^{44}Ti(a,p)^{47}V at REX – ISOLDE Implications for Core Collapse Supernovae

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Outline

I. The astrophysical case: Mechanisms for core collapse supernovae and the place for ^{44}Ti

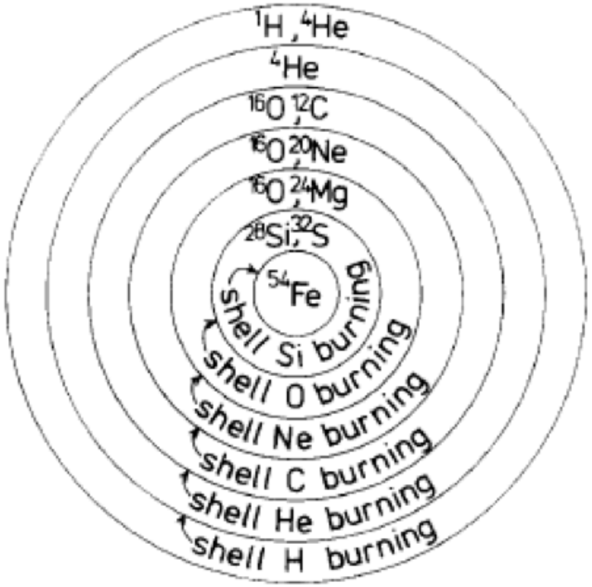
II. Previous measurement

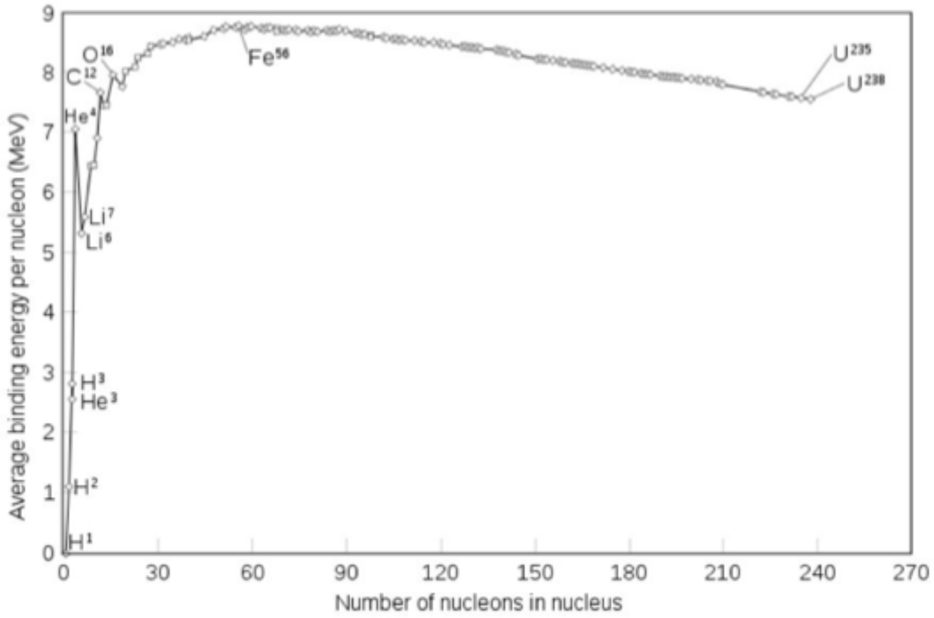
III. Production of a ^{44}Ti beam: from radioactive waste to beam source

IV. Experimental results

I. The astrophysical case: Mechanisms for core collapse supernovae and the place for ^{44}Ti

- Core collapse supernovae: $M_{\text{progenitor star}} > 8M_{\odot}$
- Onion-like structure whereby nuclear fusion balances GPE
- Maximum BE/A reached (^{56}Ni) -> material collapses onto the core
- Density in the core passes that of nuclear matter, creation and propagation of a shock wave -> photodissociation to *α, p* and *n*





I. The astrophysical case: Mechanisms for core collapse supernovae and the place for ^{44}Ti

- Short time and stagnation of the shock wave provide free *α, p* and *n* from rearranging before apparition of a neutrino wind that powers nucleosynthesis of elements

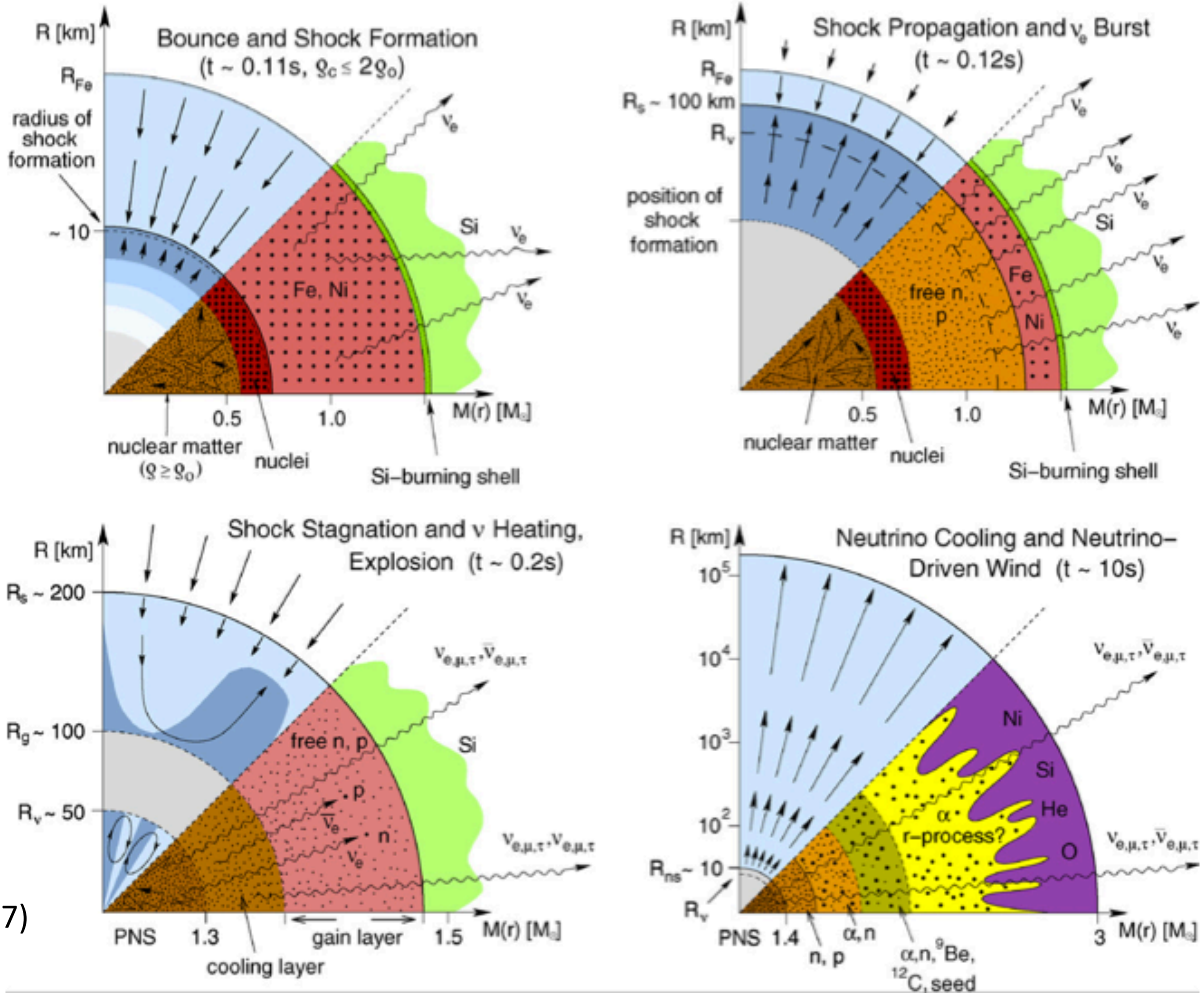


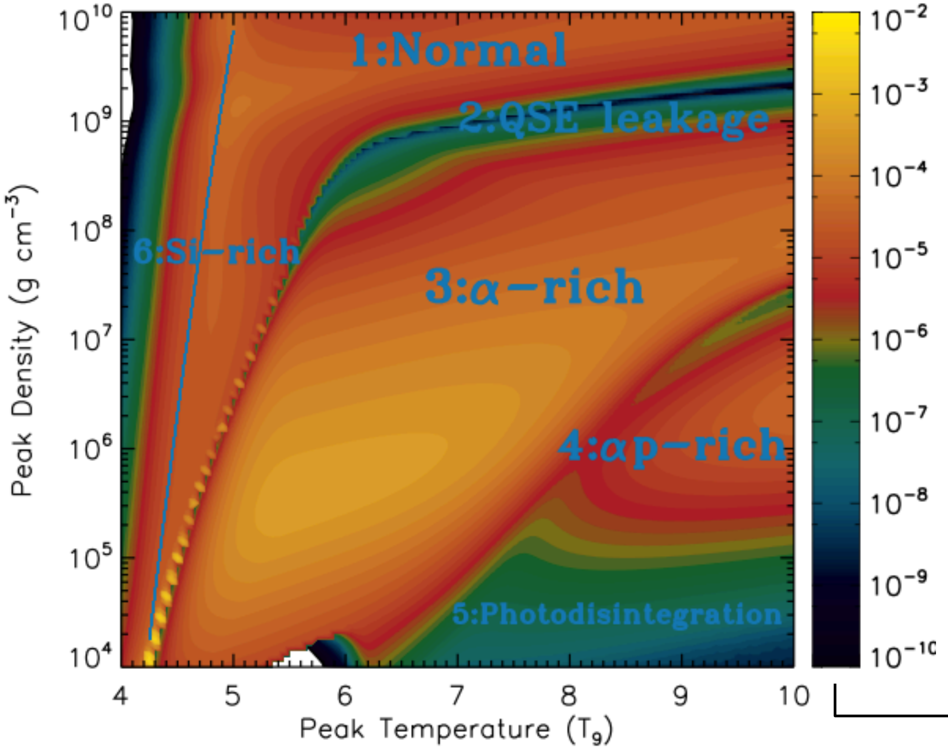
Figure from (Janka et al., 2007)

I. The astrophysical case: Mechanisms for core collapse supernovae and the place for ^{44}Ti

Production of ^{44}Ti in stars

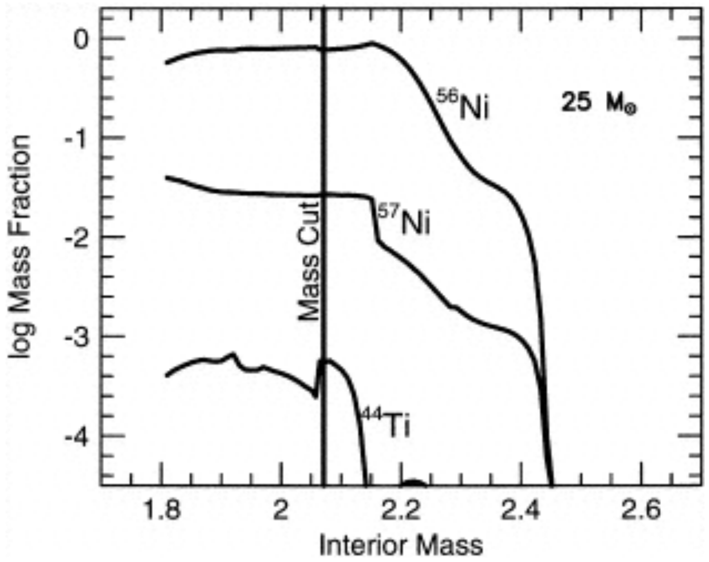
- ^{44}Ti is produced in α-rich region. Neutrino wind hits the region, production in the cooling phase, in the range **$2.0<T_9<4.0$**

- Amount in ejecta sensitive to mass cut



Mass fraction of ^{44}Ti

(Magkotsios et al, 2010)



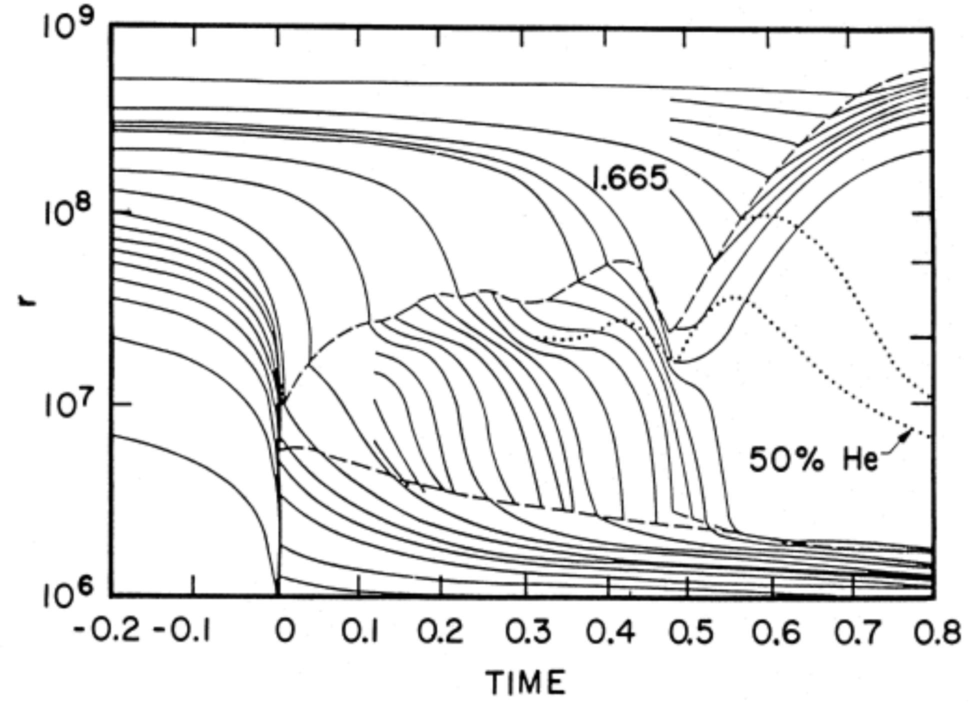
(Diehl & Timmes, 1998)

I. The astrophysical case: Mechanisms for core collapse supernovae and the place for ^{44}Ti

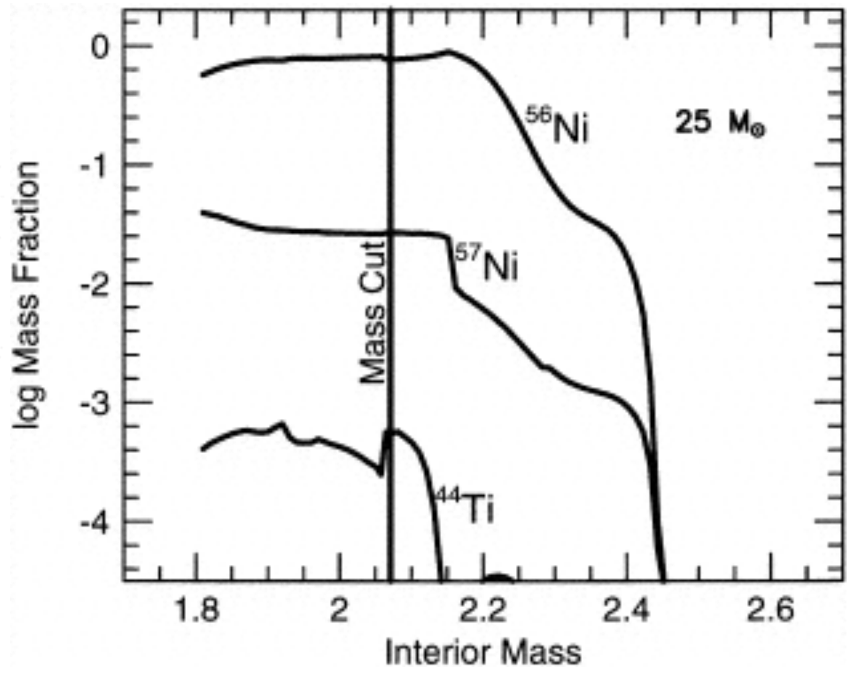
Mechanism for supernova explosion

Neutrino driven mechanism

- Without neutrino heating Si layer would fall into supernova remnant -> not observable



(Bethe & Wilson, 1985)

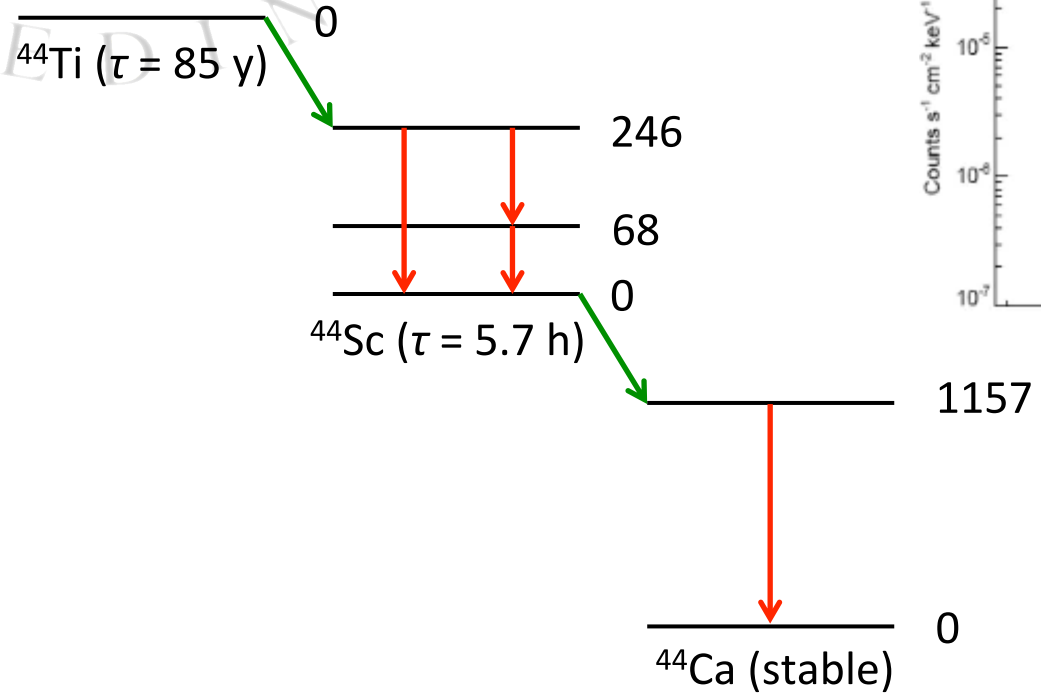


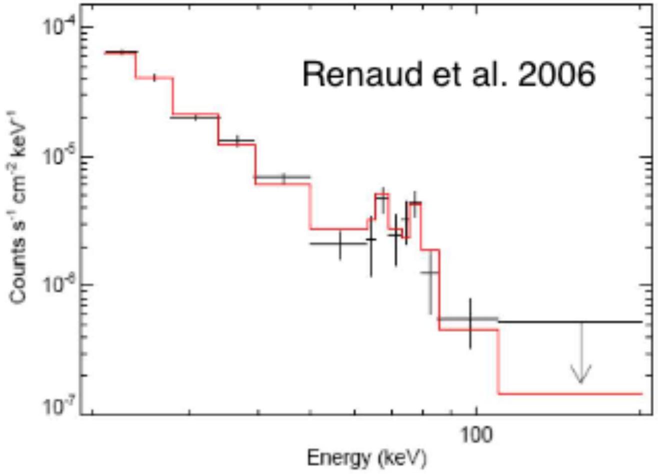
(Diehl & Timmes, 1998)

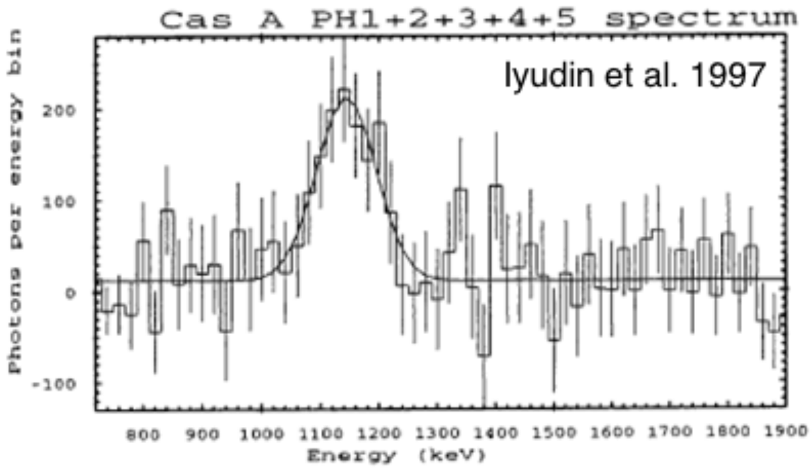
Yield of ^{44}Ti helps understand the explosion mechanism

I. The astrophysical case: Mechanisms for core collapse supernovae and the place for ^{44}Ti

- Distinctive γ-rays are emitted in the decay of ^{44}Ti
- They have been detected by in-space γ-rays observatories







I. The astrophysical case: Mechanisms for core collapse supernovae and the place for ^{44}Ti

- Distinctive γ-rays are emitted in the decay of ^{44}Ti
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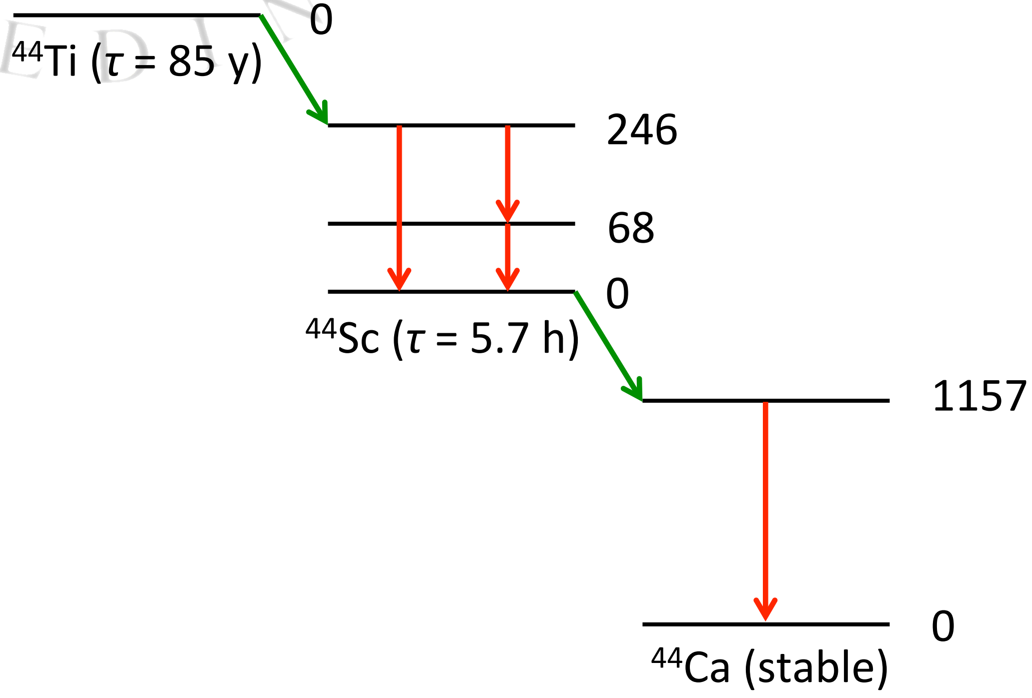
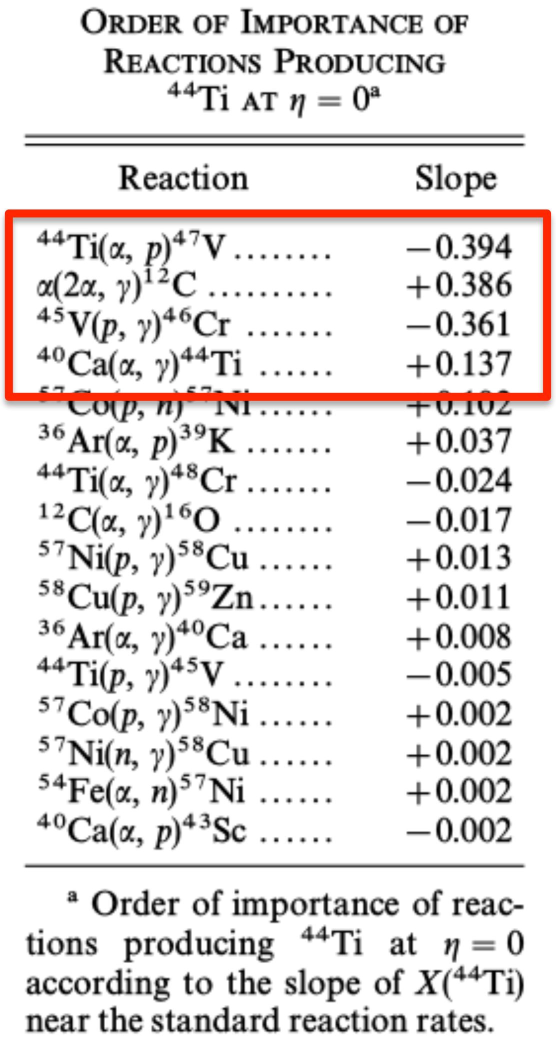


^{44}Ti(*α*, *p*)^{47}V provides a versatile tool to gain insight of those environment



ORDER OF IMPORTANCE OF REACTIONS PRODUCING ^{44}Ti AT $\eta = 0$[a]

Reaction	Slope
$^{44}\mathrm{Ti}(\alpha, p)^{47}\mathrm{V}$	−0.394
$\alpha(2\alpha, \gamma)^{12}\mathrm{C}$	+0.386
$^{45}\mathrm{V}(p, \gamma)^{46}\mathrm{Cr}$	−0.361
$^{40}\mathrm{Ca}(\alpha, \gamma)^{44}\mathrm{Ti}$	+0.137
$^{57}\mathrm{Co}(p, n)^{57}\mathrm{Ni}$	+0.102
$^{36}\mathrm{Ar}(\alpha, p)^{39}\mathrm{K}$	+0.037
$^{44}\mathrm{Ti}(\alpha, \gamma)^{48}\mathrm{Cr}$	−0.024
$^{12}\mathrm{C}(\alpha, \gamma)^{16}\mathrm{O}$	−0.017
$^{57}\mathrm{Ni}(p, \gamma)^{58}\mathrm{Cu}$	+0.013
$^{58}\mathrm{Cu}(p, \gamma)^{59}\mathrm{Zn}$......	+0.011
$^{36}\mathrm{Ar}(\alpha, \gamma)^{40}\mathrm{Ca}$	+0.008
$^{44}\mathrm{Ti}(p, \gamma)^{45}\mathrm{V}$	−0.005
$^{57}\mathrm{Co}(p, \gamma)^{58}\mathrm{Ni}$	+0.002
$^{57}\mathrm{Ni}(n, \gamma)^{58}\mathrm{Cu}$	+0.002
$^{54}\mathrm{Fe}(\alpha, n)^{57}\mathrm{Ni}$	+0.002
$^{40}\mathrm{Ca}(\alpha, p)^{43}\mathrm{Sc}$	−0.002

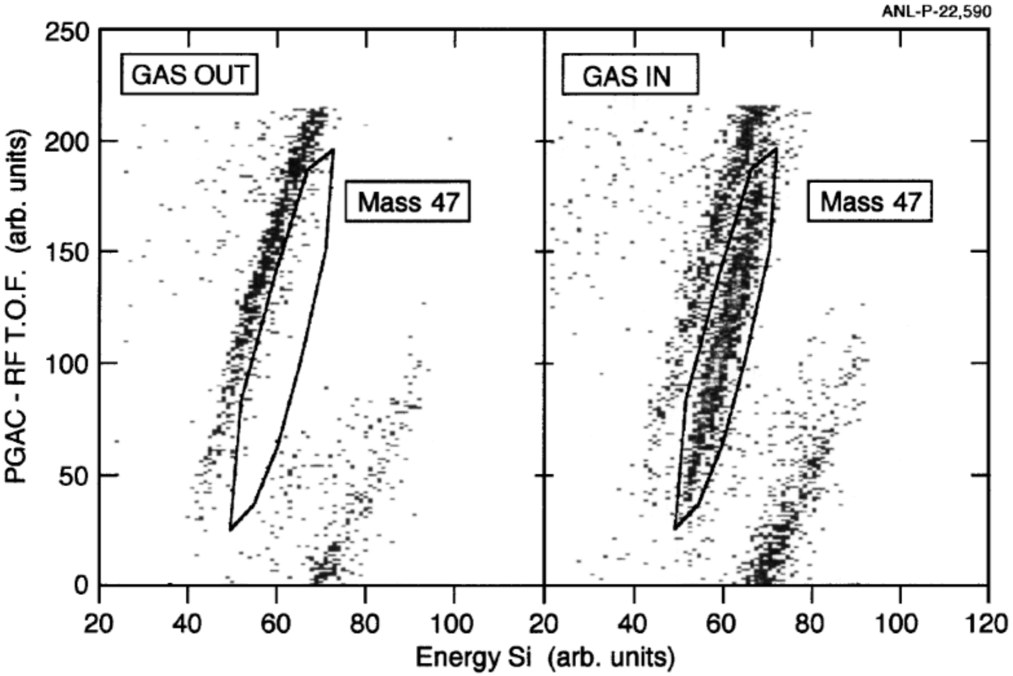
[a] Order of importance of reactions producing ^{44}Ti at $\eta = 0$ according to the slope of $X(^{44}\mathrm{Ti})$ near the standard reaction rates.

(The *et al.*, 1998)

II. Previous measurement

(Sonzogni et al.)

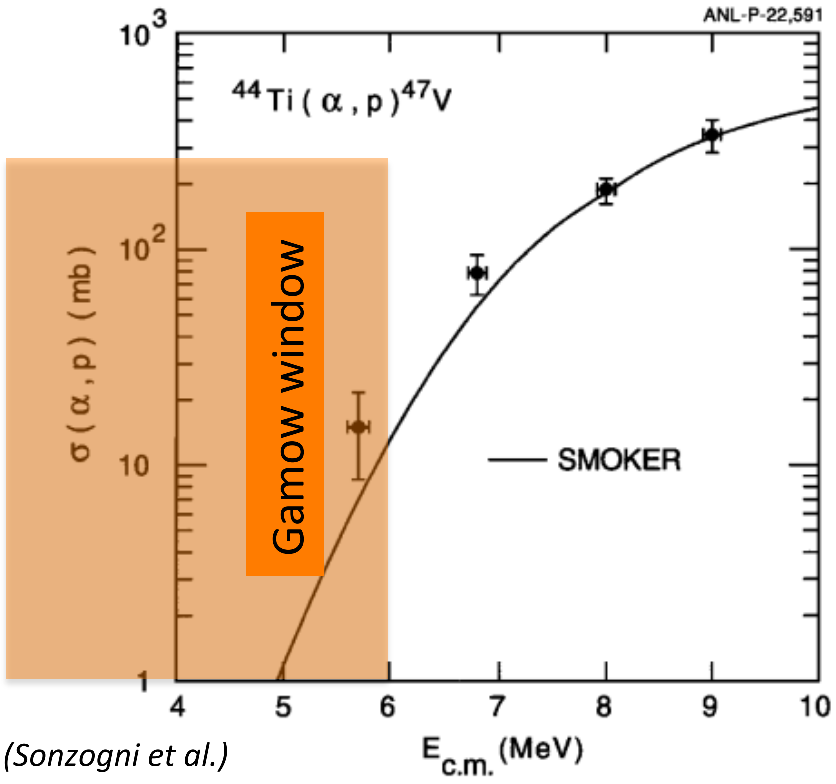
- Previous measurement made at the Argonne National Laboratory
- Protons bombarded on a ^{45}Sc disk and ^{44}Ti material was collected
- ^{44}Ti accelerated at ATLAS and impinged on ^{4}He gas target
- ^{47}V recoils were measured



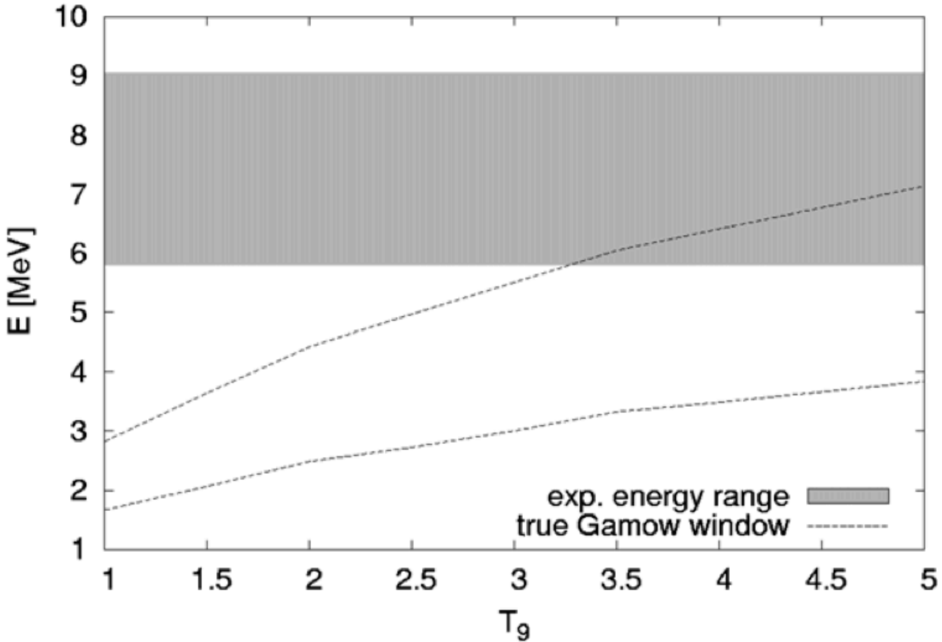
(Sonzogni et al.)

II. Previous measurement

- Reaction measured at 4 energies
- Mostly outside the Gamow window corresponding to T_9 = 2.0-4.0 GK ($E_{c.m.}$ = 2-6 MeV)



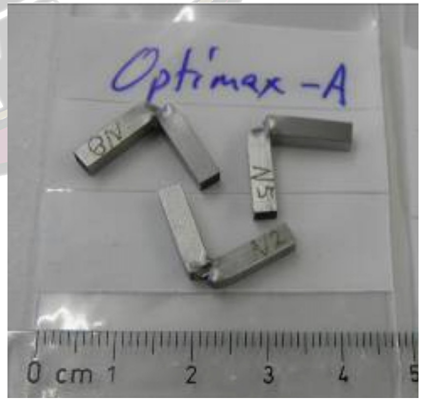
(Sonzogni et al.)



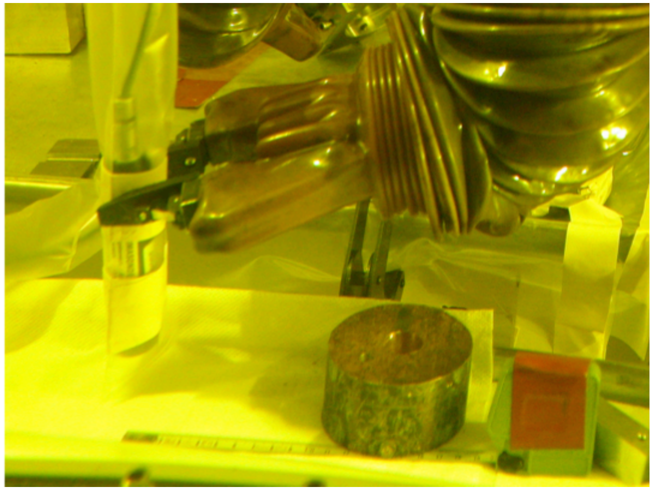
(Hoffman et al.)

III. Production of ^{44}Ti: from radioactive waste to beam source

The source of ^{44}Ti beam



Example of wastes/dumps



(Dressler et al, 2012)

- Very radioactive but radioactivity from ^{44}Ti low
- Chemical content in ^{44}Ti low but largely enough for a beam of >10^5 pps as used by Sonzogni et al (2010)

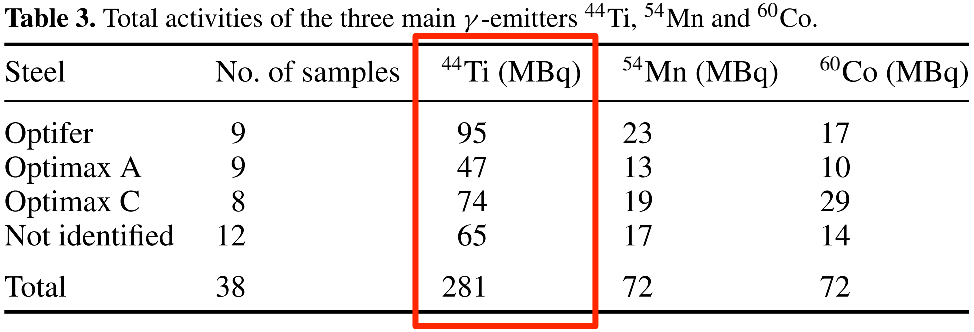
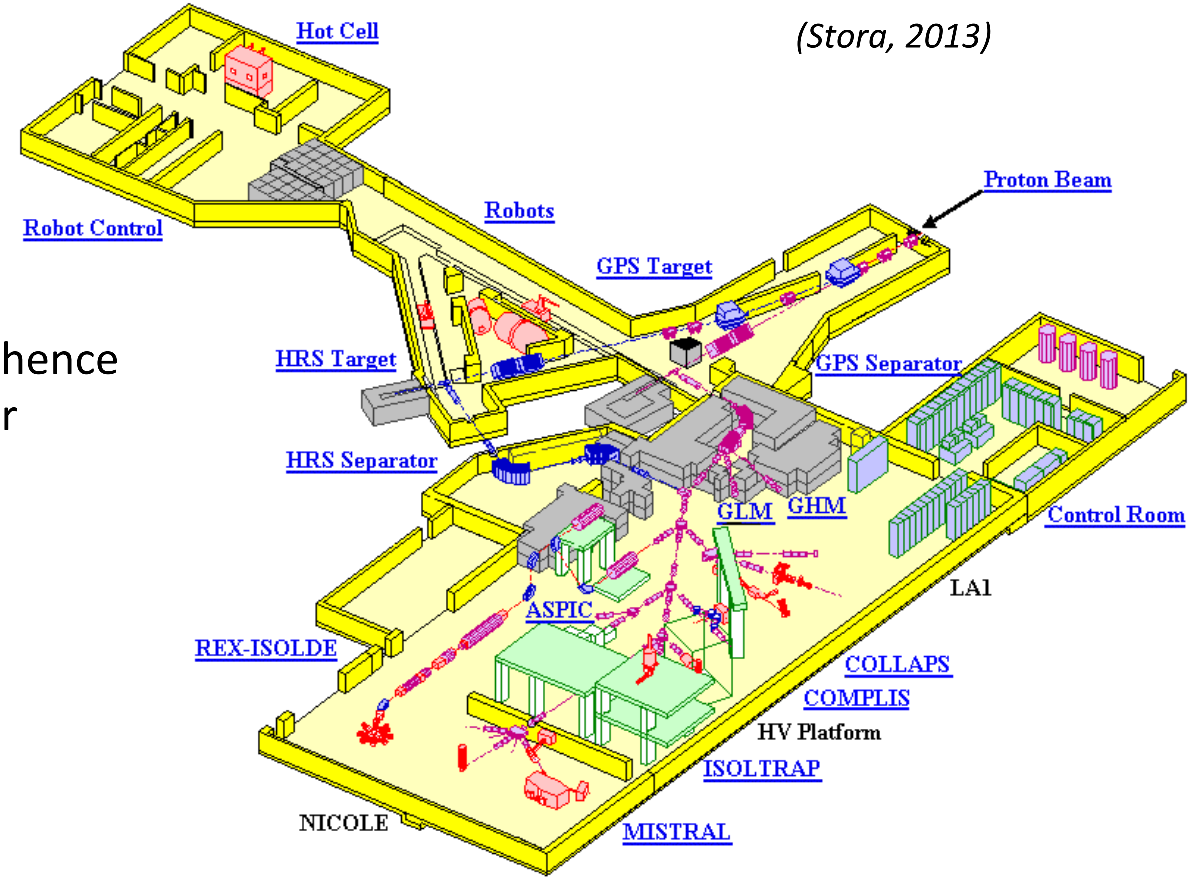


Table 3. Total activities of the three main γ-emitters ^{44}Ti, ^{54}Mn and ^{60}Co.

Steel	No. of samples	^{44}Ti (MBq)	^{54}Mn (MBq)	^{60}Co (MBq)
Optifer	9	95	23	17
Optimax A	9	47	13	10
Optimax C	8	74	19	29
Not identified	12	65	17	14
Total	38	281	72	72

III. Production of ^{44}Ti: from radioactive waste to beam source

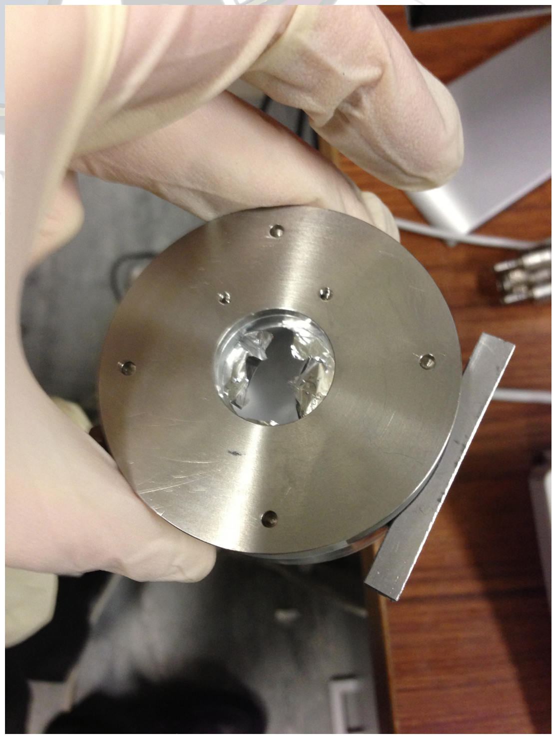
- **<u>Sample diluted in HF solution</u>** and shipped to CERN
- Ti beams as TiF^{3+} molecular ions after being evaporated into a CF4 gas leak
- Beam accelerated to 2.16 MeV/u in REX-ISOLDE



(Stora, 2013)

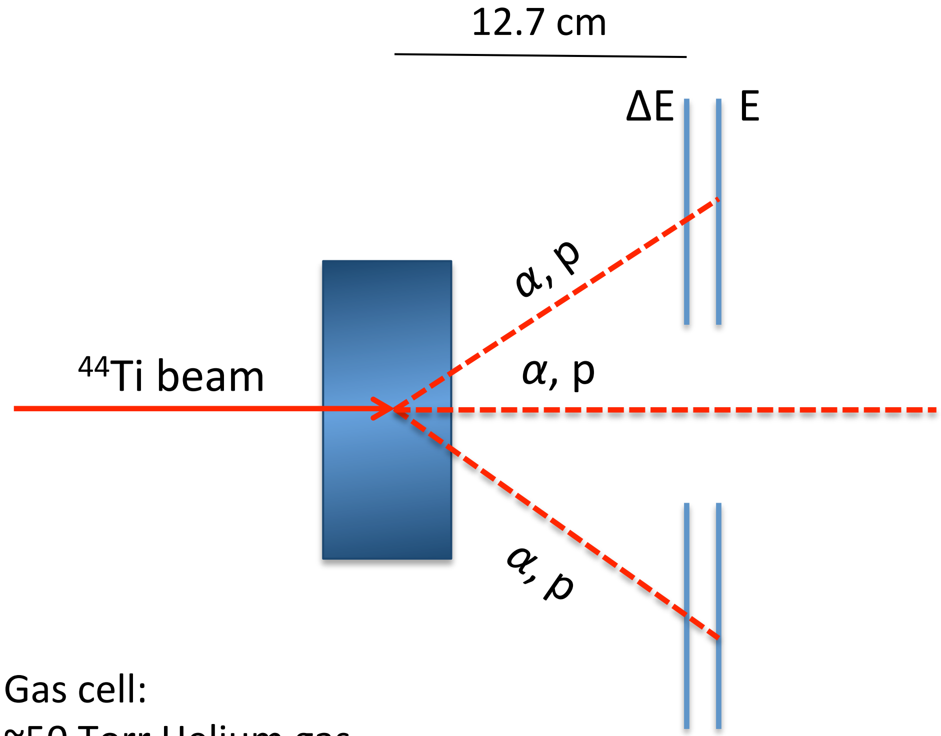
Fixing it on solid is very complex hence no target of ^{44}Ti available thus far

IV. Experiment and results



Gas cell, view from the (test-failed) entrance window

Experimental set up

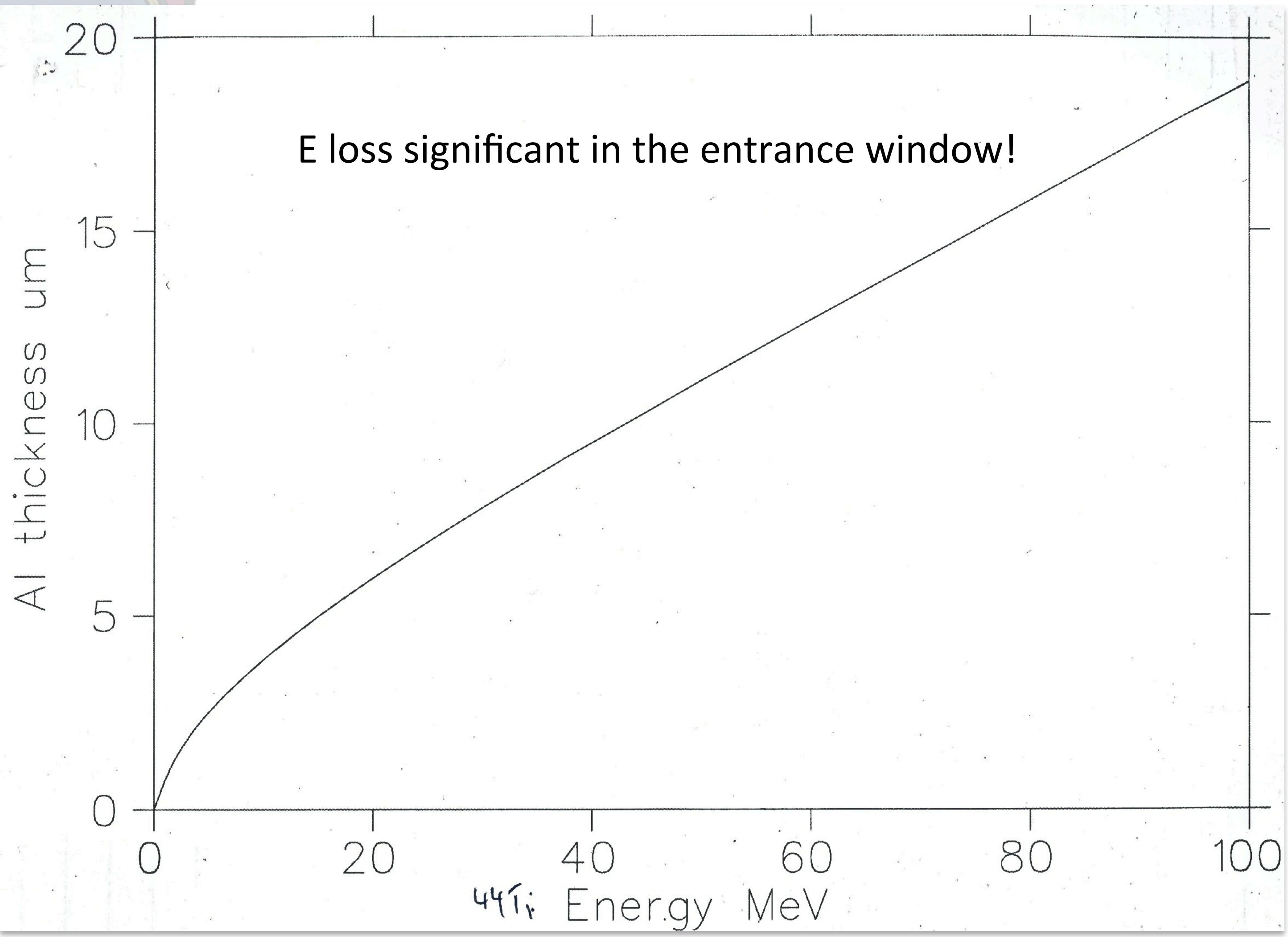


Gas cell:
~50 Torr Helium gas
Entrance window 6 μm Al
Exit window 15 μm Al

Detector:
S2-type (70 μm + 500 μm) telescope

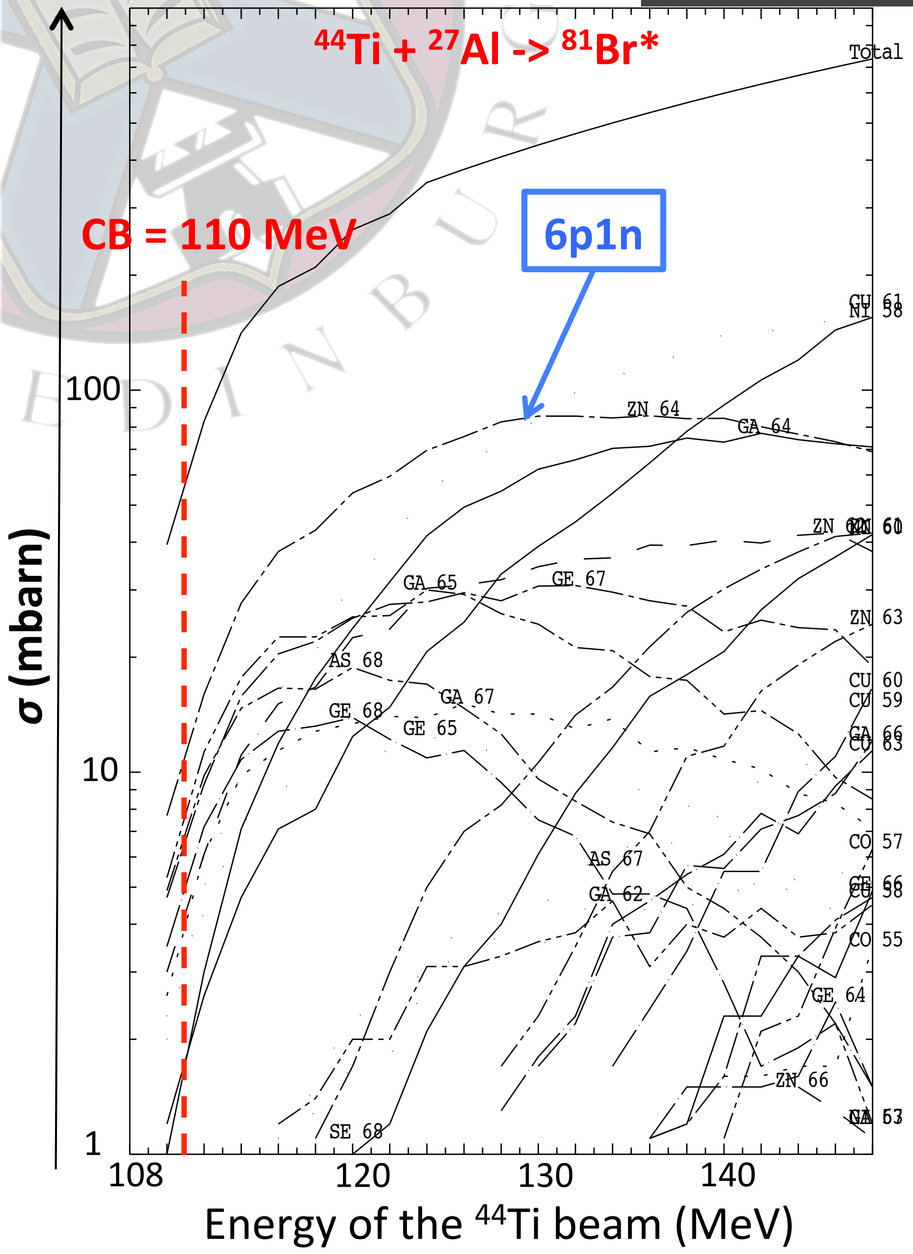
- Recoil is stopped in exit window
- Entrance window very thin because …

IV. Experiment and results



E loss significant in the entrance window!

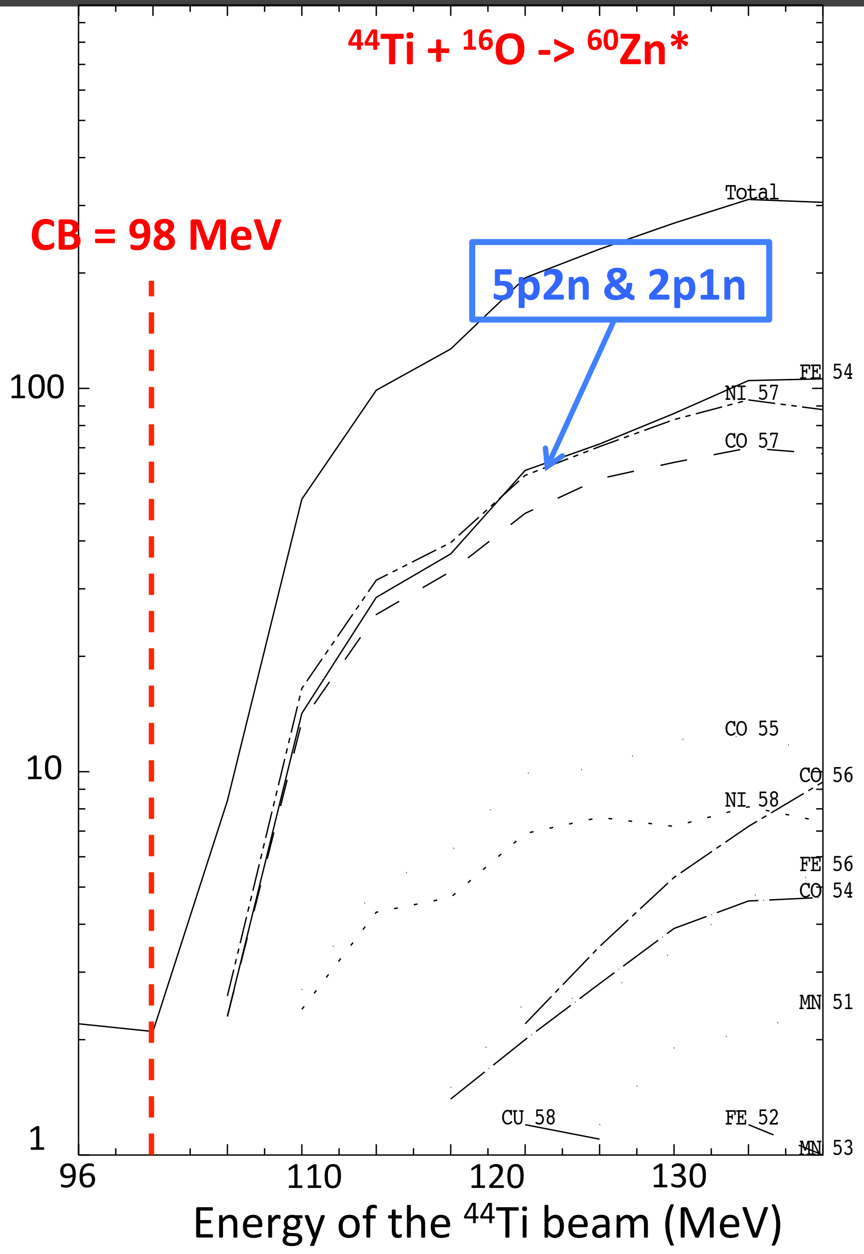
IV. Experiment and results



^{44}Ti + ^{27}Al -> ^{81}Br*

CB = 110 MeV

6p1n



^{44}Ti + ^{16}O -> ^{60}Zn*

CB = 98 MeV

5p2n & 2p1n

IV. Experiment and results

The hardships in making the gas cell

- Coulomb barrier for $^{44}Ti + ^{27}Al \rightarrow ^{71}Br^*$ is 110 MeV
  $^{44}Ti + ^{16}O \rightarrow ^{60}Zn^*$ is 98 MeV

  - Main fusion evaporation channels dominated by **<u>proton evaporation</u>**

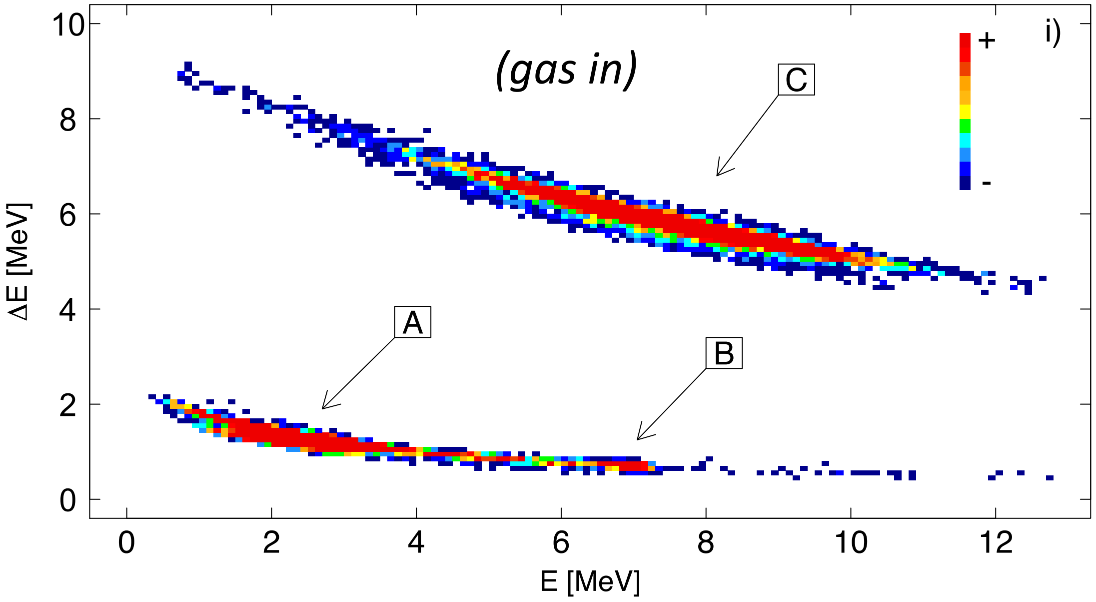
Entrance window > 9um means E_{beam}> Coulomb Barrier in order to reach desirable energies within the gas cell

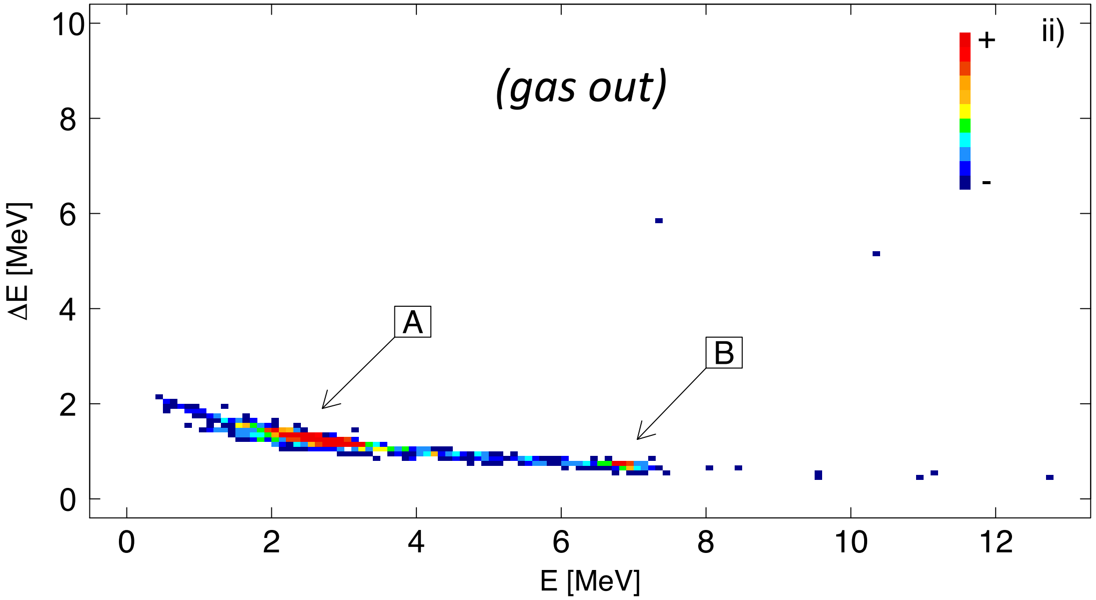
↓

Need a very thin window (6-8 μm):

- mechanical resistance to pressure is compromised
- even “light tight” foils may have pin holes

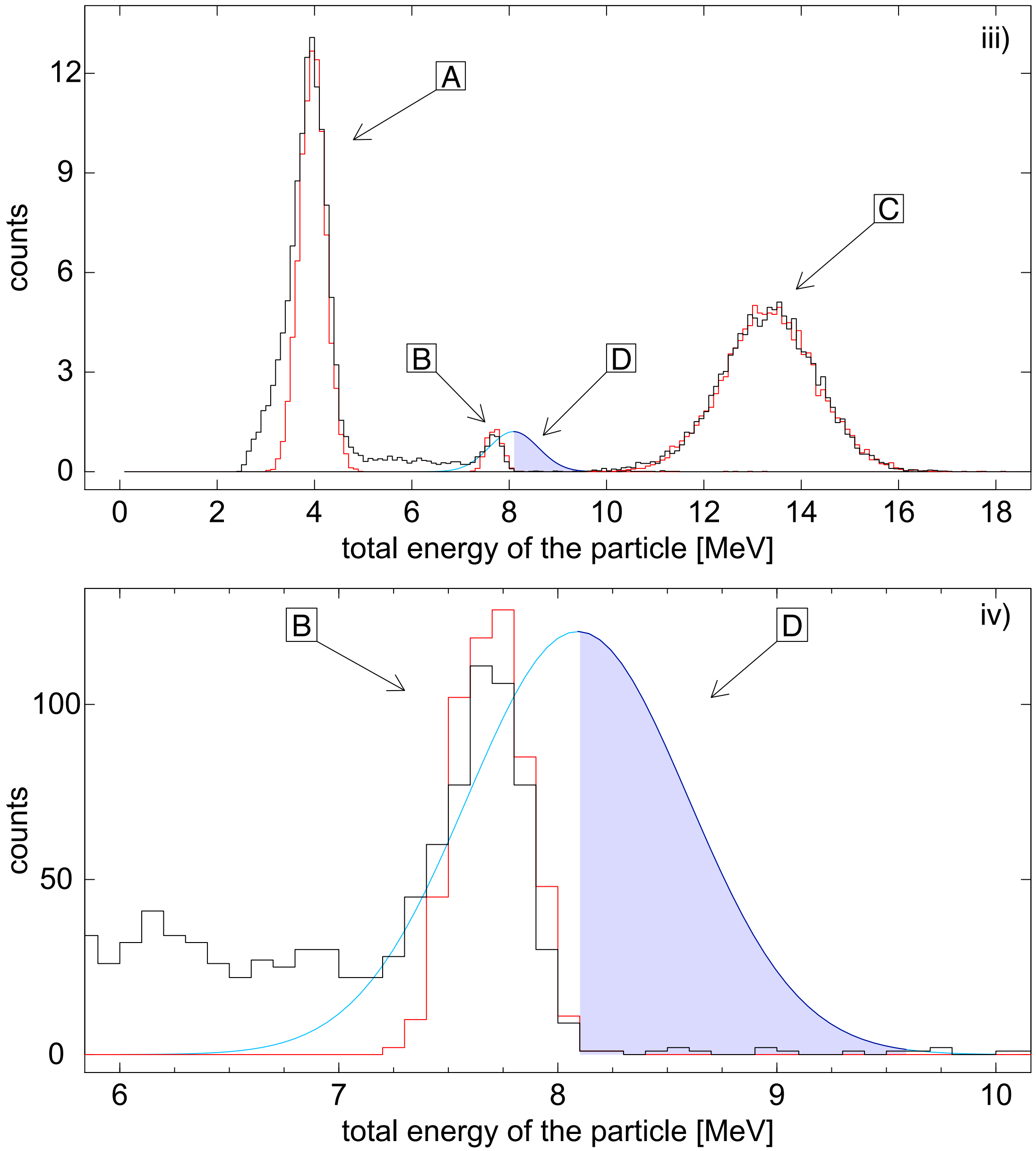
IV. Experiment and results





- **A and B:** elastically scattered protons from the windows of the gas cell
- **C:** elastically scattered α-particles (^{4}He gas)
- elastically scattered α-particles good proxy for accurate beam intensity
- Scaling of cross sections to Rutherford cross section

IV. Experiment and results



- **Red:** Simulation
- **Black:** Projection (E+dE)

- **D:** simulation for events from ^{44}Ti(α, p)^{47}V reactions:
  - $E_{p,\text{ lab}}$ = 8.09 MeV
  - 1σ width= 1.18 MeV
  - $E_{\alpha,\ cm}$ = 4.15 MeV
  - 1σ width = 0.54 MeV

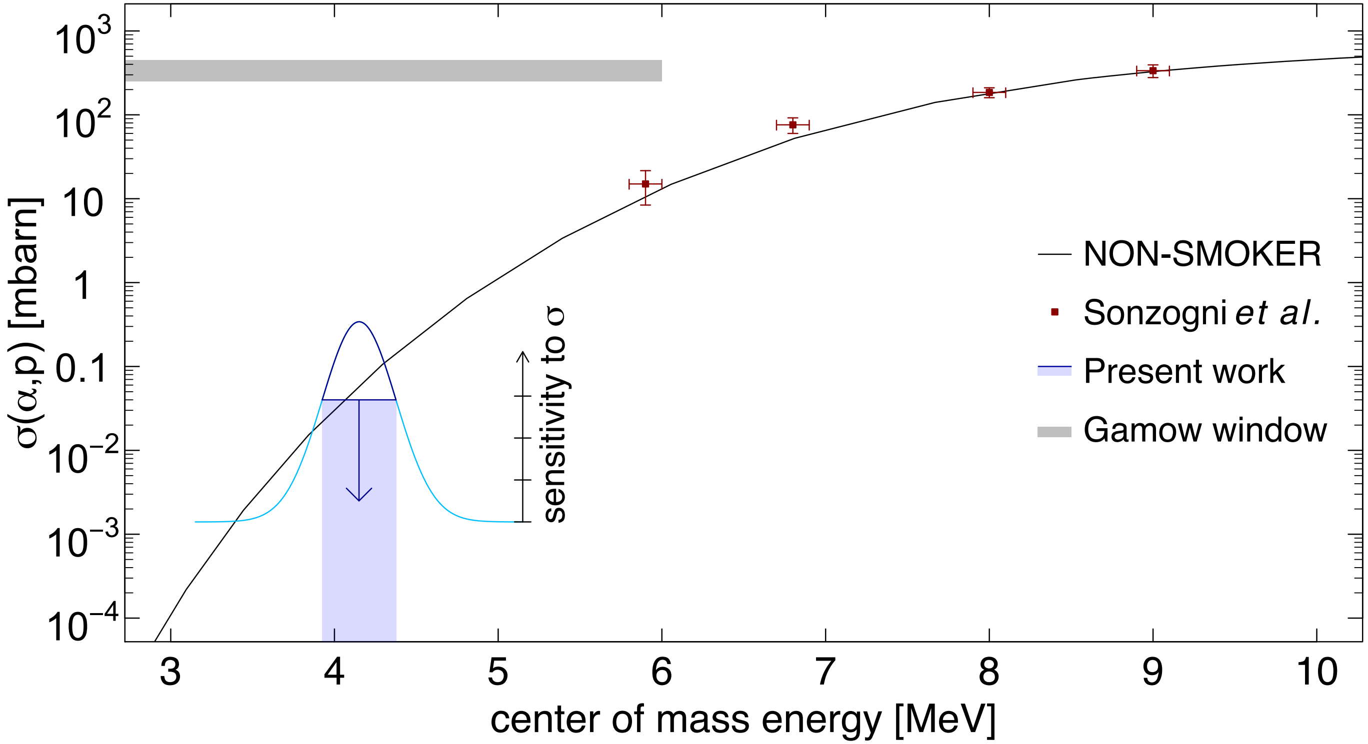
- **Shadow area:** $E_{p,\text{ lab}}$ + 3σ region -> 12 counts, gas out measurement suggests 11

IV. Experiment and results

Feldman-Cousins statistics (12 counts, background known at 11)		
Conf. Level	*σ(α, p)* [µbarn]	Reduction from NON-SMOKER
68%	40	2.2
90%	60	1.5
99%	85	1

- Upper limit could be determined using Feldman-Cousins statistics
- Folding center of mass distribution from simulation (D) to NON-SMOKER prediction: 88 μbarn

NON-SMOKER: (Rausher and Thielemann, 2000 & 2001) ADND Tables **75** (2000) 1 & **79** (2001) 47



IV. Experiment and results

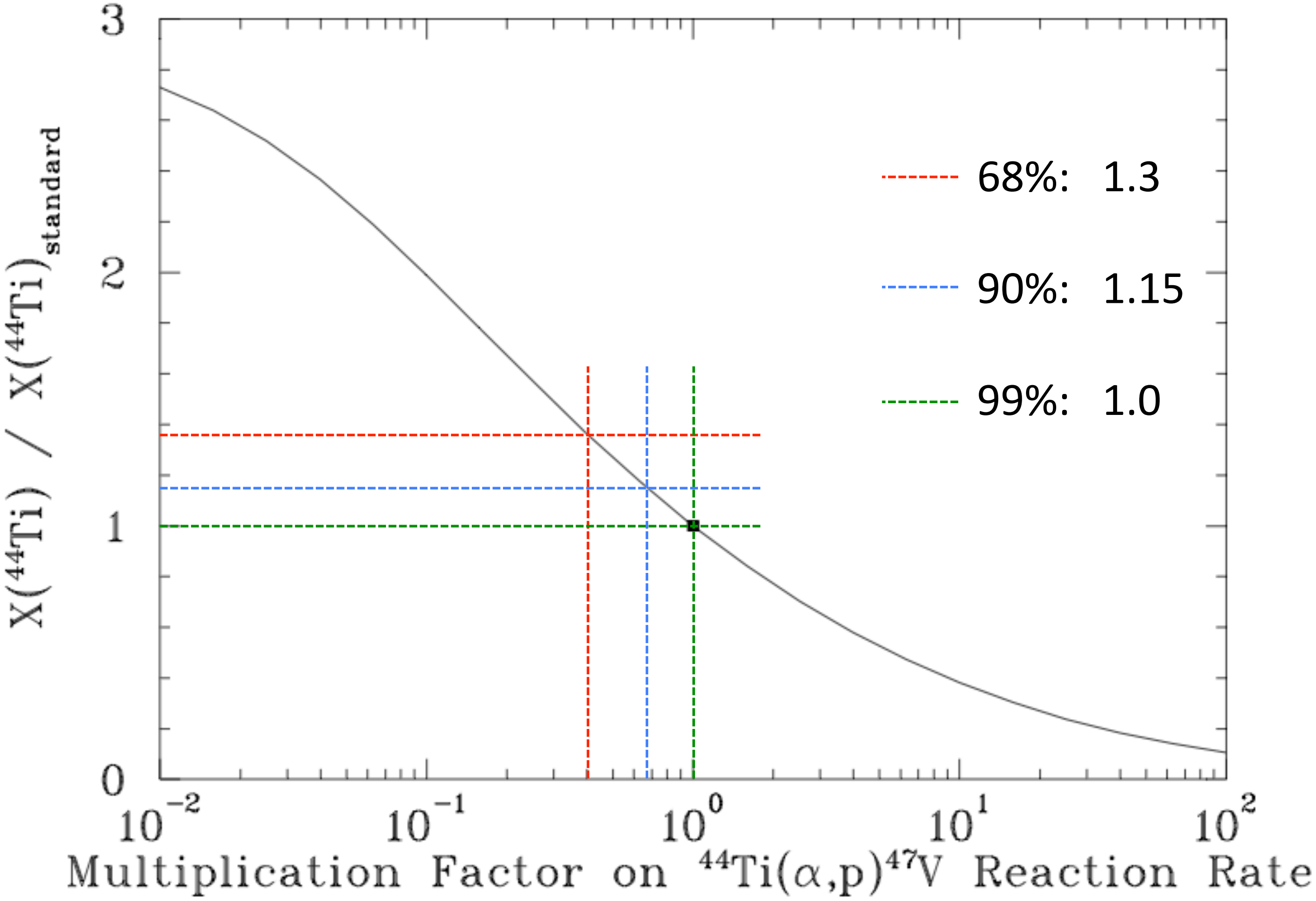


FIG. 9.—Final $X(^{44}Ti)$ dependence on the reaction rate of $^{44}Ti(\alpha, p)^{47}V$

(The et al., 1998)

IV. Experiment and results

- This implies **a <u>slower ^{44}Ti destruction rate</u>** at this energy
- Such a rate **<u>throughout the Gamow window</u>** could explain the difference between observation of ^{44}Ti and CCSNe prediction (using NON-SMOKER max is 1x$10^{-4}M_\odot$)

Cassiopeia A	1.3-2.2 x $10^{-4}M_\odot$
SN1987 A	2.3-3.9 x $10^{-4}M_\odot$

Conf. Level	Max. ejecta ^{44}Ti content implied [x $10^{-4}M_\odot$]	Agreement with Cassiopeia A
68%	1.3	0.59 – 1
90%	1.15	0.52 – 0.88
99%	1	0.47 – 0.80

IV. Experiment and results

- Are there resonances in the ^{48}Cr (*i.e.* ^{47}V+p) system ?

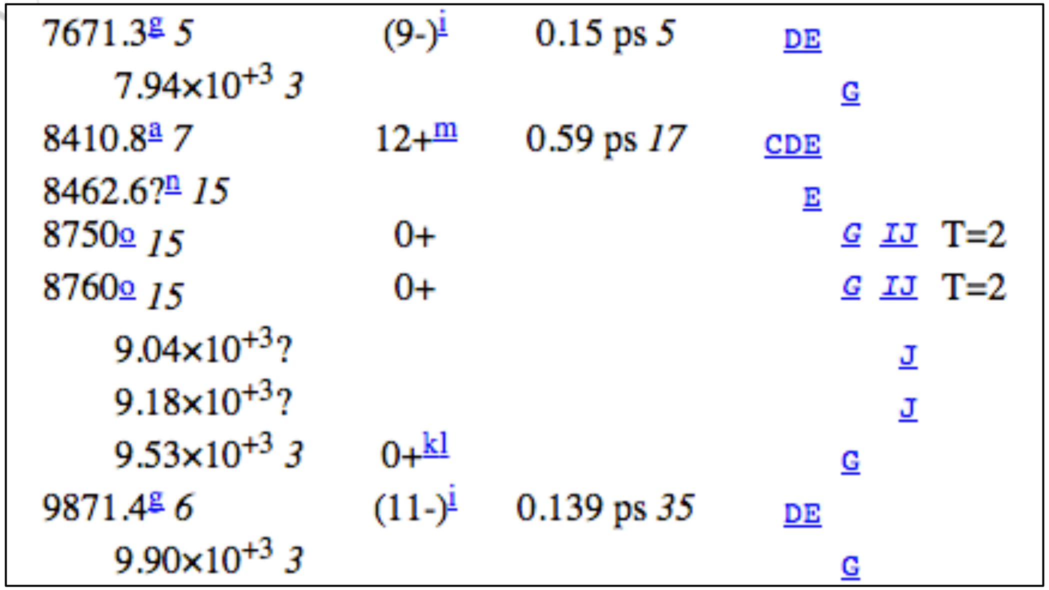
	Mass excess [MeV]
^{47}V	-42.00205
p	7.2890
^{48}Cr	-42.8192
Proton threshold in ^{48}Cr	8.106
	Ground state spin [hbar]
^{47}V	$3/2^-$
^{48}Cr	0^+

Looking for states with spin **1^- or 2^- (L=0); 0^+, 1^+, 2^+ or 3^+ (L=1)**; potentially strongly resonant 0^- to 4^- (L=2); **above 8.106 MeV**

- How does the cross section behave at other energies? (and is the *Sonzogni et al.* data correct?)

IV. Experiment and results

States known in ^{48}Cr [nndc]



7671.3[g] *5*	(9-)[i]	0.15 ps *5*	DE	
$7.94\times10^{+3}$ *3*			G	
8410.8[a] *7*	12+[m]	0.59 ps *17*	CDE	
8462.6?[n] *15*			E	
8750[o] *15*	0+		G IJ	T=2
8760[o] *15*	0+		G IJ	T=2
$9.04\times10^{+3}$?			J	
$9.18\times10^{+3}$?			J	
$9.53\times10^{+3}$ *3*	0+[kl]		G	
9871.4[g] *6*	(11-)[i]	0.139 ps *35*	DE	
$9.90\times10^{+3}$ *3*			G	

G: ^{46}Ti(^{3}He, *n*)^{48}Cr

- No known candidates
- ^{44}Ti(α, p)^{47}V only possible reaction to find these states at the moment

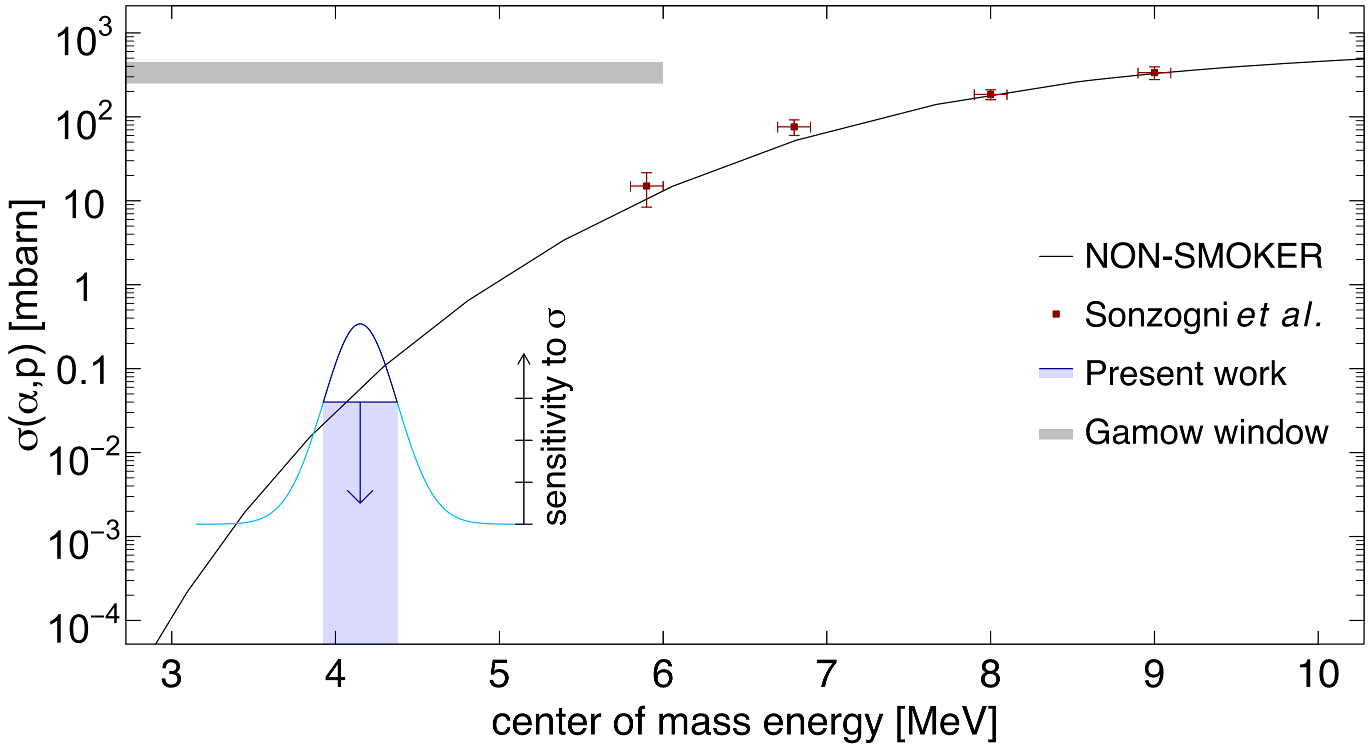
IV. Experiment and results

Lower/same energies:

- to deliver lower energy beam (1-2 MeV/u)
- higher ^{4}He pressure to compensate reaction yield
- beam intensity has to be higher (this is a new technique, future experiments should have more beam)

Higher energies:

- use of gas cells limited by induced fusion evaporation on the windows
- window-less gas target?



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(Stora, 2013) NIM B **317** (2013) 402

(Rausher and Thielemann, 2000 & 2001) ADND Tables **75** (2000) 1 & **79** (2001) 47

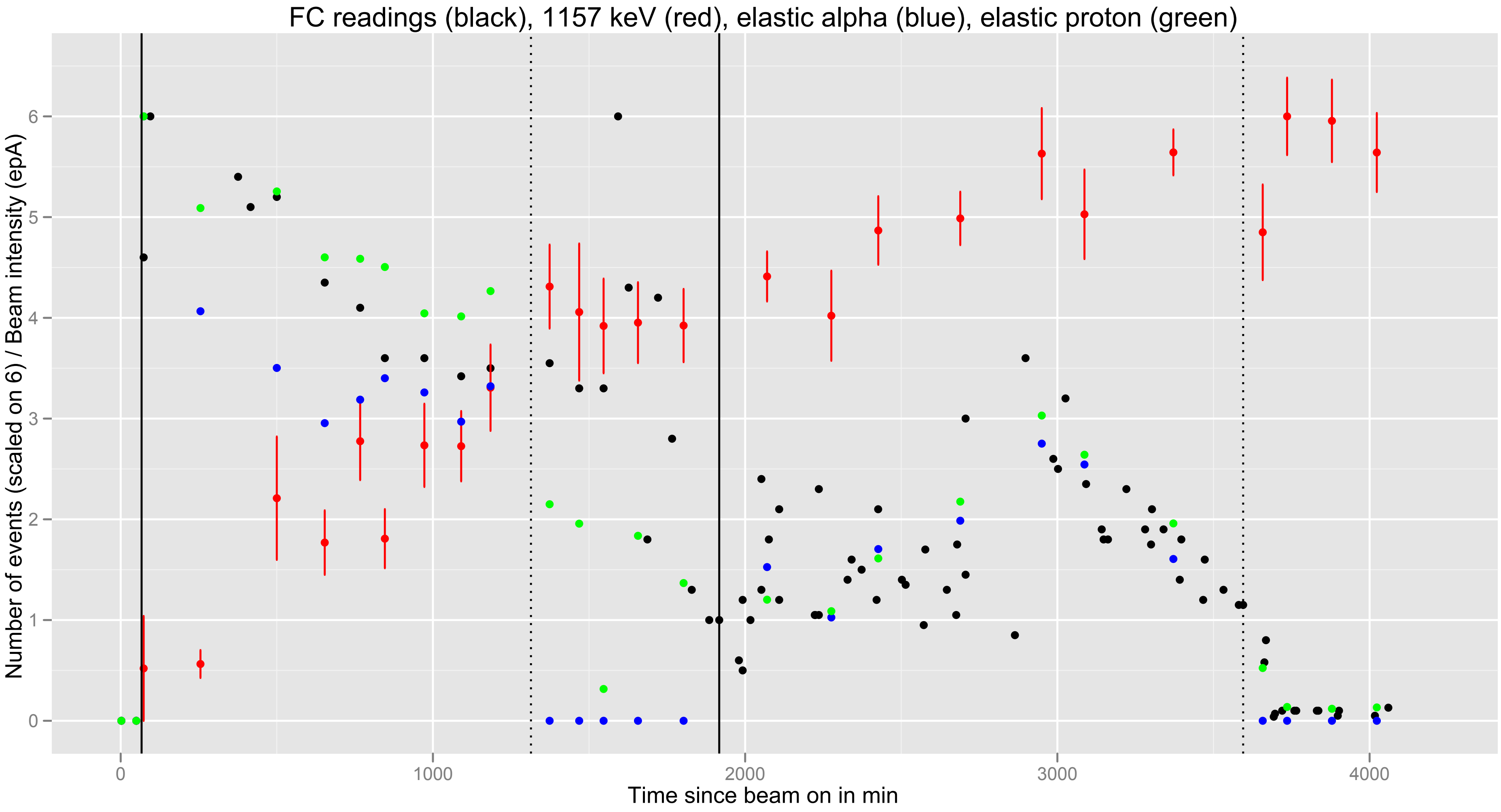
(Mohr et al., 2010 & 2013)

Could 44Ti really discriminate between different hydrodynamics model?

- “There should be some interesting differences on average between the predictions/expectations of the various mechanisms (neutrino, acoustic, magnetic, etc.), we have yet truly to determine these.”
  - Adam Burrows, Princeton, Jan 2012

- “By accident we noticed e.g. in simple parametrized explosions with the same explosion energy, that pistons (like used by Woosley and Heger) produce less ^{44}Ti than thermal bombs (like used by Nomoto, myself, Umeda). The point is just that in the innermost ejecta the entropies are higher.”
  - Friedel Thielemann, Basel, Jan 2012

Normalisation


FC readings (black), 1157 keV (red), elastic alpha (blue), elastic proton (green)

Measurement of exit window activity post-experiment