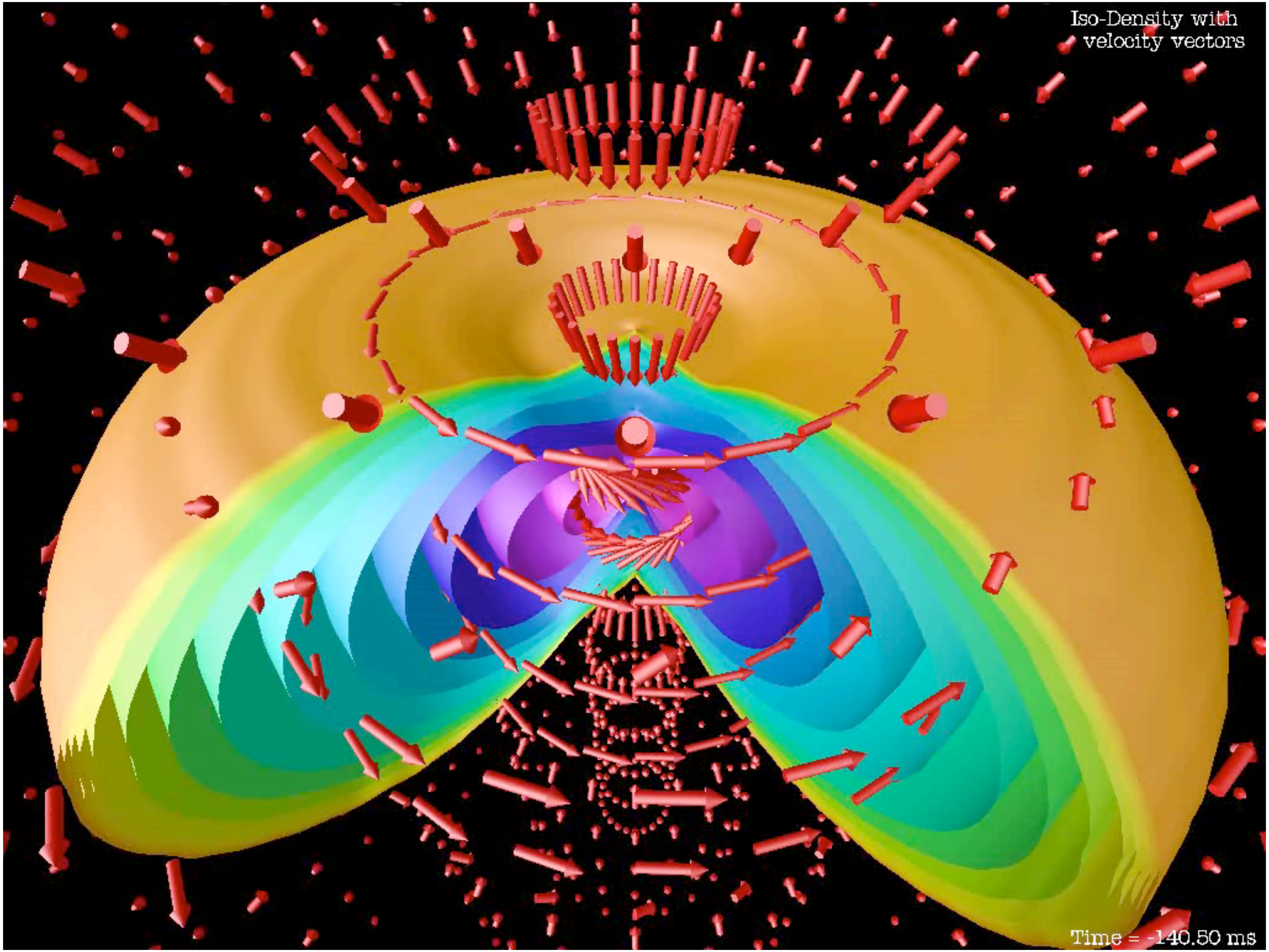
^{44}Ti and Core Collapse Supernovae

- Part 1: Introduction
- Part 2: Motivation
- Part 3: Proposal
- Part 4: Issues to solve

Core Collapse Supernovae are...

- Some of the most powerful explosions in the Cosmos
- Some of the most scrutinised objects in the Universe
- Responsible for production of many heavy elements
- Responsible for shaping our local distribution of stars
- Until recently there was consensus on the basic mechanism (perhaps there still is...)
- The best simulations still don’t reliably explode
- Neutrino driven or acoustic mode mechanism?
- Extremely complex

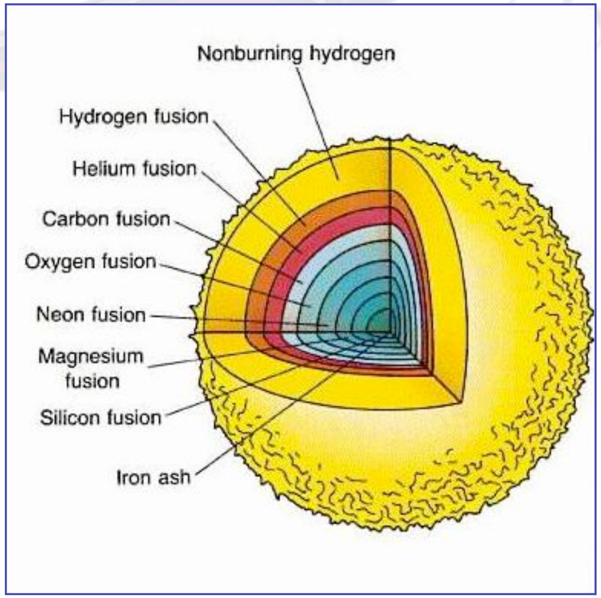
We Need a good diagnostic

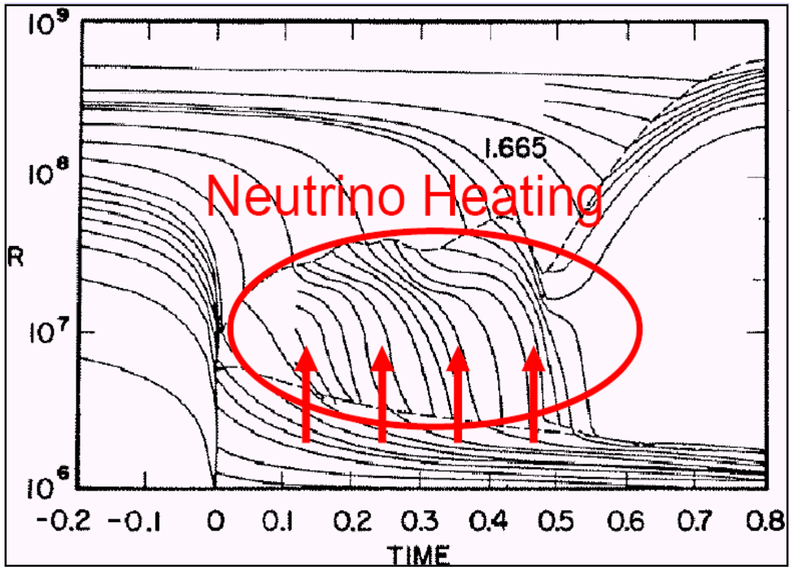

Iso-Density with velocity vectors
Time = -140.50 ms

Part 2: Motivation

The Neutrino Mechanism

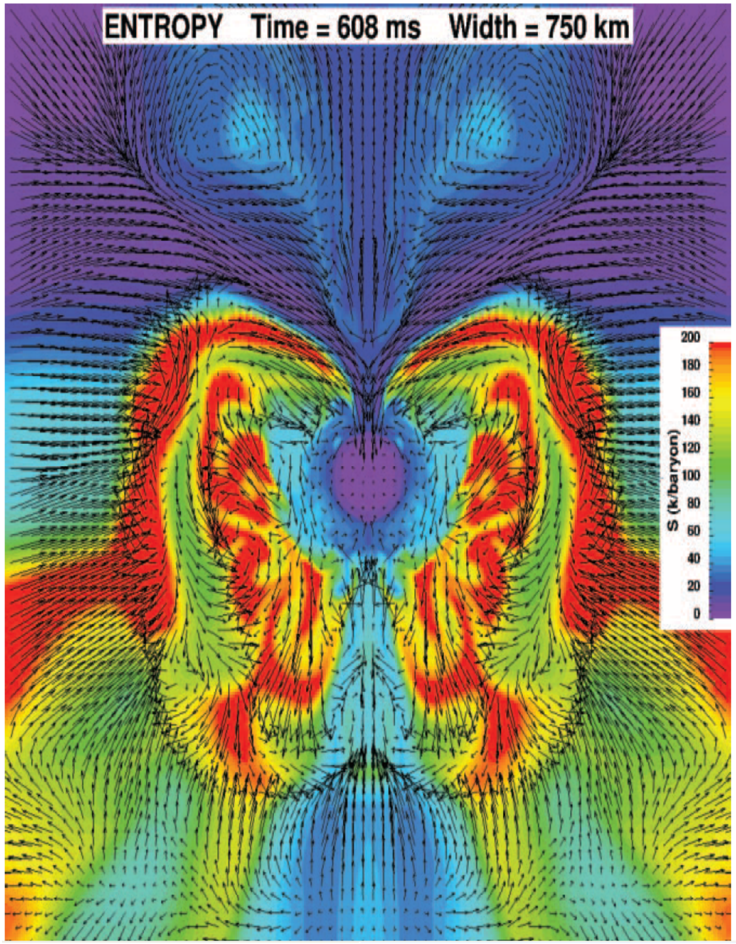
- Massive star (>8–10 $M_\odot$)
- Stellar evolution → onion-skin-like structure
- At maximum of BE/A, thermal support lost → Collapse
- Huge flux of neutrinos “re-energises” explosion
- Neutrino driven wind – an excellent candidate site for the r-process





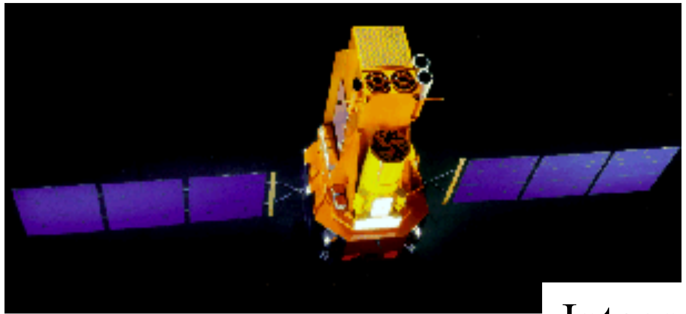
The Acoustic Mechanism

- Self-consistent simulations of neutrino driven mechanism do not produces a robust explosion
- New mechanism: Burrows et al. (ApJ 640 (April 2006) 878-890)
  - In-fall of matter on to the core induces strong gravity waves
  - These set up acoustic oscillations a few hundred milliseconds after core collapse.
  - Oscillations couple efficiently with the outer core/overlying material,
  - Intense sound waves radiated.
  - Appears to lead to robust explosion

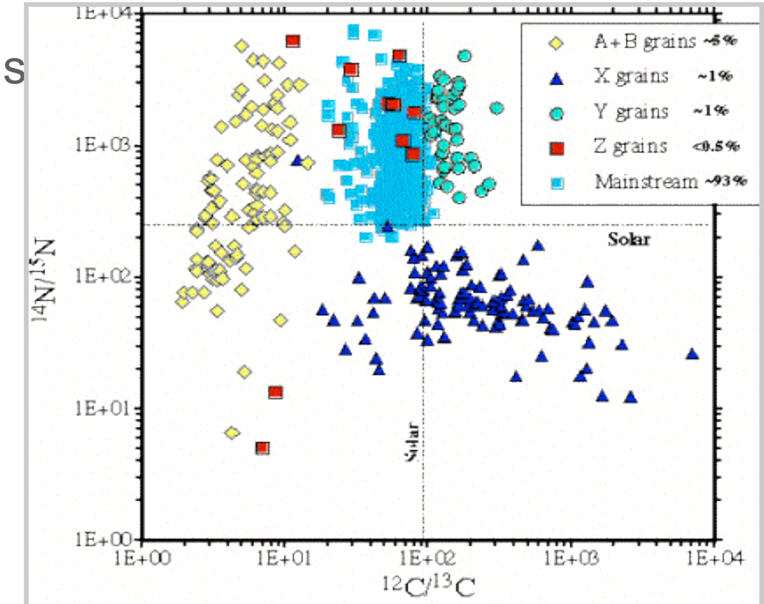


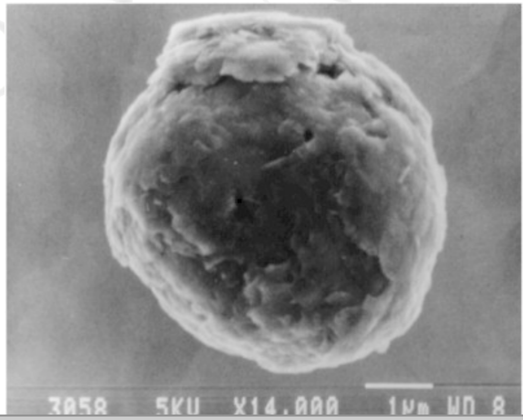
The Importance of ^{44}Ti

- ^{44}Ti that is ejected will become a γ-ray emitter
- Cassiopeia-A, Vela, not SN1987A
- τ=60 yrs, E_γ =1.157 MeV
- ‘Easily’ observable
- INTEGRAL & other missions
- Also Meteoritic data
- Enrichment of ^{44}Ca in type X presolar grains



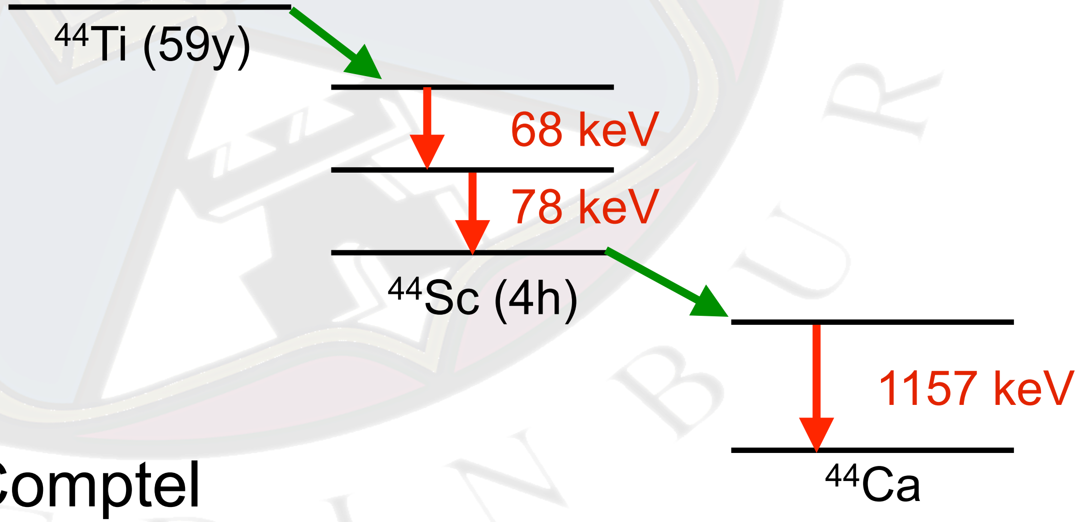
Integral



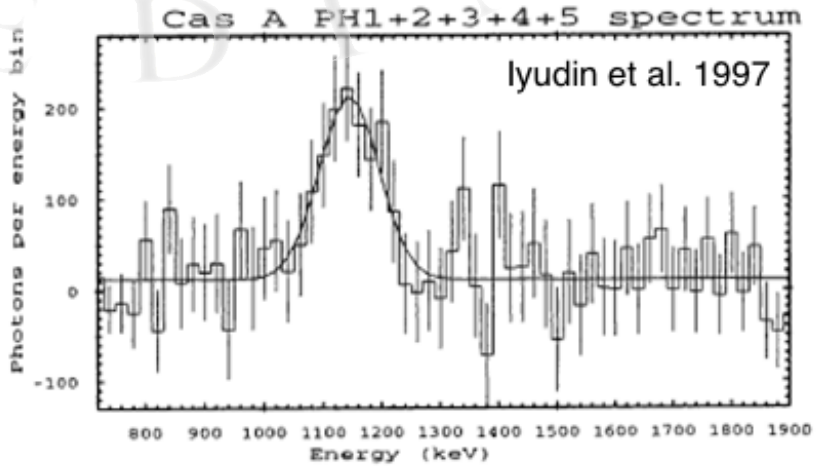


A grain from the Murchison Meteorite

^{44}Ti detection from Cas-A



Comptel



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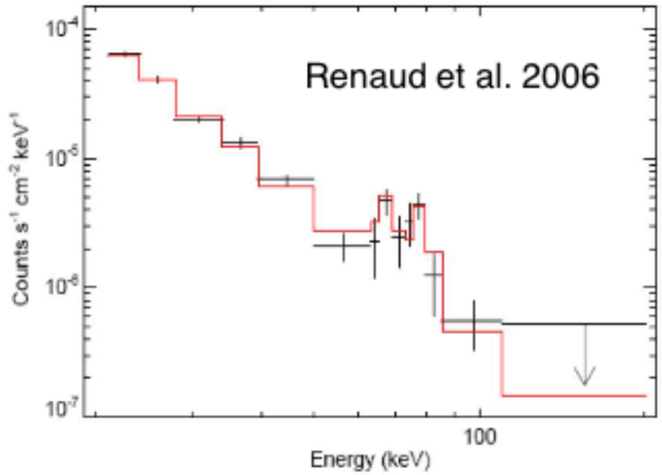
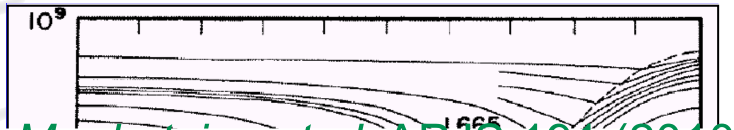
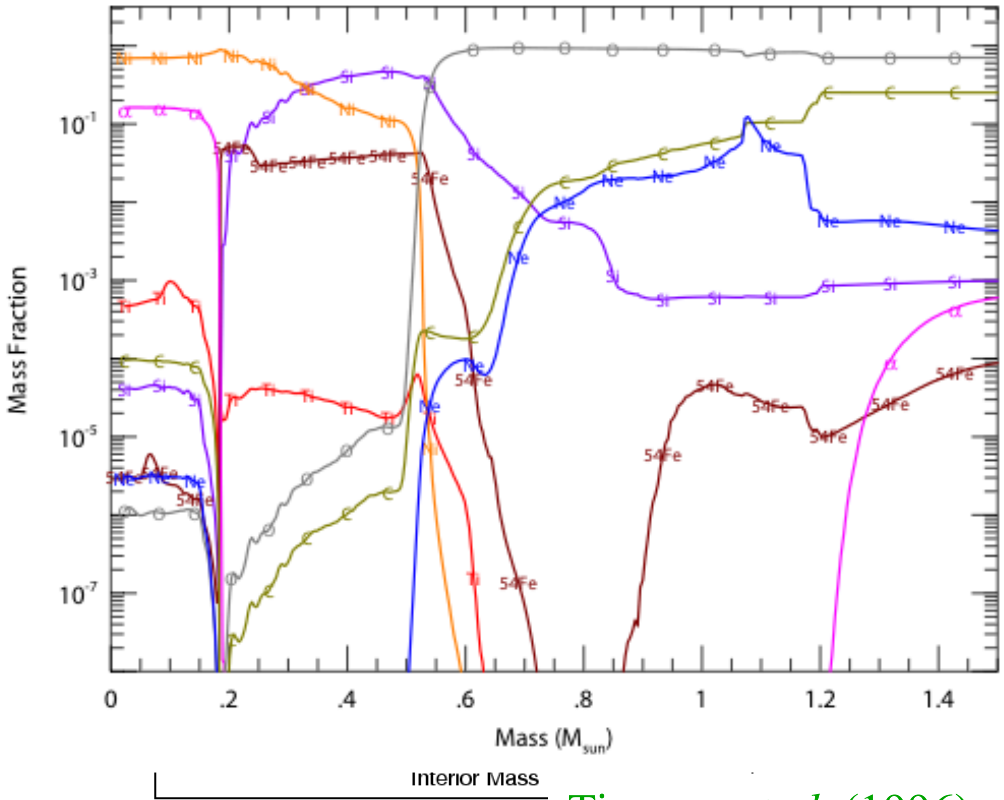


The Importance of ^{44}Ti

- Amount ejected sensitively depends on location of the 'mass cut'
- Material that 'falls back' is not available for detection
- ^{44}Ti yield a sensitive diagnostic of the explosion mechanism
- Thus, very useful for models to make comparisons against



Magkotsios et al: APJS 191 (2010) 66



Timmes *et al.* (1996)

Key Reactions

Reaction rate sensitivity studies:

- *The et al*: ApJ 504 (1998) 500
- *Magkotsios et al*: APJS 191 (2010) 66

- Papers agree, **^{44}Ti(α,p) most important reaction**
- Importance stems from it being the bottle neck in reaction flow as material drops out of QSE

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

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

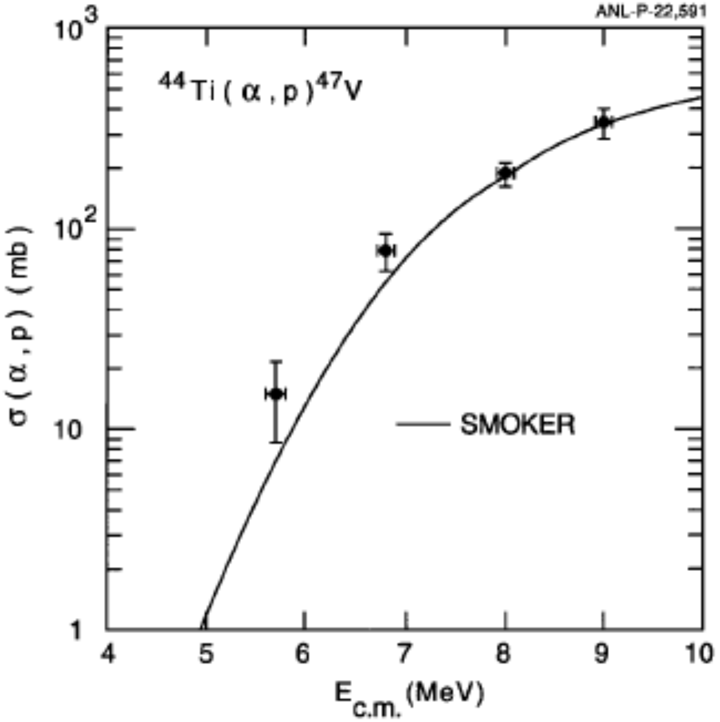
[a] Order of importance of reactions producing ^{44}Ti at $\eta = 0$ according to the slope of $X(^{44}\mathrm{Ti})$ near the standard reaction rates.

Key Reactions

$^{44}Ti(\alpha,p)$	Focus of the present work Present data: *Sonzogni et al.* PRL 84 (2000)
$\alpha(2\alpha,\gamma)^{12}C$	Ubiquitous
$^{45}V(p,\gamma)$	Intriguing, but hard: [*The et al*, *Horoi et al*. PRC 66 2002, *He & ASM* PRC 75 (2007)],
$^{40}Ca(\alpha,\gamma)$	Measured: DRAGON [*Vockenhuber et al*. PRC 76 (2007) 035801]
$^{44}Ti(\alpha,\gamma)$	No data available: DRAGON proposal Fallis & Murphy, S1289
$^{44}Ti(p,\gamma)$	No data available: DRAGON?

$^{44}Ti(\alpha,p)$ Present status

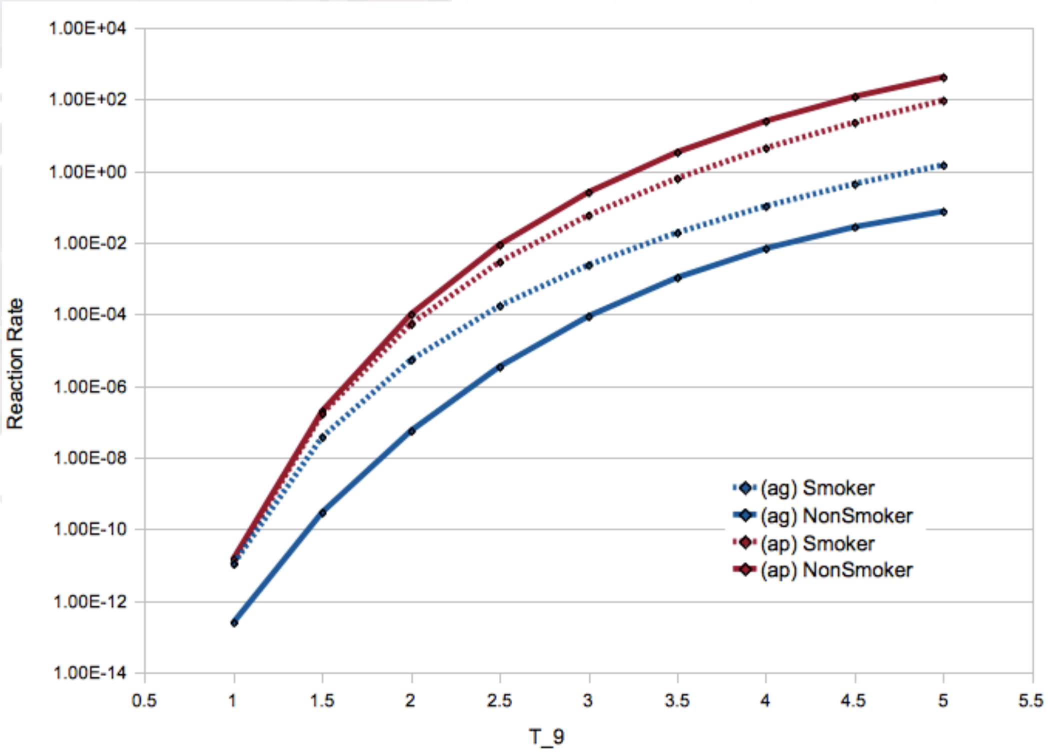
Sonzogni et al. PRL 84 (2000)



- Astrophysical region is 1-4 MeV
- *Hoffman et al.* APJ 715 (2010) 1383
  - New evaluation on $^{44}Ti(\alpha,p)$ reaction rate
  - Conclude that $^{44}Ti(\alpha,p)$ uncertainty has been underestimated (x3)
- Sonzogni compared to SMOKER
- NON-SMOKER provides significant update

Data achieved with ~10^5 pps on target

$^{44}Ti(\alpha,p)$ Reaction Rates



SMOKER → NONSMOKER: $^{44}Ti(\alpha,p)$ little effect

$^{44}Ti(p,\gamma)$ major effect

$^{44}Ti(\alpha,p)$ Reaction Rates

- NON-SMOKER includes better treatment of isospin suppression for alpha-capture reactions on N = Z nuclei
- Vockenhuber *et al*. states that $^{44}Ti(\alpha,p)$ NON-SMOKER rate is 100x smaller than SMOKER rate
  [J. Phys G: Nucl. Part. Phys. 35(2008)]
- Rauscher [priv. comm.] says this is in error. Only a factor of 20.
- Consequences if $^{44}Ti(\alpha,\gamma)$ rate > $^{44}Ti(\alpha,p)$ rate

Part 3: Proposal

Direct measurement of $^{44}Ti(\alpha,p)$ at astrophysical energies

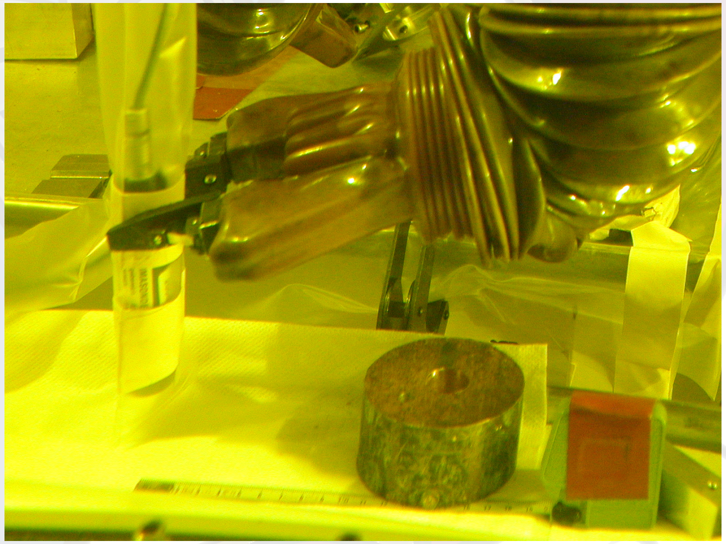
- Sonzogni used a ^{44}Ti beam: $^{45}Sc(p,2n)^{44}Ti$ produced 180 μCi of ^{44}Ti, ~ 1.8×10^{16} atoms. About 38μCi were used in a copper insert for a negative ion Cs sputter source.
- Priv. Comm.: Sonzogni approach has limited further capability
- Production of a ^{44}Ti target is viable: Daniel Bremmerer leads; Timescale 'few years'.
- Production of a ^{44}Ti ISOL beam is viable: beam development at GANIL, TRIUMF. Timescale is 'few years'
- Production of offline ^{44}Ti beam... this proposal

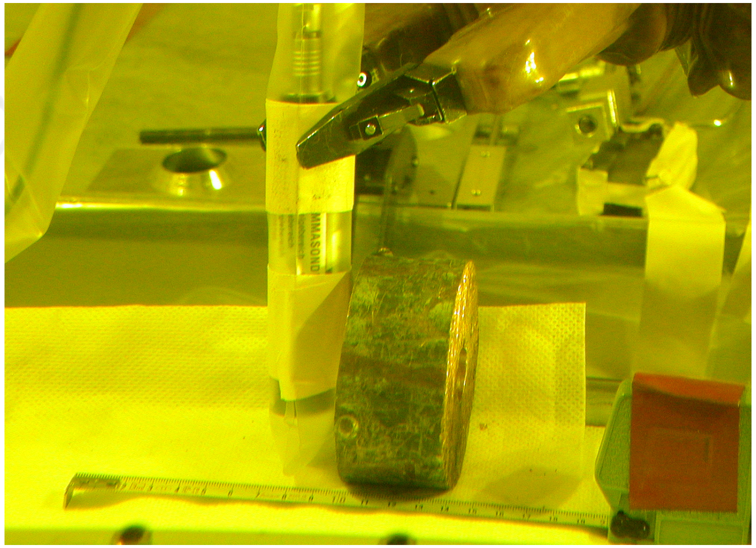
ERAWAST

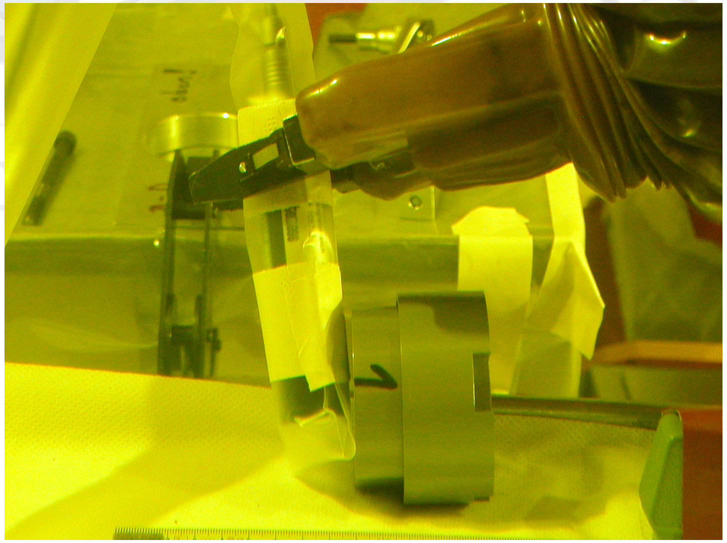
Exotic Radionuclides from Accelerator Waste for Science and Technology

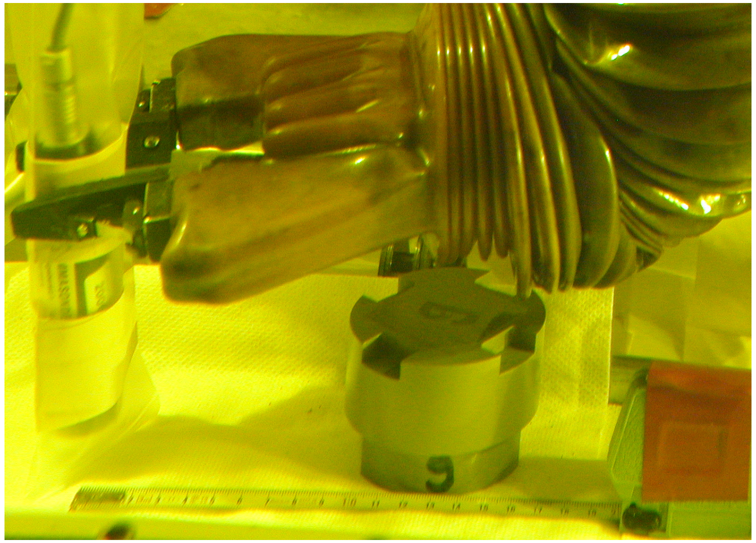
- A project to utilise long lived activity generated in PSI beam dumps
- Copper beam bumps, exposed to 1.5mA protons for ~12 years, dismantled ~15 years ago.
- ^{26}Al, ^{59}Ni, ^{53}Mn, ^{60}Fe or ^{44}Ti have been separated.
- SINQ facility material also available: other isotopes, e.g. ^{182}Hf
- S.Steel - no ^{60}Co contamination

Applications: Nuclear physics, nuclear astrophysics, Geophysics, Radio-pharmacy, AMS, RIMS,...









ERAWAST

Second Workshop

Four talks 'dedicated' to ^{44}Ti

- Separation of ^{44}Ti from stainless steel by Maruta Bunka of the ERAWAST group,
- ^{44}Ti beams at CERN by Thierry Stora,
- Measurement of ^{44}Ti(α,p) with a radioactive ^{44}Ti target by Tariq Al-Abdullah (Daniel Bemmerer's group). Issues over safety: Au containment layers etc.
- Uses of at reclaimed beams of ^{44}Ti at TRIUMF, Jennifer Fallis

Plus

- Iris Dillmann in the "Dreams and Illusions" section
  Measurement of stellar half-life of ^{44}Ti in a storage ring.
  Efficiency at GSI to get the ions from the source to the storage ring is too low, but maybe could be considered once the Heidelberg storage ring moves to ISOLDE...?

^{44}Ti availability

"The bottom line on the ^{44}Ti is that there is more of it than we are going to know what to do with. They have actually stopped processing the copper beam dump because they have been having a lot more luck with stainless steel test samples that were put in their SINQ facility (spallation neutron source). These samples have the added benefit that no ^{60}Co is produced, so they don't have to wait very long before they can handle the material.

"They have determined that they have ***300MBq*** of ^{44}Ti in the samples produced to-date, and there are more experiments yet to be run. There are also tests on V-metal and V+Ti-metal and each of these samples is expected to contain ***500MBq*** of ^{44}Ti. There is plenty to share with the ^{44}Ti target experiment, and the medical people have moved on and are now producing their own. ***The only limits for how much ^{44}Ti we can use to produce a beam will be set by the safety people."***

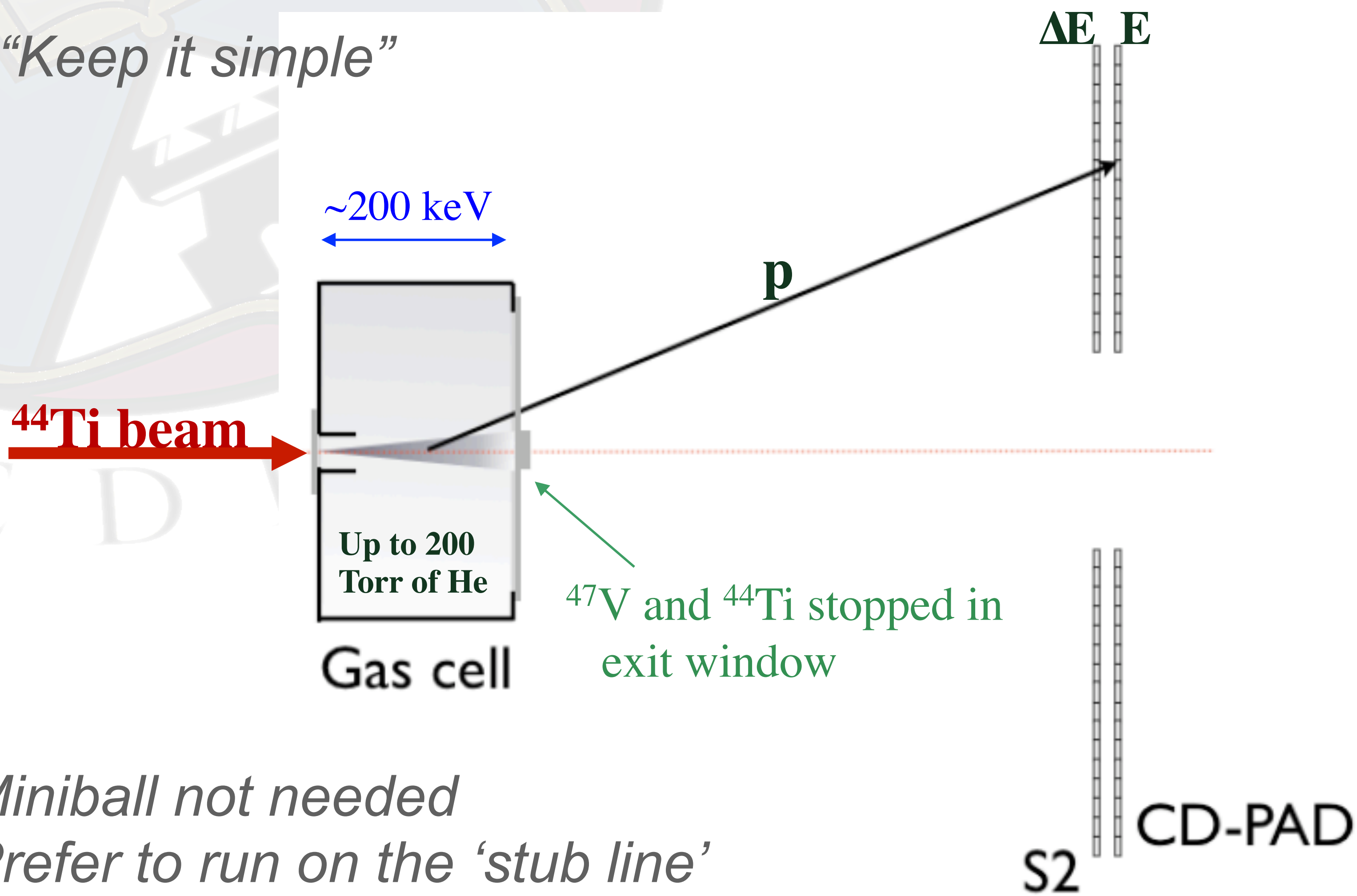
Jennifer Fallis, 6/9/2011

^{44}Ti Beam Production

- Development ongoing at ISOLDE, TRIUMF and GANIL
- 1 week at 10^5 pps is about 10^{12} ions
- With 10^{16} ions, 0.01 total is efficiency required for a significantly improved measurement
- ^{44}Ti can be provided in several forms (e.g. TiF_4, sublimates at 284^{o}C, melting point 115^{o}C / boiling point 445^{o}C
- TRIUMF didn't even have to turn on oven to get a good vapour pressure!
- There is a good chance of getting up to 1% efficiency out of source when using TiF_4.
- "Should contact Andreas Türler (GSI) who has been developing Ti beams from an ECR source for heavy element studies."

^{44}Ti Experiment configuration

"Keep it simple"

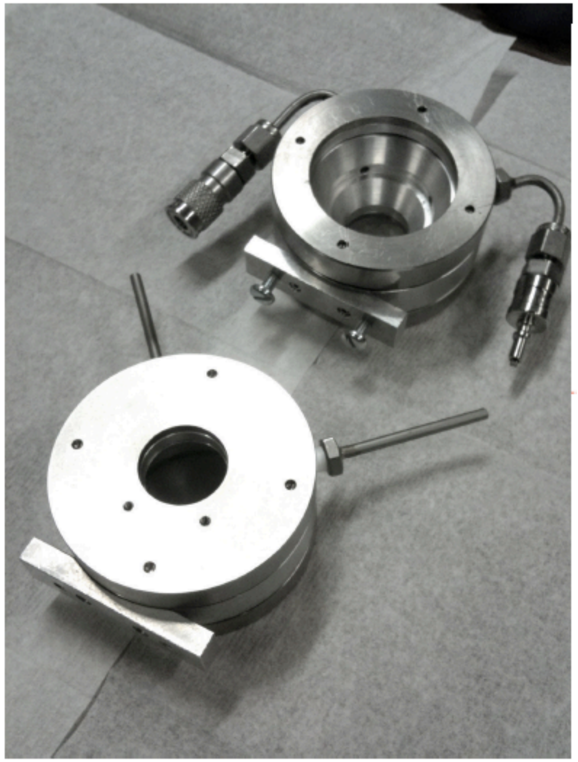


Miniball not needed

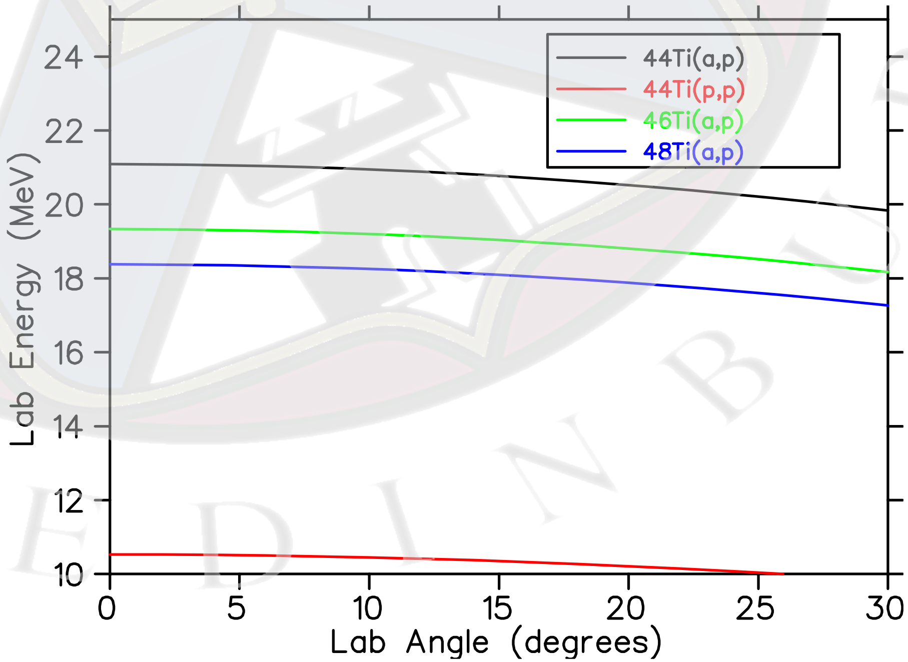
Prefer to run on the 'stub line'

^{44}Ti Experiment configuration

- This will be a challenging measurement
- Keep things as simple as reasonably possible
- 'Singles' protons and alpha's measured
- Exit window removes heavier particles
- Energy-ToF and/or E-DE particle identification
- Well understood gas cell
- Well understood detectors
- Require good beam monitoring
  - Intensity, **Purity**, Alignment
- Analysis is then, hopefully, relatively straightforward



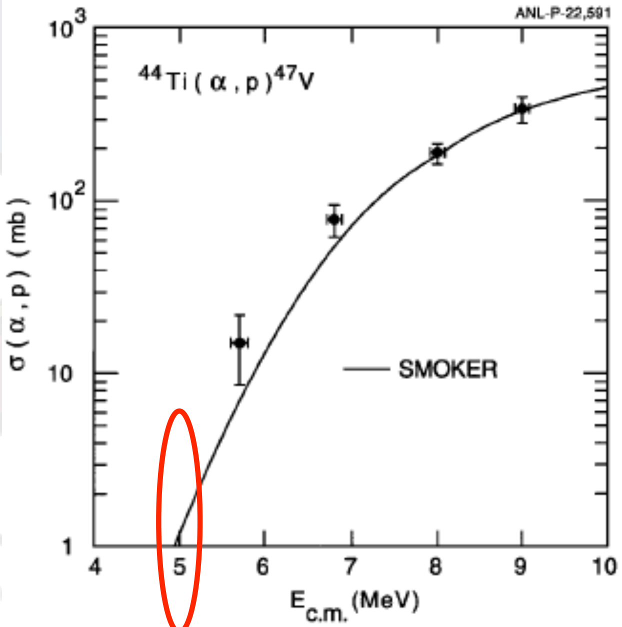
Expected issues



^{22}Ne source gas...?

Charge state	A/Q (44Ti)
1	44
2	22
3	14.67
4	11
5	8.8
6	7.33
7	6.29
8	5.5
9	4.89
10	4.4

^{44}Ti Event rate estimate



Assuming 10^6 pps on target

E/u MeV/u	Ecm MeV	Cross section mb	Events/day	#12 hours shifts
1.363	5	4	195	2
1.090	4	1	65	4
0.818	3	0.5	14	10

Scheduling

- 44Ti ions are available 'now'
- Experimental apparatus (gas cell, silicon, DAQ) is available now
- Gas cell windows need a little work
- Monte Carlo optimisation is ongoing
- Experimental team is already sufficient (additional collaborators welcome)
- Safety situation?
- Assessment of measures required to prevent activation?
- Window of opportunity during CERN 'shutdown year'?

Remaining Questions

- Management:
  - What formal beam requests / proposals are still required by ISOLDE?
  - What is the status of Safety requirements?
  - Scheduling issues? Can we run during shutdown year?
- Beam Development
  - How much ^{44}Ti will be required?
  - What form would be required (liquid, solid, salt, oxide).
  - Containment vessel? (It is of course better not to transfer the material at CERN from one vessel to another).
  - Could the ^{44}Ti be recovered? (10^8 pps 1 wk = 22k dps)
- Facility:
  - Assessment of measures required to prevent activation of beamlines, magnets, slits, etc?
- Costs:
  - Transport fees, development fees, running fees?

Thank you