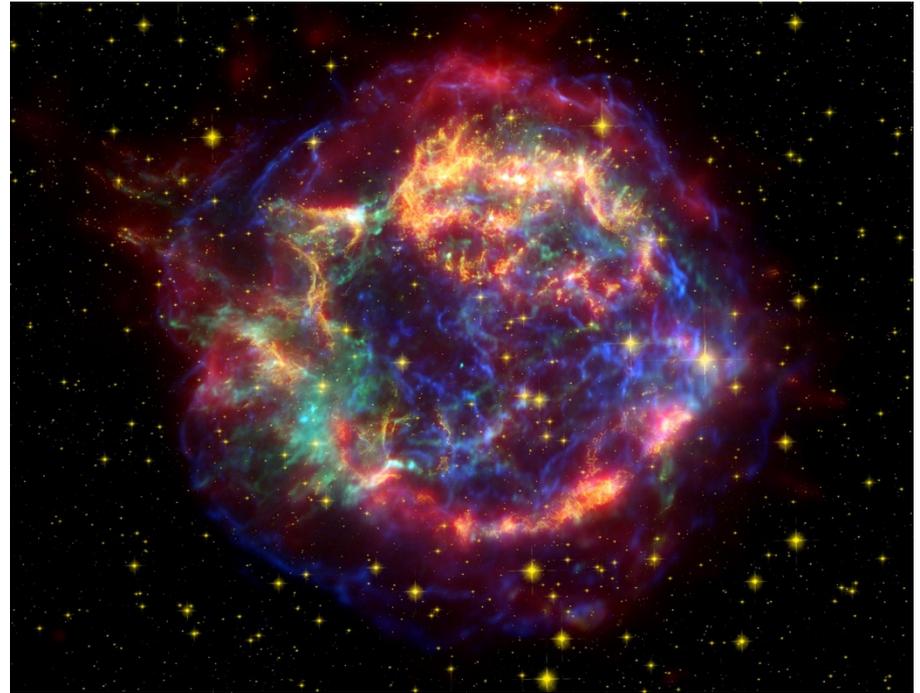

Towards a Study of the $^{44}\text{Ti}(\alpha, p)^{47}\text{V}$ reaction at CRYRING

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- ^{44}Ti in Astrophysical Scenarios
- Previous Measurements
- Injecting Ti into CRYRING from local ion source
- Measuring alpha-capture reaction at CRYRING



False color image of the supernova remnant Cassiopeia A (Cas A). The picture is composited of data from the Spitzer Space Telescope, the Hubble Space Telescope and the Chandra X-ray Observatory.

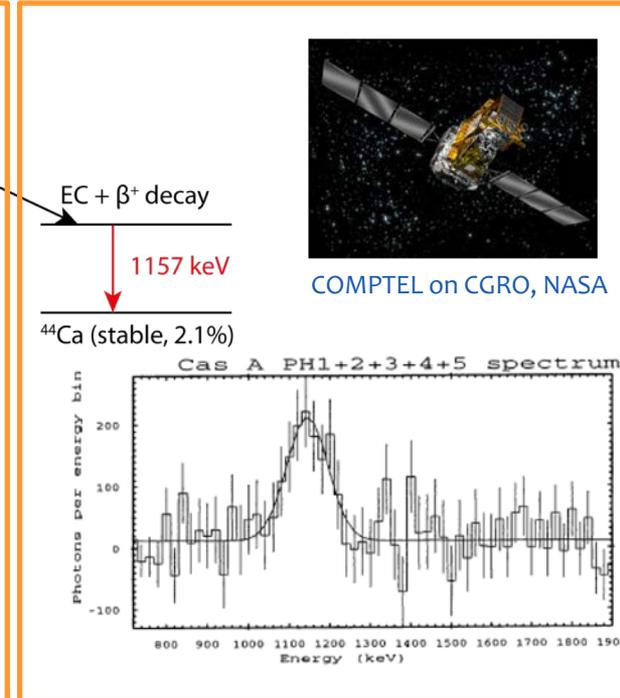
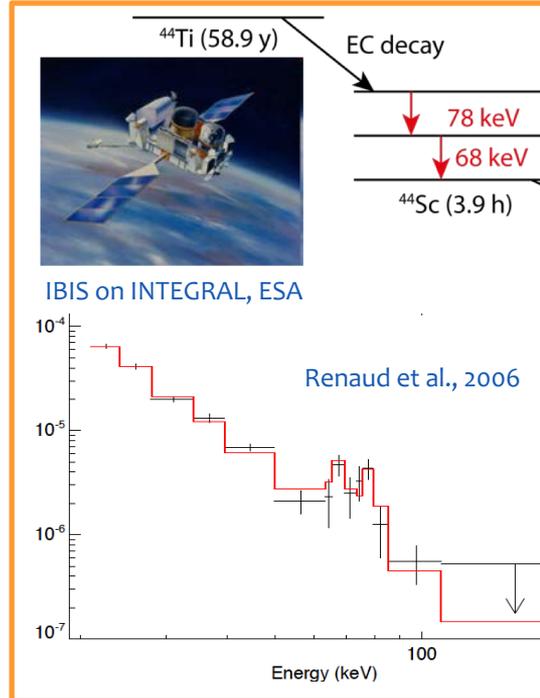
Picture: NASA/JPL-Caltech

^{44}Ti detected in SN remnants

^{44}Ti γ -emission detectable at space observatories

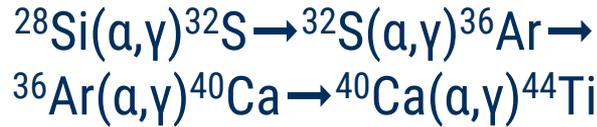
Dominates light curve over ^{56}Ni about 4 yrs after explosion

First detected in CasA SNR (~1667 AD, Milky Way), later in SN1987A (LMC)



^{44}Ti SN Production

Produced in α -rich freeze out of core-collapse SN



Dominant consumption reaction:



^{44}Ti amount in SNR dependent on reaction rate ratio of both reactions!

Cr 44 42.8 ms β^+ β_p 0.887, 1.353 1.701 γ 677	Cr 45 60.9 ms β^+ β_p 2.041... γ 1083*, 1323 1370*	Cr 46 0.26 ms β^+	Cr 47 472 ms β^+ 6.4... γ 87	Cr 48 21.6 h ϵ γ 308, 112	Cr 49 42 m β^+ 1.4, 1.5... γ 91, 153, 62... σ 15	Cr 50 4.345 ϵ γ 320 $\sigma < 10$	Cr 51 27.7010 d ϵ γ 320 $\sigma < 10$	Cr 52 83.789 σ 0.8
V 43 79.3 ms β^+ β_p	V 44 150 ms 111 ms β^+ γ 1083 1371, 1561 2634	V 45 547 ms β^+ 6.1... γ 40	V 46 422.6 ms β^+ 6.0... γ (2611)	V 47 32.6 m β^+ 1.9... γ (1794...)	V 48 15.97 d ϵ β^+ 0.7 γ 984, 1312 944...	V 49 330 d ϵ σ no γ	V 50 0.250 $1.4 \cdot 10^{17}$ a ϵ, β^+ γ 1054, 783 σ 21, $\sigma_{n,0}$ 0.007	V 51 99.750 σ 4.9
Ti 42 208.14 ms β^+ 5.4, 6.0... γ 611... g	Ti 43 509 ms β^+ 5.8... γ 2288, 845...	Ti 44 58.9 a ϵ γ 78, 68... g σ 1.1	Ti 45 3.08 h β^+ 1.0... γ (720...)	Ti 46 8.25 σ 0.6	Ti 47 7.44 σ 1.6	Ti 48 73.72 σ 7.9	Ti 49 5.41 σ 1.9	Ti 50 5.18 σ 0.179
Sc 41 596 ms β^+ 5.5... γ (2575, 2959)	Sc 42 61 s 0.68 s β^+ 2.8 γ 438 1525 1227	Sc 43 3.89 h β^+ 1.2... γ 373...	Sc 44 58.61 h 3.92 h β^+ 2.71 ϵ γ (1002 1261 1157)	Sc 45 100 σ 10 + 17	Sc 46 18.75 s 83.79 d β^+ 0.4, 1.5 γ 1121 889 σ 8.0	Sc 47 3.35 d β^- 0.4, 0.6 γ 159	Sc 48 43.67 h β^- 0.7... γ 984, 1312 1038...	Sc 49 57.2 m β^- 2.0 γ (1762, 1623)
Ca 40 96.941 σ 0.41 $\sigma_{n,\alpha}$ 0.00013	Ca 41 1.03 $\cdot 10^5$ a ϵ , no γ σ -4 $\sigma_{n,\alpha}$ 0.18 $\sigma_{n,p}$ 0.007	Ca 42 0.647 σ 0.65	Ca 43 0.135 σ 6	Ca 44 2.086 σ 0.8	Ca 45 163 d β^- 0.3... γ (12), e^- σ -15	Ca 46 0.004 σ 0.70	Ca 47 4.54 d β^- 0.7, 2.0... γ 1297, 808 489...	Ca 48 0.187 $1.9 \cdot 10^{10}$ a $2\beta^-, \beta^-$ σ 1.09

Extract from the Karlsruhe Nuclide Chart showing the region around calcium and titanium isotopes.

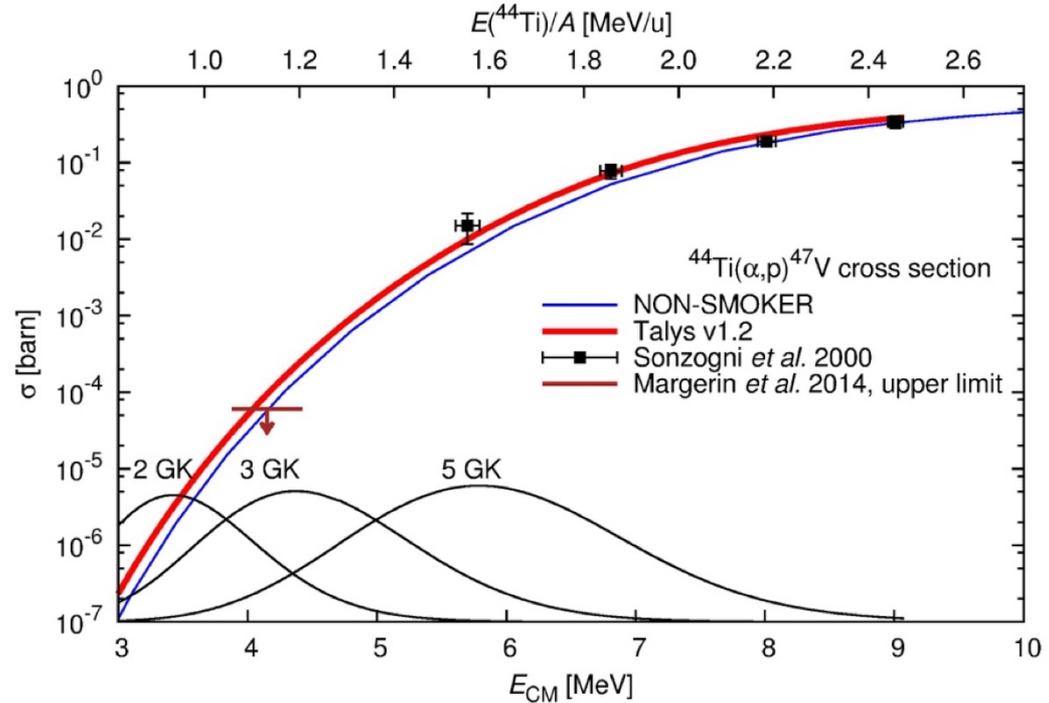
Nucleonica GmbH

Reaction Cross Section

Previous measurements above the Gamow window for core collapse SN

Margerin et al. @ ISOLDE → upper limit at 3 GK Gamow window

→ more data needed between 3 and 6 MeV E_{cm}



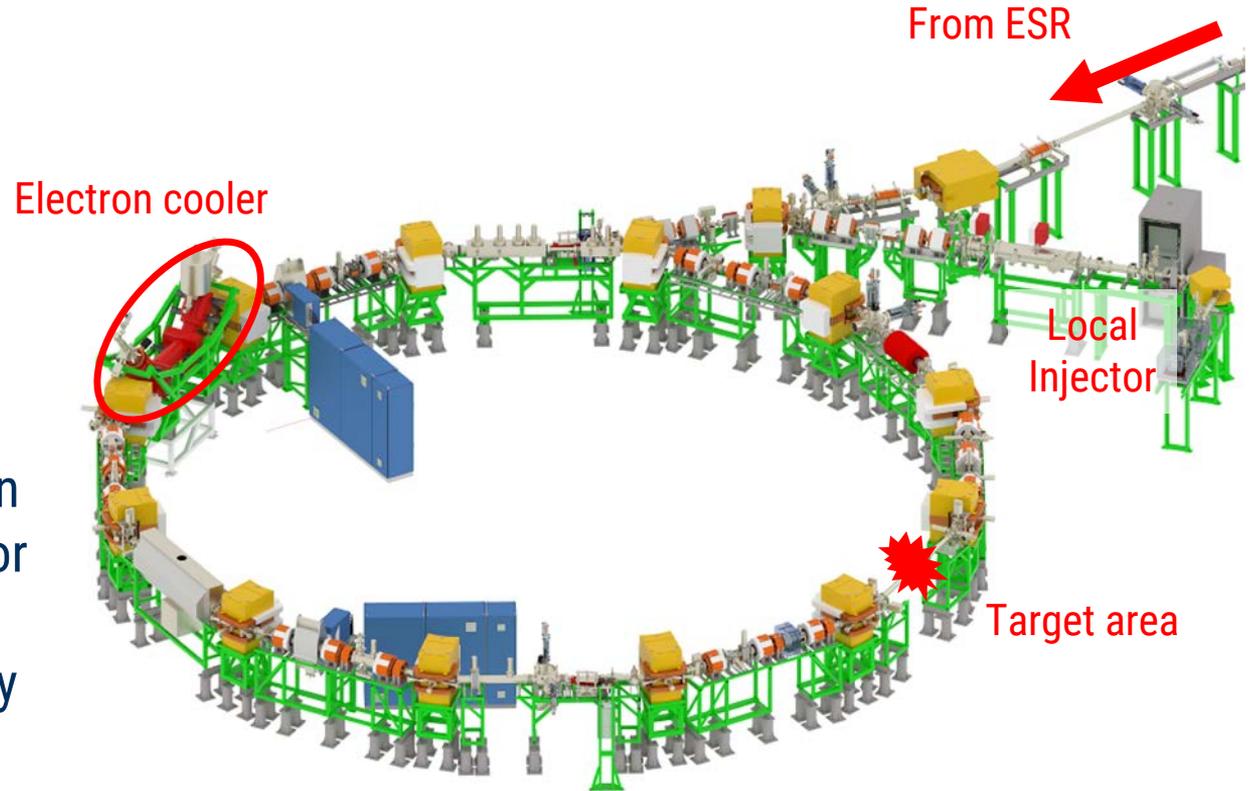
Al-Abdullah et al., Eur. Phys. J. A 50, 140 (2014)

CRYRING @ ESR

Magnetic storage ring,
 $B_p \leq 1.44 \text{ Tm}$

Highly-charged ions from
ESR or local ion source

Limitation due to injection
RFQ: $q/A > 0.35 \rightarrow \text{Ti}^{16+}$ or
higher, bare (Ti^{22+}) would
intrinsically remove decay
products

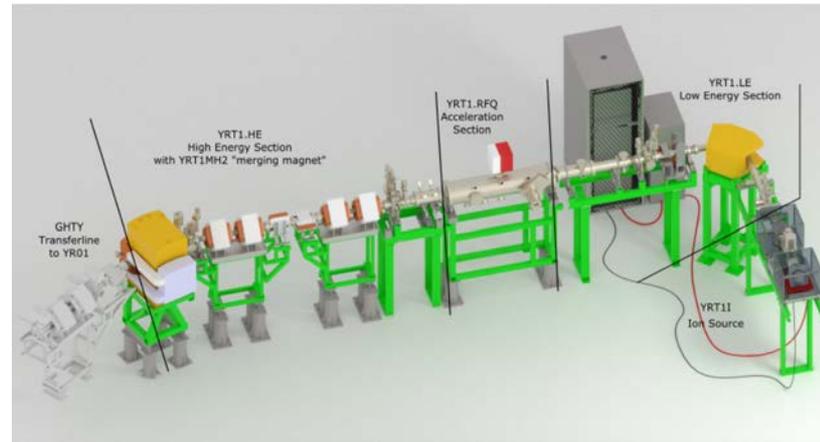


CRYRING Local Injector

Production of highly charged Ti-ions in EBIS:
E.g. EBIS-A from DREEBIT GmbH, Ar^{18+} (fully ionized): 10^5 at 1Hz

Injection of Ti into EBIS: MIVOC (Metal Ions from Volatile Organic Compounds), (trimethyl)pentamethyl-cyclopentadienyl-titanium, $(\text{CH}_3)_5\text{C}_5\text{Ti}(\text{CH}_3)_3$, solid material, [Koivisto et al., NIMB 187 (2002) 111]

^{44}Ti available from PSI beam dump, up to 50 MBq (D. Schumann)



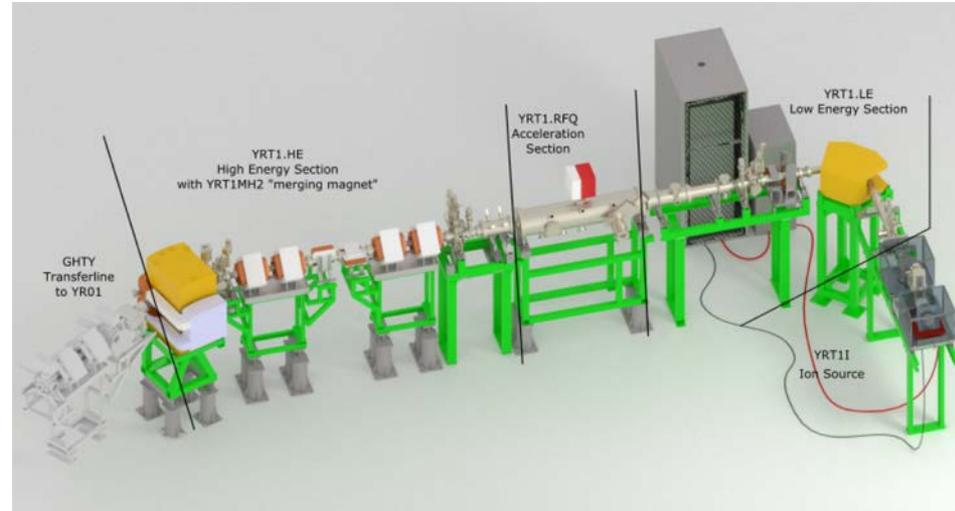
Dresden EBIS-A:
DREEBIT GmbH

CRYRING

Ions accelerated with RFQ to 300 keV/u
and injected into CRYRING

Acceleration in CRYRING to required
beam energy: 0.8 – 1.6 MeV/u
(corresponds Gamow window of 2 –
5 GK)

Expected storage time of highly
charged Ti ions: some tens of seconds
Rev. freq.: ^{44}Ti @1.1 MeV/u: 270 kHz



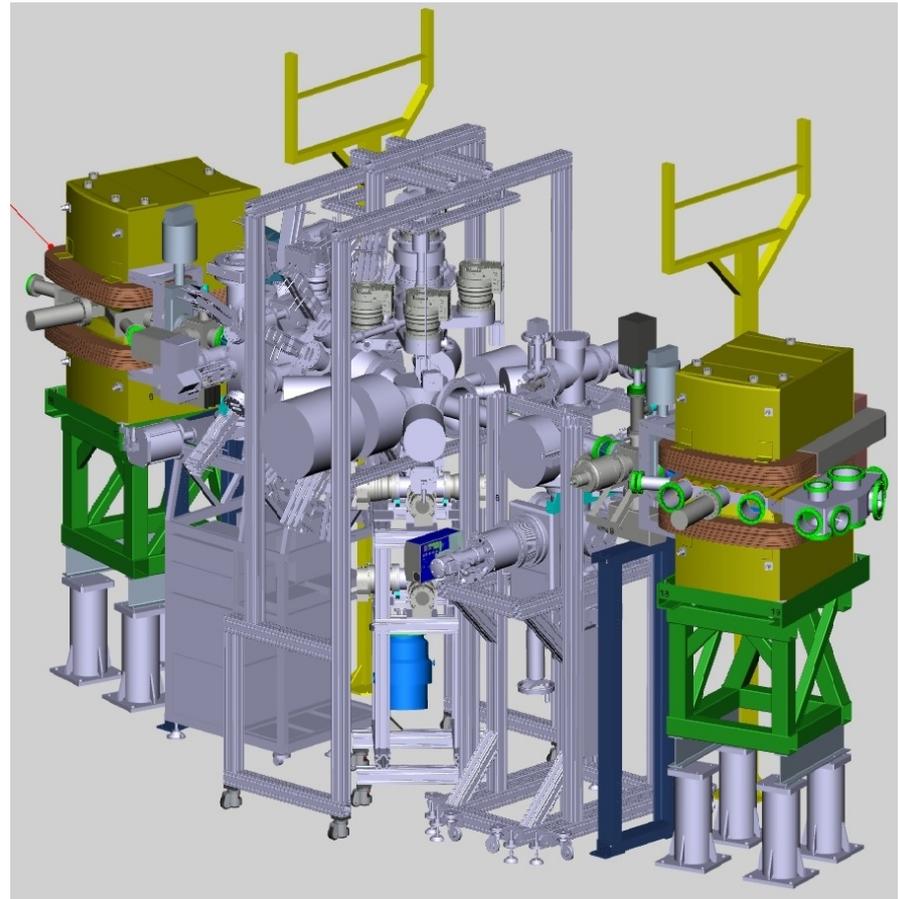
CRYRING Gas-jet Target

$^{44}\text{Ti}(\alpha, p)^{47}\text{V}$ reaction in inverse kinematics at CRYRING gas-jet target with helium

Expected jet density: up to 10^{14} at/cm²

Detection of p with Si detectors close to target, energy $\sim 7 - 9$ MeV

Rate estimation: with 10^5 stored particles $\rightarrow \sim 1$ event/h



Reaction Kinematics

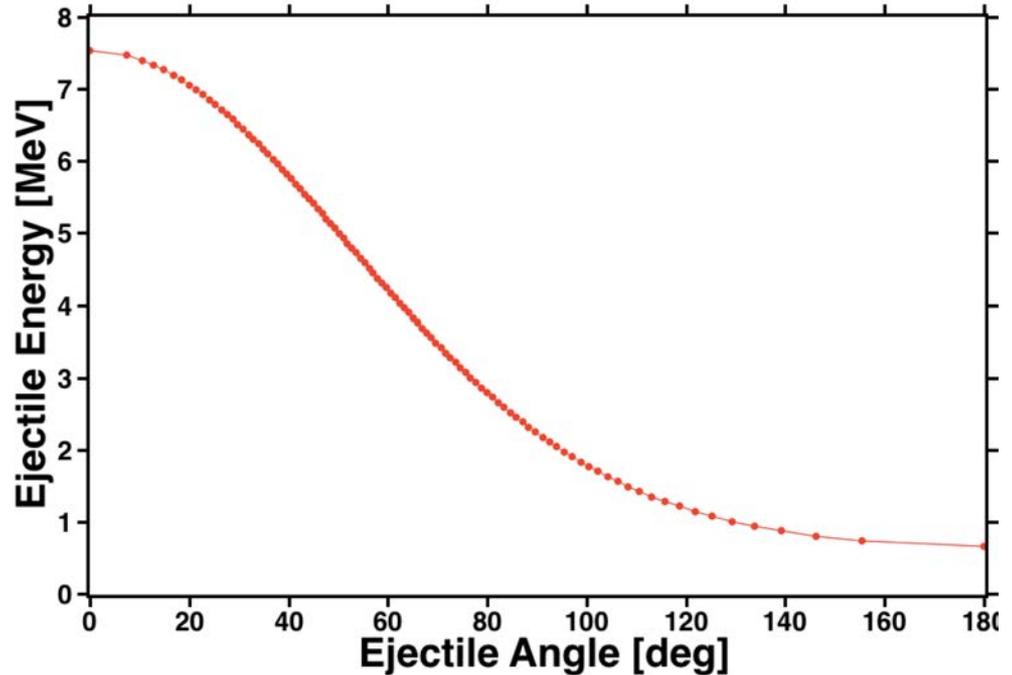
Two options because of long ^{44}Ti lifetime:

- ^4He -beam, ^{44}Ti target
- ^{44}Ti -beam, ^4He gas target

^{44}Ti beam: α -capture reaction in inverse kinematics

Maximum recoil angle in Gamow window: $\sim 2.4^\circ$

Protons emitted in all directions



Energy distribution of the proton, $E(^{44}\text{Ti})=1.1$ MeV/u

Reaction Kinematics

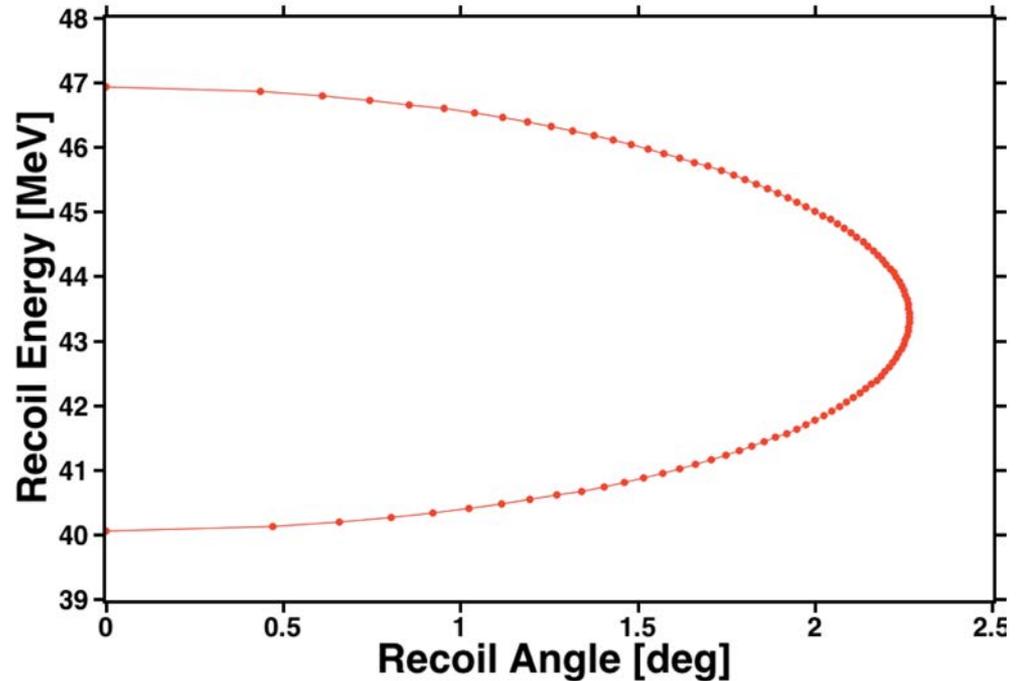
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Maximum recoil angle in Gamow window: $\sim 2.4^\circ$

Protons emitted in all directions



Energy distribution of the recoil, $E(^{44}\text{Ti})=1.1$ MeV/u

Comparison to Previous Experiments

ATLAS / Sonzogni et al.

- ^{44}Ti beam
- ^{47}V detected with recoil mass separator

ISOLDE / Margerin et al.

- ^{44}Ti beam, single-pass
- Detection of p after reaction
 - large emission angles
- 67 mbar He gas-cell
 - + high density
 - windows
 - energy loss

CRYRING

- ^{44}Ti beam, multi-pass
- Detection of p after reaction
 - large emission angles
- Gas-jet target
 - "low" density
 - + windowless
 - + well defined reaction energy

Summary & Outlook

- ^{44}Ti of great interest, provides “smoking gun” for recent supernova
- Calculations and observations not in agreement → more experimental data in Gamow window needed
- Newly installed CRYRING@ESR provides excellent opportunity to measure alpha-capture reaction rate
- Accessible energies in the range of Gamow window for core-collapse SN
- Radioactive ^{44}Ti available in sufficient amounts from PSI beam dump
- More efficient use of precious ^{44}Ti material in storage ring

Participating Groups

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TU Dresden

K. Zuber



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R. Dressler, D. Schumann

SPARC Collaboration