Beta Decay of Highly-Charged Ions

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Radioactive decays of highly-charged ions

Nuclear weak decay in general form:

$$n + \nu_e \leftrightarrow p + e^-$$

i) continuum beta decay:

$$n \rightarrow p + e^- + \bar{\nu}_e \qquad \beta^- - \text{decay}$$

$$p \rightarrow n + e^+ + \nu_e \qquad \beta^+ - \text{decay}$$

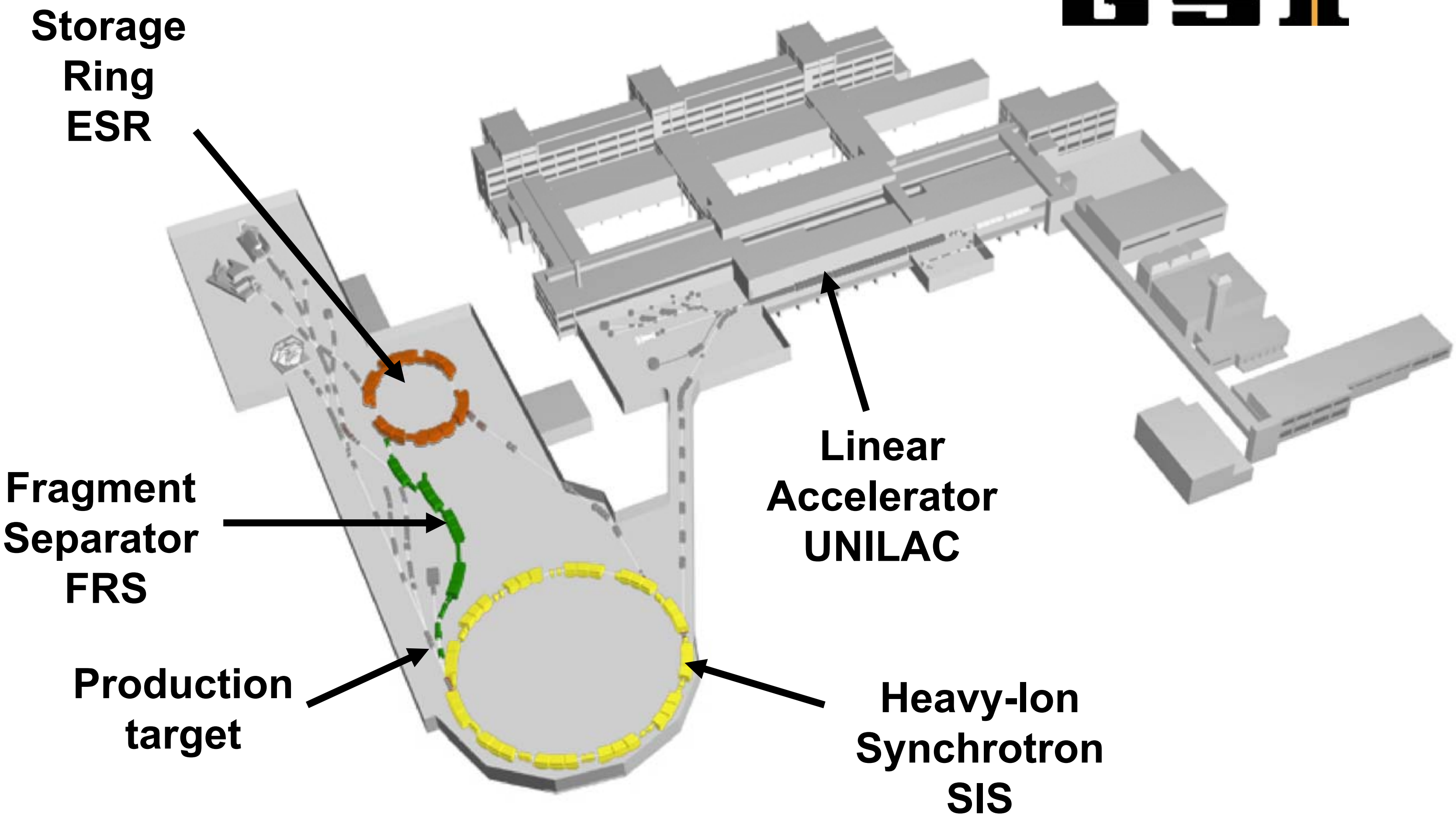
ii) two-body beta decay:

$$p + e_b^- \rightarrow n + \nu_e \qquad \text{Orbital electron capture (EC)}$$

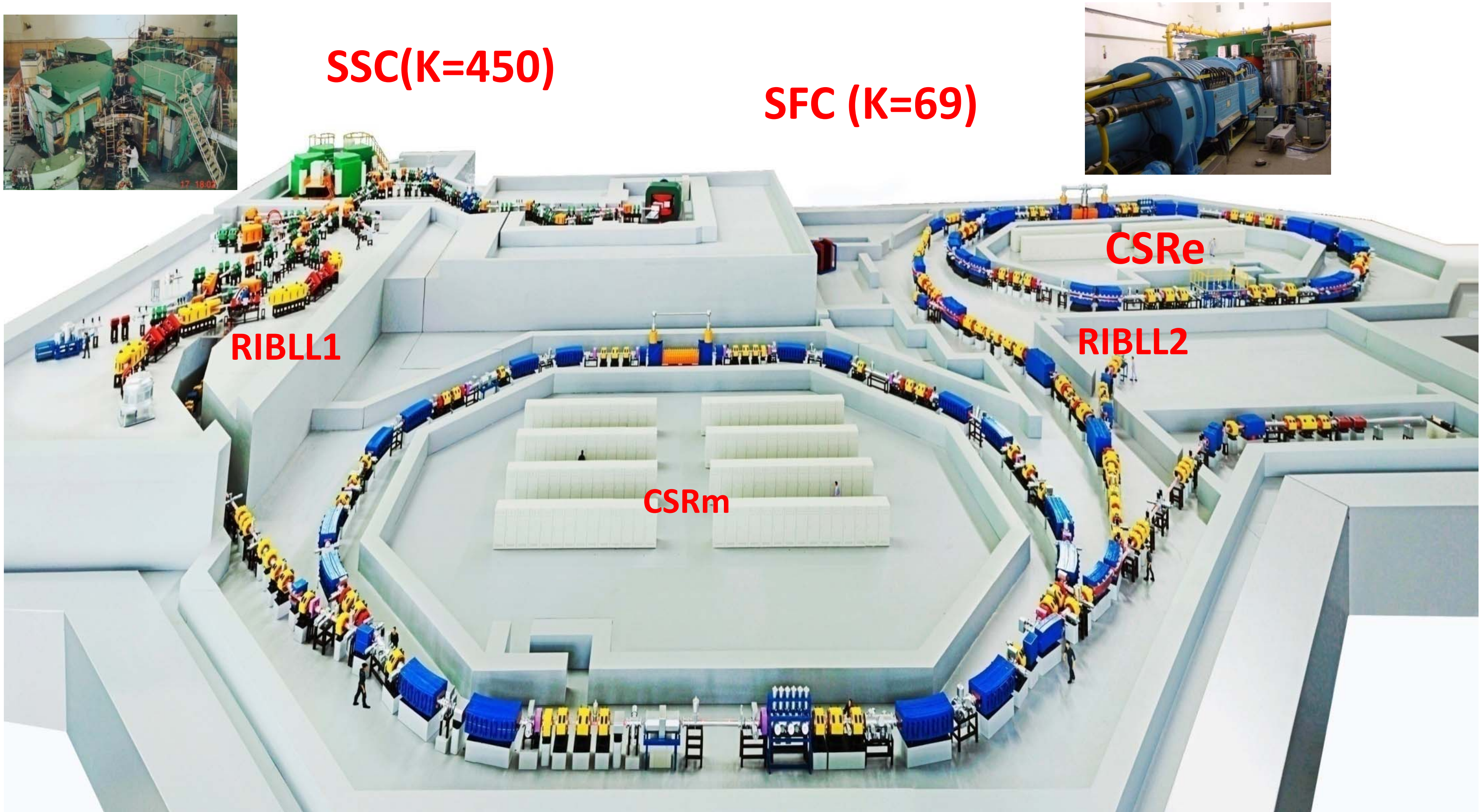
$$n \rightarrow p + e_b^- + \bar{\nu}_e \qquad \text{Bound state beta decay } (\beta_b^-)$$

$$p + e^- \rightarrow n + \nu_e \qquad \text{Free electron capture}$$

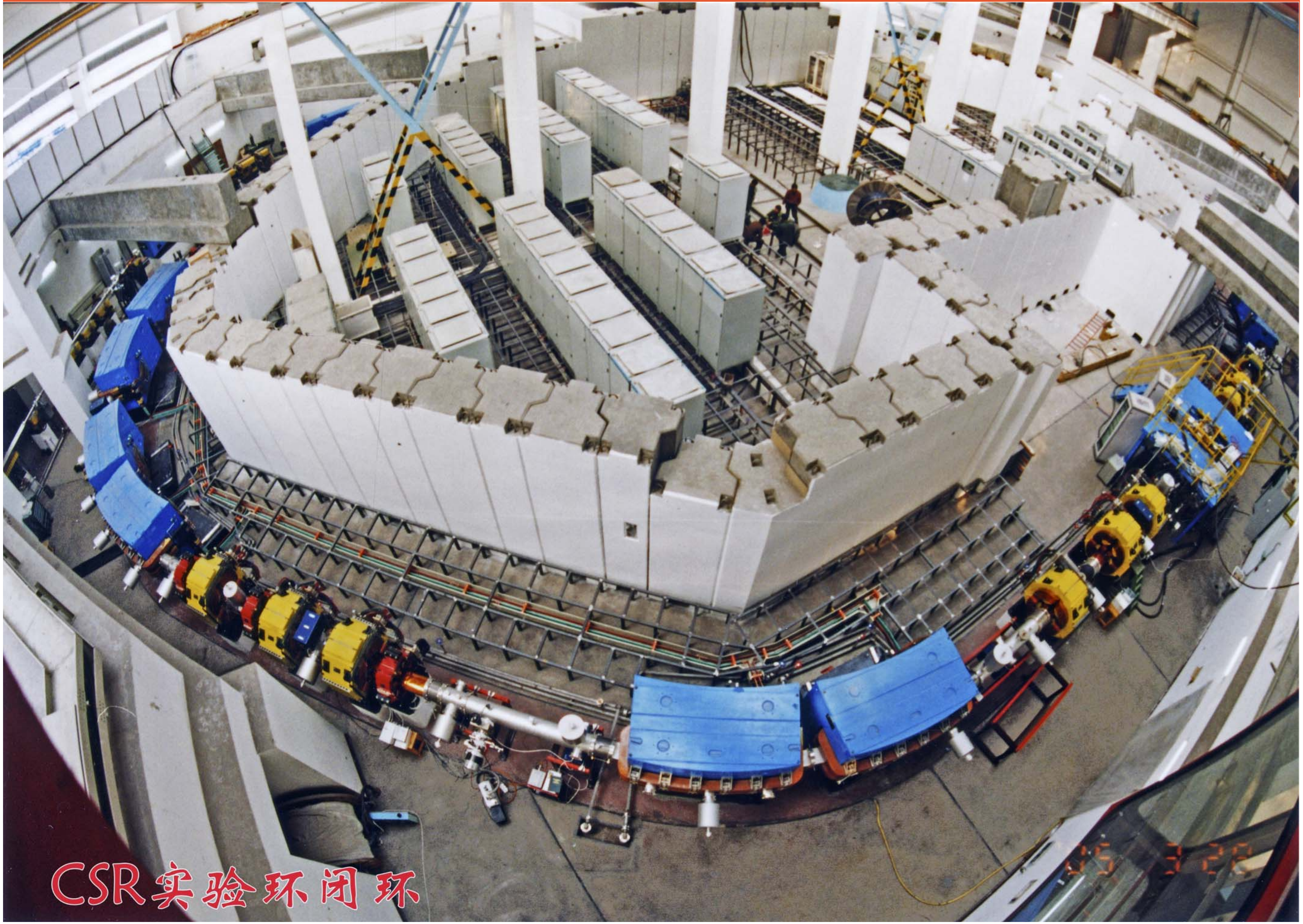
Secondary Beams of Short-Lived Nuclei



Heavy Ion Research Facility in Lanzhou (HIRFL)



Experimental Cooler Storage Ring CSRe



Radioactive decays of highly-charged ions

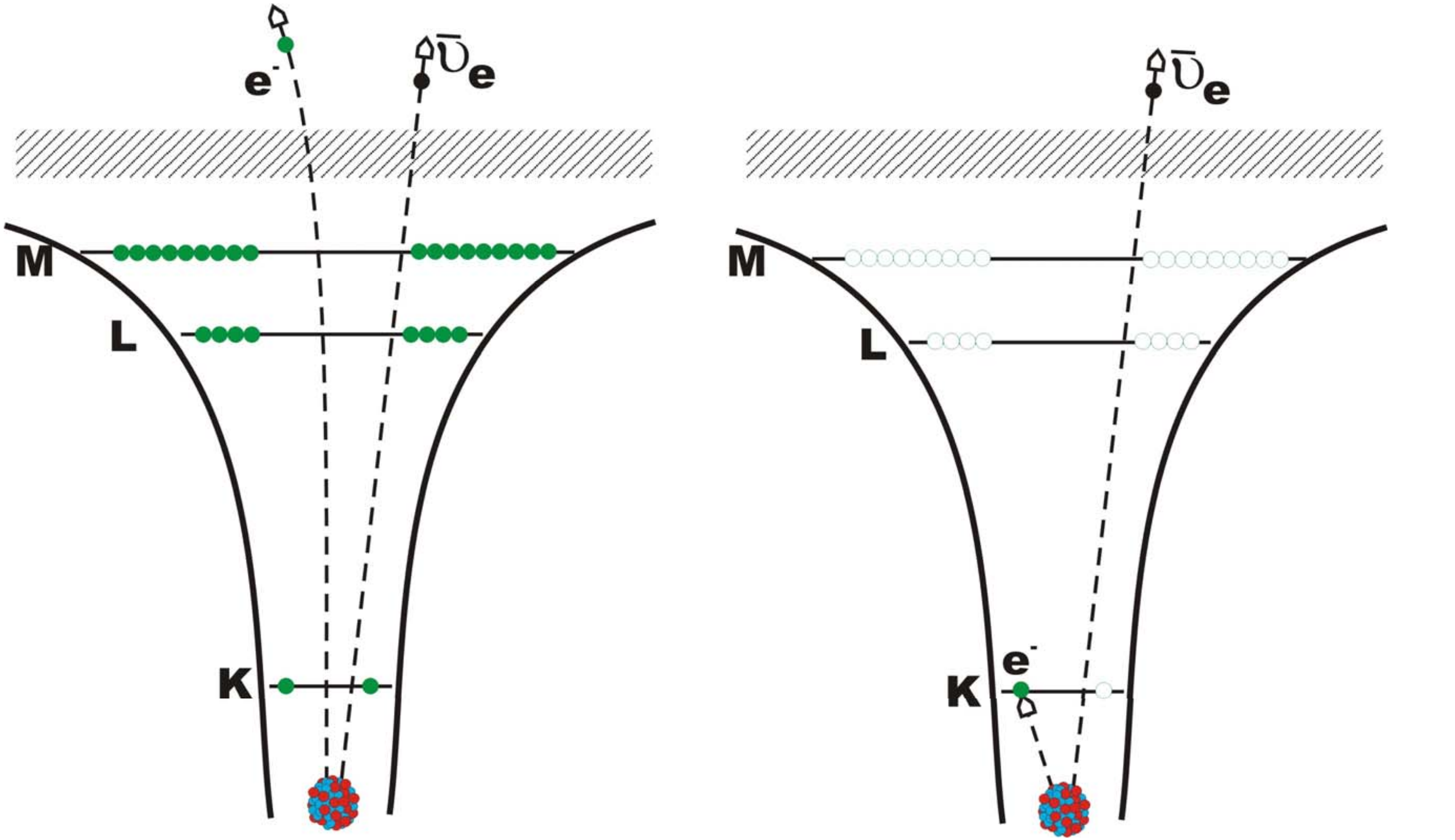
Few-electron ions
well-defined quantum-mechanical systems

New decay modes
(bound-pair-creation, bound-state beta decay, etc.)

Influence of electrons on radioactive decay

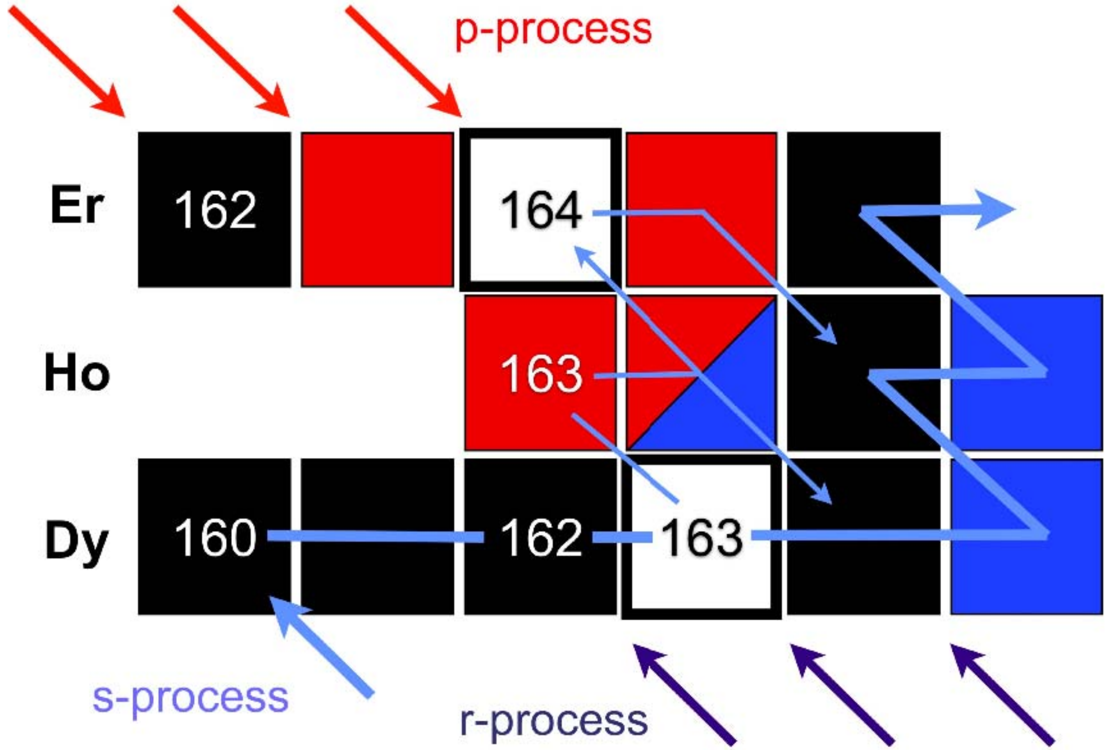
Astrophysical scenarios:
high temperature = high degree of ionization

Bound-State β-decay



Bound-State ®-decay of ^{163}Dy

s process: slow neutron capture and β- decay near valley of β stability at kT = 30 keV; → high atomic charge state → bound-state β decay

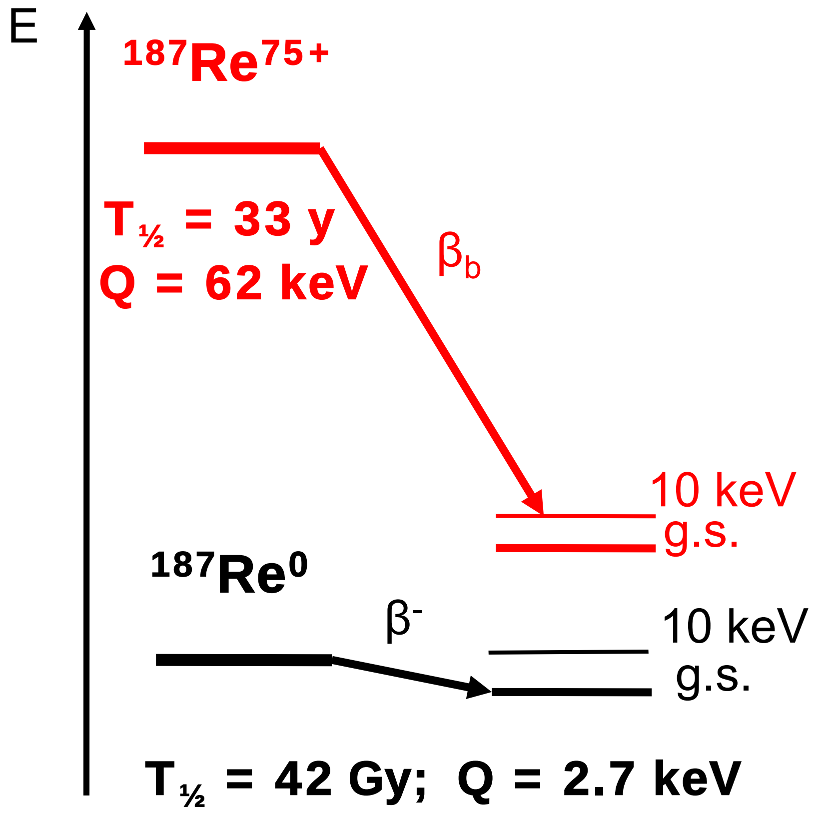


$T_{1/2}$ = 48 days

branchings caused by bound-state β decay

M. Jung et al., Phys. Rev. Lett. 69 (1992) 2164

Bound-State β-decay of ^{187}Re



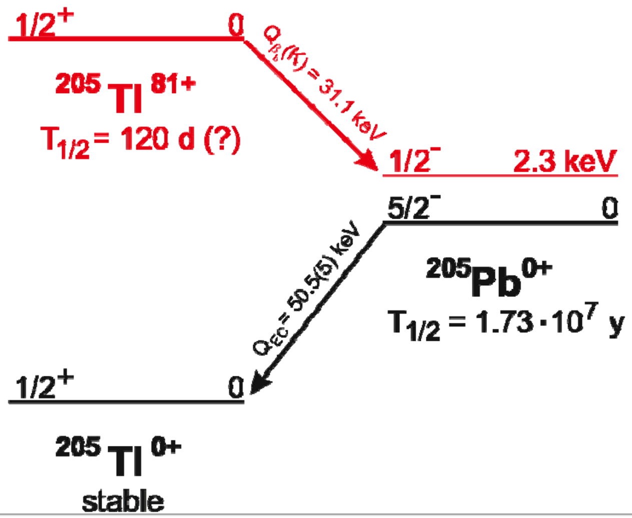
F. Bosch et al., Phys. Rev. Lett. 77 (1996) 5190

The 7 Nuclear Clocks for the Age of the Earth, the Solar System, the Galaxy, and the Universe

clock	$T_{1/2}[10^9$ y]
^{40}K/^{40}Ar (®)	1.3
^{238}U…Th…^{206}Pb (〈 ,®)	4.5
^{232}Th…Ra…^{208}Pb (〈 ,®)	14
^{176}Lu/^{176}Hf (®)	30
^{187}Re/^{187}Os (®)	42
^{87}Rb/^{87}Sr (®)	50
^{147}Sm/^{143}Nd (〈)	100

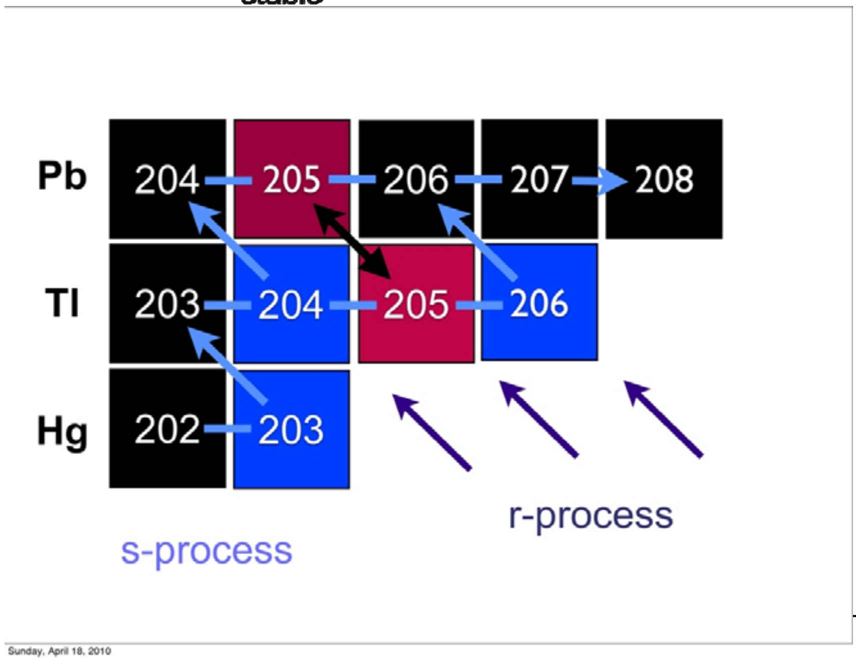
Clayton (1964): *a mother-daughter couple (^{187}Re/^{187}Os) is the "best" radioactive clock*

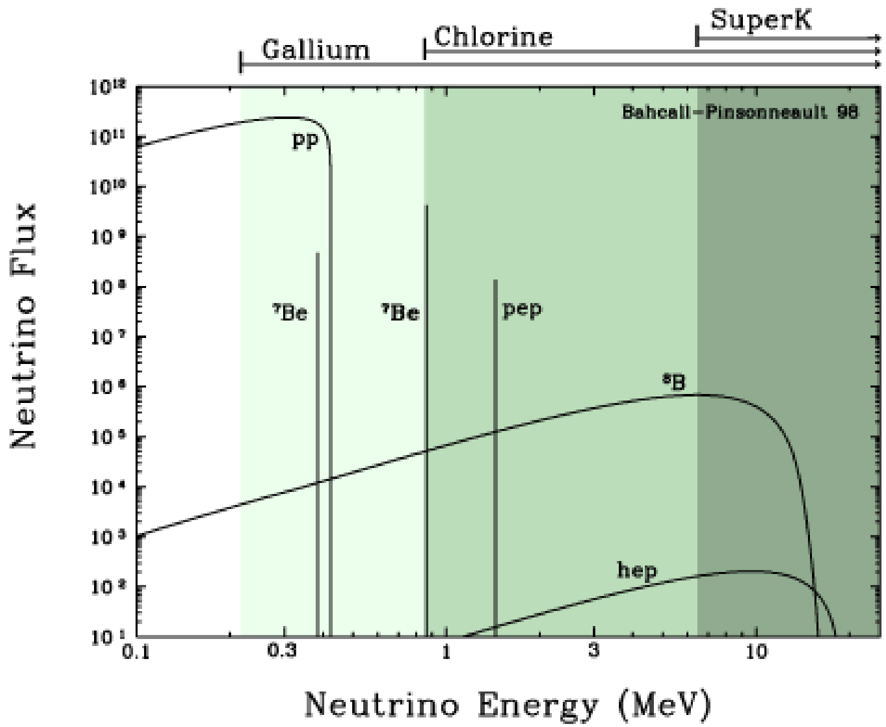
Bound-State Beta Decay of ^{205}Tl Nuclei



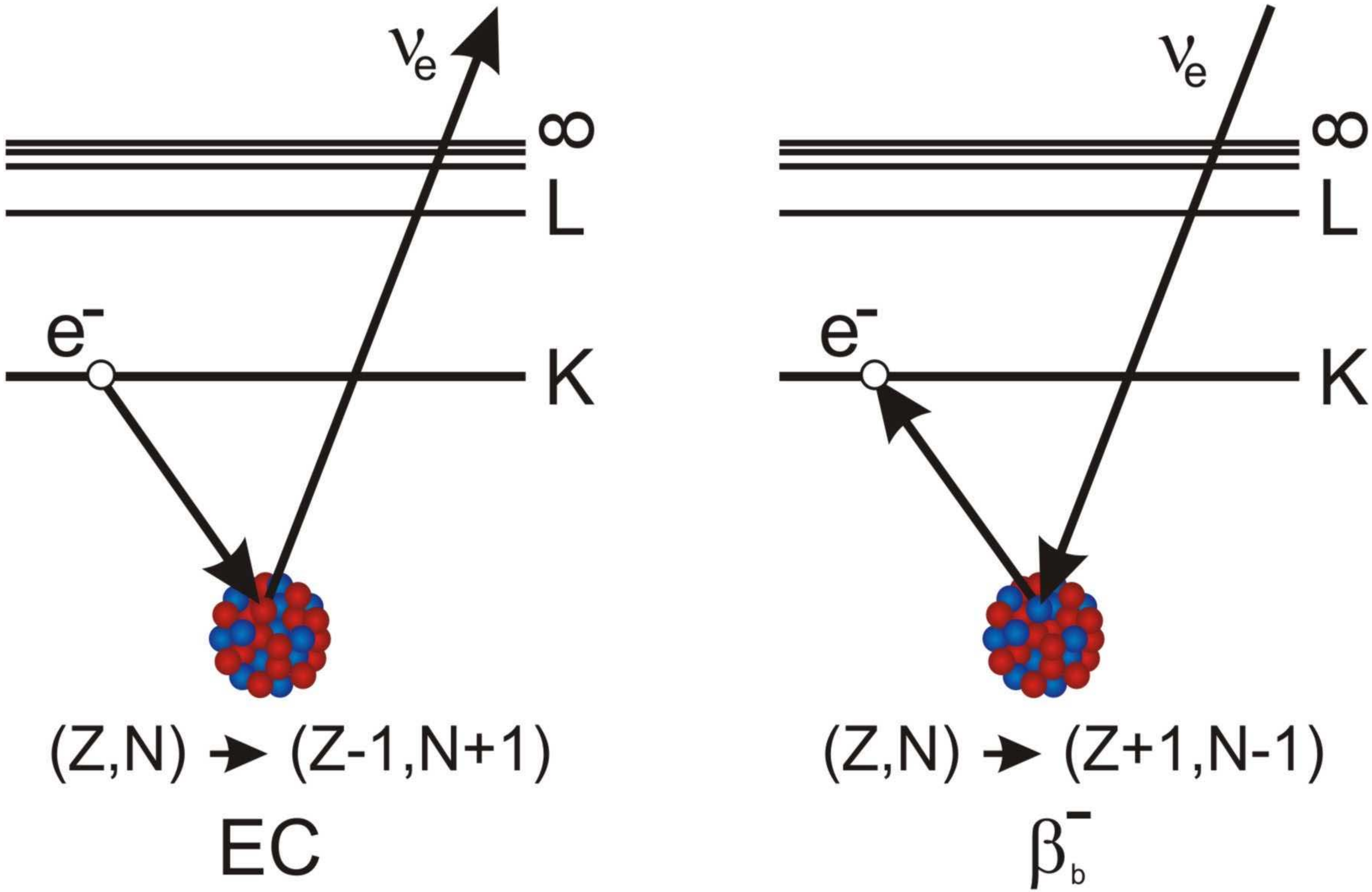
New ESR proposal to study $^{205}Tl^{81+}$

Was scheduled for 2014 at GSI, but now cancelled





Two-Body Beta Decay

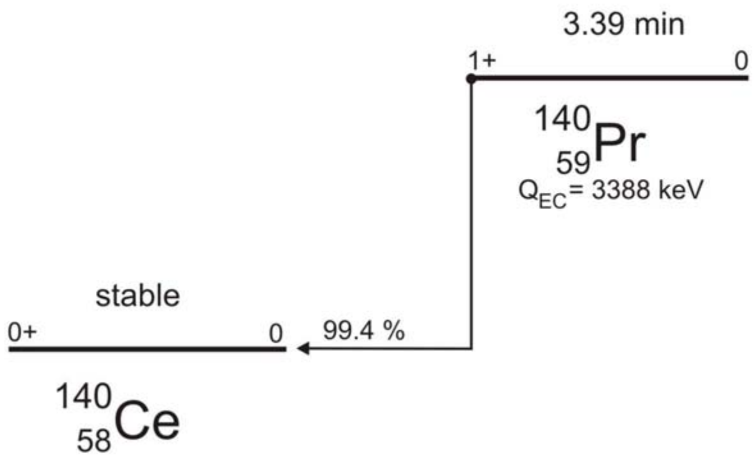


Orbital Electron Capture

Conventional EC-theory:

W. Bambynek et al., Rev. Mod. Phys. 49, 1977

Gamow-Teller allowed transition $1^+ \rightarrow 0^+$



S-electron density at the nucleus:

$|f_S(0)|^2 \propto 1/n^3$

P_{EC} (neutral atom) $\propto 2 \times 1/n^3 = 2.4$

P_K (H-like) $\propto 1 \times 1/1^3 = 1$

Conclusion:
H-Like ion should have 41% longer half-life

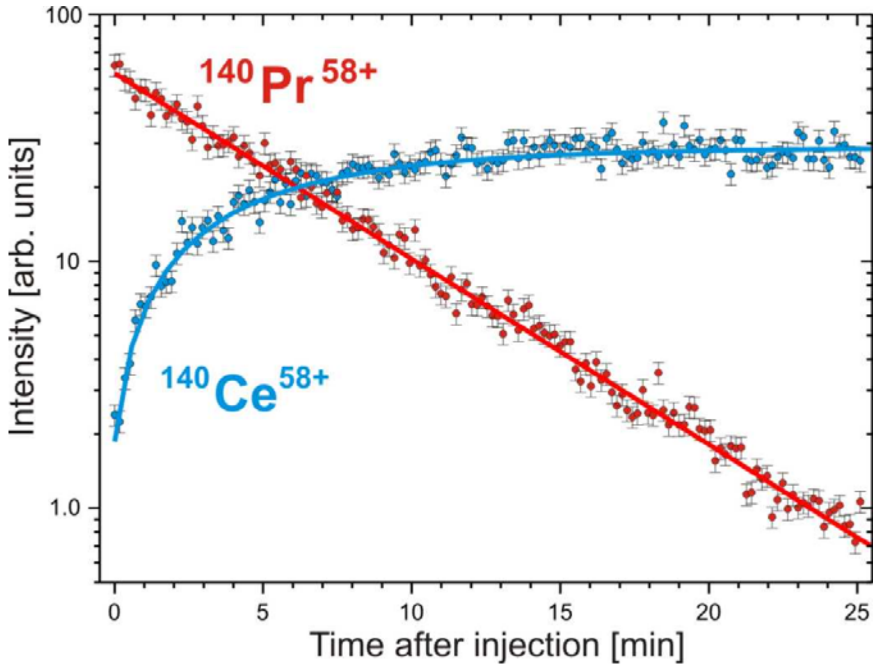
λ_{EC}(H-like)/λ_{EC}(He-like) ≈ 0.5

Orbital Electron Capture Decay of Few-Electron Ions

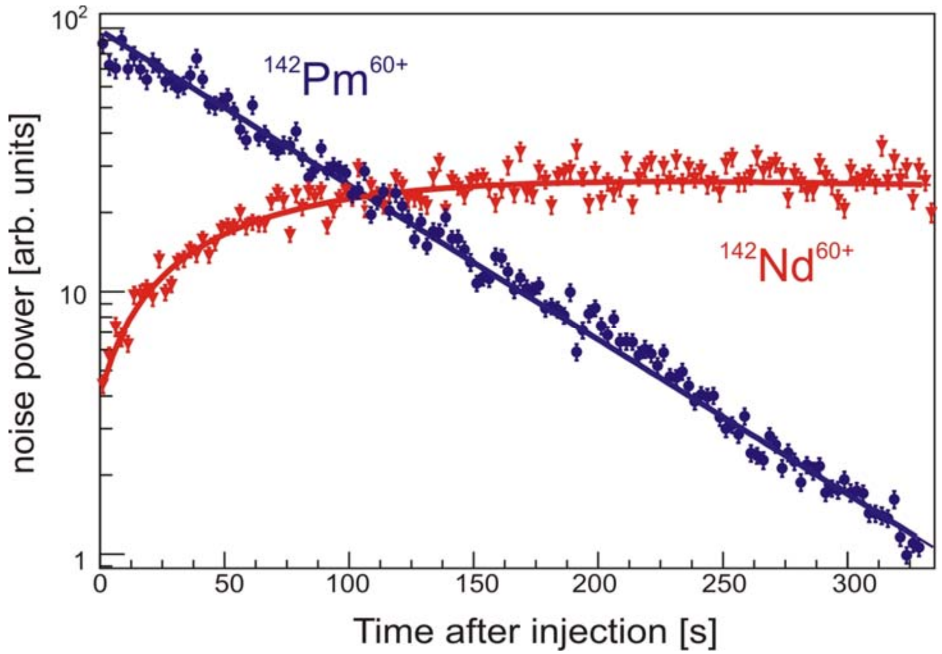
Expectations: $\lfloor_{EC}$(H-like)/$\lfloor_{EC}$(He-like) ≈ 0.5

$\lfloor_{EC}$(H-like)/$\lfloor_{EC}$(He-like) = 1.49(8)

$\lfloor_{EC}$(H-like)/$\lfloor_{EC}$(He-like) = 1.44(6)



Yu.A. Litvinov et al., Phys. Rev. Lett. 99 (2007) 262501



N. Winckler et al., Phys. Lett. B579 (2009) 36

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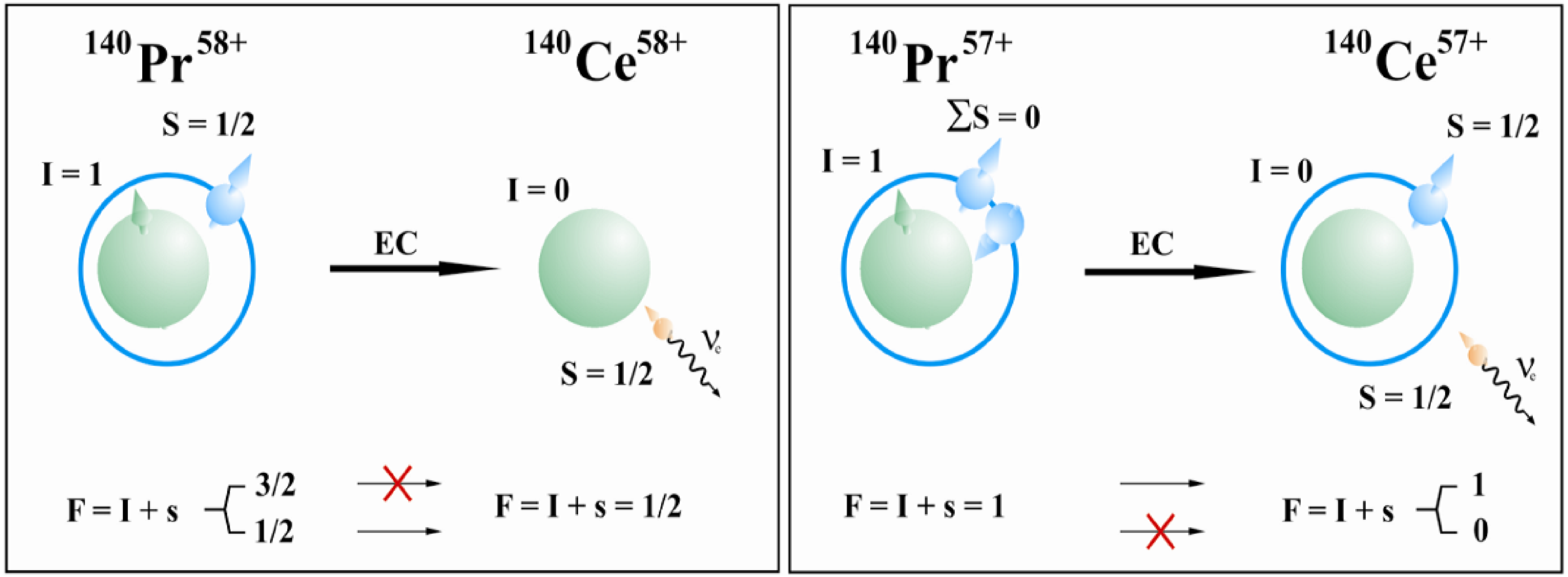
Orbital Electron Capture Decay of Few-Electron Ions

Gamow-Teller transition $1^+ \rightarrow 0^+$



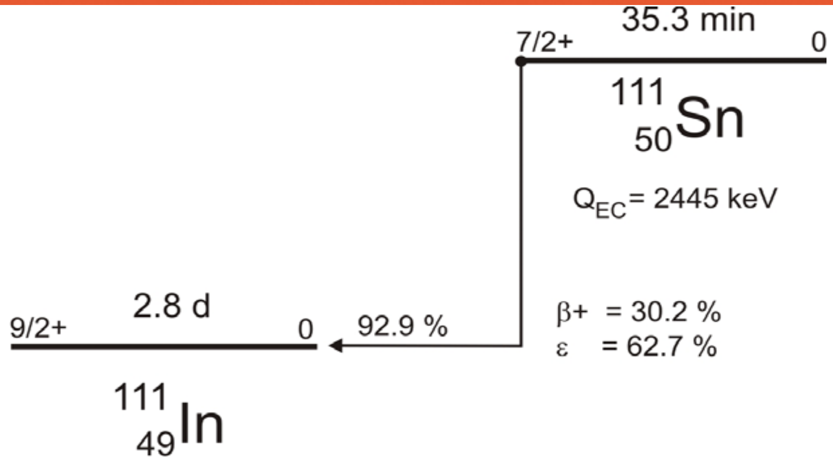
$\mu = +2.7812\mu_N$

Theory: $\lambda(H)/\lambda(He) = (2I+1)/(2F+1)$

I. N. Borzov et al., Phys. At. Nucl. (2009)

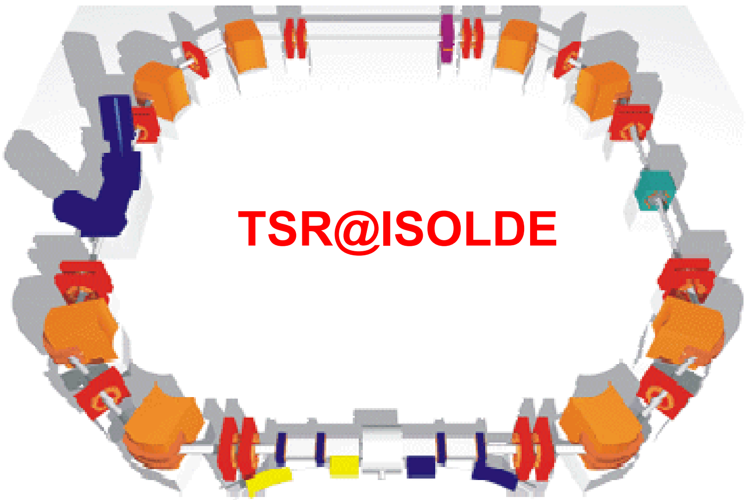
Z. Patyk et al., Phys. Rev. C 77 (2008) 014306

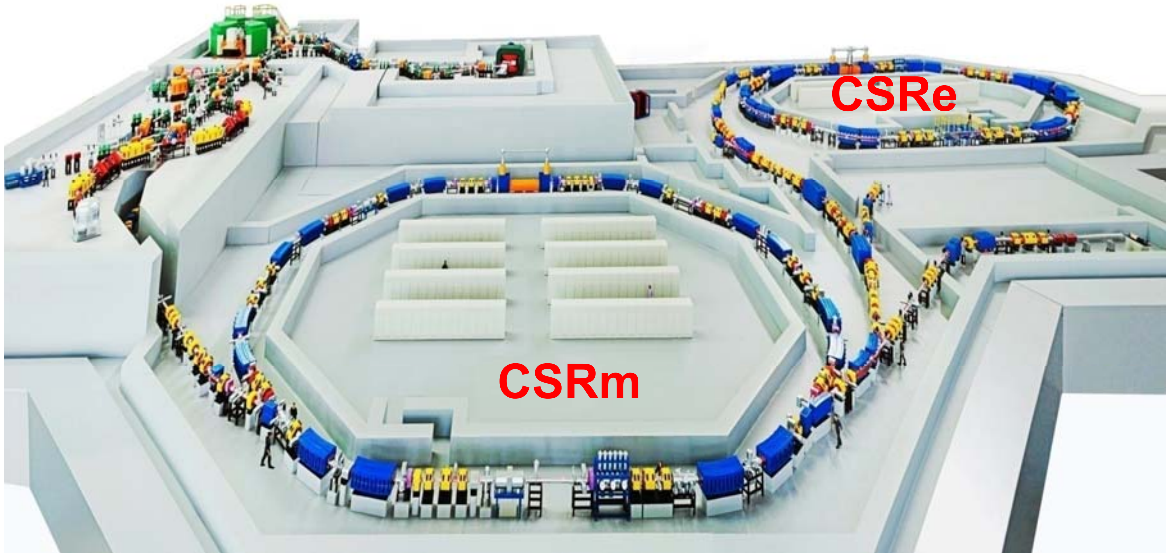
Electron Capture in Hydrogen-like Ions



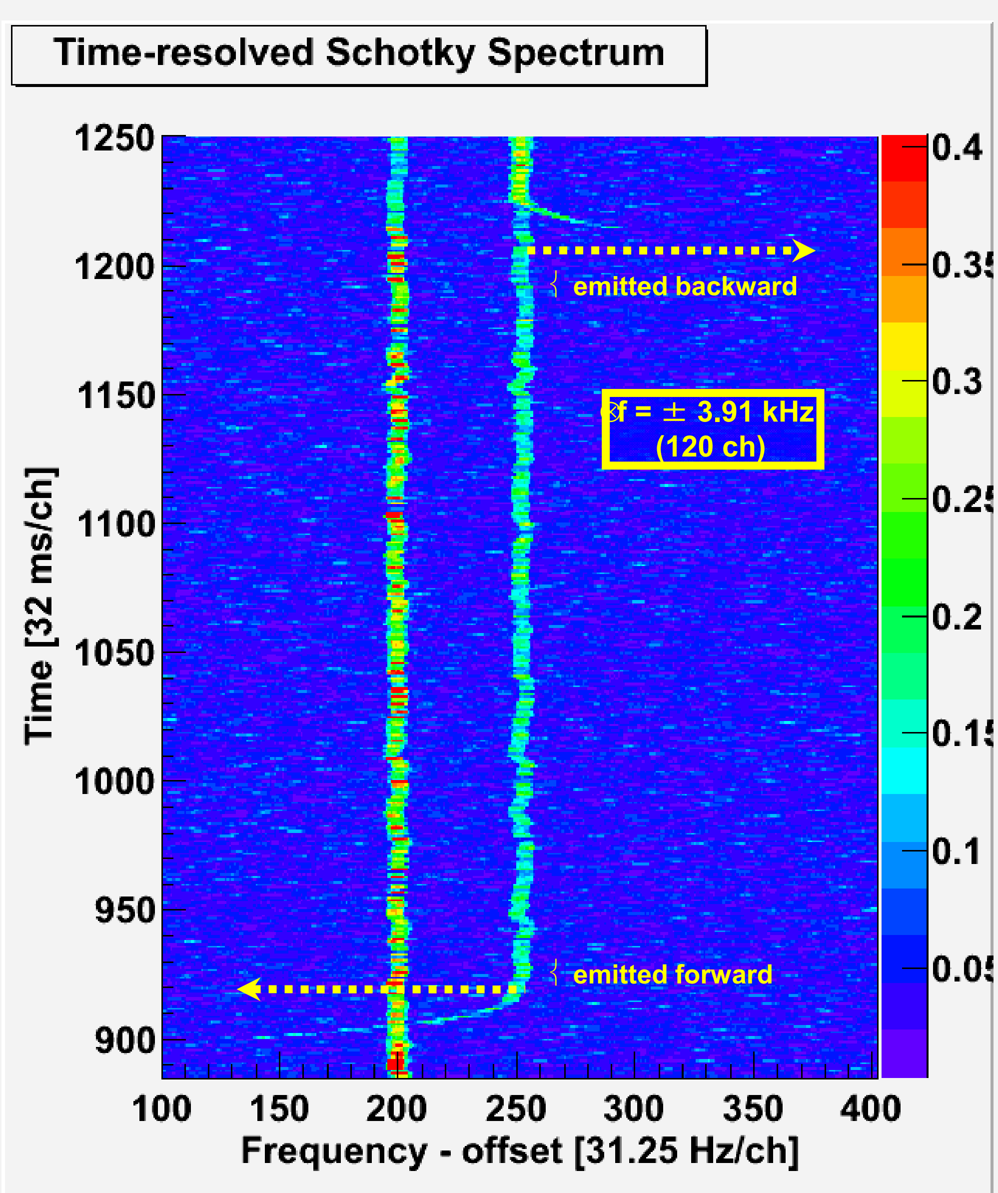
Addressing electron screening in beta decay under very clean conditions !

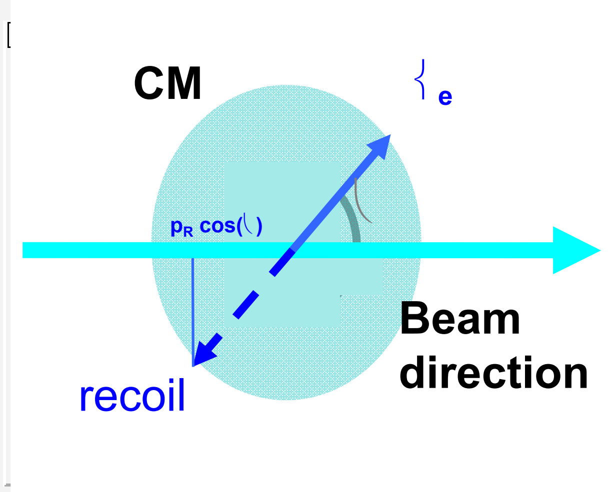
$$F = I + s \; \begin{cases} 4 \\ 3 \end{cases} \longrightarrow F = I + s \; \begin{cases} 5 \\ 4 \end{cases}$$

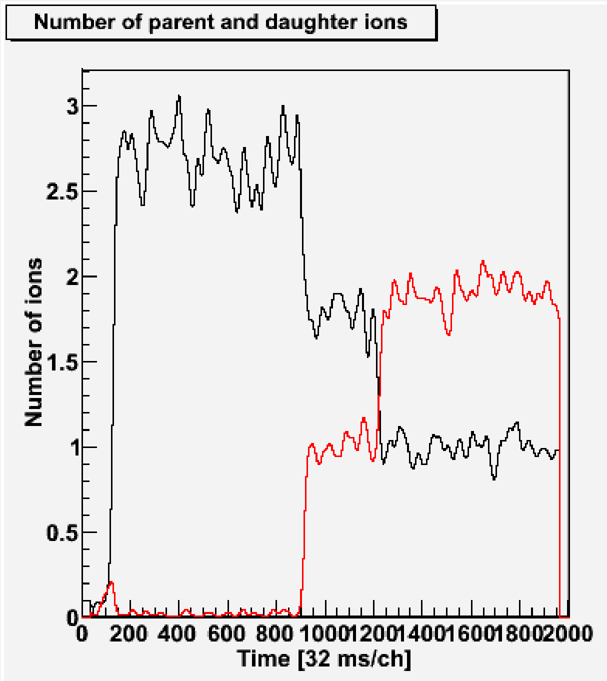




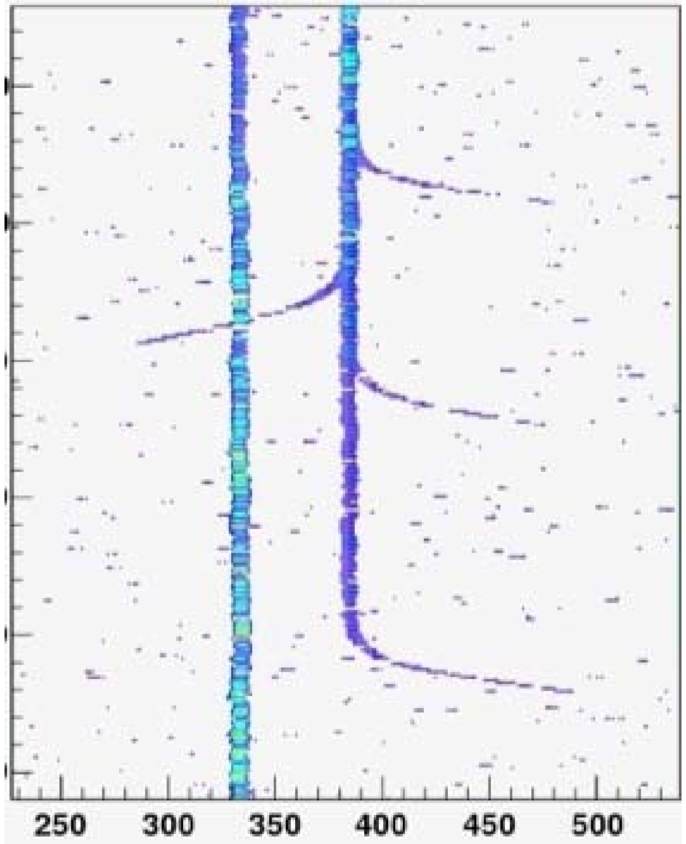
Three Parent He-Like ^{142}Pm Ions

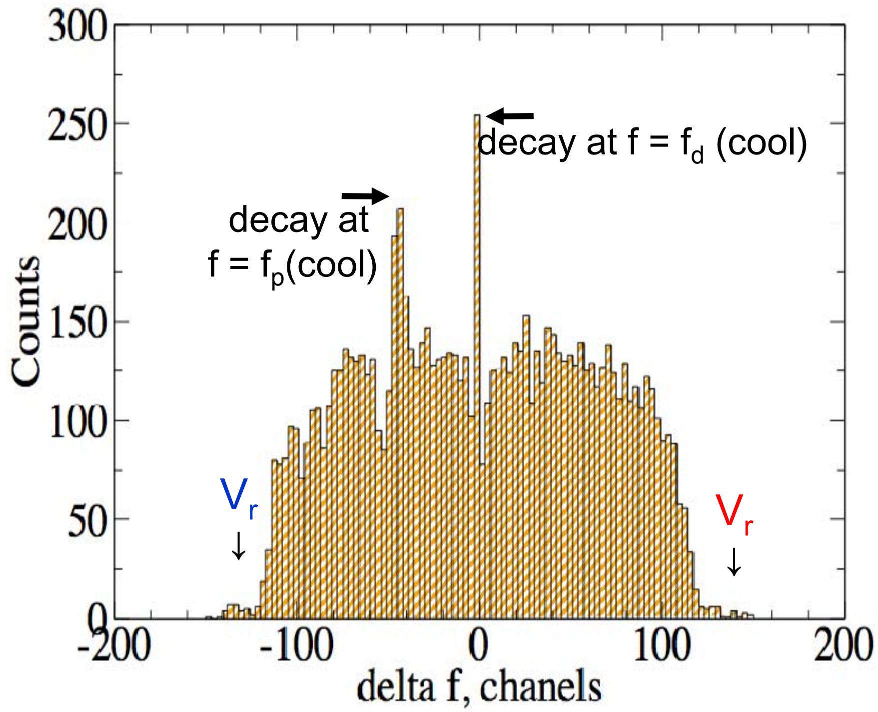






Revolution-frequency difference δf of the recoils just after decay: $\delta f = f_{dec} - f_{cool}$





For a (longitudinally) unpolarized beam the distribution should have a rectangular shape

For a (steadily controlled) polarized beam the distribution would provide the helicity of the neutrino

From v_r and m_r one gets the momentum of the (monochromatic) neutrino: $(pc)_d = m_d\, cv_d = (pc)_\nu$

From m_p and m_d one gets its energy: $E_\nu = (m_p - m_d)\, c^2$ and then $\beta_\nu = E_\nu / (pc)_\nu$

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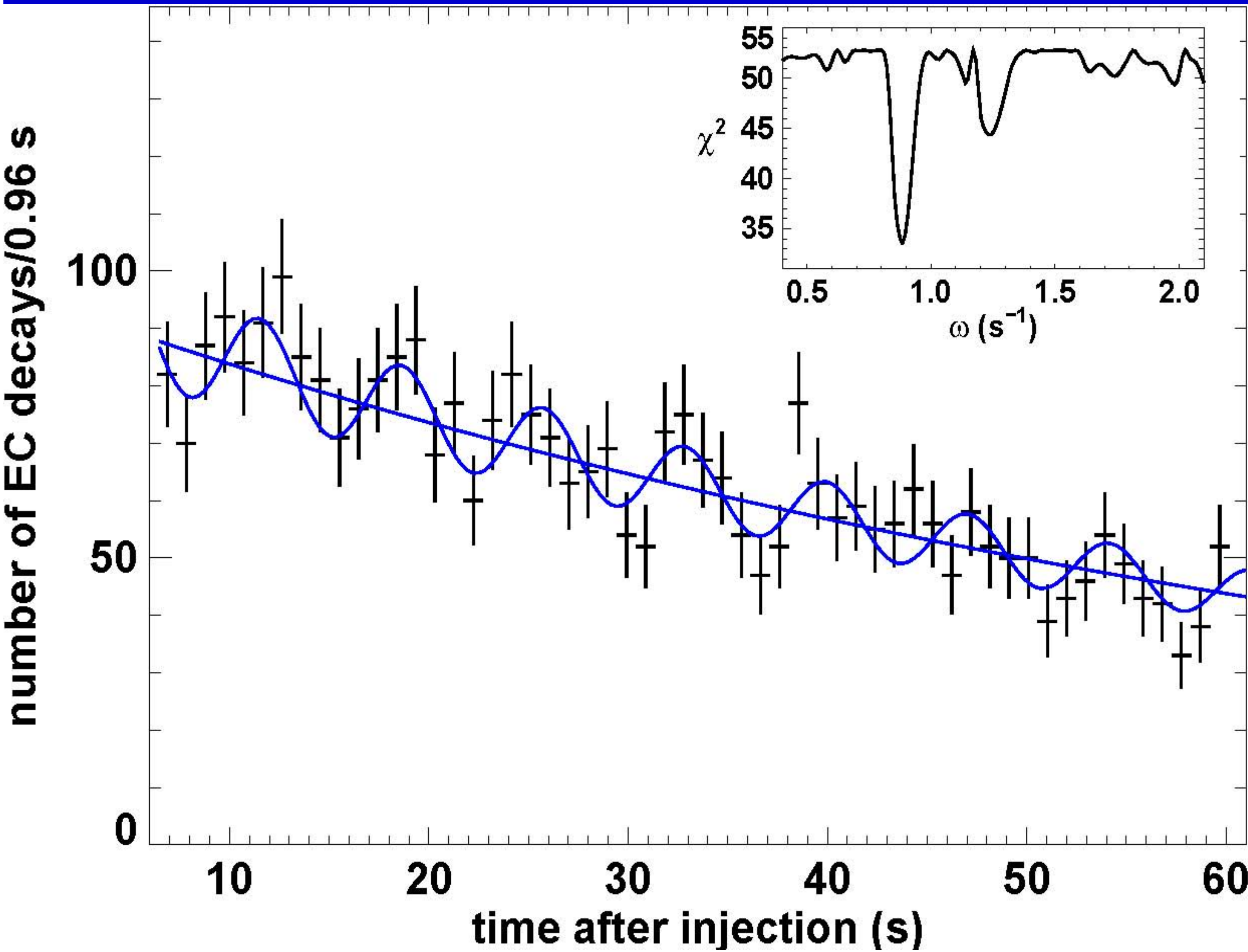
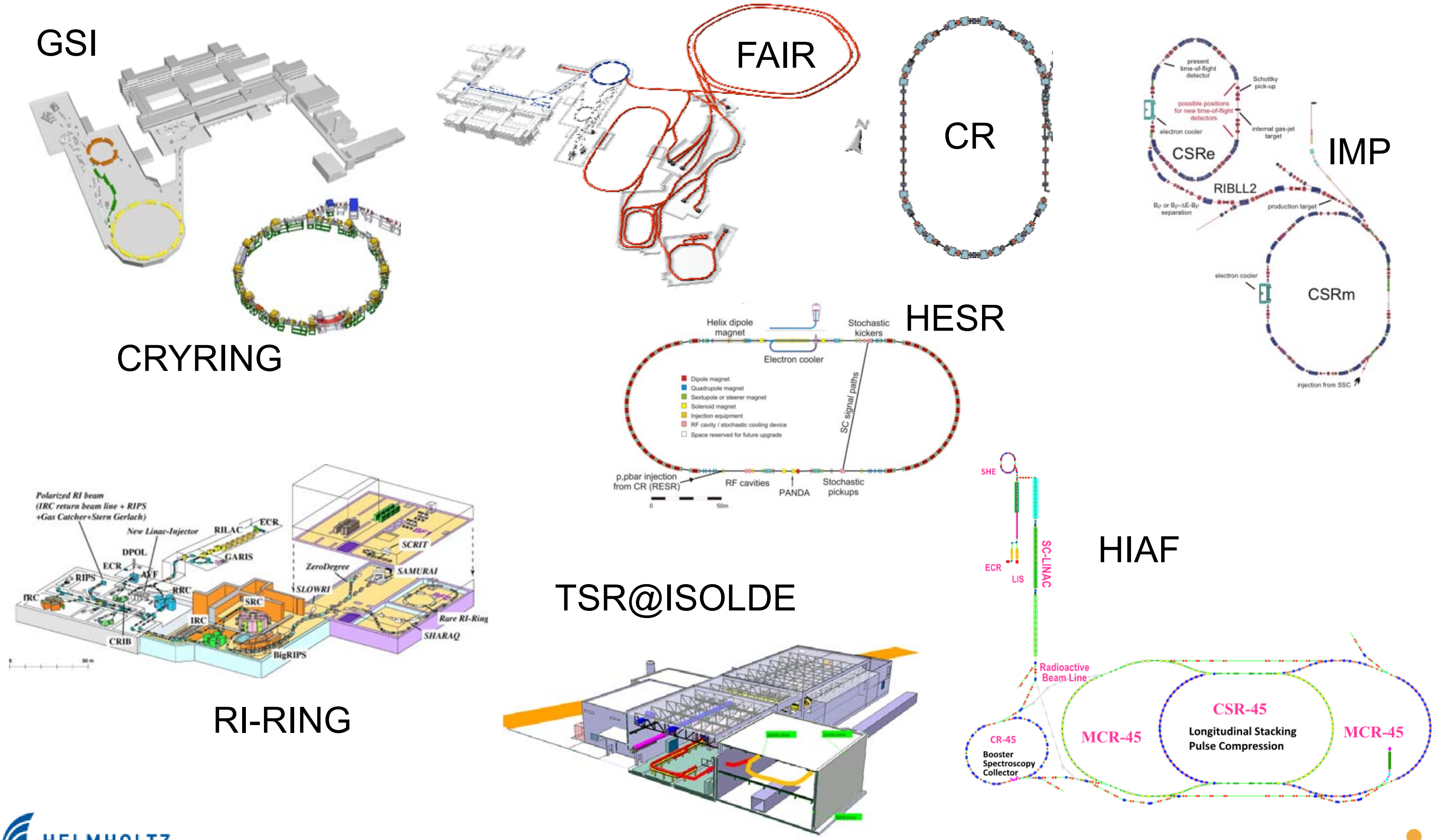
245 MHz Resonator: ω = 2π/T = 0.884(14)/s, **T = 7.11(11) s**, a = 0.107(24)



We need novel tools & methods

Physics at Storage Rings



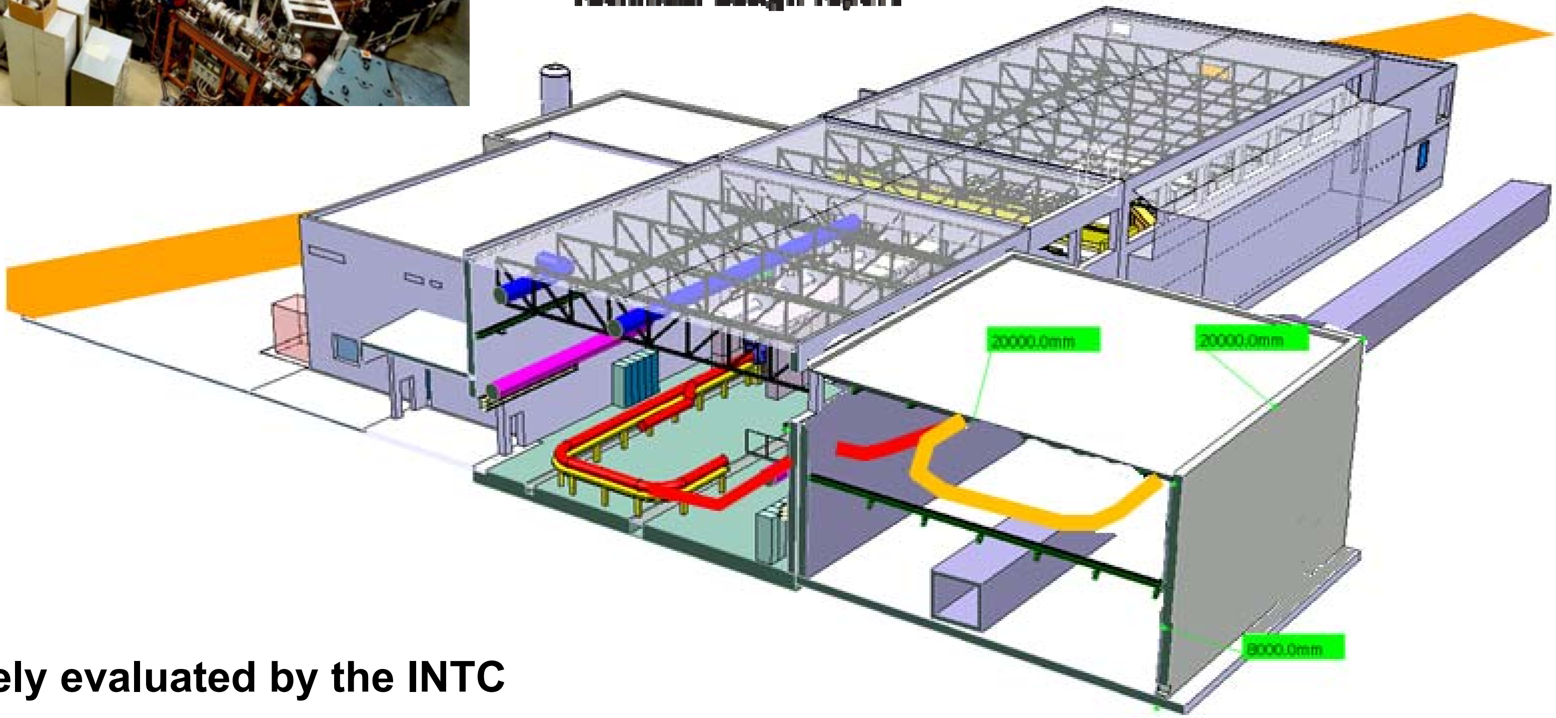
TSR @ Hie-Isolde

THE EUROPEAN PHYSICAL JOURNAL
SPECIAL TOPICS

Review

Storage ring at HIE-ISOLDE

Technical design report



TDR positively evaluated by the INTC

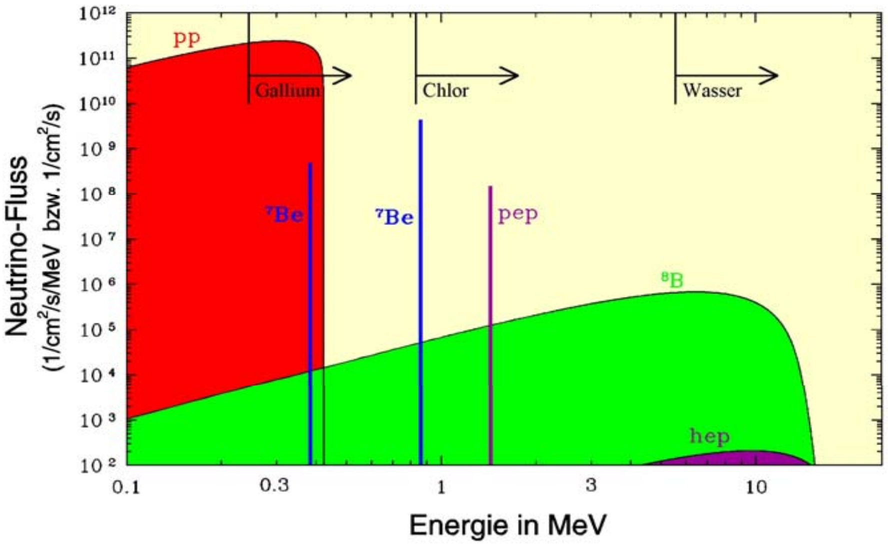
Some speculations on the EC-decay of ^{7}Be

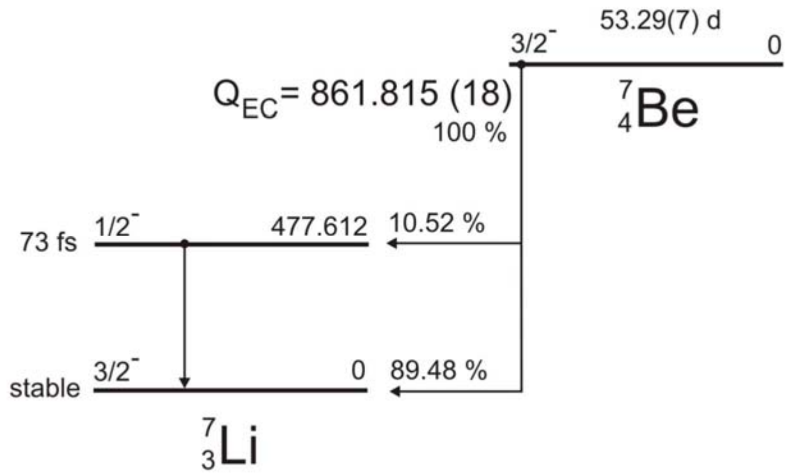
A.V. Gruzinov, J.N. Bahcall, Astroph. J. 490 (1997) 437

Ionization of ^{7}Be in the Sun can be ~ 20-30 %

^{7}Be + e^- → ^{7}Li + { $_e$

^{7}Be + p → ^{8}B + ©

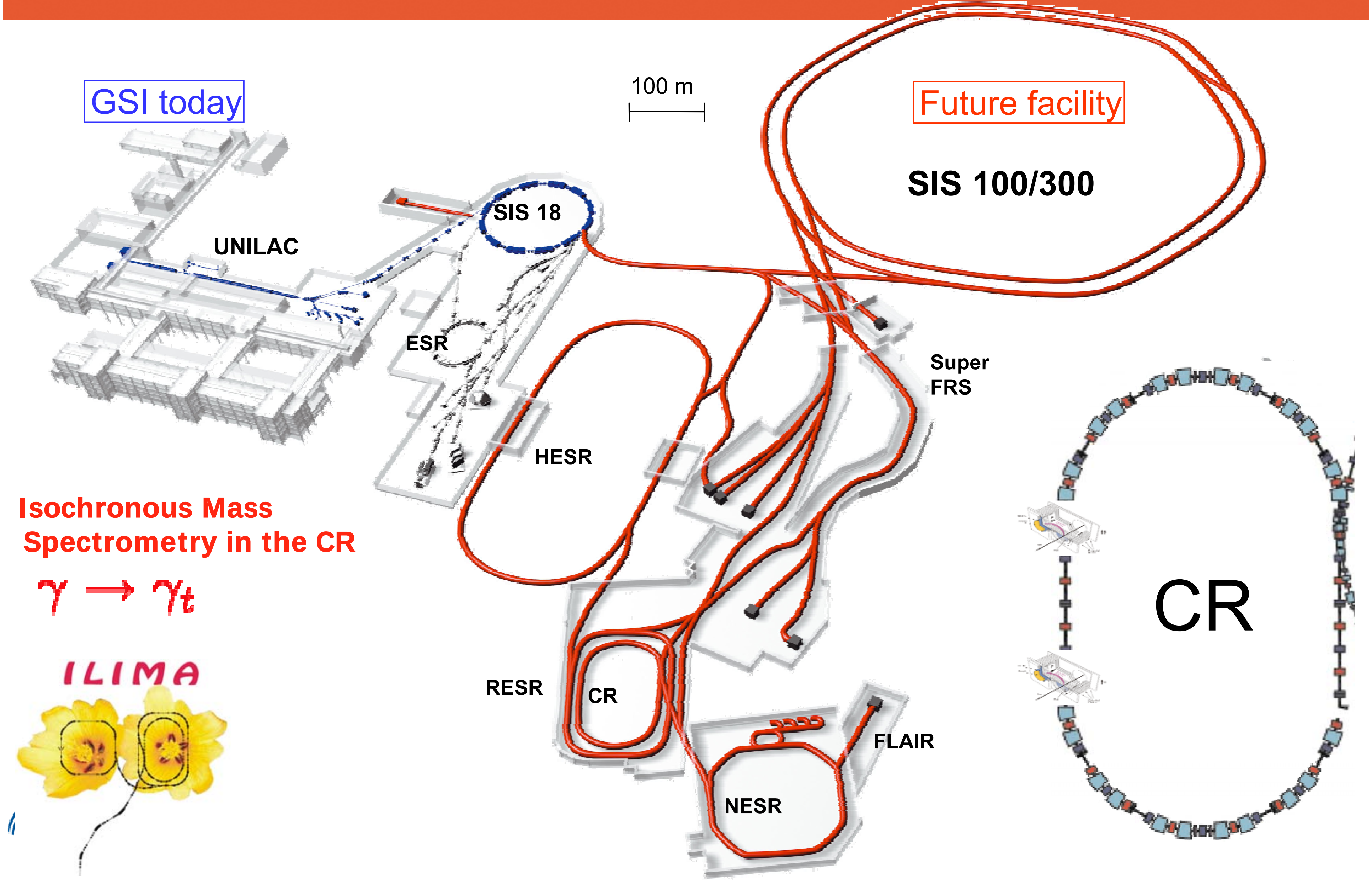




Transition (F=1→F=1) is accelerated by **$(2I+1)/(2F_1+1)$** i.e. by 8/3

However, there are only **$(2F_1+1)/((2F_1+1)+(2F_2+1)) = 3/8$** of ^{7}Be in this state

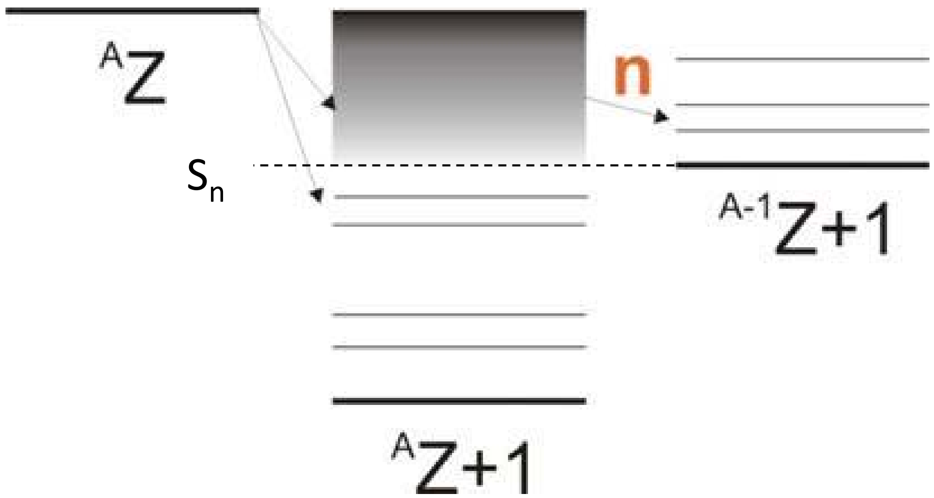
FAIR - Facility for Antiproton and Ion Research



Isochronous Mass Spectrometry in the CR

$\gamma \rightarrow \gamma_t$

β-delayed neutron emission probability



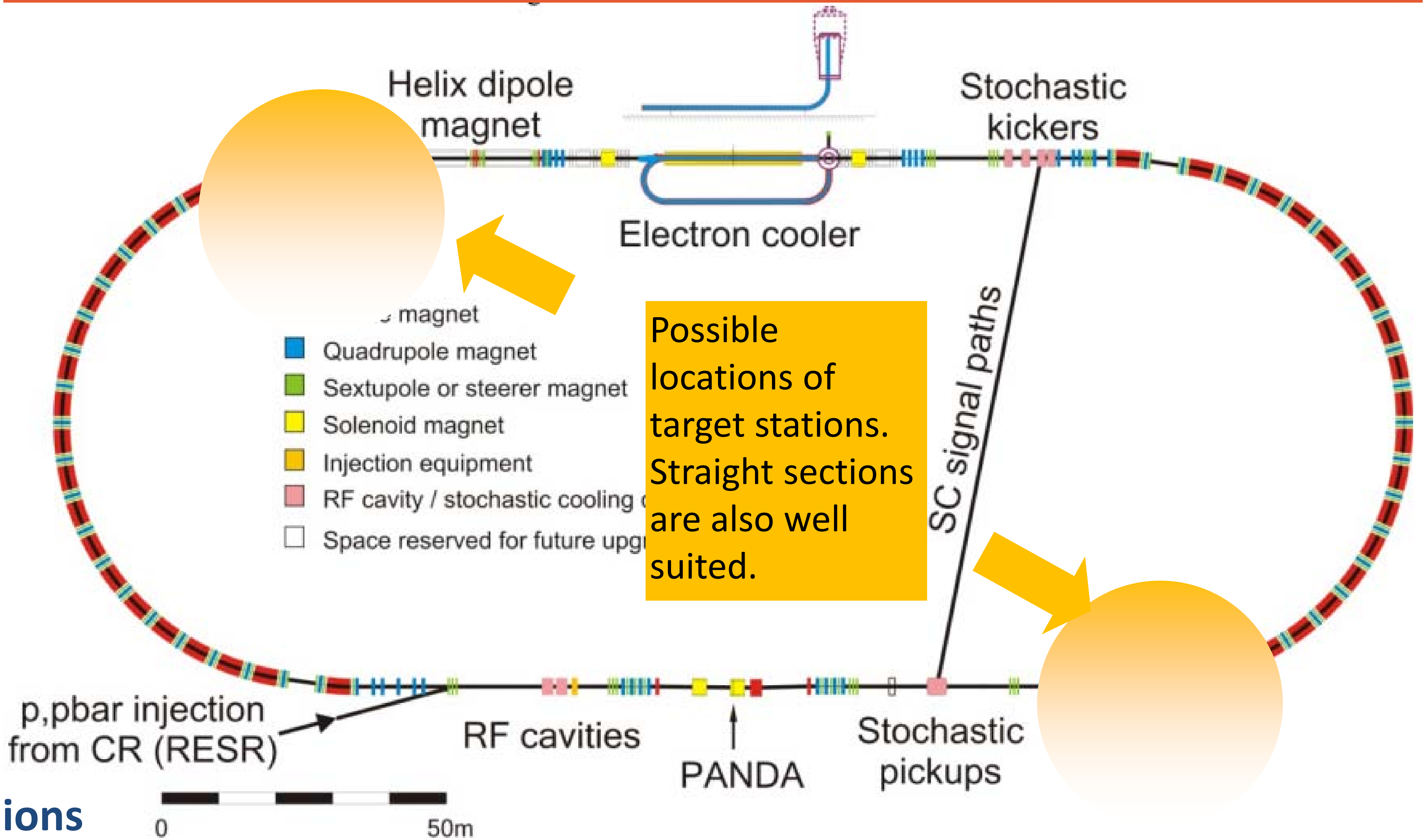
$S_n < Q_\beta$

Important nuclear structure information
P_n : β-strength above S_n
$t_{1/2}(^{A}Z+1)$: sensitive to low-lying β-strength

- Important for nuclear structure, astrophysics (r-process), and reactor physics
- ^{8}He- ^{150}La: ~200 datasets available, ~75 in non-fission region (A<70)

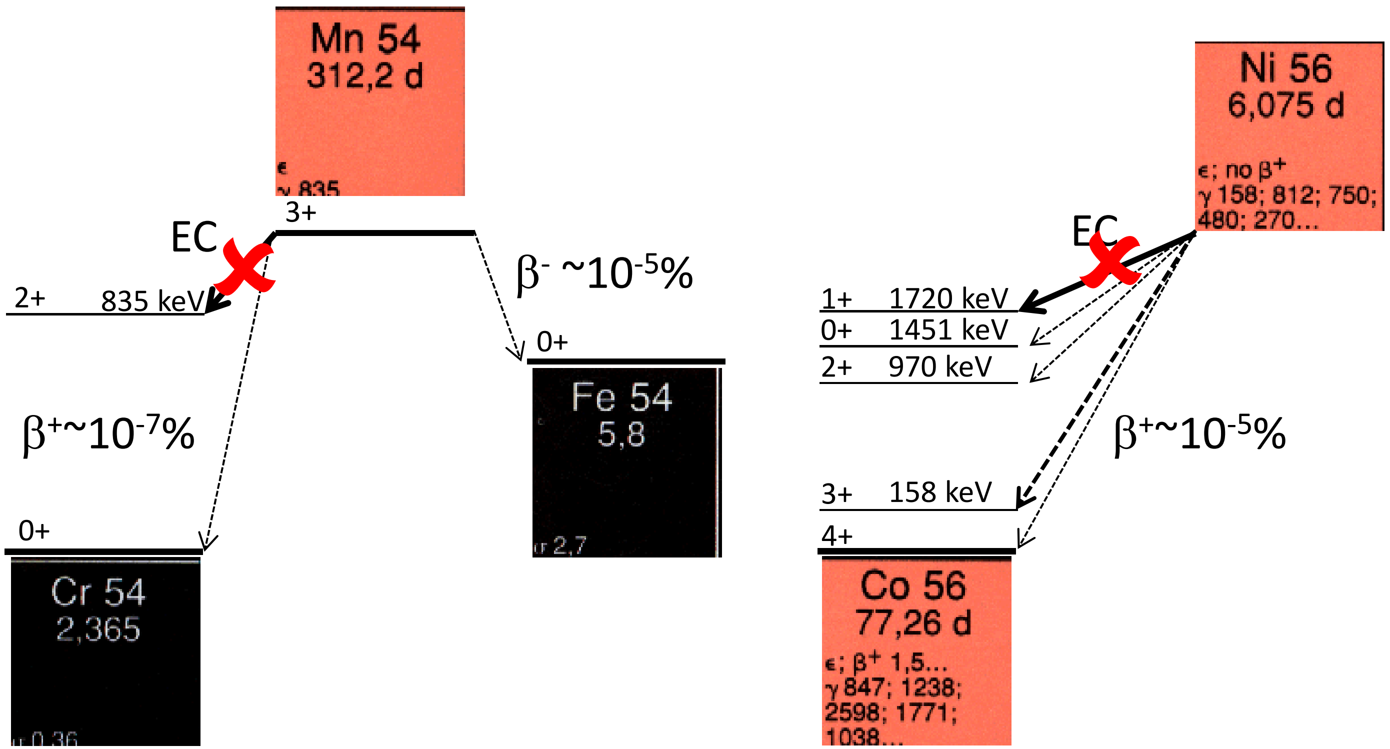
A. Evdokimov et al., Proc. NIC XI, PoS (NIC XII) 115

Experimental Conditions at the HESR



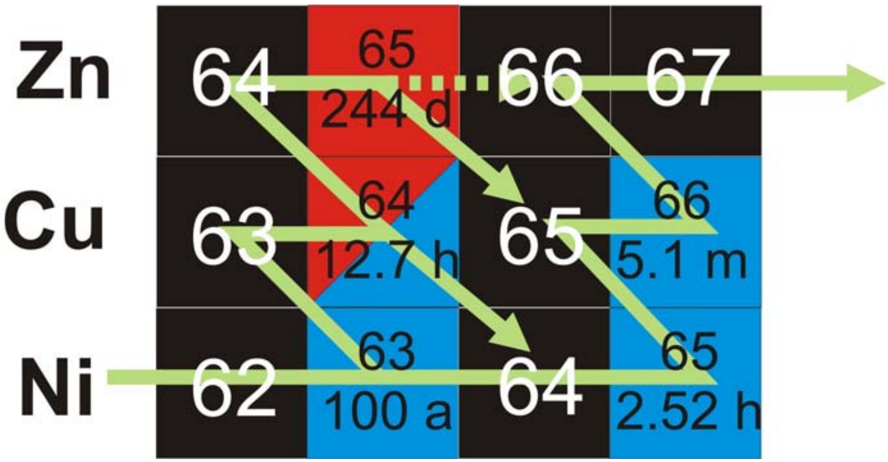
Mixed EC/β-decay isotopes

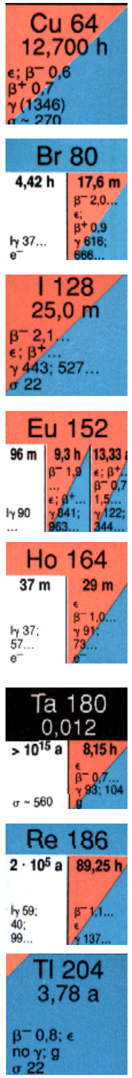
- Stellar conditions: EC hindered, weak β^+/β^- decay channel determines $t_{1/2}$
- 10^7 pps injected, 30min measured ⇨ ~1 event/d if partial $t_{1/2}$= 25000 y



Mixed EC/β-decay isotopes: s process

- s-process "branchings"
- Determines how much material is transferred to next isotope
- Interior of stars: high recombination rates but also high temperatures
- T≈30-1000 MK





43.9% EC/17.6% β^+

6.1% EC/ 2.2% β^+

6.9% EC

28 (4)% EC

72.1% EC

60 (5)% EC

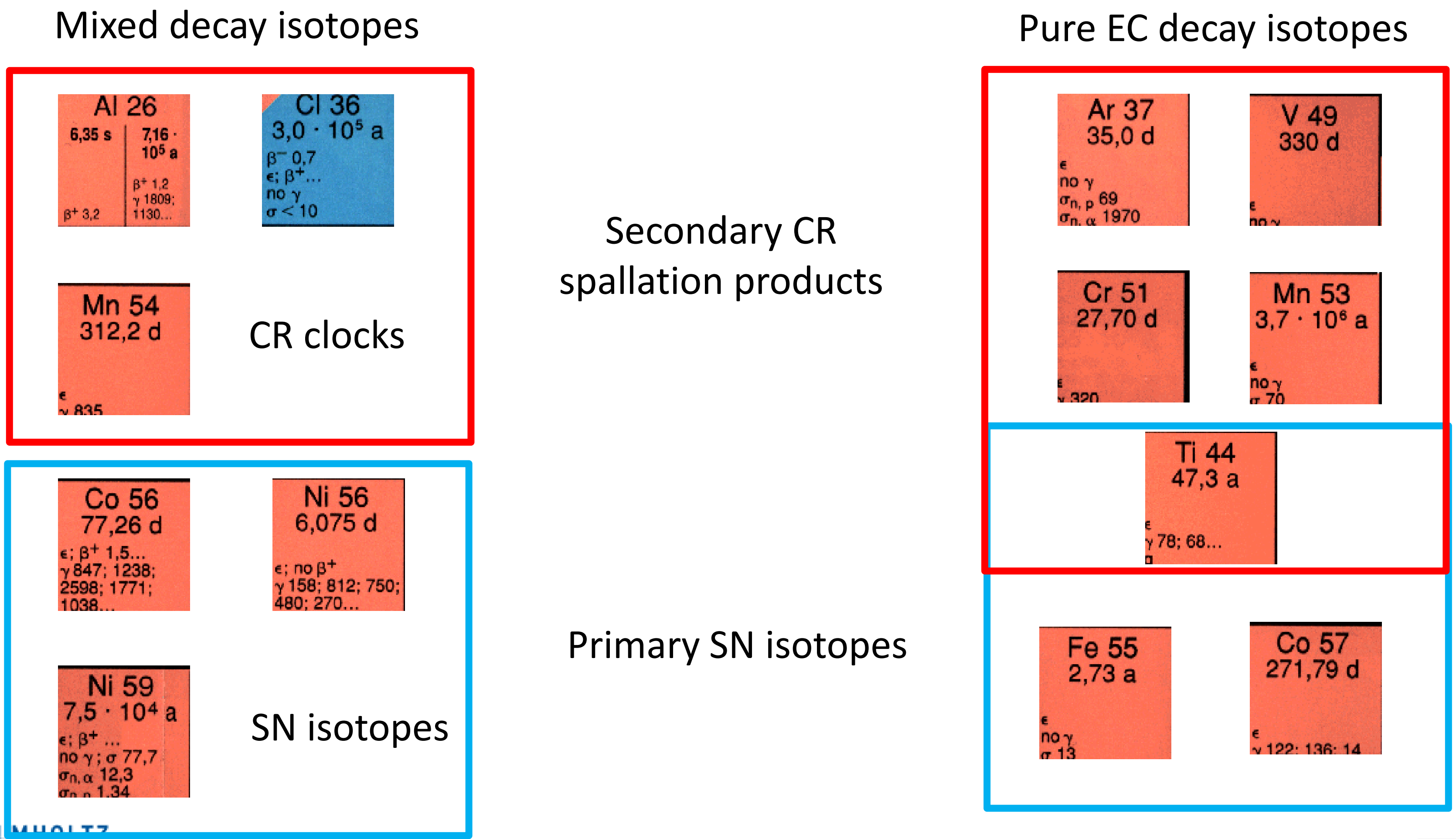
86 (3)% EC

7.47% EC

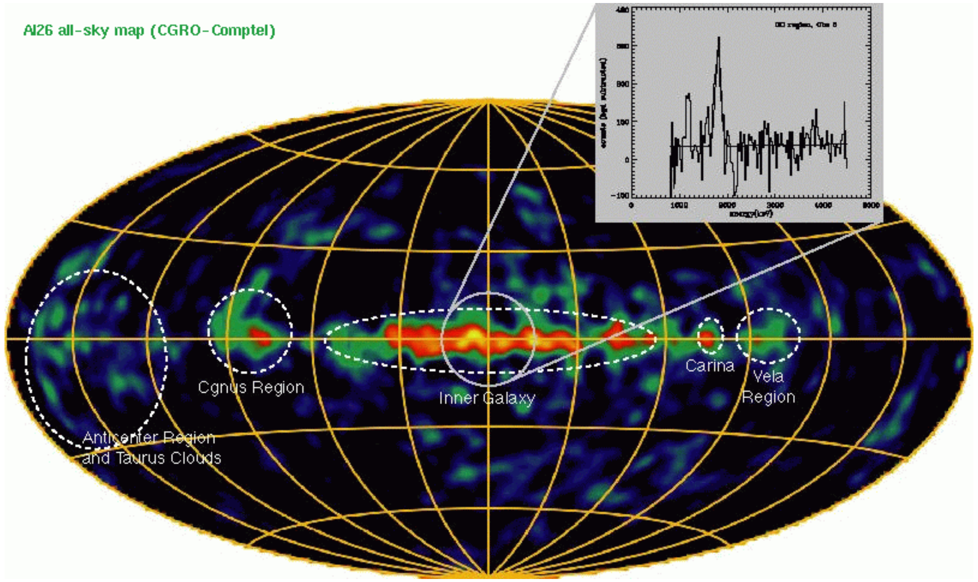
2.92% EC

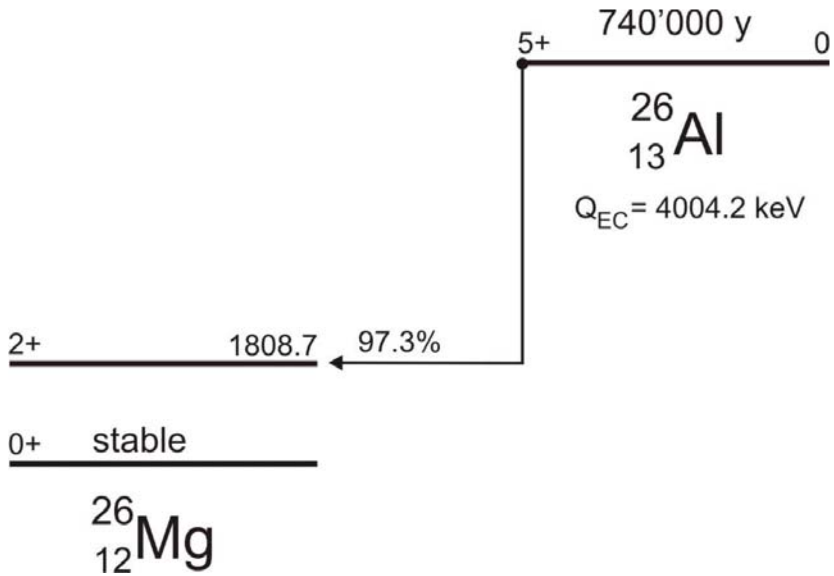
Physics cases

⇨ "Stellar lifetimes of SN isotopes“

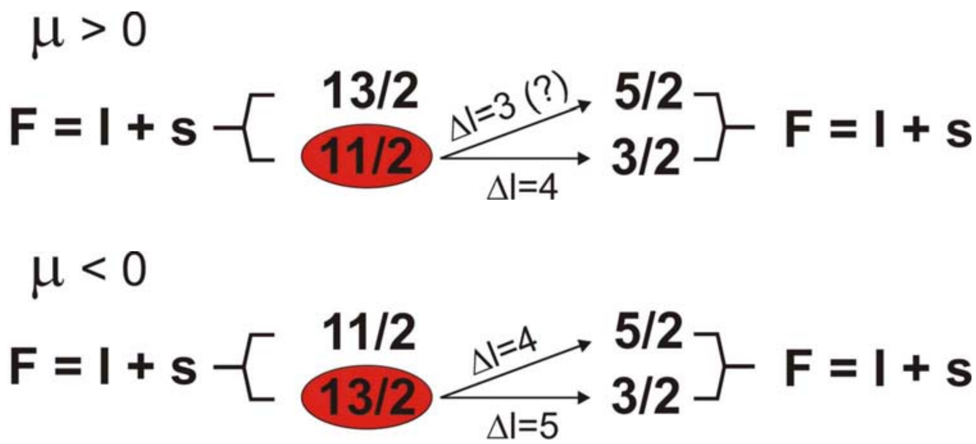


Stellar Gamma-Ray Emitters





Hydrogen-like ^{26}Al



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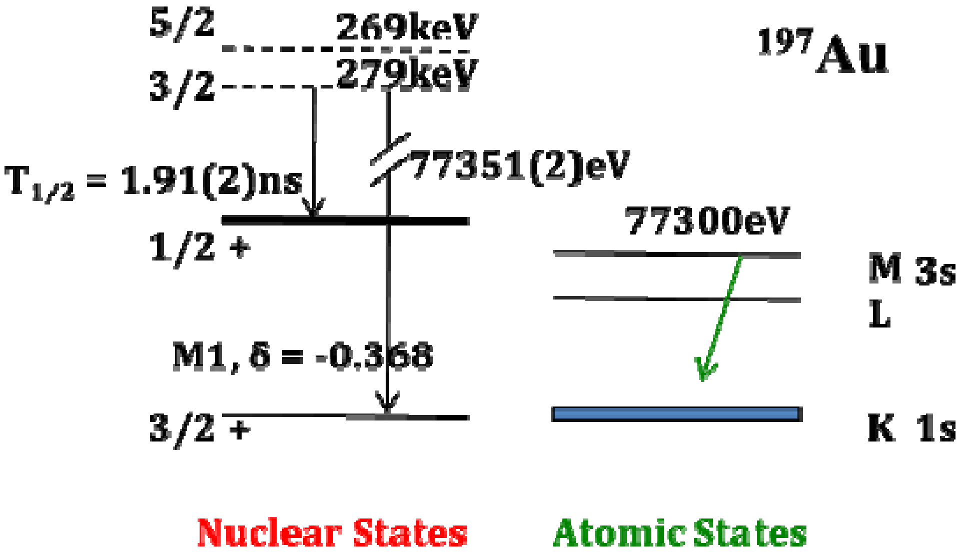
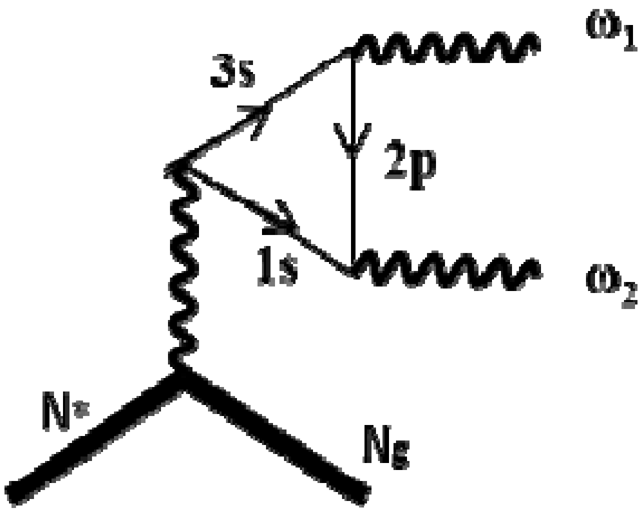
Speculation: Pauli forbidden decay





Conversion on L, M,....shells; Γ_{1s} = 59eV

F. Karpeshin

Thank you for your attention

A. Atanasov, F. Bosch, D. Boutin, C. Brandau, P. Bühler, I. Dillmann, Ch. Dimopoulou, H.G. Essel, Th. Faestermann, B. Franzke, H. Geissel, R. Hess, P.-M. Hillebrand, V. Ivanova, T. Izumikawa, P. Kienle†, O. Klepper, R. Knöbel, Ch. Kozhuharov, J. Kurcewicz, N. Kuzminchuk, M. Lestinsky, S.A. Litvinov, Yu.A. Litvinov, X.W. Ma, L. Maier, M. Mazzocco, G. Münzenberg, I. Mukha, A. Musumarra, G. Münzenberg, C. Nociforo, F. Nolden, T. Ohtsubo, Zs. Podolyak, M.W. Reed, M.S. Sanjari, D. Shubina, Ch. Scheidenberger, U. Spillmann, M. Steck, Th. Stöhlker, B.H. Sun, F. Suzaki, T. Suzuki, K. Takahashi, S. Yu. Torilov, M. Trassinelli, X. L. Tu, M. Wang, P.M. Walker, H. Weick, M. Winkler, N. Winckler, D. Winters, N. Winters, P. Woods, T. Yamaguchi, H.S. Xu, X. L. Yan, G. L. Zhan, Y.H. Zhang, X.H. Zhou