Decoupling the production and the Acceleration stages

Long lived rare isotope beams prodused in batch mode

An example: 85Kr s-process waiting point

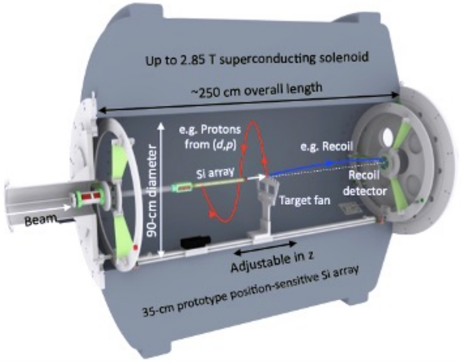
Common

batch mode.

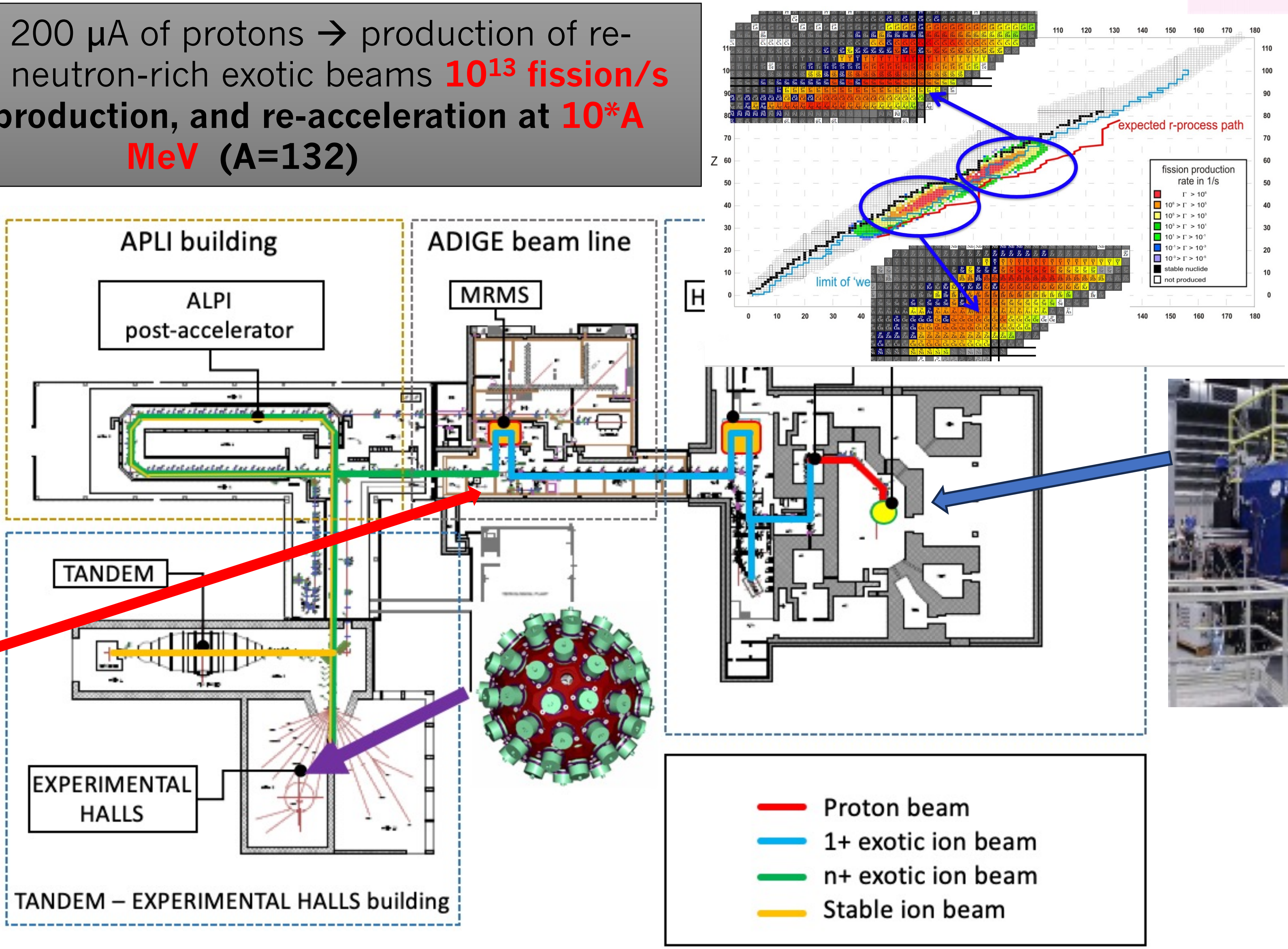
means

A computer operation in which a specific task, ticketing, for example, is performed on a group of records.

40 MeV - 200 µA of protons → production of re-accelerated neutron-rich exotic beams **10^{13} fission/s in-target production, and re-acceleration at 10*A MeV (A=132)**

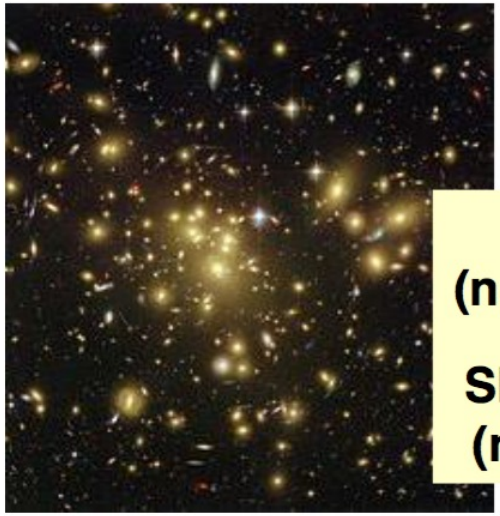


ECR ion source for pilote beams



Nuclear Structure and EDM search

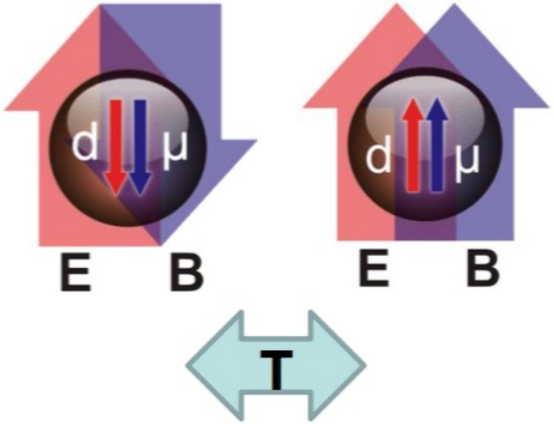
- Explanations of the Baryon Asymmetry of the Universe require additional CP violation
- Permanent EDM of fundamental spin systems are the most sensitive probes for bejond Standard Model CP violation
- Axion like Dark Matter probe?



Observed:
$(n_B-n_{\bar{B}})/n_\gamma=6x10^{-10}$

SM expectation:
$(n_B-n_{\bar{B}})/n_\gamma \sim 10^{-18}$

Sakharov 1967:
B-violation
C & CP-violation
non-equilibrium
JETP Lett.5(1967)24



Octupole enhanced atomic EDM moment

V Spevak, N Auerbach, and VV Flambaum
PR C **56** (1997) 1357

related to Q_3

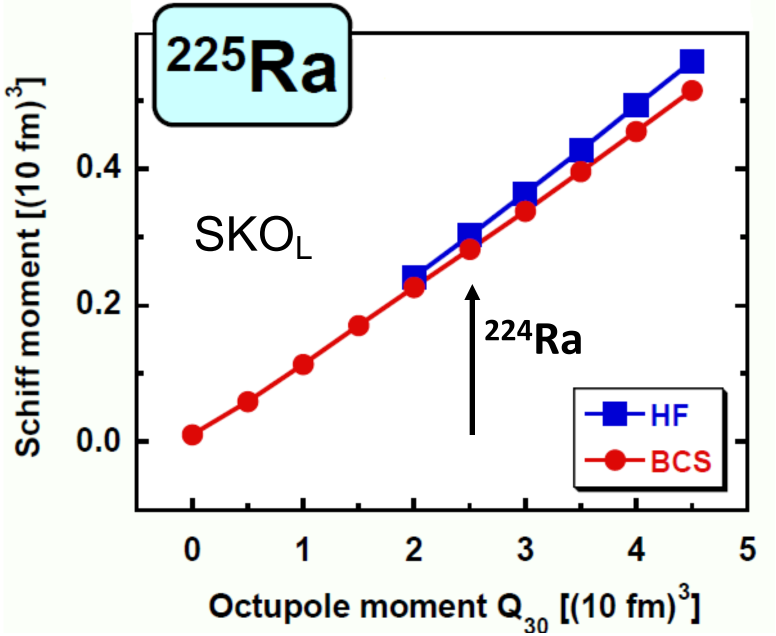
P,T-violating n-n interaction

Schiff moment:

$$S = -2\frac{J}{J+1}\frac{< \hat{S}_z >< \hat{V}_{PT} >}{\Delta E}$$

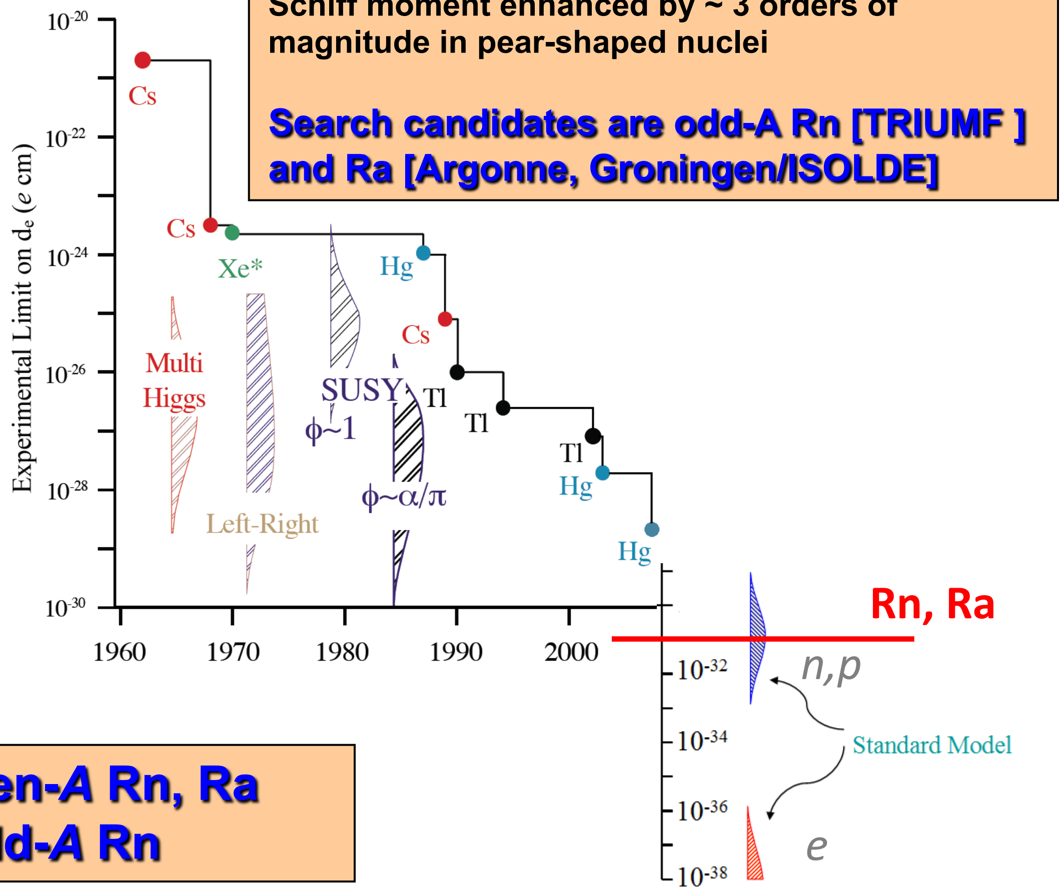
energy splitting of parity doublet

J Dobaczewski (Trento, 2010)



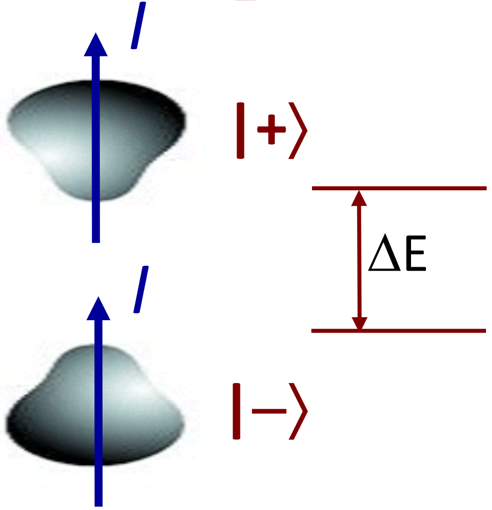
Schiff moment enhanced by ~ 3 orders of magnitude in pear-shaped nuclei

Search candidates are odd-A Rn [TRIUMF] and Ra [Argonne, Groningen/ISOLDE]



Measure: Q_3 in even-*A* Rn, Ra
ΔE in odd-*A* Rn

Octupole Enhancement



$$\Psi^+ = (|+\rangle + |-\rangle)/\sqrt{2}$$

$$\Psi^- = (|+\rangle - |-\rangle)/\sqrt{2}$$

$$\xrightarrow{\cancel{P},\ \cancel{T}}$$

$$\Psi^+ = ((1+\alpha)|+\rangle + (1-\alpha)|-\rangle)/\sqrt{2}$$

$$\Psi^- = ((1-\alpha)|+\rangle + (1+\alpha)|-\rangle)/\sqrt{2}$$

$$\alpha = \frac{\langle \Psi^- | V^{PT} | \Psi^+ \rangle}{\Delta E} \sim \frac{\beta_3 A^{-1/3}}{\Delta E}$$

$S_{intr} \sim eZA\beta_2\beta_3$ $\quad$ $S_{lab} \sim e\,Z\,A^{2/3}\,\beta_2\,\beta_3^{\,2}/\Delta E$ $\quad$ $\beta_2,\ \beta_3 \sim 0.1$

Haxton & Henley; Auerbach, Flambaum & Spevak; Hayes, Friar & Engel; Dobaczewski & Engel

	^{223}Rn	^{223}Ra	^{225}Ra	^{223}Fr	^{225}Ac	^{229}Pa	^{199}Hg	^{129}Xe
$t_{1/2}$		23.2 m	11.4 d	14.9 d	22 m	10.0 d	1.5 d	
I	7/2	3/2	1/2	3/2	3/2	5/2	1/2	1/2
Δe_{th} (keV)	37	170	47		75	49	5	
ΔE_{exp} (keV)	--		50.2	55.2	160.5	40.1	0.22	
10^5 S ($e$fm^3)	1000	400	300	500	900	12000	-1.4	1.75
10^{28} d_A (e cm)	**2000**	**2700**	**2100**	**2800**		30000	-5.6	0.8

Octupole Enhancement

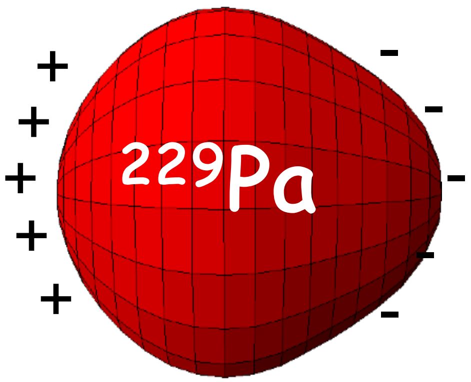
Cannot be transported with the present SPES infrastructure

HIE-ISOLDE for ^{223}Fr ~ 2x10^6 s^{-1}

SPES for ^{229}Pa by ^{232}Th(p,4n)

I ≈ 10^{16} atoms in 10 days

SPIRAL2 (Linag) for ^{229}Pa by ^{232}Th(p,4n)



30000 more sensitive then ^{199}Hg

$S_{intr} \sim eZA\beta_2\beta_3$ $\quad$ $S_{lab} \sim e\,Z\,A^{2/3}\,\beta_2\,\beta_3^2/\Delta E$ $\quad$ $\beta_2\,,\beta_3 \sim 0.1$

Haxton & Henley; Auerbach, Flambaum & Spevak; Hayes, Friar & Engel; Dobaczewski & Engel

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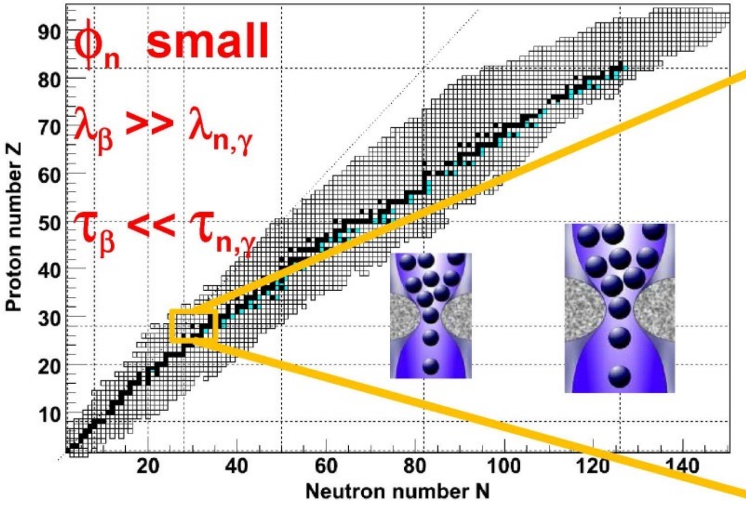
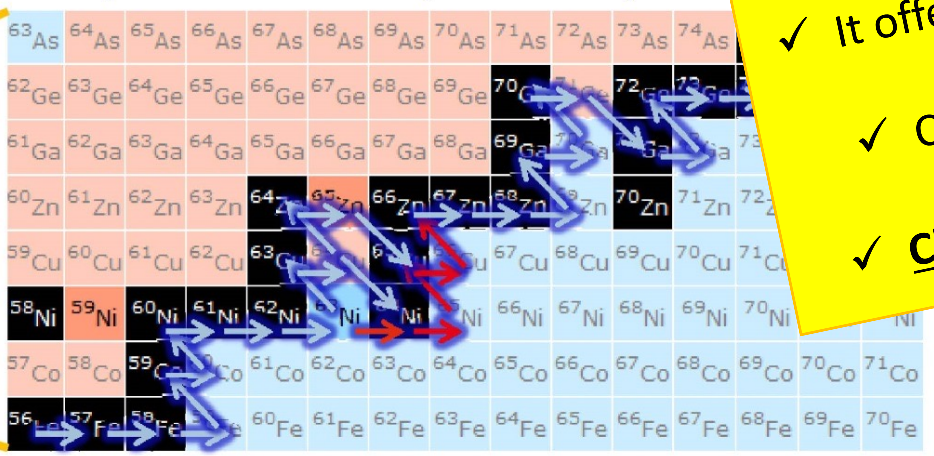
s-process nucleosynthesis and stellar n-flux

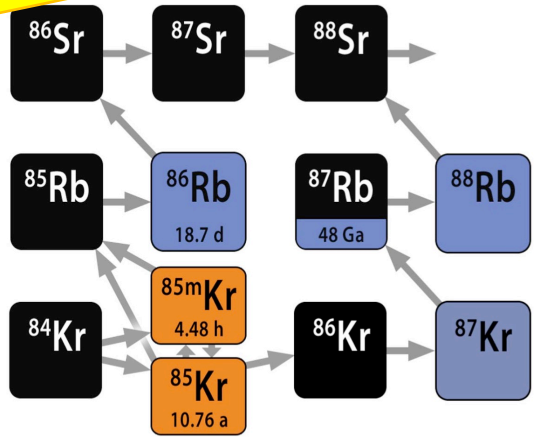
Stellar nucleosynthesis: the **s process**

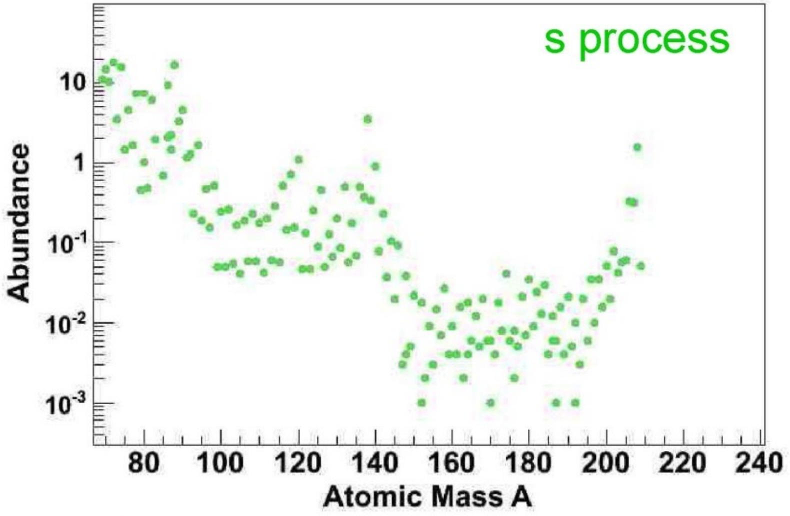
- ✓ The branching is important for Rb and Sr abundances
- ✓ It offers an estimation of the neutron density
- ✓ Crucial for both main and weak component
- ✓ ***Challenge present understanding!***



s process in AGB (Red Giant) Sta





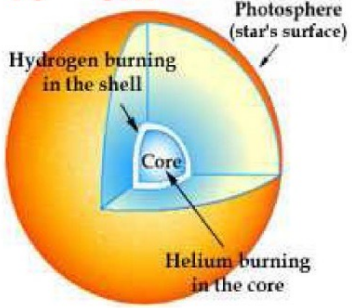


core He-burning
$3\text{-}3.5\cdot10^8$ K
kT=25 keV
10^6 cm^{-3}

shell C-burning
$\sim1\cdot10^9$ K
kT=90 keV
10^{11}-10^{12} cm^{-3}

^{22}Ne(α,n)

$\sigma(^{85}$Kr$) = (55 \pm 45)$ mb



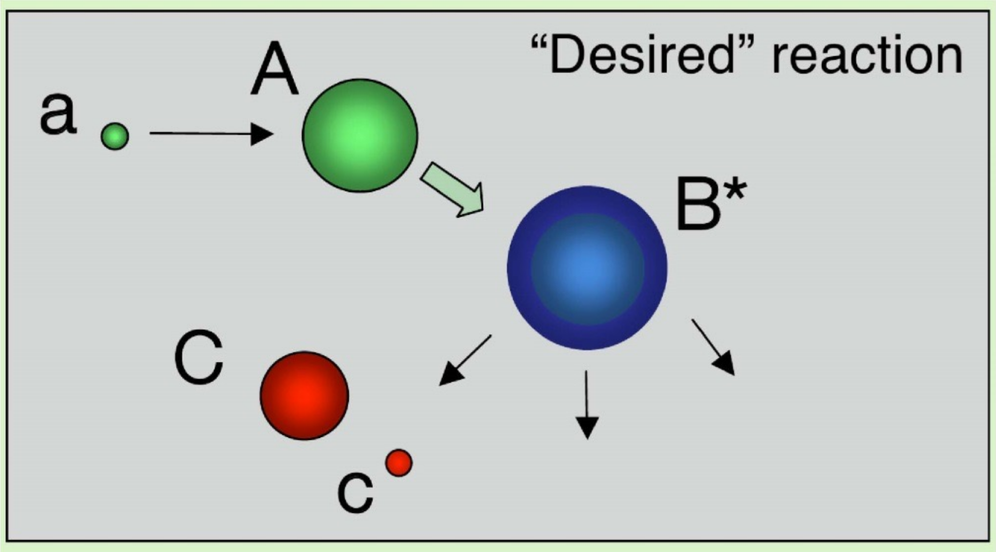
At high neutron densities (5 x 10^8 n/cm^3), 80% of the flux goes through ^{85}Kr producing ^{86}Kr, ^{87}Rb:

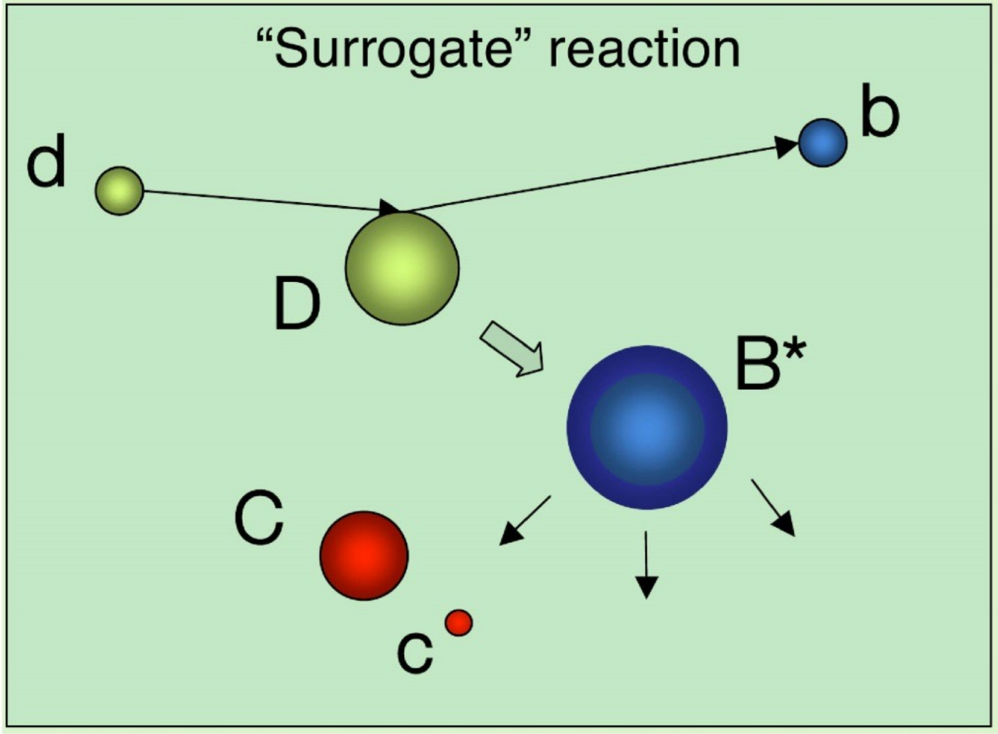
--> ^{87}Rb in AGB stars is an indicator of the neutron density!

- ✓ In low-mass stars: ^{88}Sr produced
- ✓ In massive AGB: ^{87}Rb

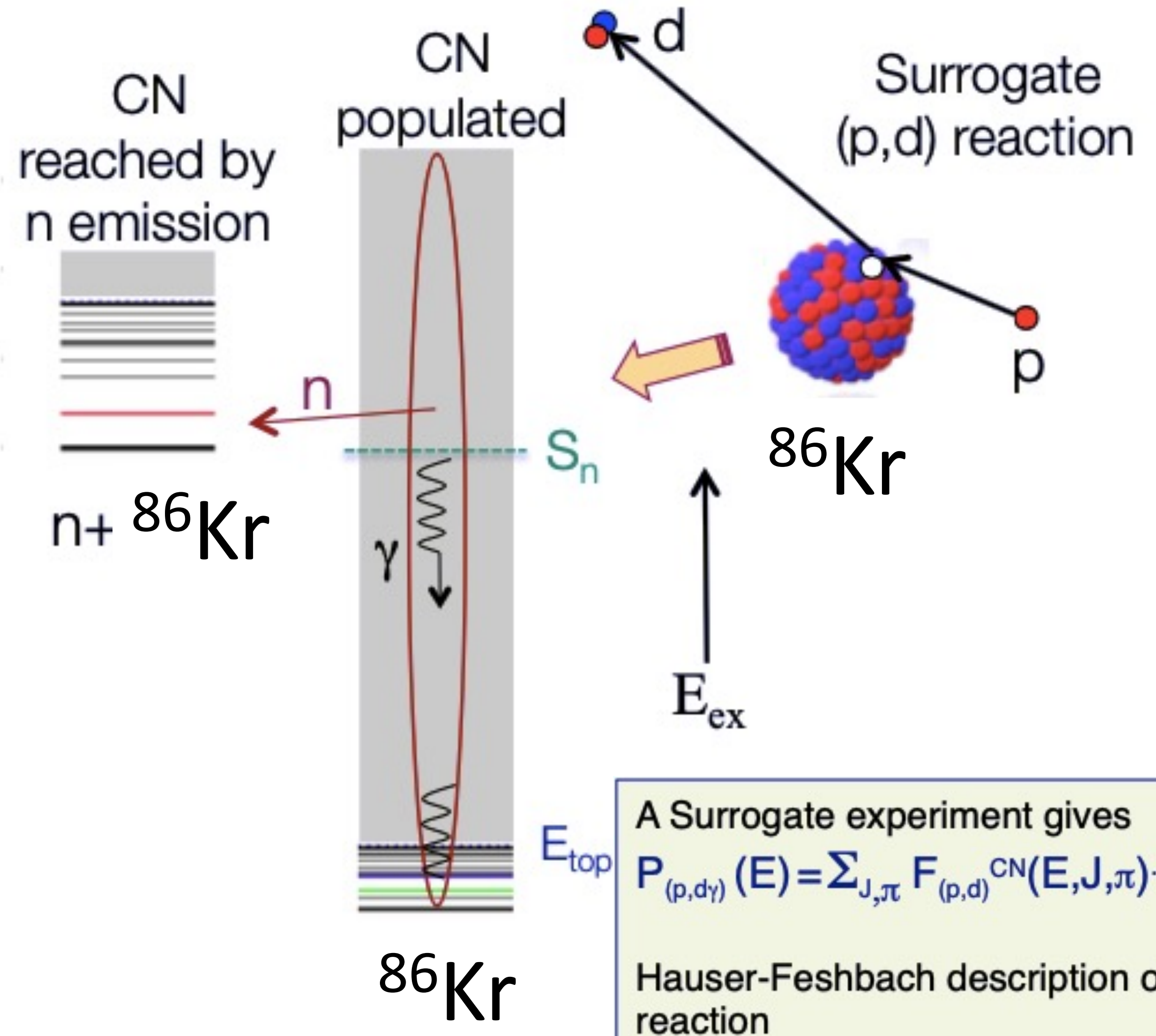
Arlandini et al. , Ap. J. 525 (1999)
Gallino et al., Ap. J. 497 (1998)
Raiteri et al. , Ap. J. 419 (1993)

Indirect Determination of Cross Sections **Surrogate Reactions**





A. Ratkiewicz et al. "Towards Neutron Capture on Exotic Nuclei: Demonstrating (d,pγ) as a Surrogate Reaction for (n,γ)" Phys. Rev. Lett. 122, 052502 (2019)



A Surrogate experiment gives

$$P_{(p,d\gamma)}(E) = \Sigma_{J,\pi} F_{(p,d)}^{CN}(E,J,\pi)\cdot G^{CN}_{\gamma}(E,J,\pi)$$

Hauser-Feshbach description of "desired" CN reaction

$$\sigma_{(n,\gamma)} = \Sigma_{J,\pi}\, \sigma_{n+target}^{CN}(E,J,\pi)\cdot G^{CN}_{\gamma}(E,J,\pi)$$

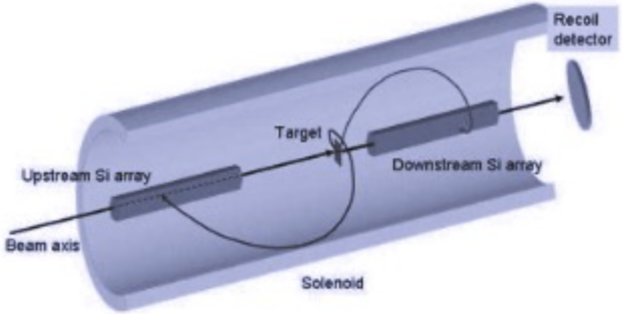
^{85}Kr(d,pγ)^{86}Kr for ^{85}Kr(n,γ) capture rate

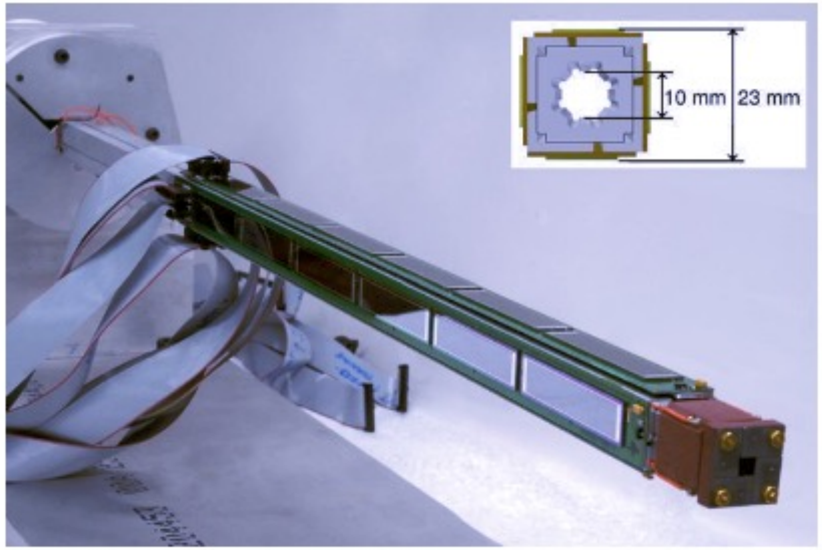
^{85}Kr + CD$_2$ 10 MeV/n & HELIOS I=10^6 pps

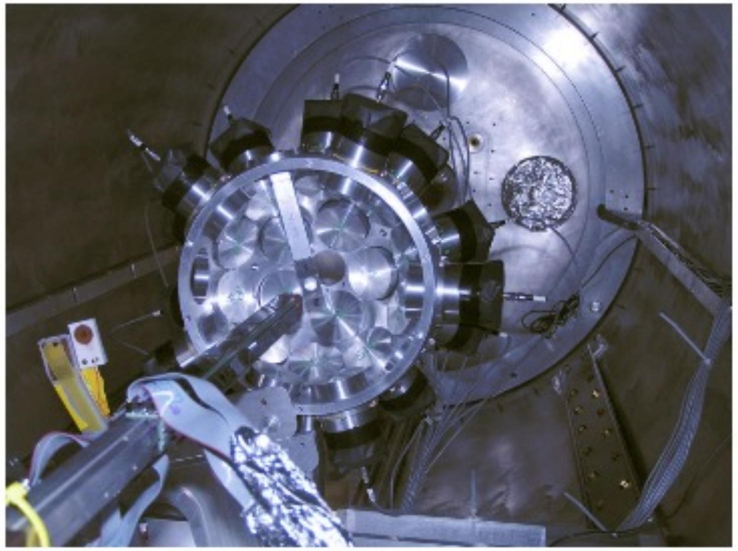
HELIOS: Solenoidal magnetic spectrometer with 2.0 T field

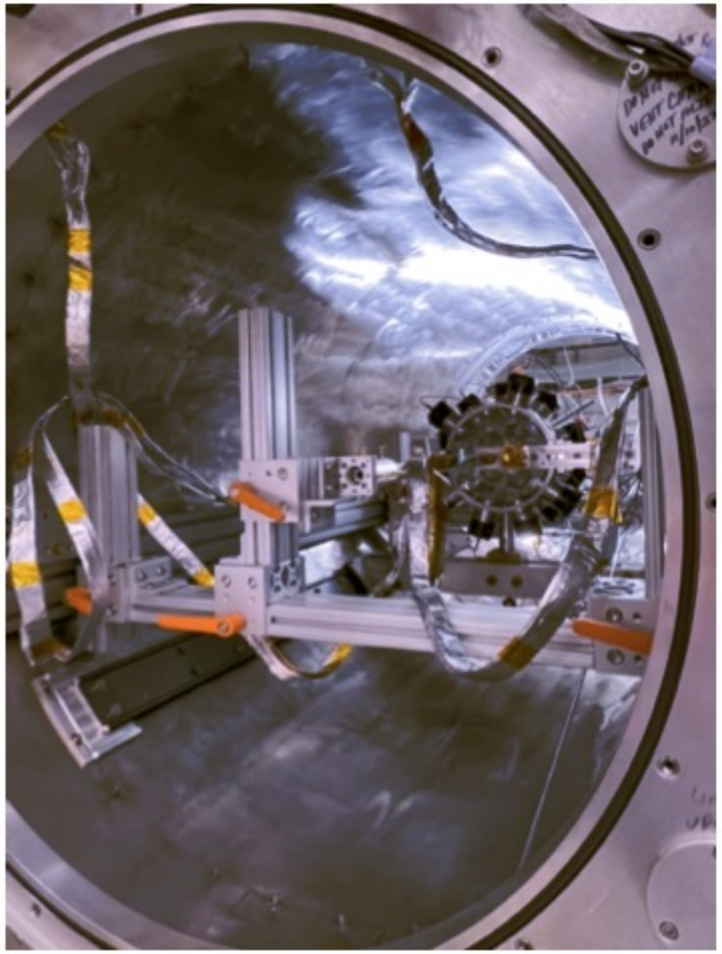
For protons: position sensitive Si array

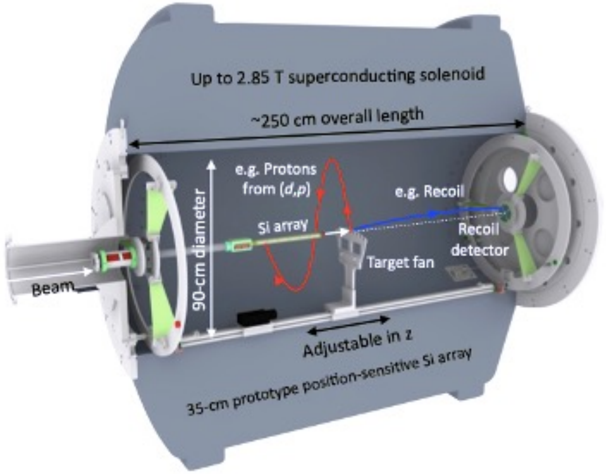
For gammas: Apollo scintillator array, 5 LaBr and 15 CsI





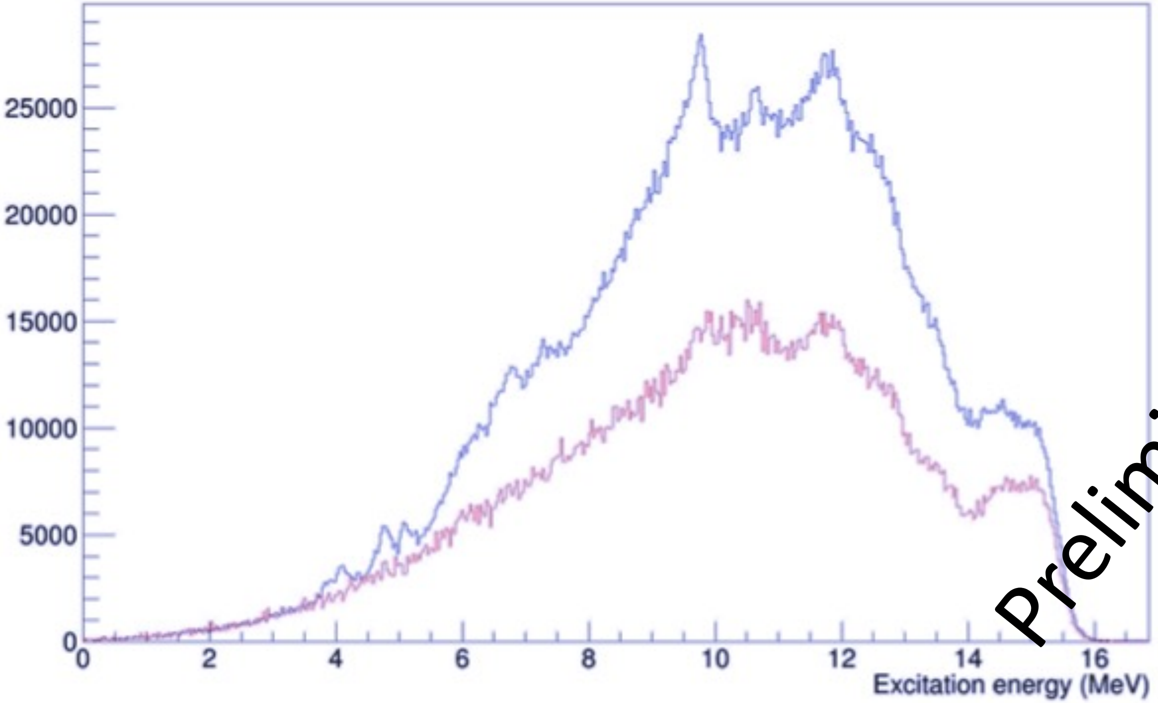




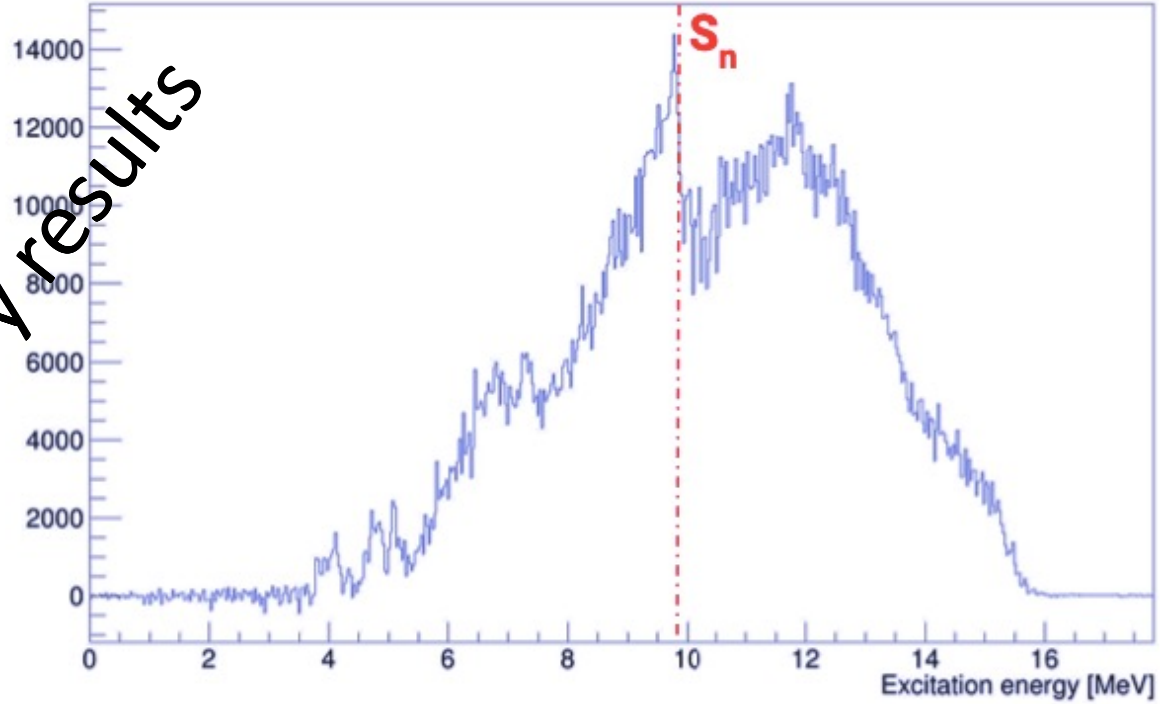


Excitation spectrum (coincidence p-γ)

^{85}Kr (10 MeV/n) -> CD$_2$ I=10^6 pps



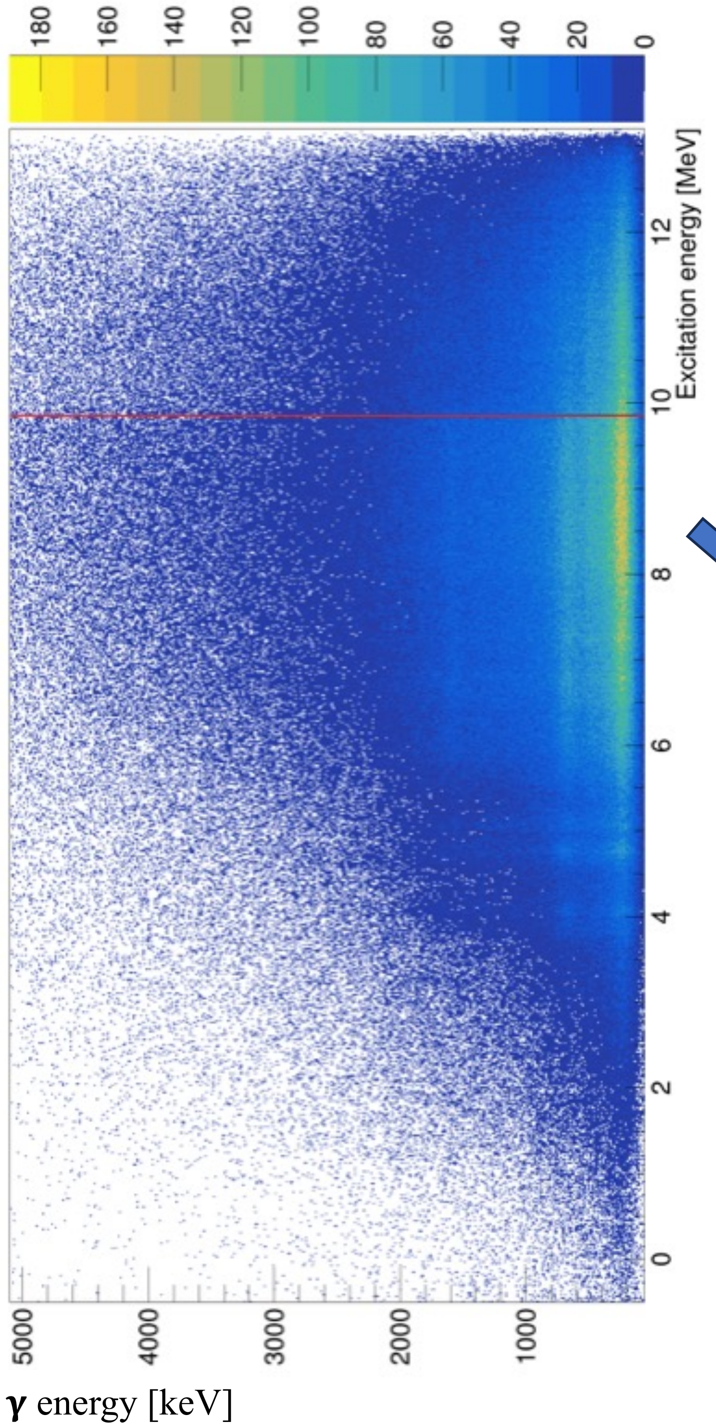
C (normalized)
CD$_2$ (real statistics)

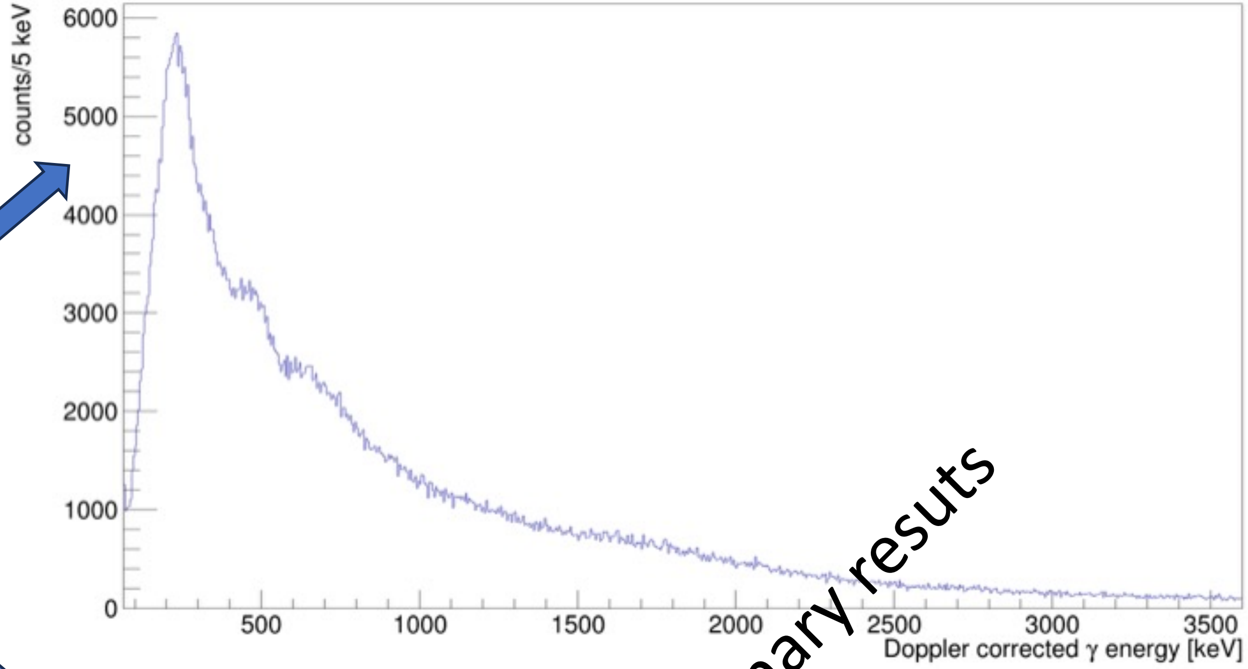


CD$_2$ with C subtraction

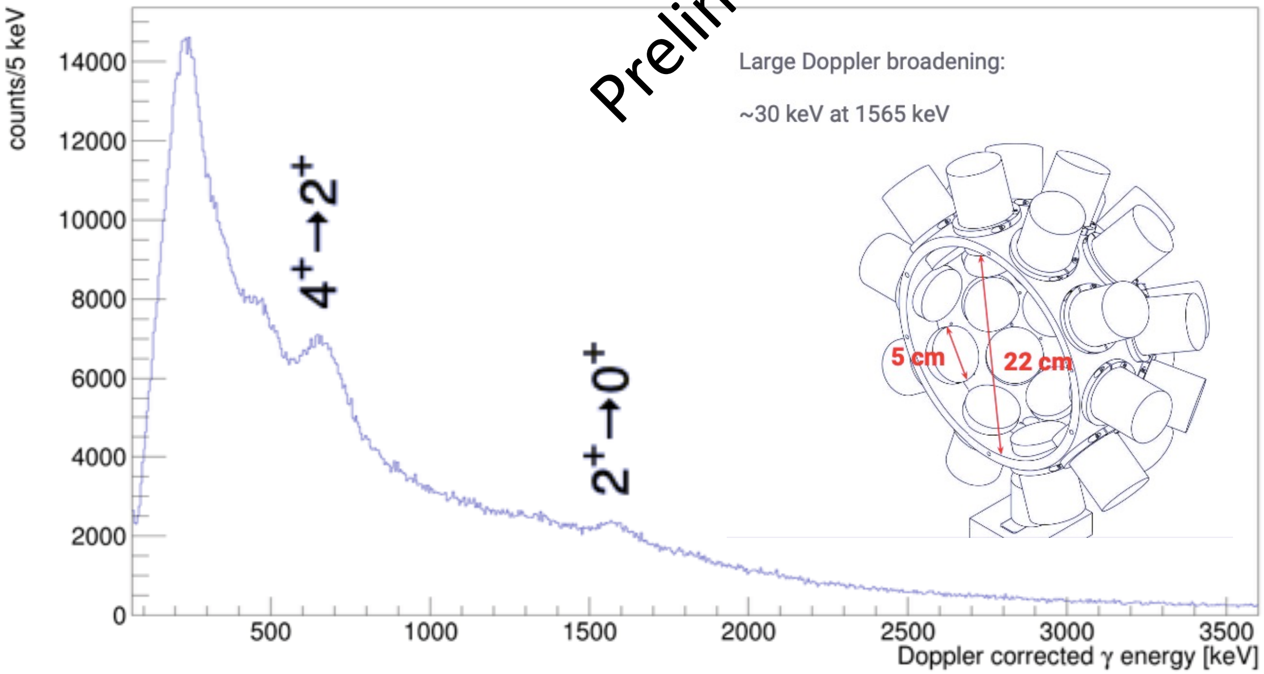
Preliminary results

Sn





Preliminary resuts



Large Doppler broadening:

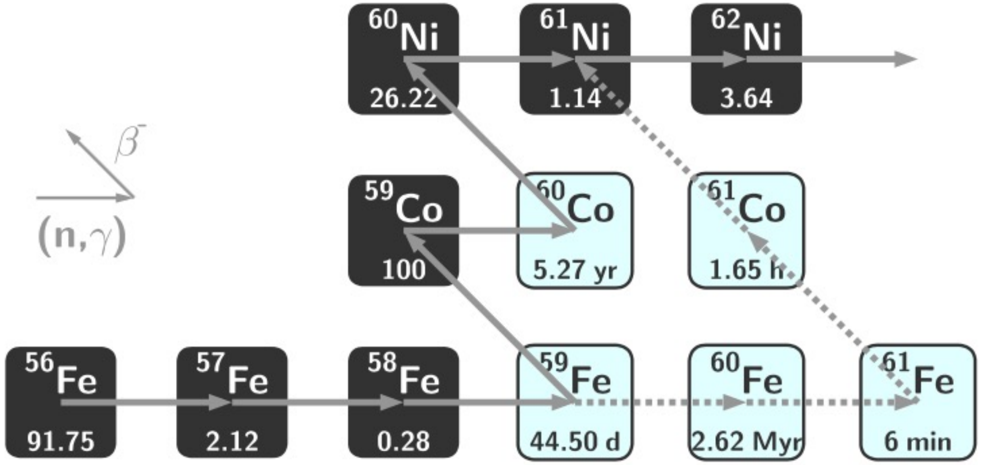
~30 keV at 1565 keV

THE ^{60}FE

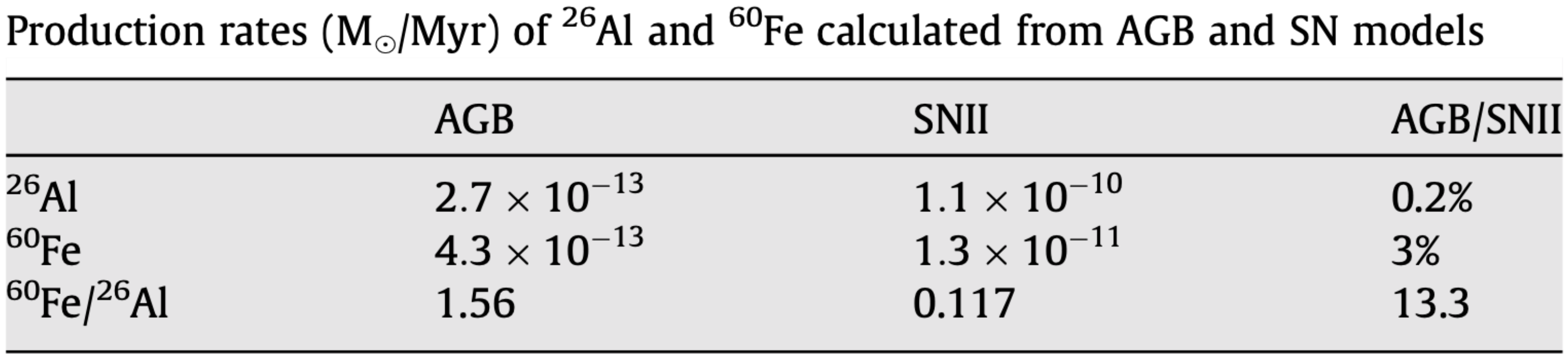
^{60}Fe half life is 2,62•10^6 y

A high ^{60}Fe/^{59}Fe would represent a smoking gun for stellar nucleosynthesis

There is the need of two neutron capture especially passing through the ^{59}Fe that is a branching point due to its half life of 44.5 days. Observed in the galactic disk by INTEGRAL, <u>in meteoritic solar grains and in oceanic sediments 100 million of years old.</u>



Production source under discussion and several candidates have been proposed: AGB, supernova core-collapse ….

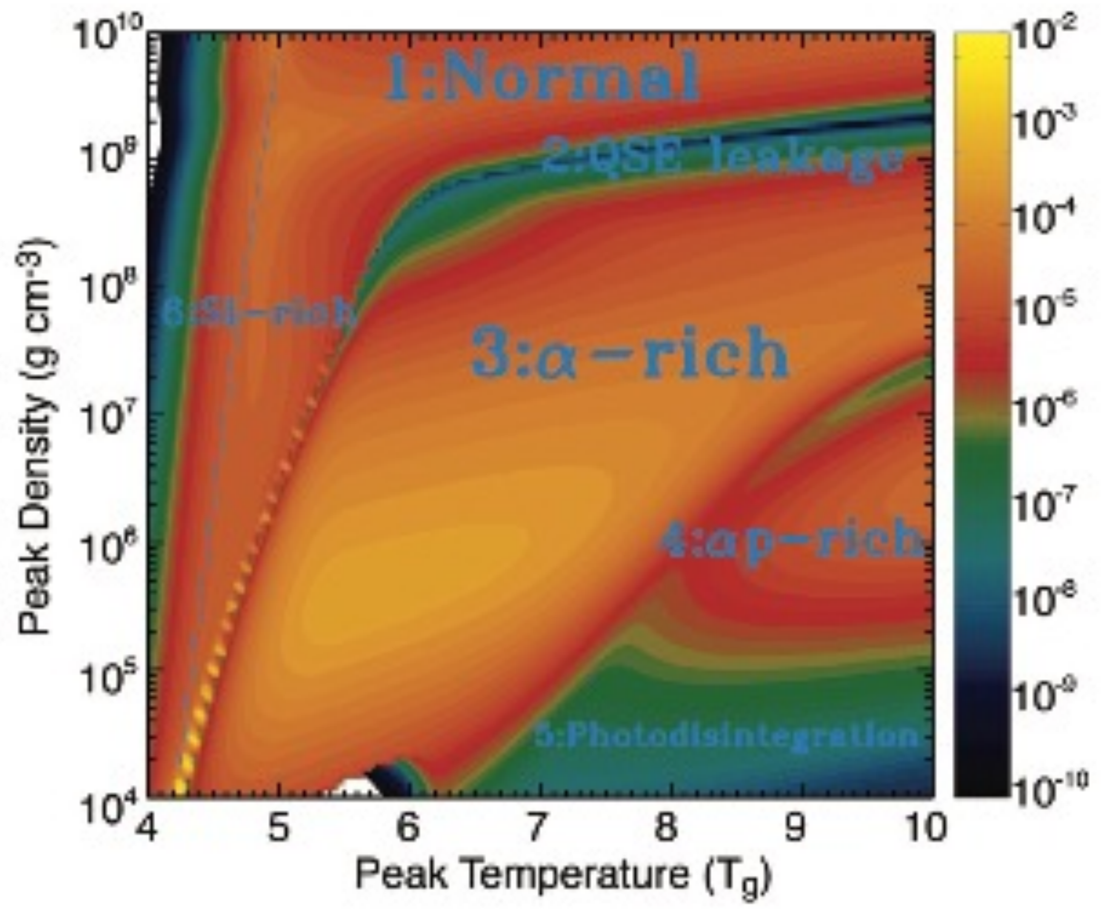


Production rates (M$_\odot$/Myr) of ^{26}Al and ^{60}Fe calculated from AGB and SN models

	AGB	SNII	AGB/SNII
^{26}Al	2.7×10^{-13}	1.1×10^{-10}	0.2%
^{60}Fe	4.3×10^{-13}	1.3×10^{-11}	3%
^{60}Fe/^{26}Al	1.56	0.117	13.3

Batch Mode Beams: ^{44}Ti(alpha,p)^{47}V

- ^{44}Ti, ^{56}Ni, ^{68}Ge, ^{72}Se, ^{82}Sr, ^{88}Zr
- Reaction used for the production:
- ^{46}Ti (p,p2n) ^{44}Ti $T_{1/2} = 47.3$y
- ^{58}Ni (p,p2n) ^{56}Ni $T_{1/2} = 6.1$d
- ^{70}Ge(p,p2n) ^{68}Ge $T_{1/2} = 288$d
- ^{74}Se (p,p2n) ^{72}Se $T_{1/2} = 8.5$d
- ^{84}Sr (p,p2n) ^{82}Sr $T_{1/2} = 25.5$d
- ^{88}Zr (p,p2n) ^{88}Zr $T_{1/2} = 83.4$d
- Proton beam, energy of 40-45 MeV from LNL SPES cyclotron. I up to 100-200μA.



Ti production (color- coded) versus T and density in the supernova shock. Six regions appear where different nuclear rates play primary roles in determining the Ti yield

- ^{46}Ti(p,p2n)^{44}Ti $T_{1/2}$=47.3a
- N(t) = 1.4 10^{16} atoms (10 days irradiation).
- dN/dt = -λN(t) = 6.6 10^6 Bq
- Dose = 2.2 10^{-5} Gy/h
- **I=3 10^7** ions/s on target (previous 10^4)

- ^{58}Ni(p,p2n)^{56}Ni $T_{1/2}$=6.1d
- N(t) = 2.6 10^{15} atoms (10 days irradiation).
- dN/dt = -λN(t) = 3.4 10^9 Bq
- Dose = 0.05 Gy/h
- **I=3 10^6** ions/s on target (previous 10^4)

- ^{70}Ge(p,p2n)^{68}Ge $T_{1/2}$=288d
- N(t) = 2.7 10^{17} atoms (10 days irradiation).
- dN/dt = -λN(t) = 7.3 10^9 Bq
- Dose = 0.16 Gy/h
- **I=4 10^8** ions/s on target (previous 10^4)

- ^{74}Se(p,p2n)^{72}Se $T_{1/2}$=8.5d
- N(t) = 3.2 10^{14} atoms (10 days irradiation).
- dN/dt = -λN(t) = 3.4 10^9 Bq
- Dose = 5.1 10^{-4} Gy/h
- **I=5 10^5** ions/s on target (previous 10^4)

- Radioactive beam estimates using a static target.
- ^{46}Ti(p,p2n)^{44}Ti $T_{1/2}$ =47.3 y **I= 3 10^{7}** ions/s on target
- ^{58}Ni(p,p2n)^{56}Ni $T_{1/2}$ =6.1 d **I= 3 10^{6}** ions/s on target
- ^{70}Ge(p,p2n)^{68}Ge $T_{1/2}$ =288d **I= 4 10^{8}** ions/s on target
- ^{74}Se(p,p2n)^{72}Se $T_{1/2}$ =8.5d **I= 5 10^{5}** ions/s on target
- ^{84}Sr(p,p2n)^{82}Sr $T_{1/2}$ =25.5d **I= 7 10^{8}** ions/s on target
- ^{88}Zr(p,p2n)^{88}Zr $T_{1/2}$=83.4d **I= 7 10^{7}** ions/s on target