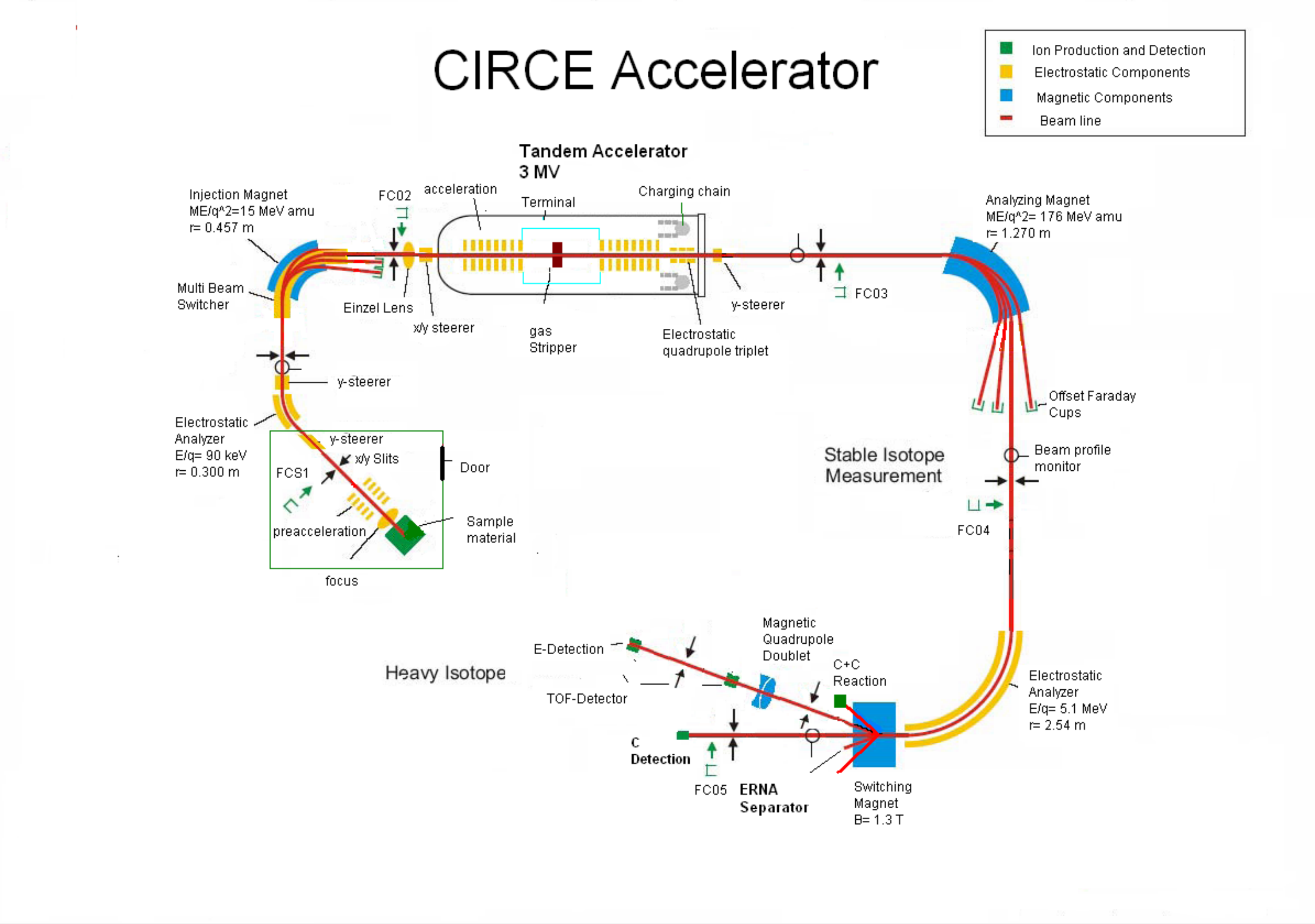
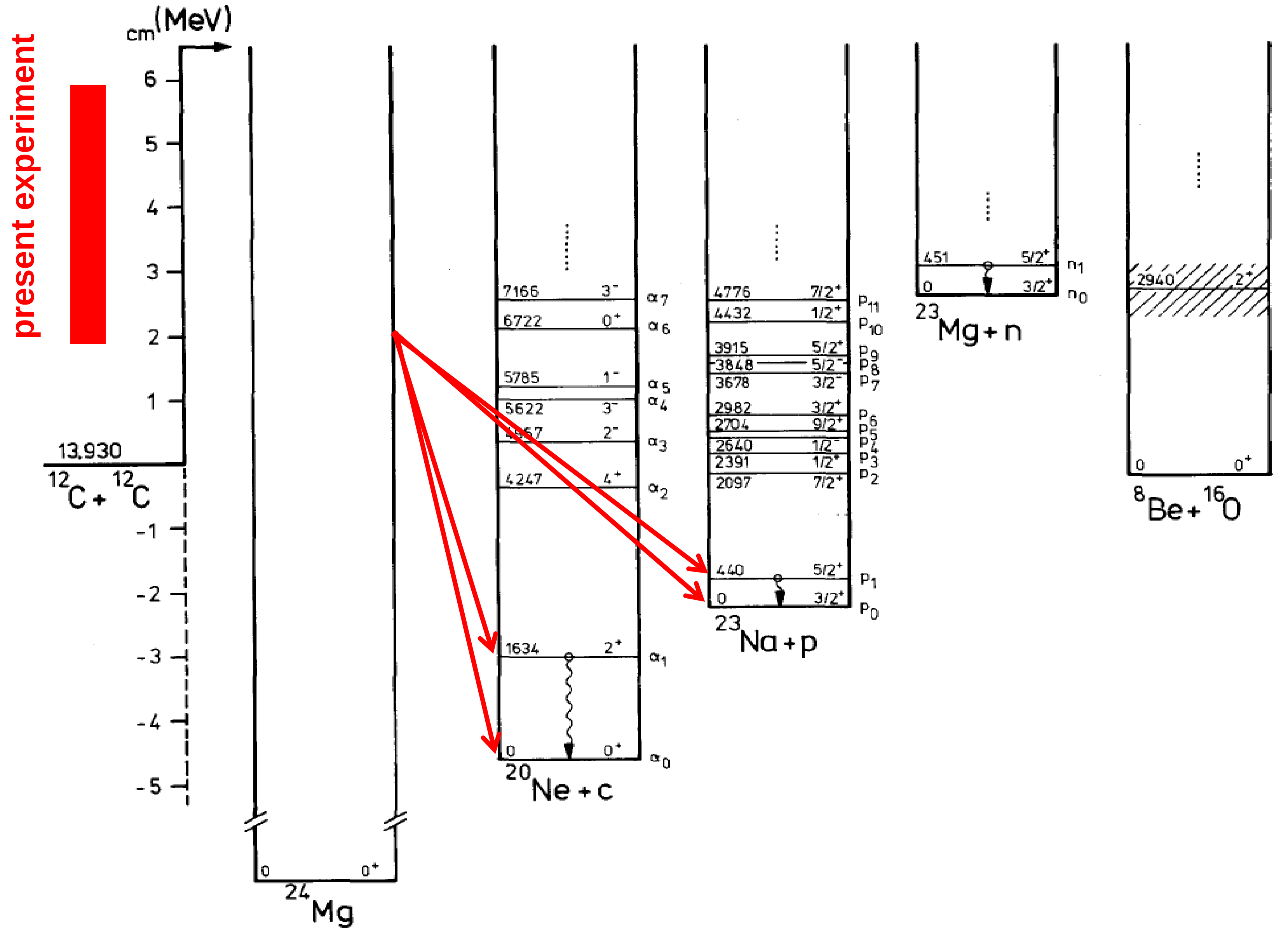
natural next step

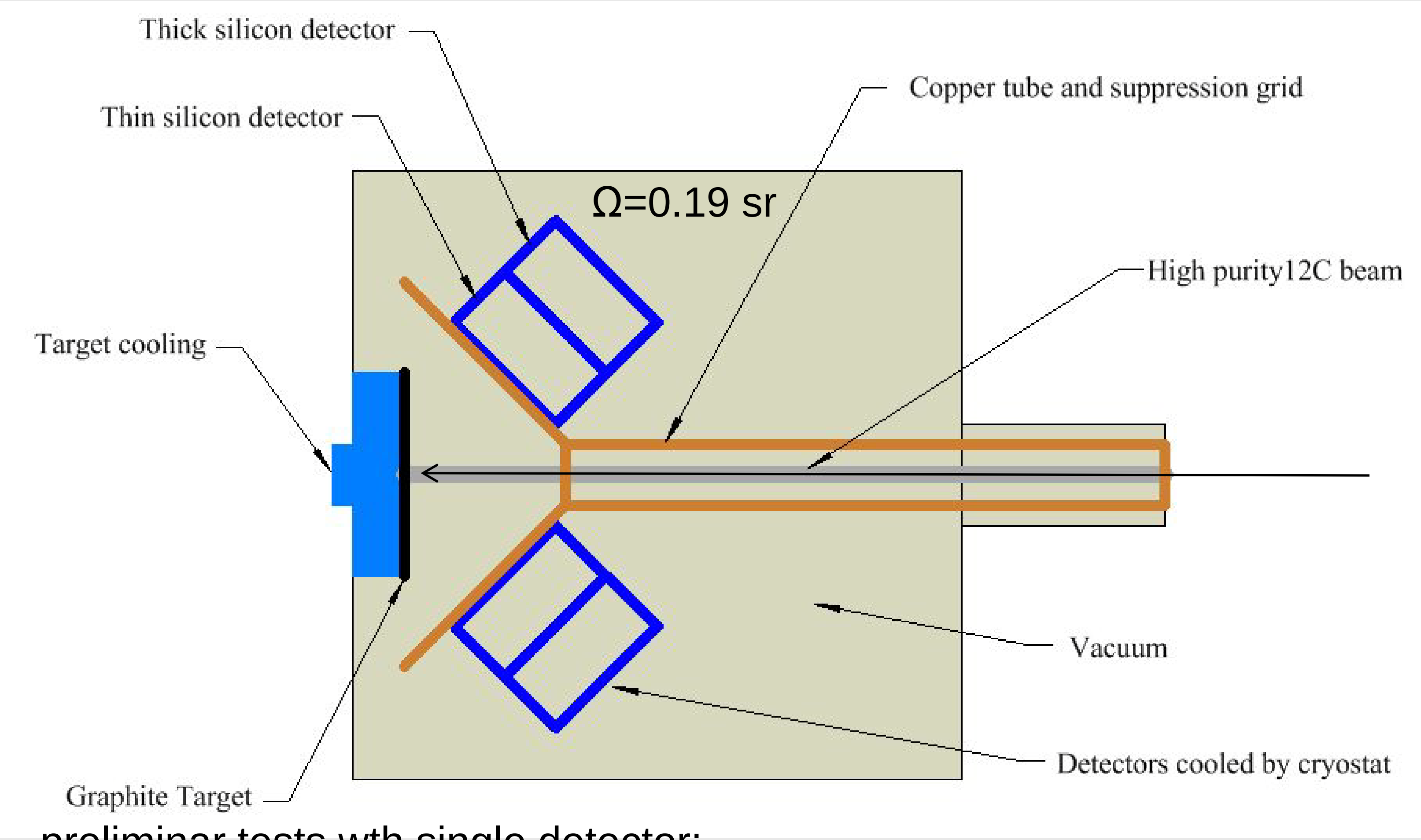




Level Scheme - particle spectroscopy



Experimental Setup - particle spectroscopy

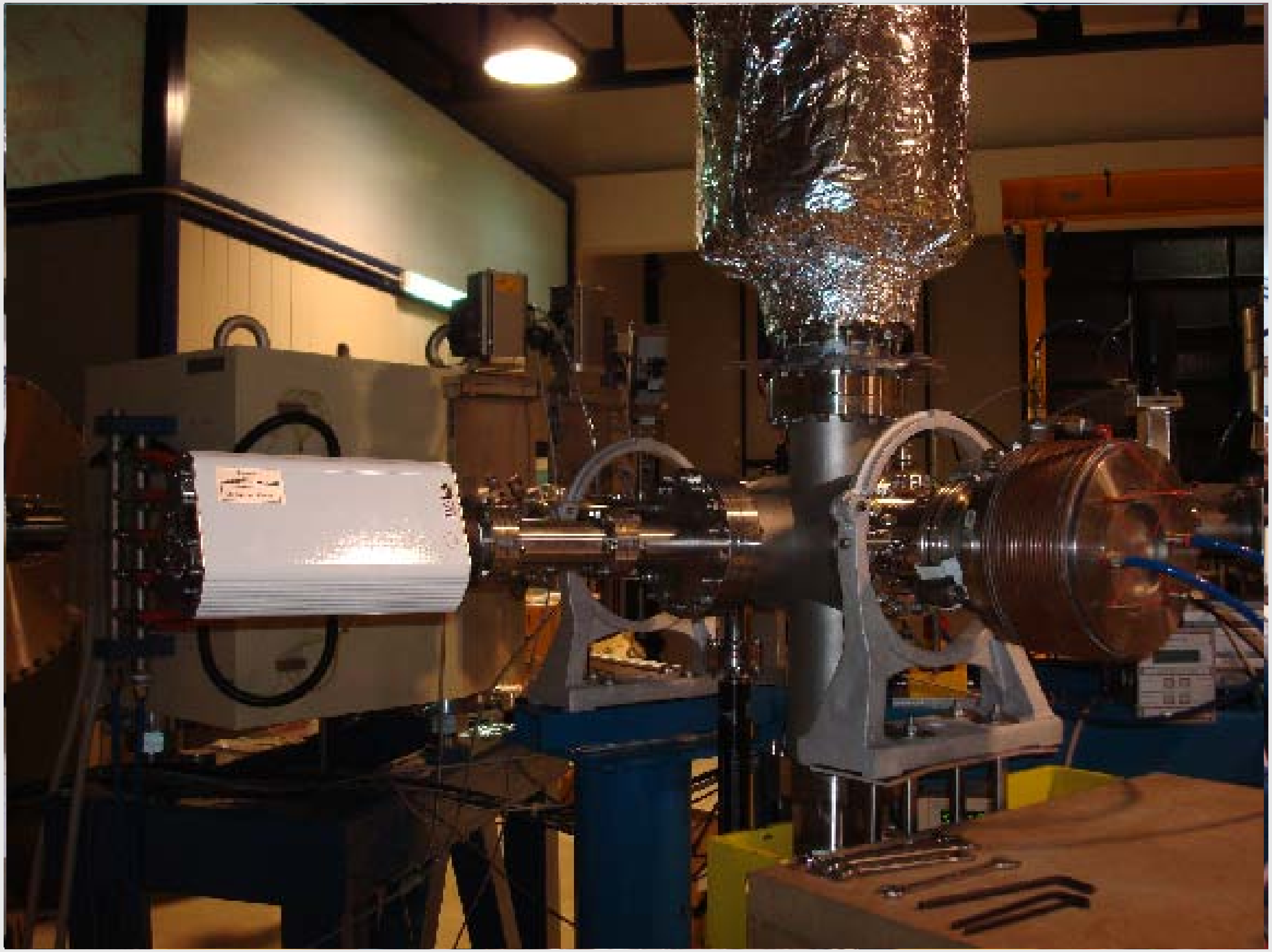


preliminar tests wth single detector:

→ beam induced background
too high at lower energies

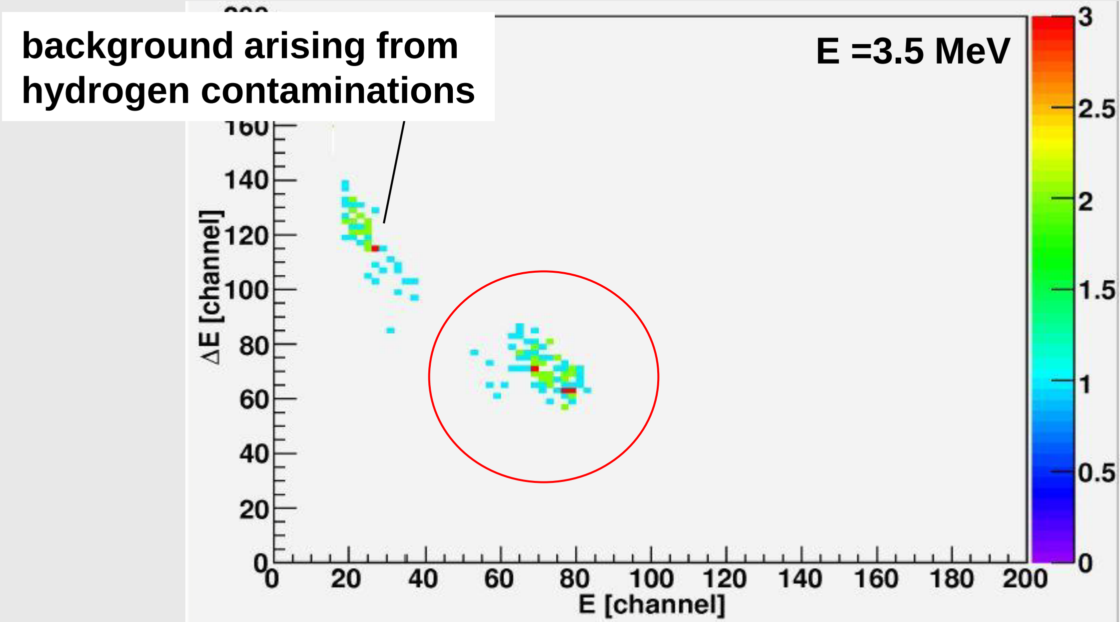
→ ΔE-E particle detector telescope

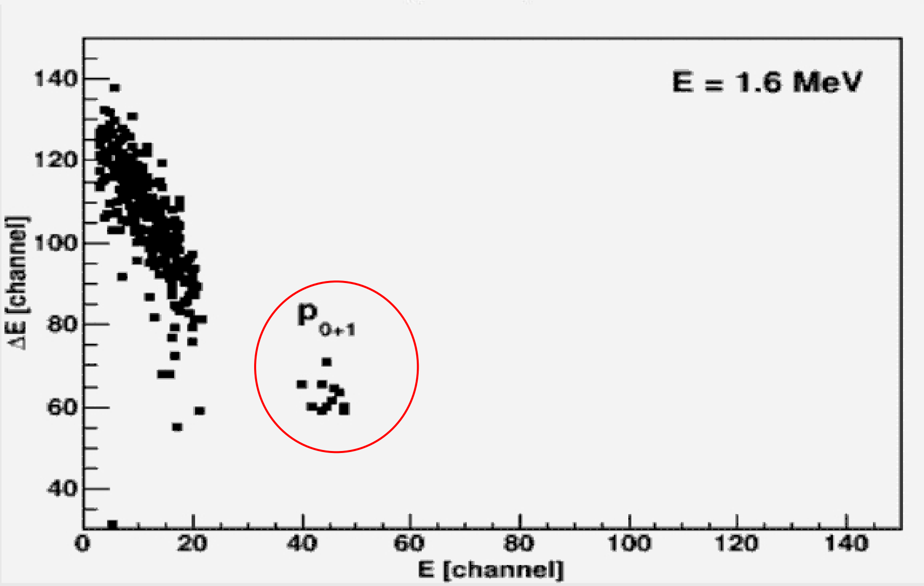
Experimental Setup - particle spectroscopy



Completely separate detector volume from target using foils and sheet metal
→ Target sputtering causing large leak currents on silicon detectors

Experimental Results - particle spectroscopy





first phase:

- only p channel is detected
- $^{12}C(^{12}C,p_{0,1})^{23}Na$
- ΔE detector too thick
- α particles are stopped
- background tests

second phase:

- $^{12}C(^{12}C,\alpha_{0,1})^{20}Ne$ with Bragg curve detector

Background Considerations

disadvantage of particle spectroscopy:

very poor energy resolution
from kinematics as well as experimental technique

→ background discrimination not as „easy“ as for γ-ray spectroscopy

→ test with various beams and targets (^{7}Li, ^{9}Be, ^{10,11}B, ^{13}C)

no impact observed so far

but:

water, i.e. deuterium, remains as a huge problem

Background Considerations

in γ-ray spectroscopy measurements main source of background

$^{12}C(d,\mathbf{p}\gamma)^{13}C$ or $d(^{12}C,\mathbf{p}\gamma)^{13}C$

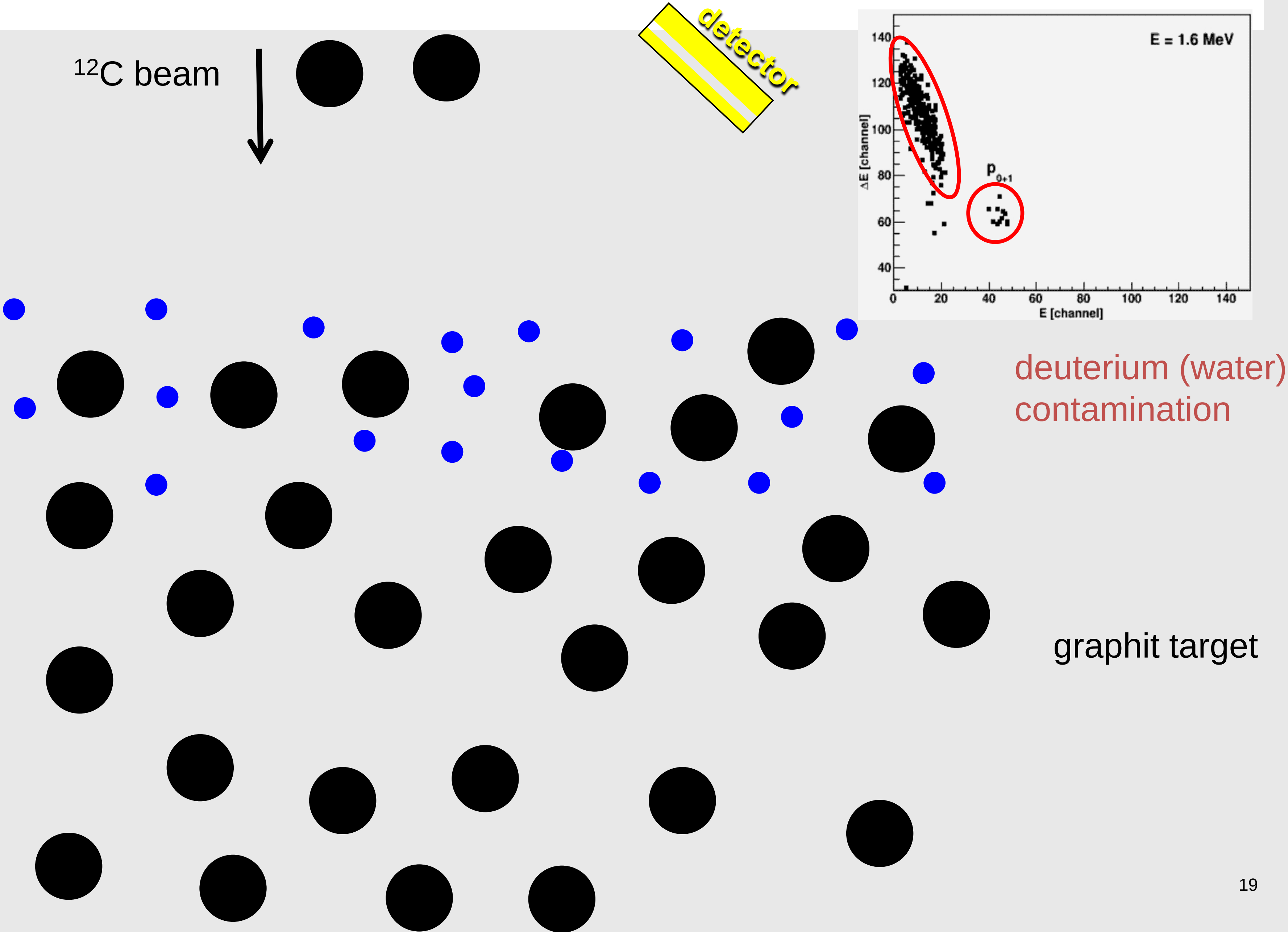
→ Proton from this contaminat reaction too low in energy

but:

→ Elastic scattering under forward anlges $d(^{12}C,d)^{12}C$

→ followed by $^{12}C(d,\mathbf{p}\gamma)^{13}C$, but then at <u>higher</u> CM energy

Background Considerations



Background Considerations

in γ-ray spectroscopy measurements main source of background

^{12}C(d,pγ)^{13}C or d(^{12}C,pγ)^{13}C

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but:

→ Elastic scattering under forward anlges d(^{12}C,d)^{12}C

→ followed by ^{12}C(d,pγ)^{13}C, but then at higher CM energy

→ higher proton energy, in the region of ^{12}C(^{12}C,**p**)^{23}Na (!!!!)

→ checked with ^{16}O beam (advantage: contamination can be monitored)

Background Considerations

in γ-ray spectroscopy main source of background $^{12}C(d,p\gamma)^{13}C$ or $d(^{12}C,p\gamma)^{13}C$

Improvements:

→ all vacuum components in CF – on vacuum level of 10^{-7} mbar a build up of water is likely, at 10^{-9} mbar sputtering is fast than the build up

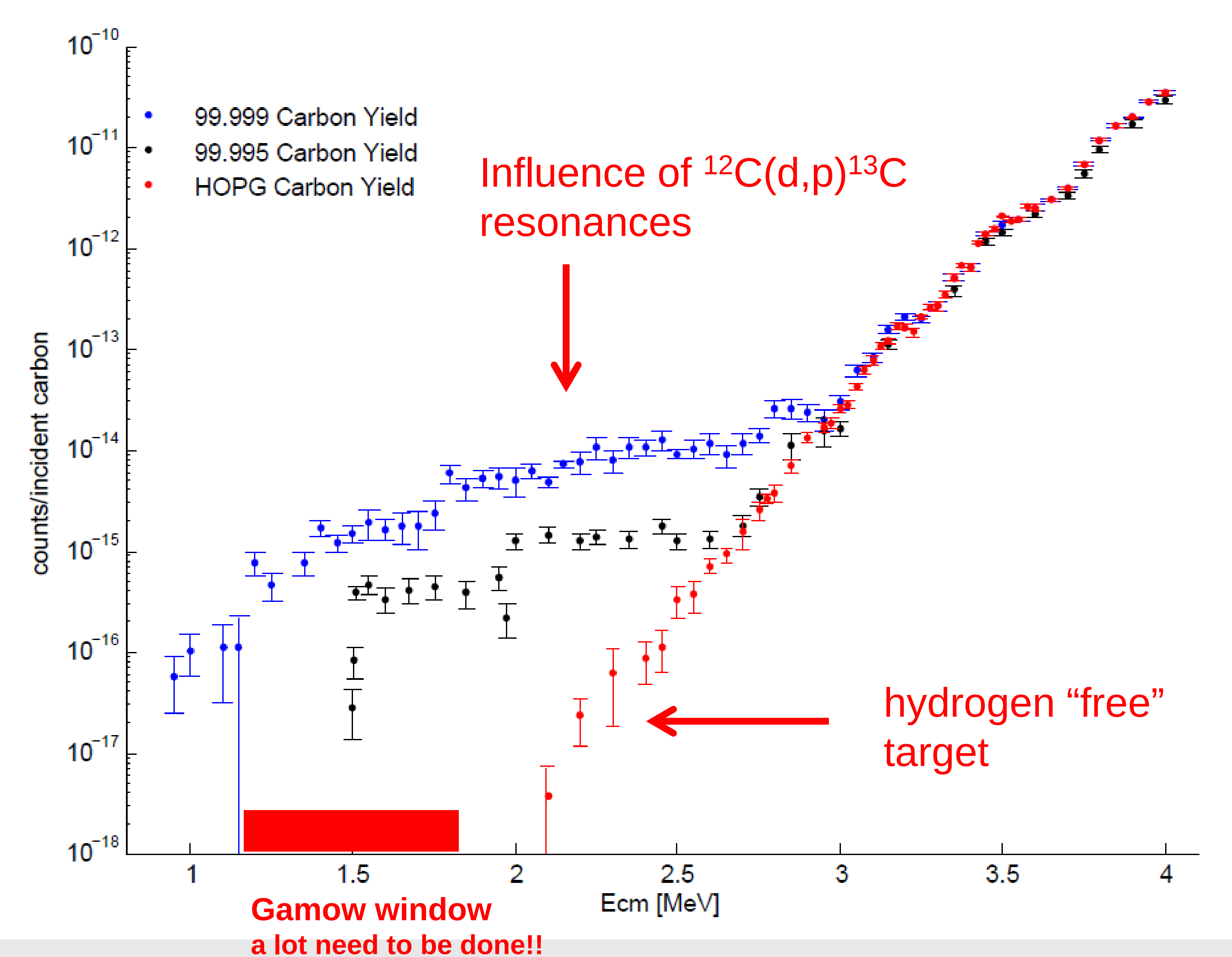
→ „radon“ box: experimental setup closed in a box flushed with argon suppression of hydrogen and nitrogen (water to a lesser extend)

→ HOPG targets: graphite almost free of hydrogen and oxygen

→ cold trap with liquid nitrogen (suppression of water)

Impact on the α-channel: hydrogen suppression is probably a problem too due to the gas in Bragg detectors, hydrogen in the rest gas cannot be avoided, but most likely there is no similar contamination in the α-channel.
However, you never know before you have done the experiment at such low-level

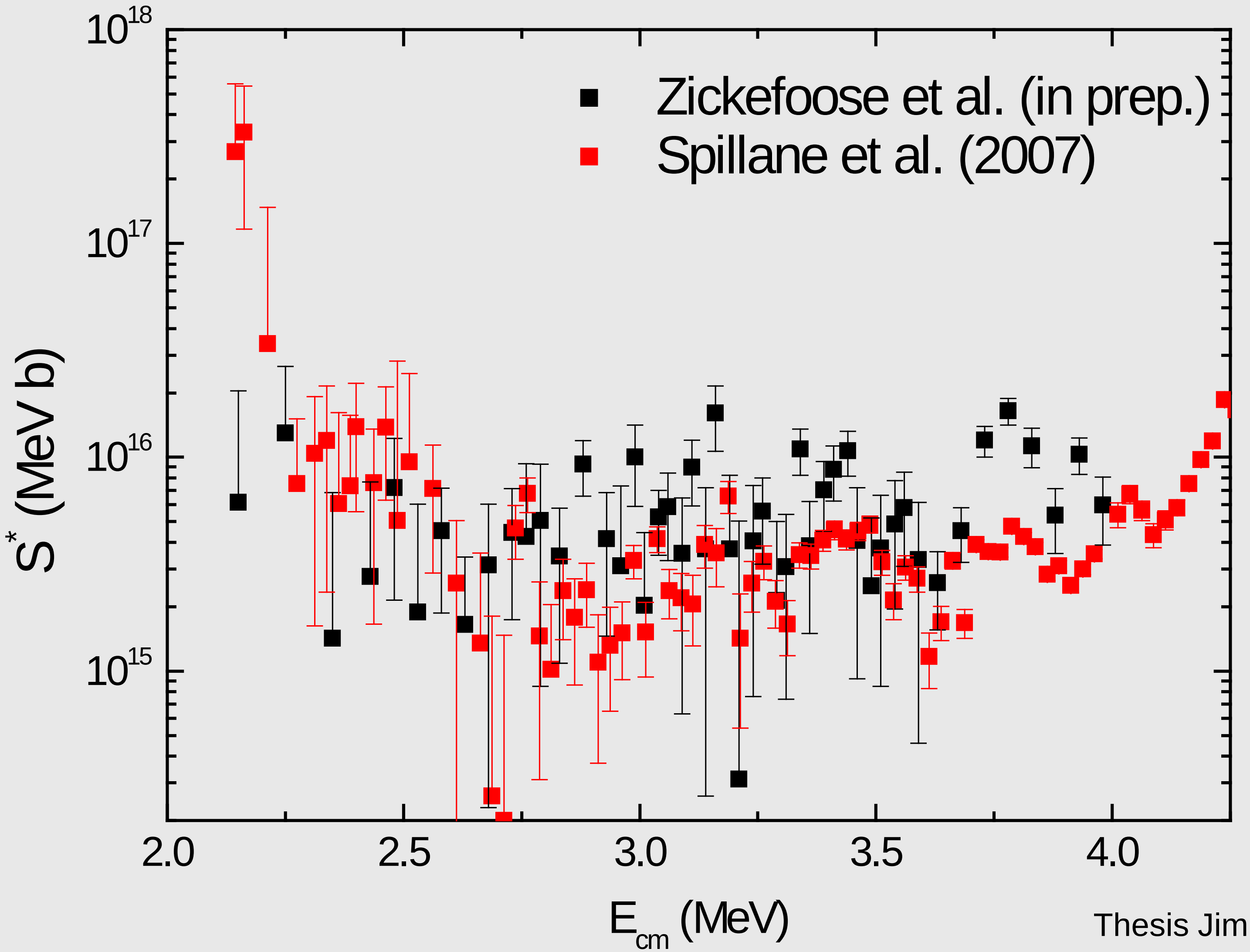
Preliminary New Results (very recent)



Courtesy Jim Zickefoose

RUB

Preliminary results - particle spectroscopy



Thesis Jim Zickefoose

$$\sigma(E) = S(E)^* E^{-1} \exp(-87.21E^{-1/2} - 0.46E)$$

comparison of the two methods

at

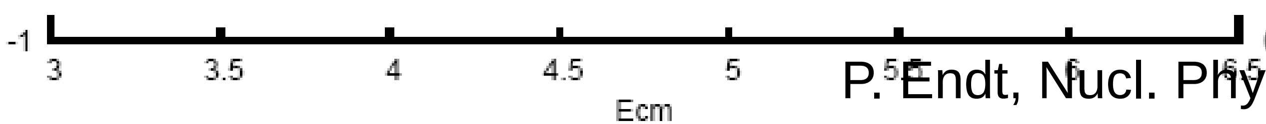
p

^{24}Mg

TABLE 23.10

Branching ratios (in %) of ^{23}Na levels

$2J_i^\pi;2T$	$2J_f^\pi$: E_x	3^+ 0	5^+ 0.44	7^+ 2.08	1^+ 2.39	1^- 2.64	9^+ 2.70
5^+	0.44	100					
7^+	2.08	8.9 *1*	91.1 *1*				
1^+	2.39	65.7 *4*	34.3 *4*				
1^-	2.64	100	< 0.6	< 0.6			
9^+	2.70	< 1	64.9 *8*	35.1 *8*			
3^+	2.98	58.6 *2*	41.1 *2*	< 0.04	0.3 *1*		
3^-	3.68	< 0.3	78.6 *6*	< 2	1.3 *1*	19.6 *5*	< 0.09
5^-	3.85	22.9 *6*	9.5 *9*	61.1 *7*	< 0.3	4.5 *1*	< 0.3
5^+	3.91	79.5 *3*	8.1 *1*	9.0 *2*	1.1 *1*	< 0.07	< 0.7
1^+	4.43	94 *2*			6 *2*		
7^+	4.77	< 1	66.8 *13*	29.4 *12*	< 4	< 2	3.8 *1*



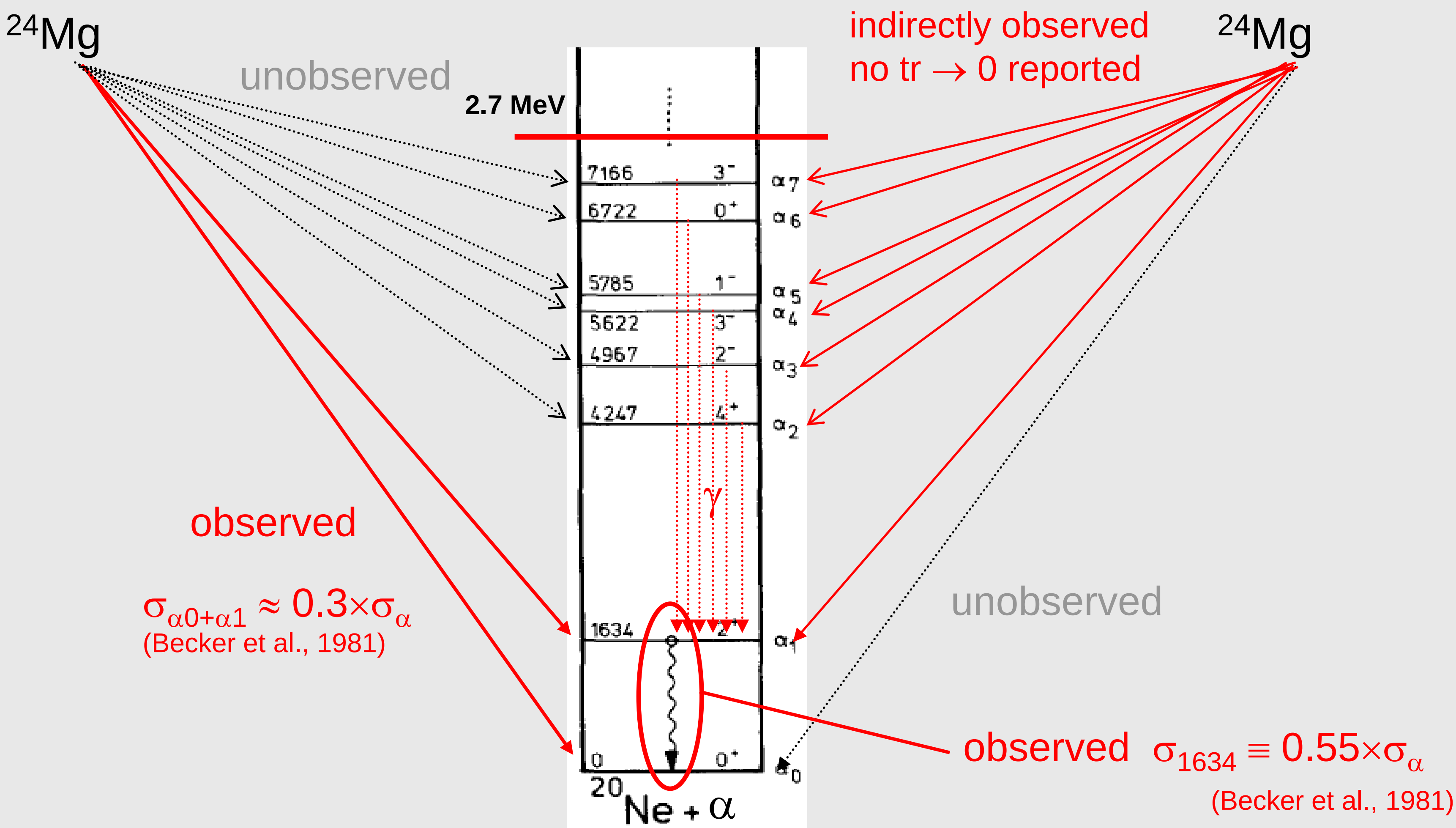
P. Endt, Nucl. Phys. A, 1991

comparison of the two methods

at low energies (below $E \leq 2.7$ MeV)

particle spectroscopy

γ-ray spectroscopy



comparison of the two methods

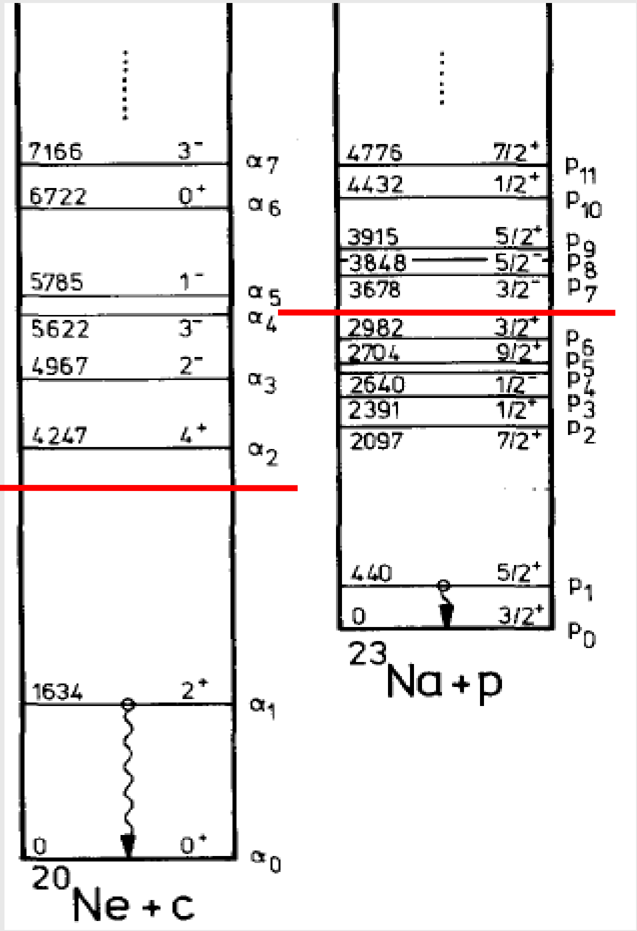
Table 20.18: Radiative decays in ^{20}Ne

E_i (MeV)	$J_i^\pi; T$	E_f (MeV)	Branch (%)
1.63	$2^+; 0$	0	100
4.25	$4^+; 0$	1.63	≈ 100
4.97	$2^-; 0$	0	0.6 ± 0.2
		1.63	99.4 ± 0.2
5.62	$3^-; 0$	0	7.6 ± 1.0
		1.63	87.6 ± 1.0
		4.97	4.8 ± 1.6
5.79	$1^-; 0$	0	18 ± 5
		1.63	82 ± 5
6.73	$0^+; 0$	0	
		1.63	100
7.00	$4^-; 0$	1.63	0.5 ± 0.2
		4.25	13
		4.97	64.5
		5.62	22
7.16	$3^-; 0$	4.25	60 ± 5
		5.79	40 [illegible]

D.R. Tilley[a,b], C.M. Cheves[a,c], J.H. Kelley[a,c], S. Raman[d] and H.R. Weller[a,c] re-analysis of the existing γ-ray spectra from Spillane et al. in progress

transitions which are visible in the spectrum
441 $\rightarrow$ 0
2390 $\rightarrow$ 0
2640 $\rightarrow$ 0
2980 $\rightarrow$ 0

$\rightarrow$ new data
with larger E_γ range needed



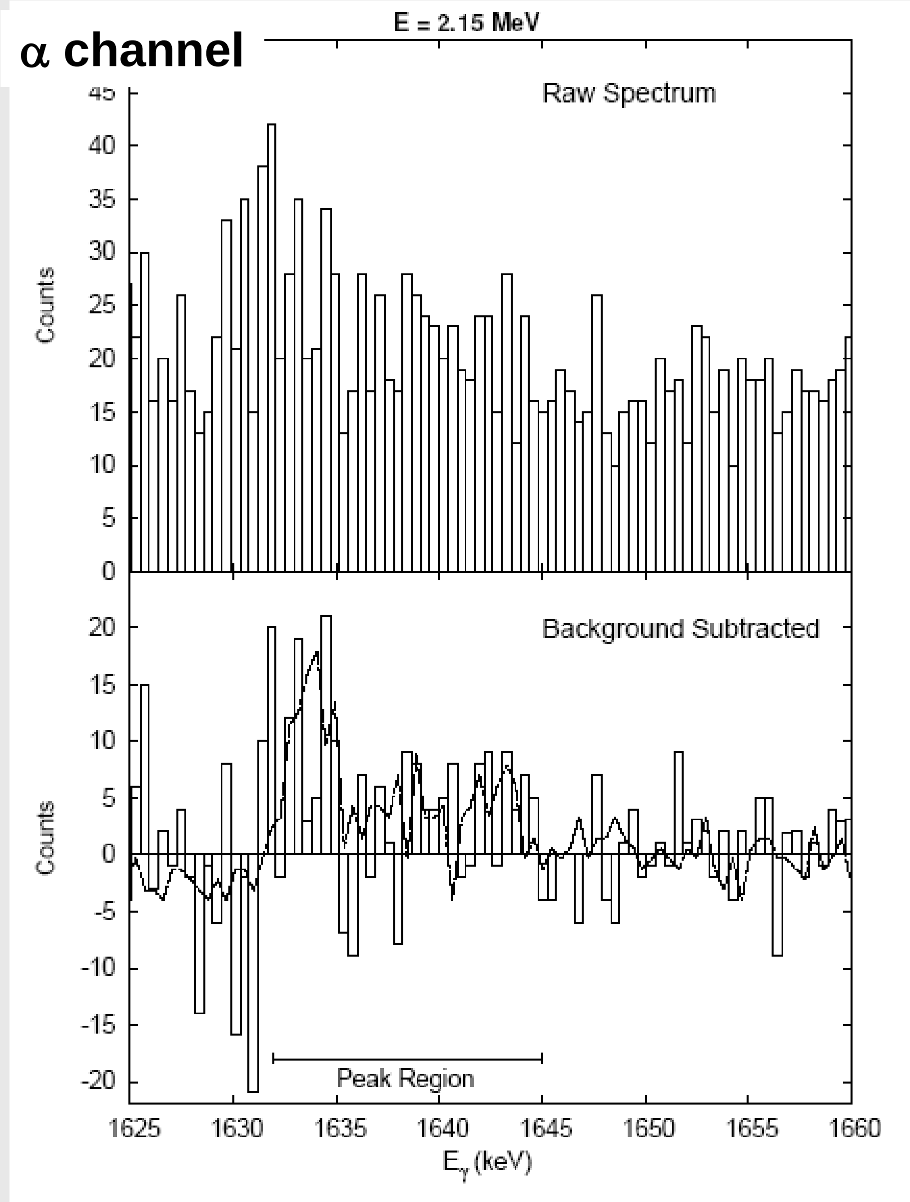
Summary of Presentation

The $^{12}C+^{12}C$ key reaction for astrophysics applications

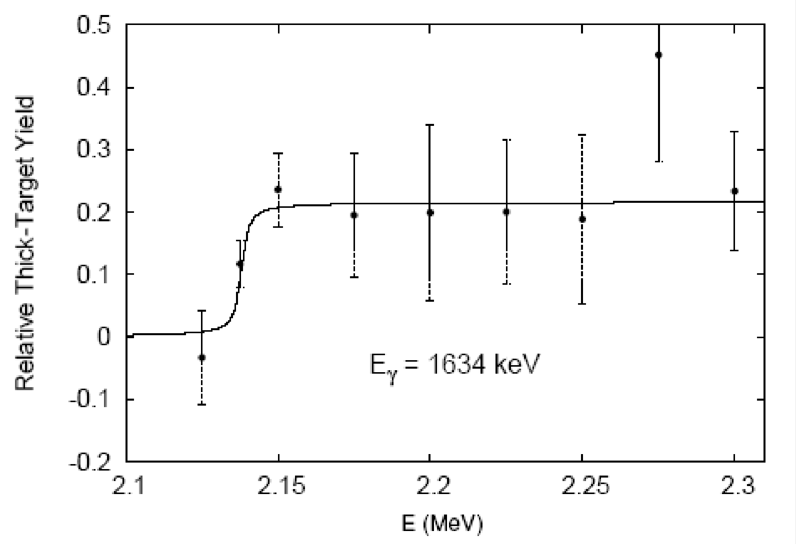
- astrophysical implications: stellar evolution, supernovae
- difficult measurement due to beam induced background
- low energy limit hás been moved downward
- problem of extrapolation might be even more severe
- solution need both approaches, i.e. γ-ray and particle spectroscopy
- perspectives for measurements in underground lab,
  $\rightarrow$ need larger accelerator

Extra slides

Experimental Results - γ-ray spectroscopy



Thick-Target Yield curve



new resonance $E_R = 2.14$ MeV
$\omega\gamma = 0.11 \pm 0.02$ meV (α channel)

reaction rate enhanced by factor 5