Influence of Atomic Shell on Nuclear Decays

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Weak decays

Nuclear weak decay in general form:

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

i) continuum beta decay:

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

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

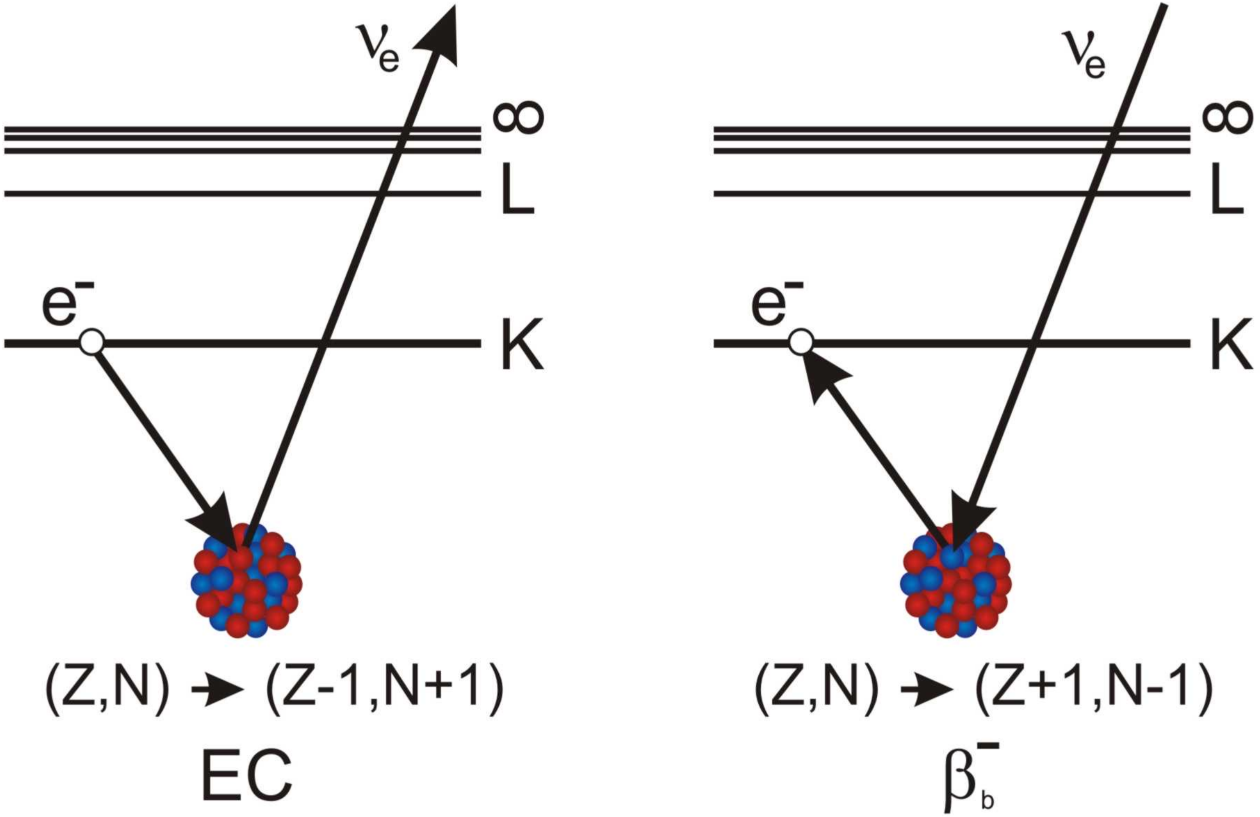
ii) two-body beta decay:

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

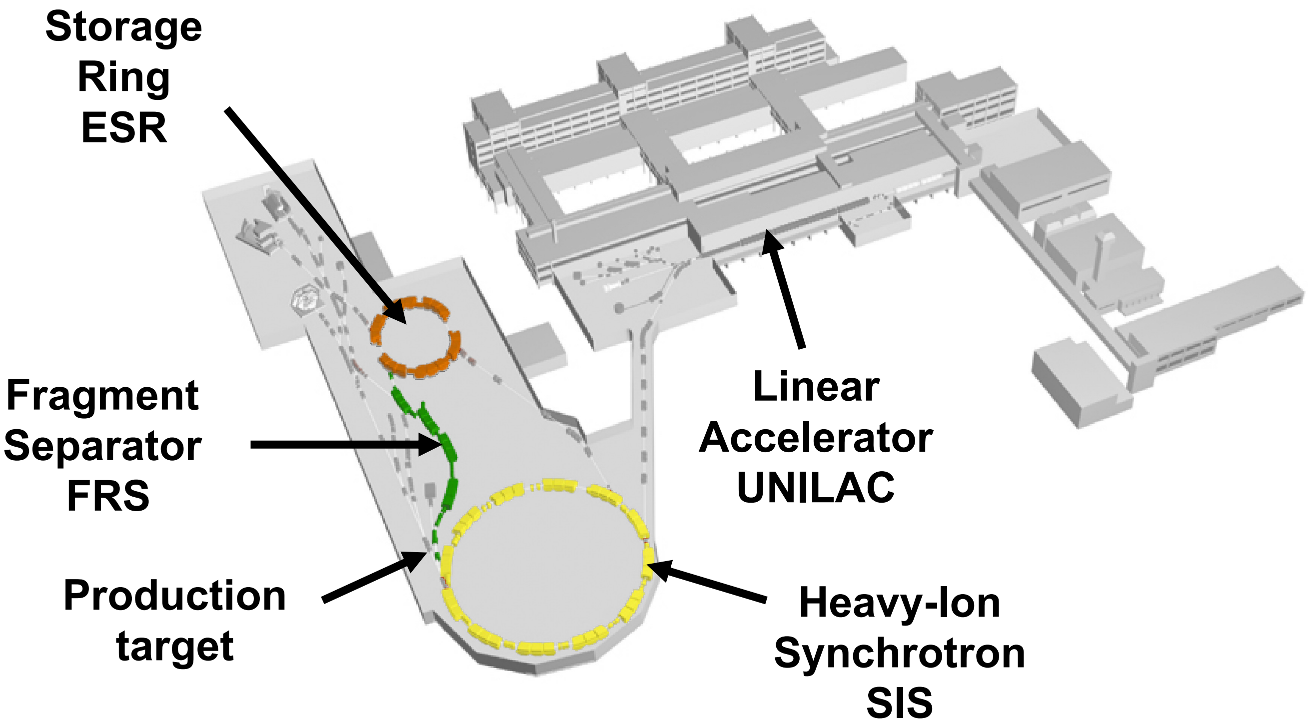
$$n \rightarrow p + e_b^- + \bar{\nu}_e \qquad \text{Bound state beta decay } (\beta_b^-)$$

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

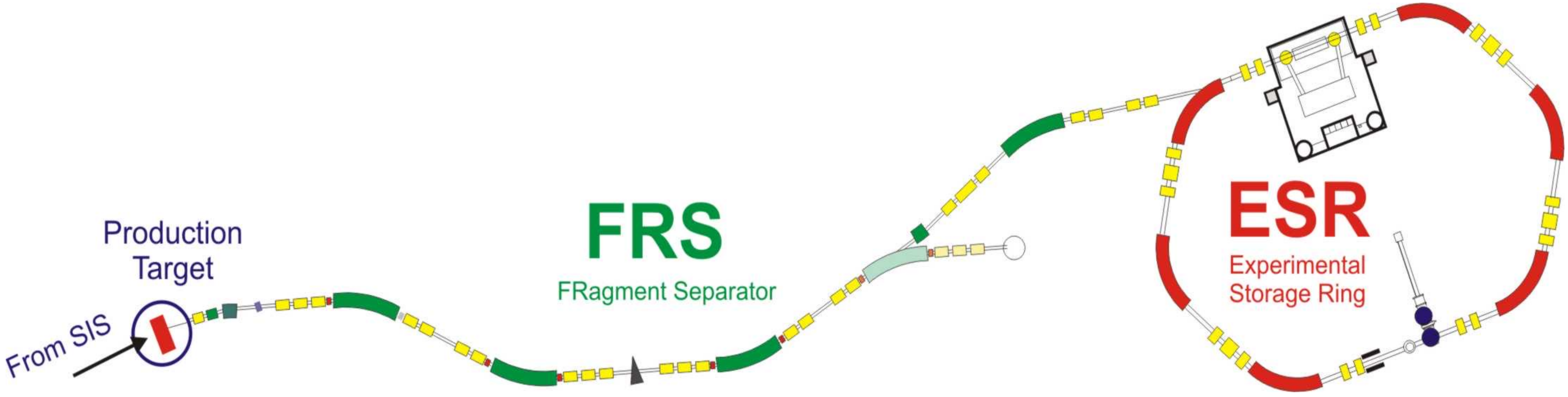
Two-Body Beta Decay



Secondary Beams of Short-Lived Nuclei



Production & Separation of Exotic Nuclei



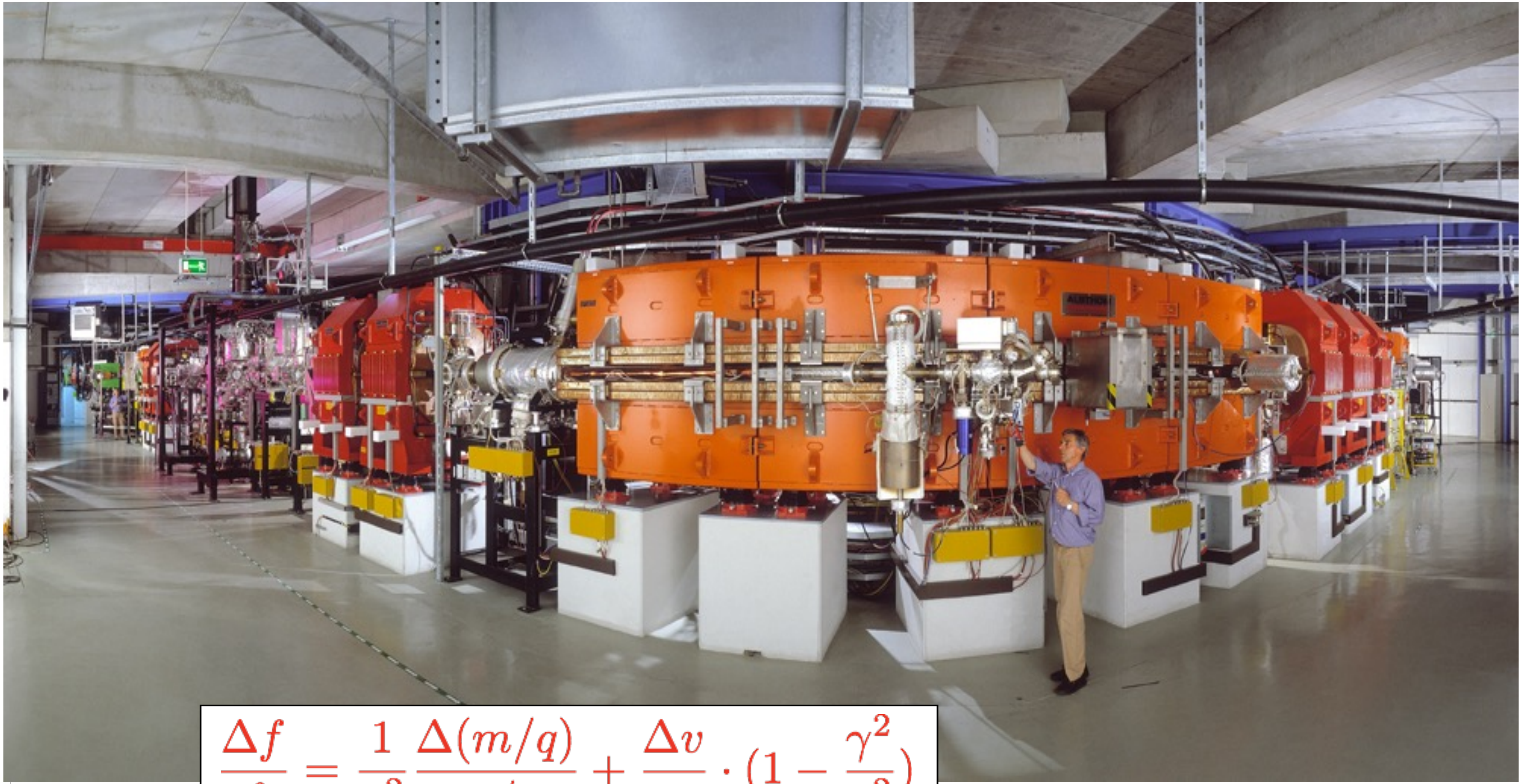
Primary beams @ 400-1000 MeV/u

Highly-Charged Ions (0, 1, 2 … bound electrons)

In-Flight separation within ~ 150 ns

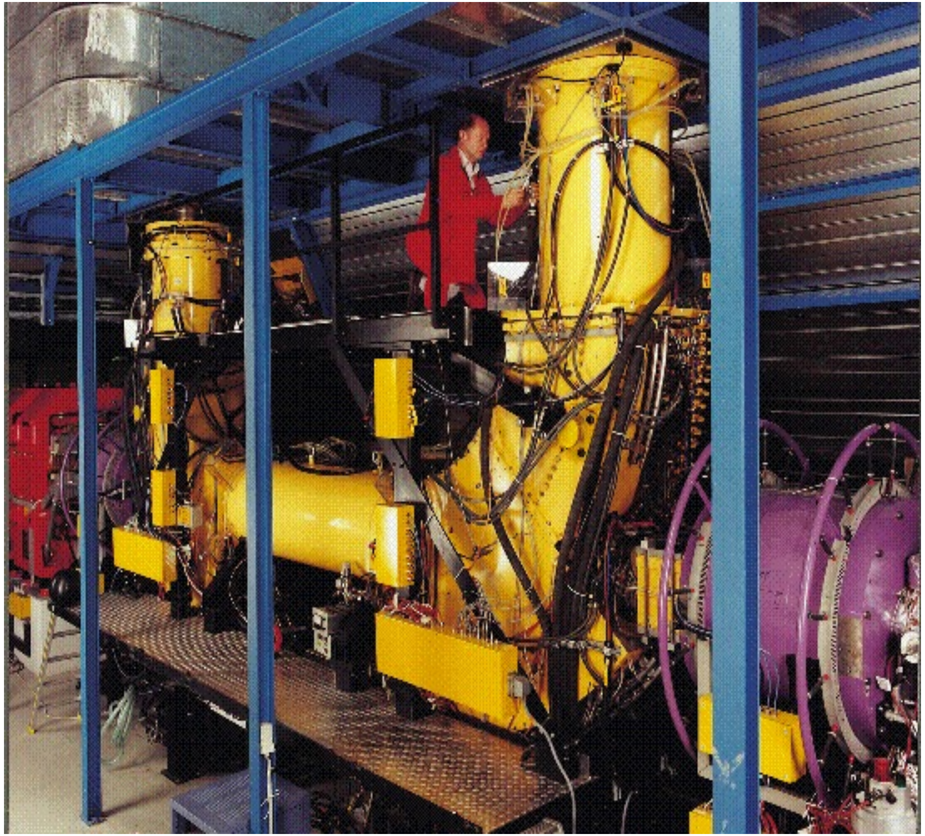
Cocktail or mono-isotopic beams

ESR: The experimental Storage Ring

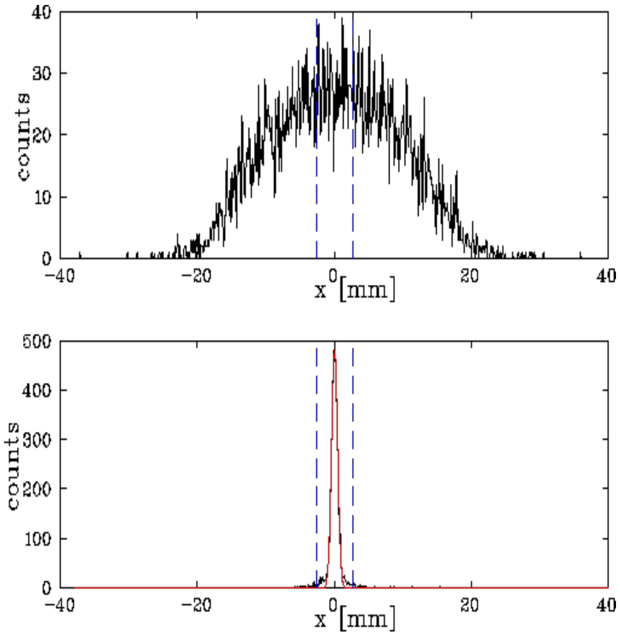


$$\frac{\Delta f}{f} = \frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\cdot(1-\frac{\gamma^2}{\gamma_t^2})$$

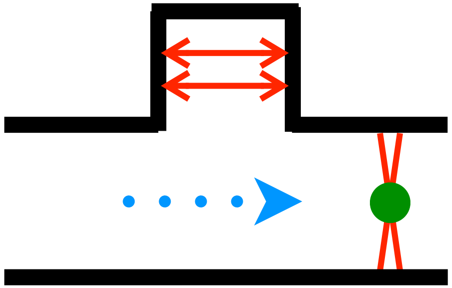
Electron Cooling

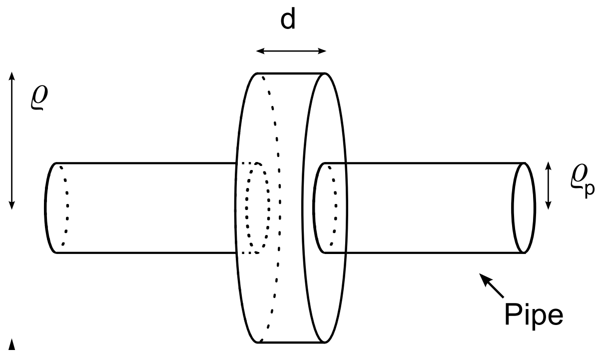


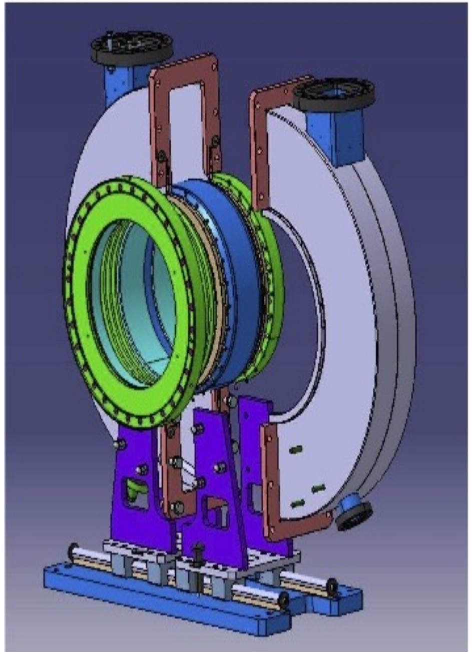
momentum exchange with 'cold', collinear e- beam. The ions get the sharp velocity of the electrons, small size and divergence



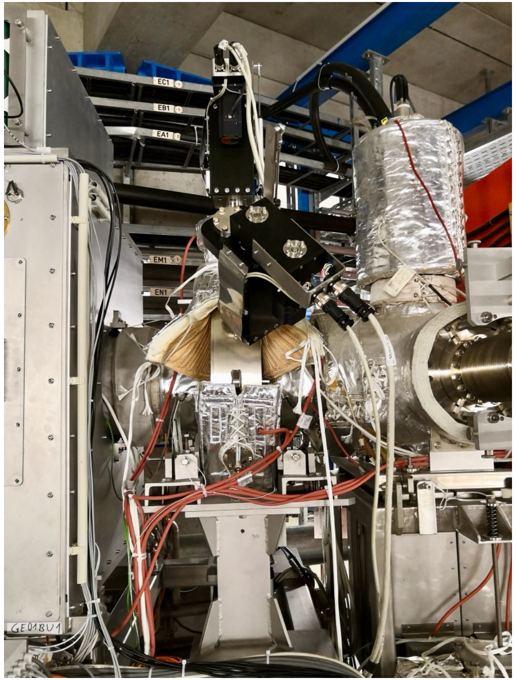
Non-Destructive Particle Detection







F. Nolden et sl., Nucl. Instr. Meth. A (2011)



S. Sanjari et al., Rev. Sci. Instr. (2020)

The goal: to measure non-destructively the revolution frequency of a single ion within a few miliseconds

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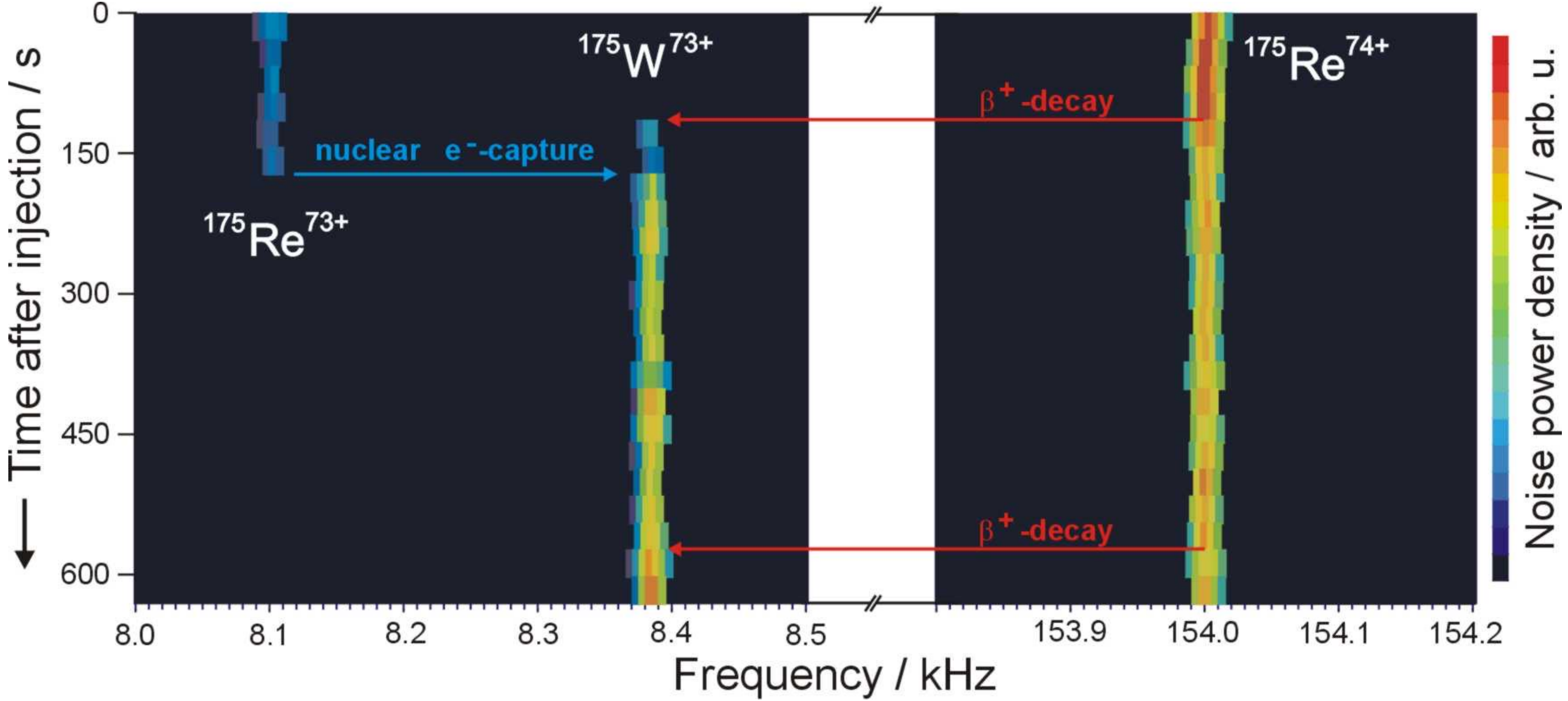
Courtesy F. Nolden and M. S. Sanjari

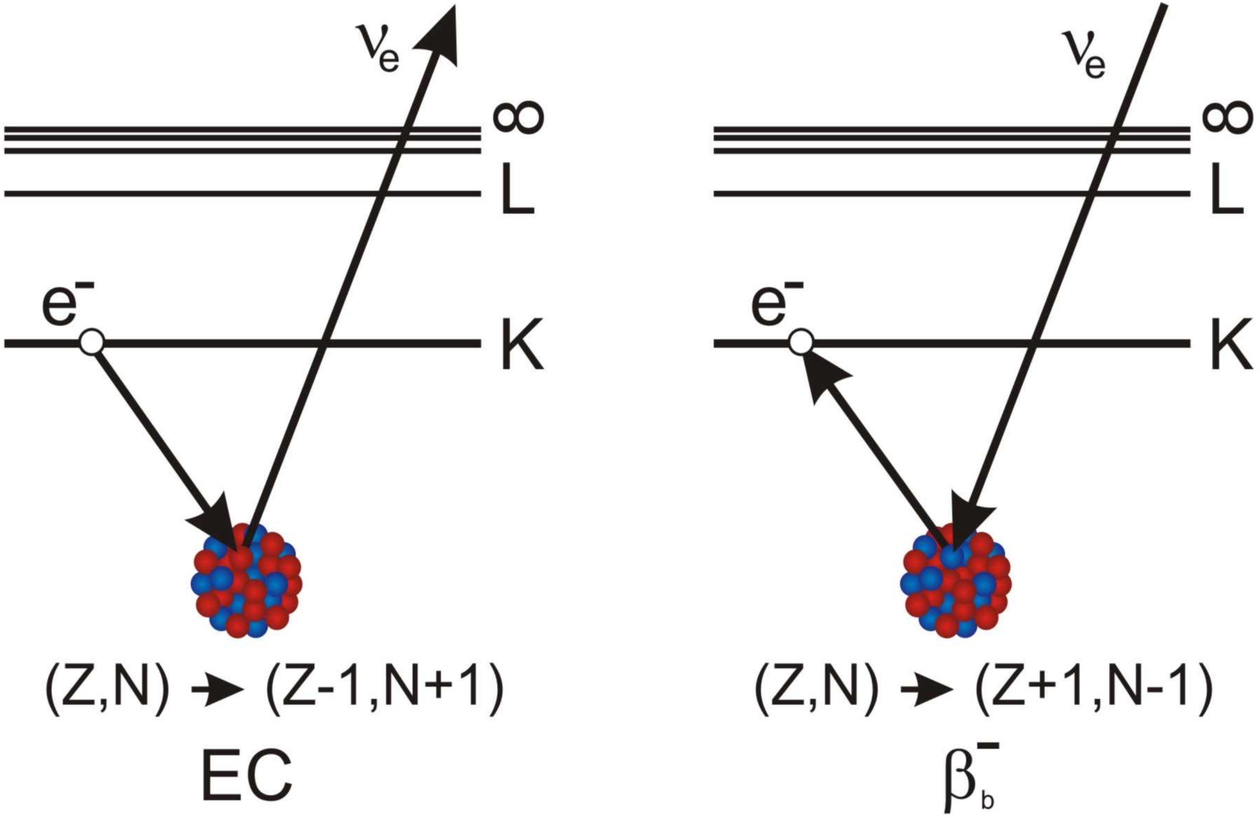
HELMHOLTZ GSI

Nuclear Decays of Stored Single Ions



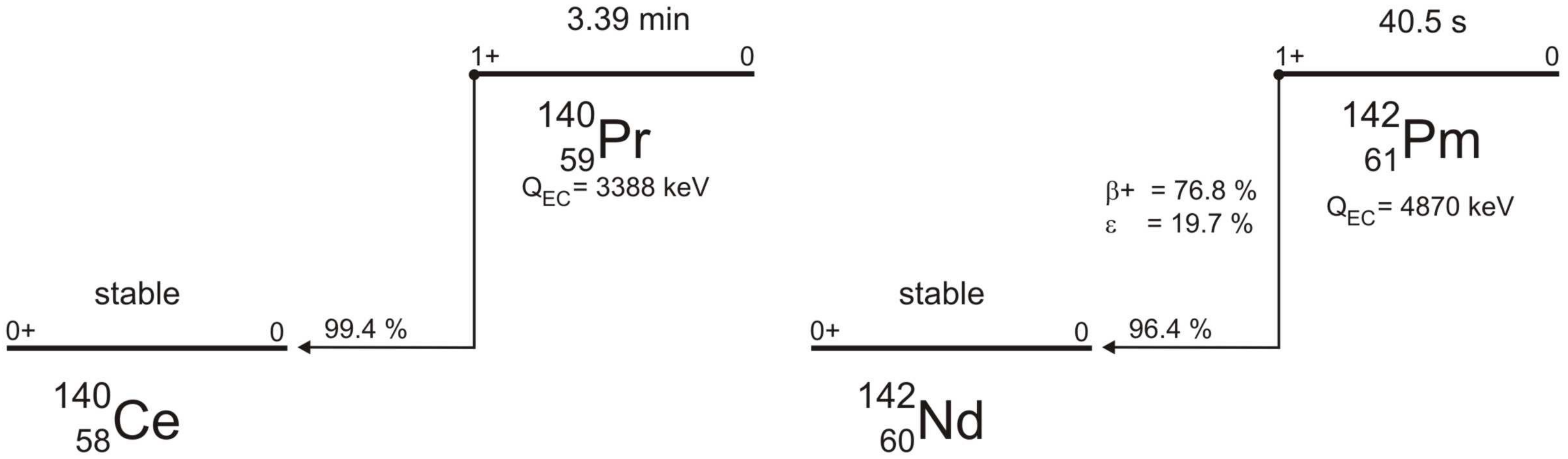
Time-resolved SMS is a perfect tool to study decays in the ESR

Two-Body Beta Decay



Orbital Electron Capture Decay of Few-Electron Ions

Allowed Gamow-Teller Transitions



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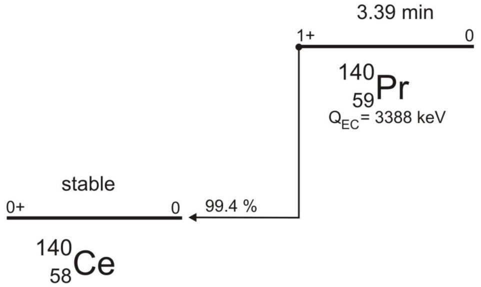

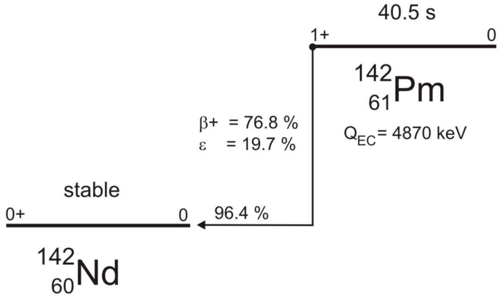

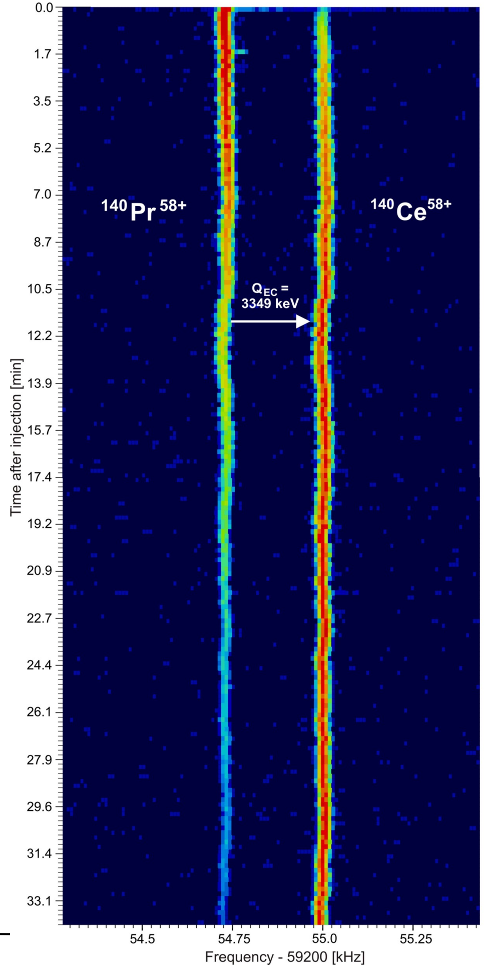

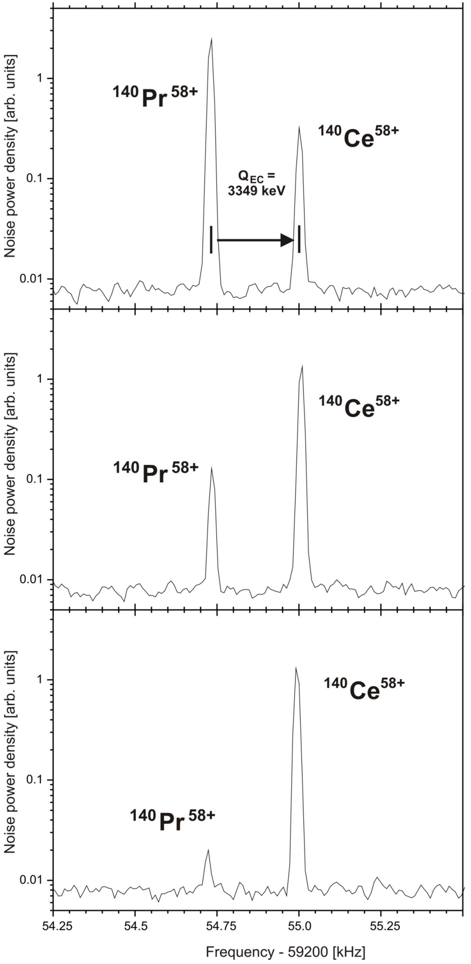

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Orbital Electron Capture Decay of Few-Electron Ions

Conventional EC-theory: *W.Bambynek et al., Rev. Mod. Phys 49, 1977*

S-electron density at the nucleus:

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

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

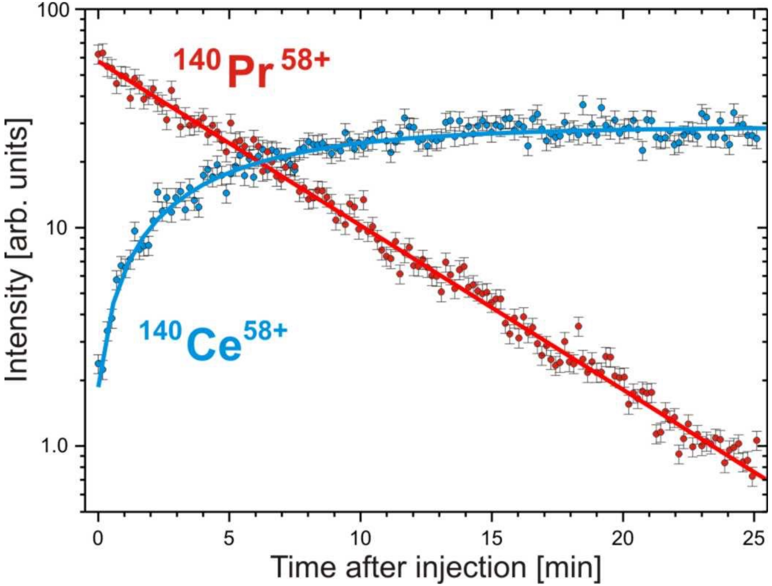
P_K (H-like) $\propto 1 * 1/1^3 = 1$

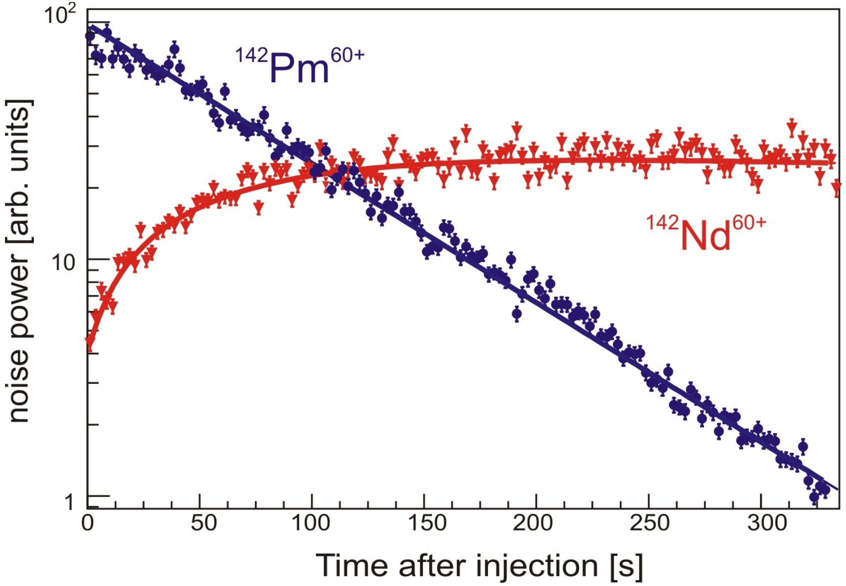
Conclusion:
H-Like ion should have 41% longer half-life

λ_{EC}(H-like)/λ_{EC}(He-like) ≈ 0.5

Orbital Electron Capture Decay of Few-Electron Ions

Expectations: λ_{EC}(H-like)/λ_{EC}(He-like) ≈ 0.5





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

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

Orbital Electron Capture Decay of Few-Electron Ions

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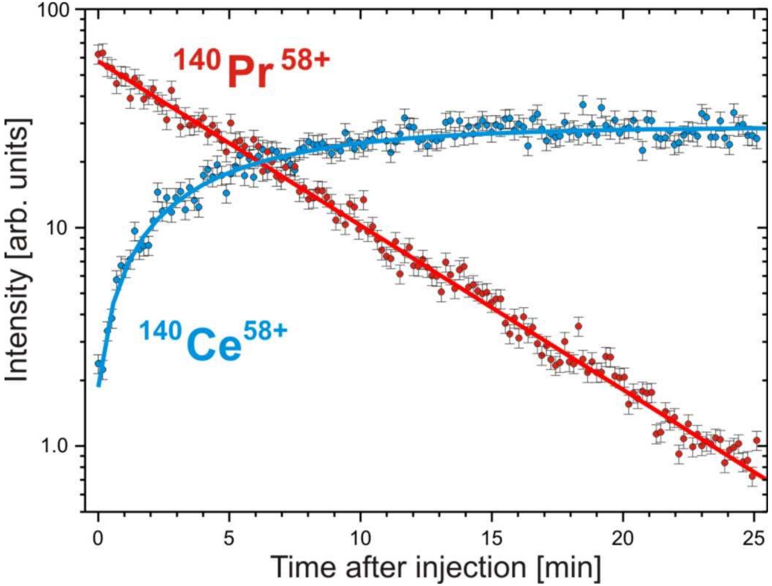
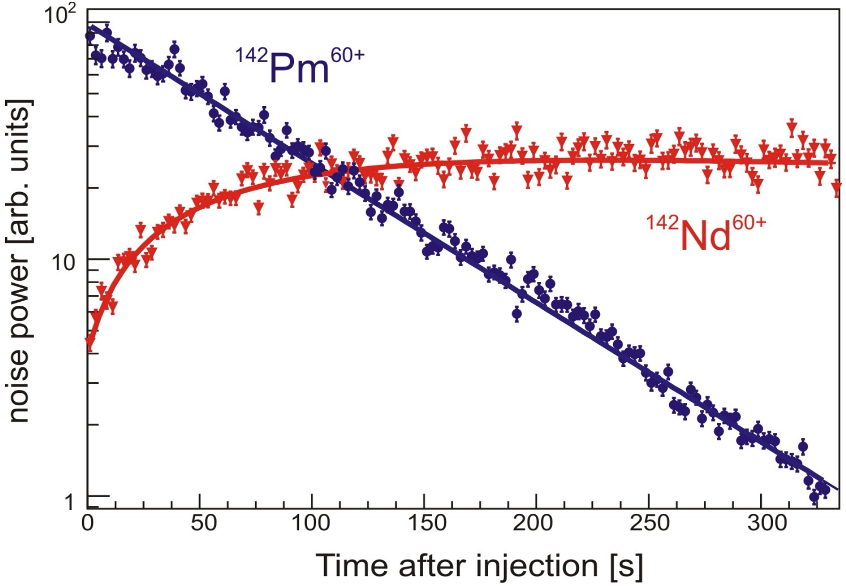




λ_{EC}(H-like)/λ_{EC}(He-like) = 1.49(8)

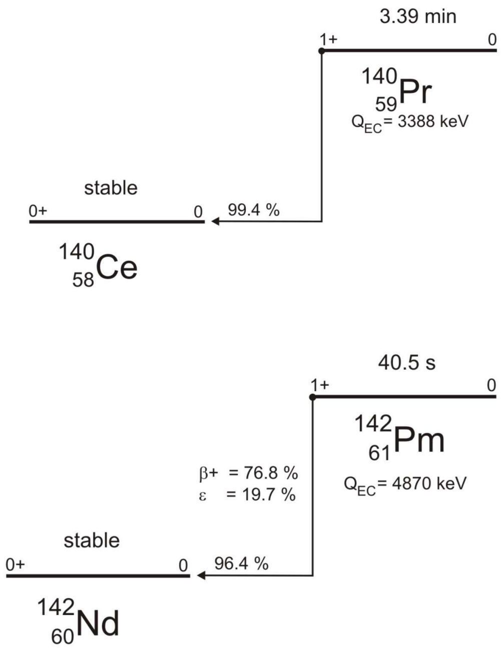
λ_{EC}(H-like)/λ_{EC}(He-like) = 1.44(6)

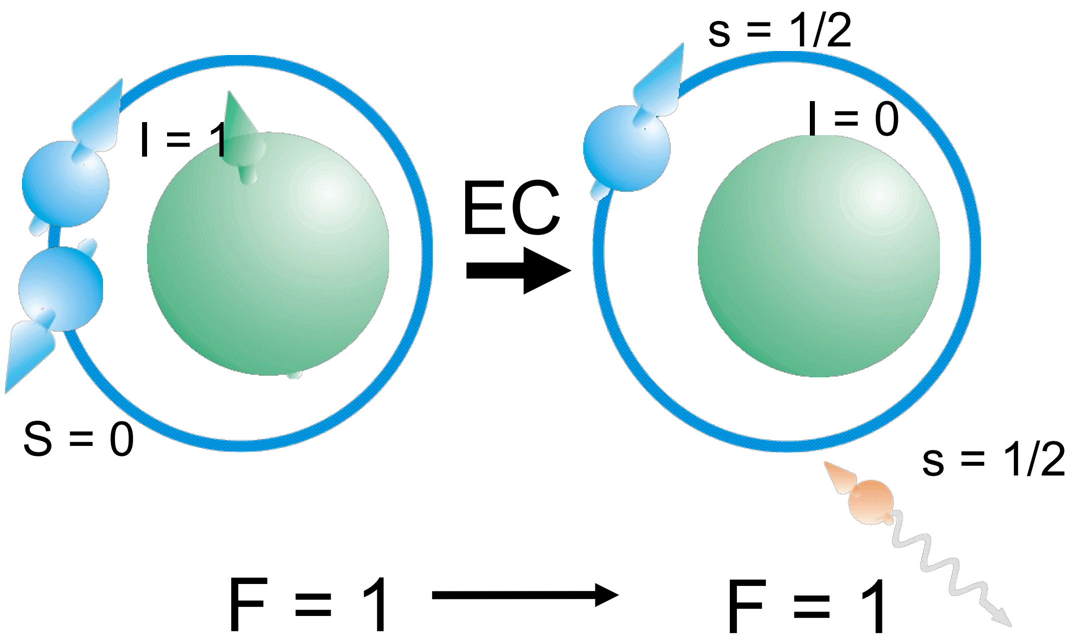
Yu.A. Litvinov et al., Phys. Rev. Lett. 99 (2007) 262501

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

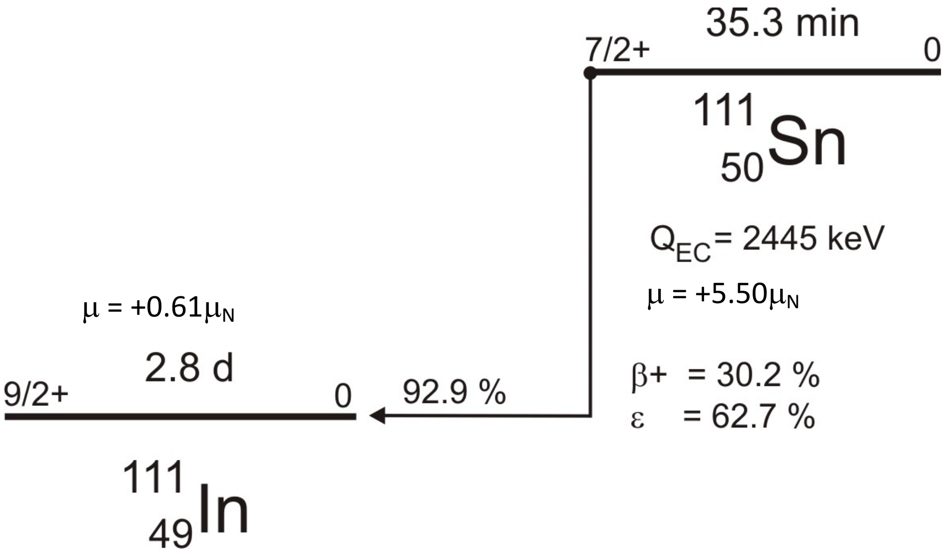
Orbital Electron Capture Decay of Few-Electron Ions

Allowed Gamow-Teller Transitions





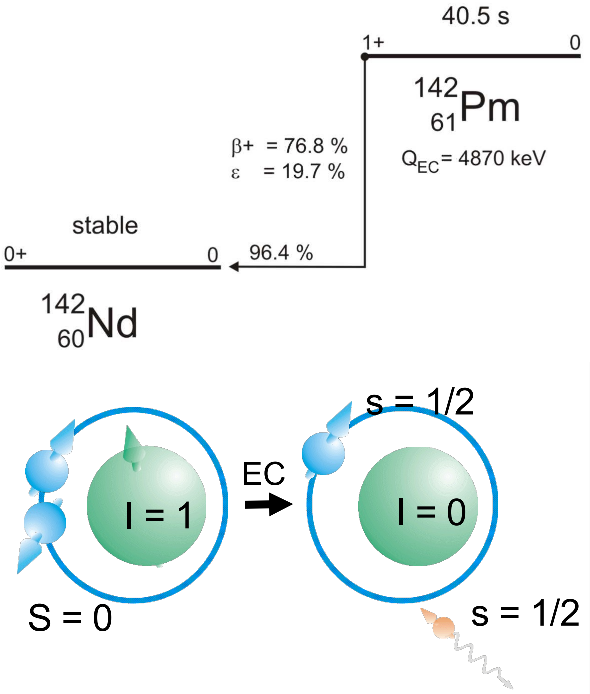
What happens in ^{111}Sn ?

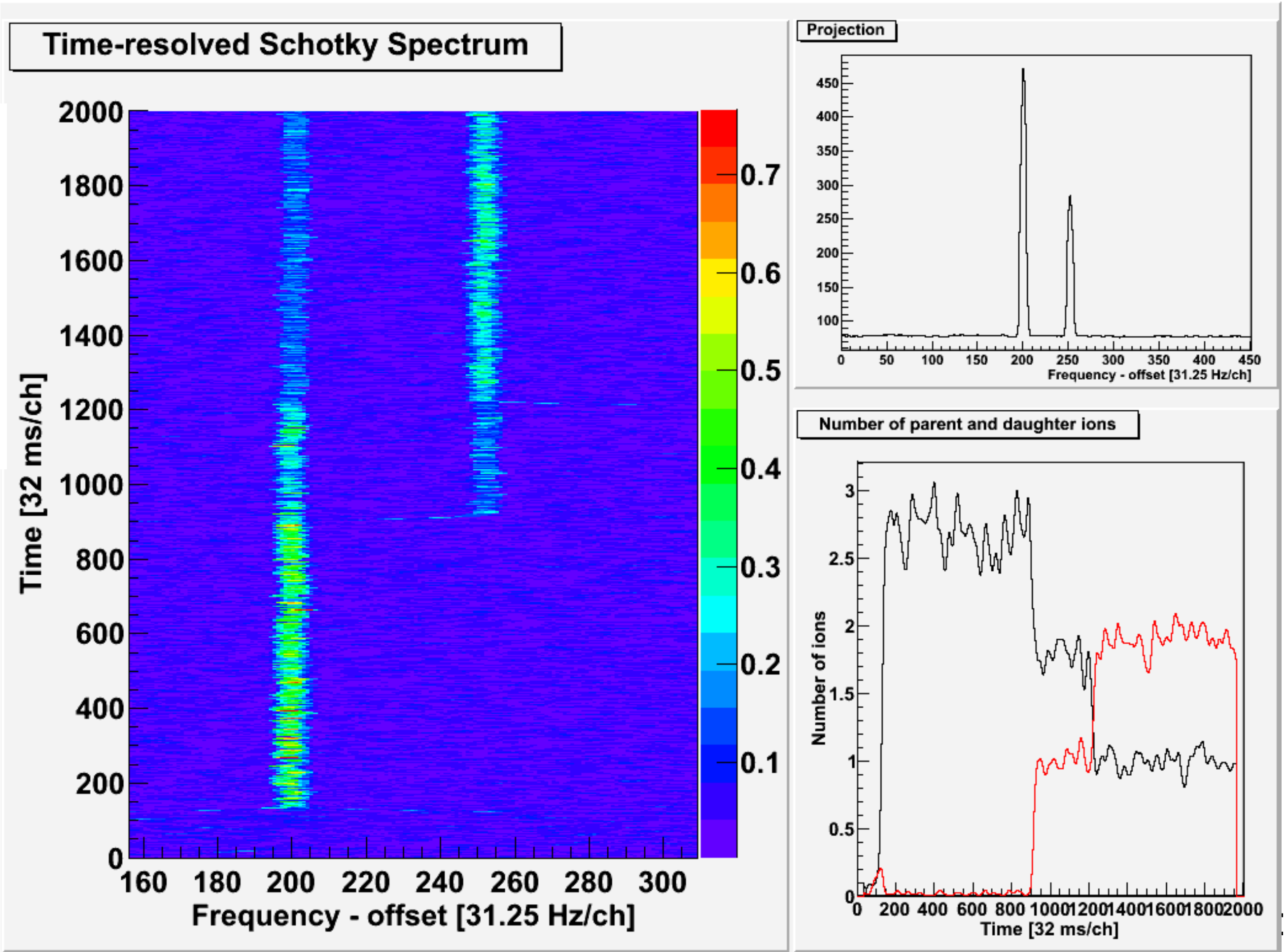


Electron screening in beta decay

Yu.A. Litvinov, Int. J. Mod. Phys. E18 (2009) 323

Three Parent He-Like ^{142}Pm Ions





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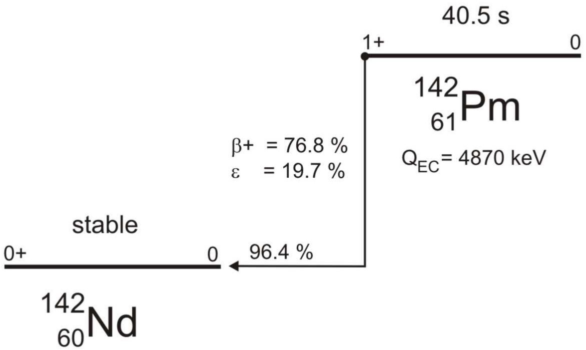

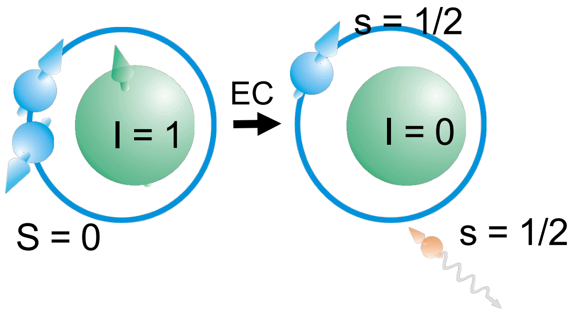

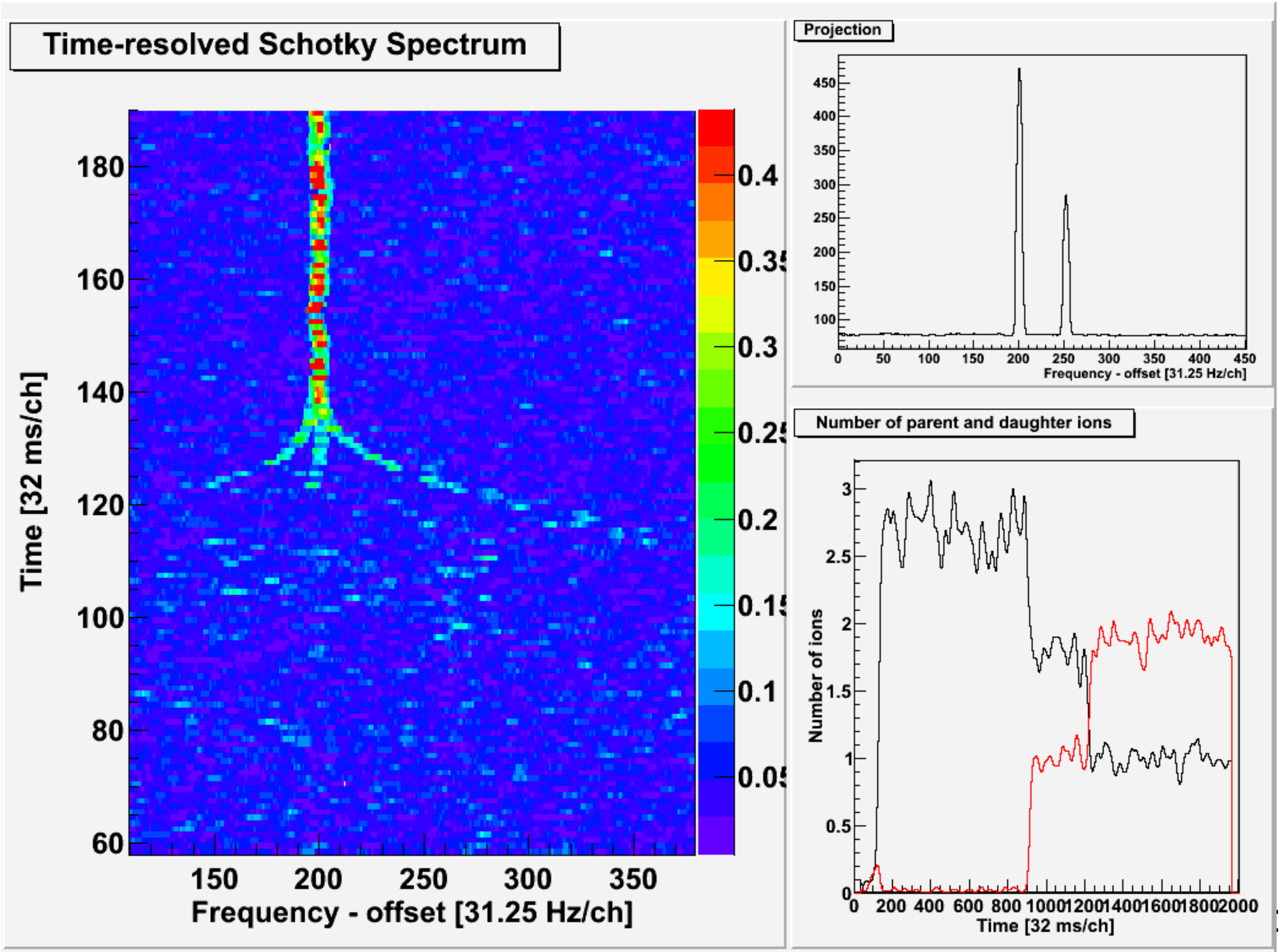

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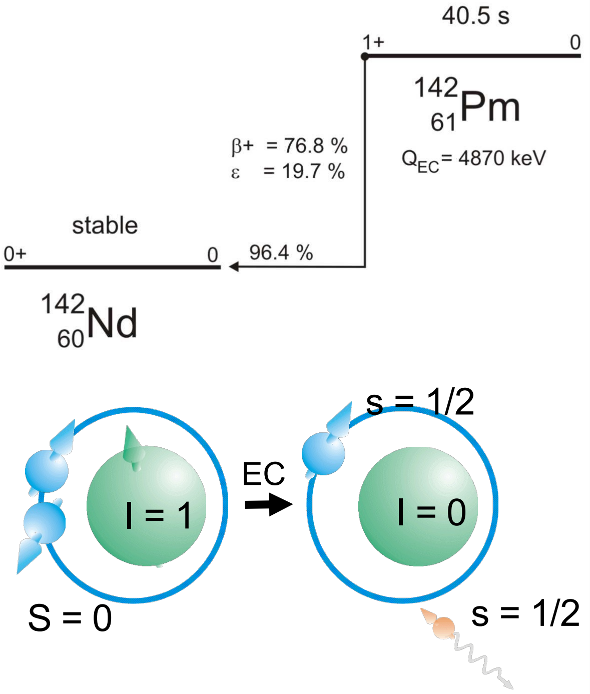

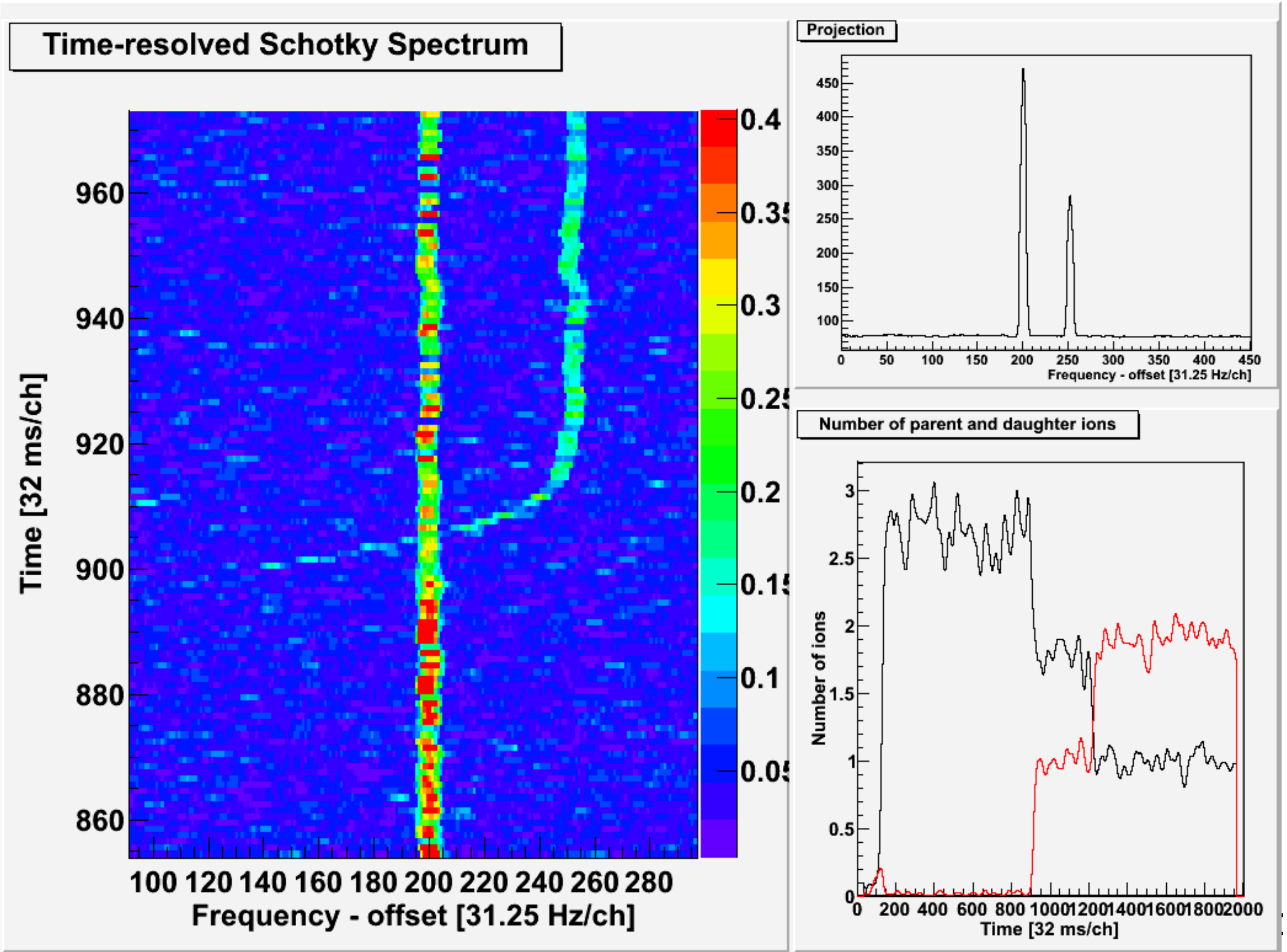

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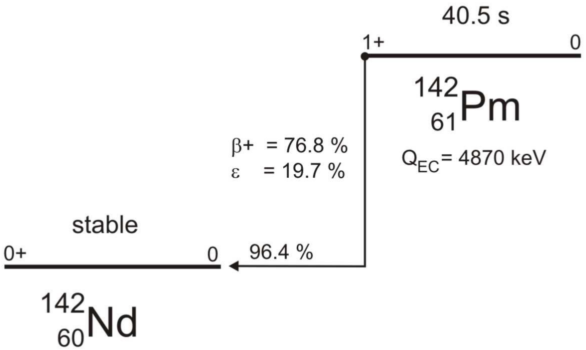
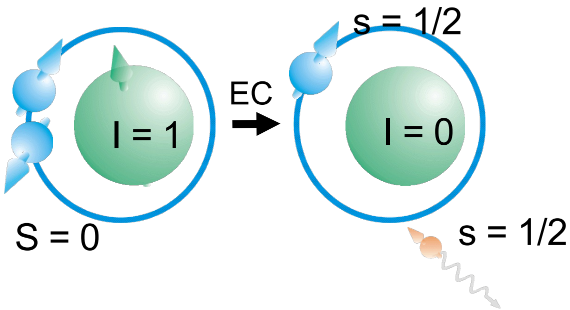
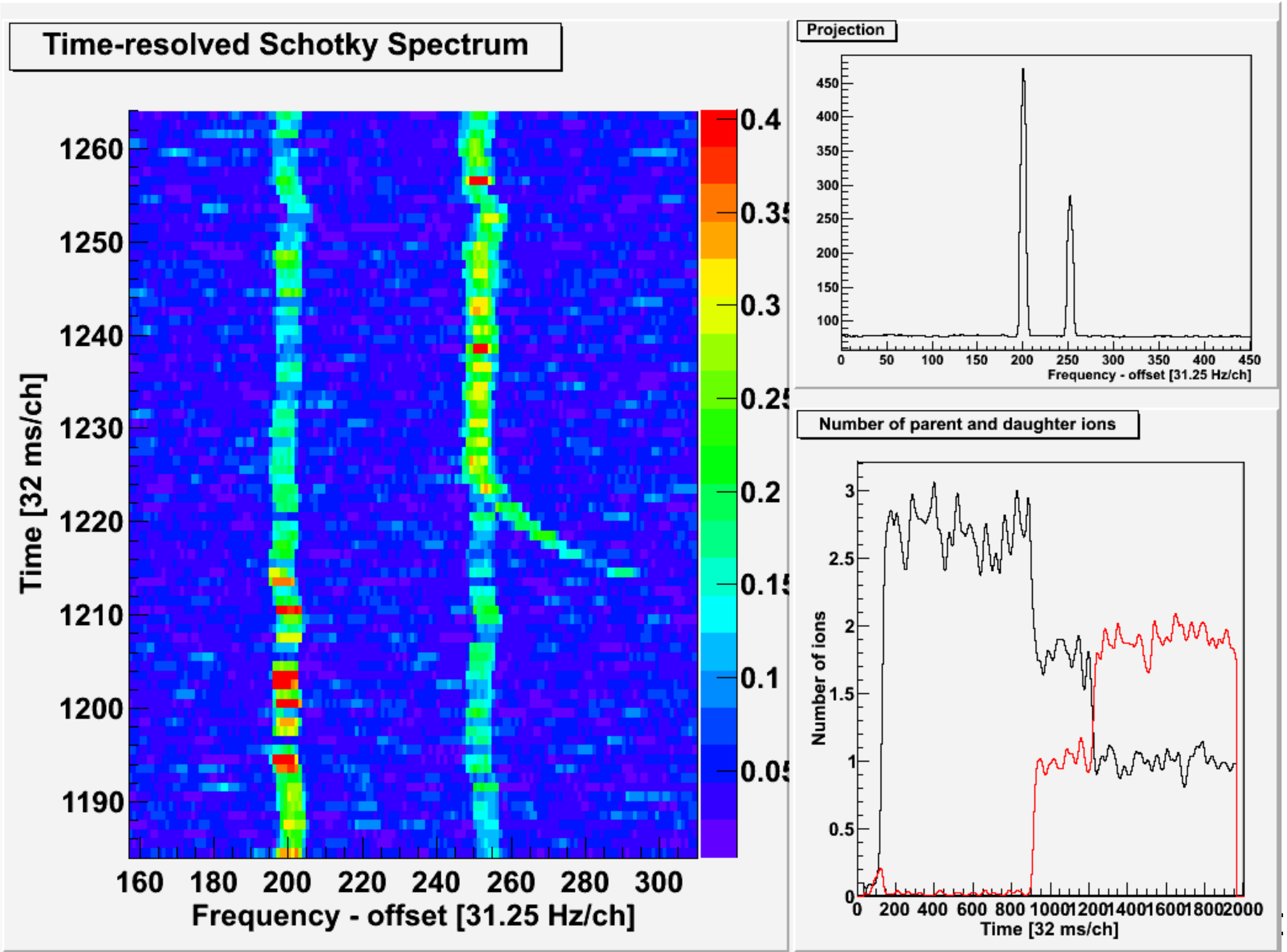
Three Parent He-Like ^{142}Pm Ions







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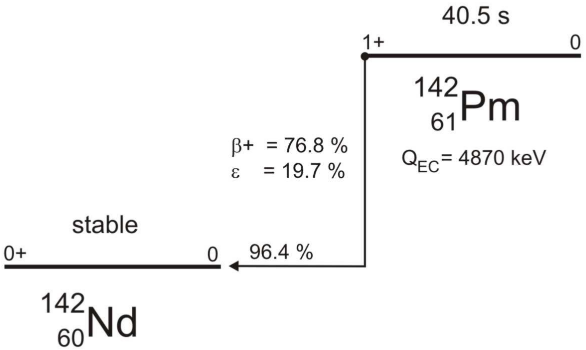
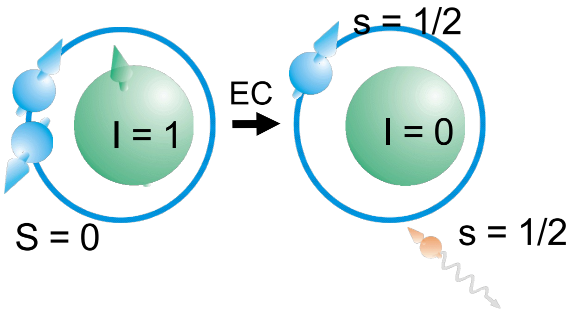
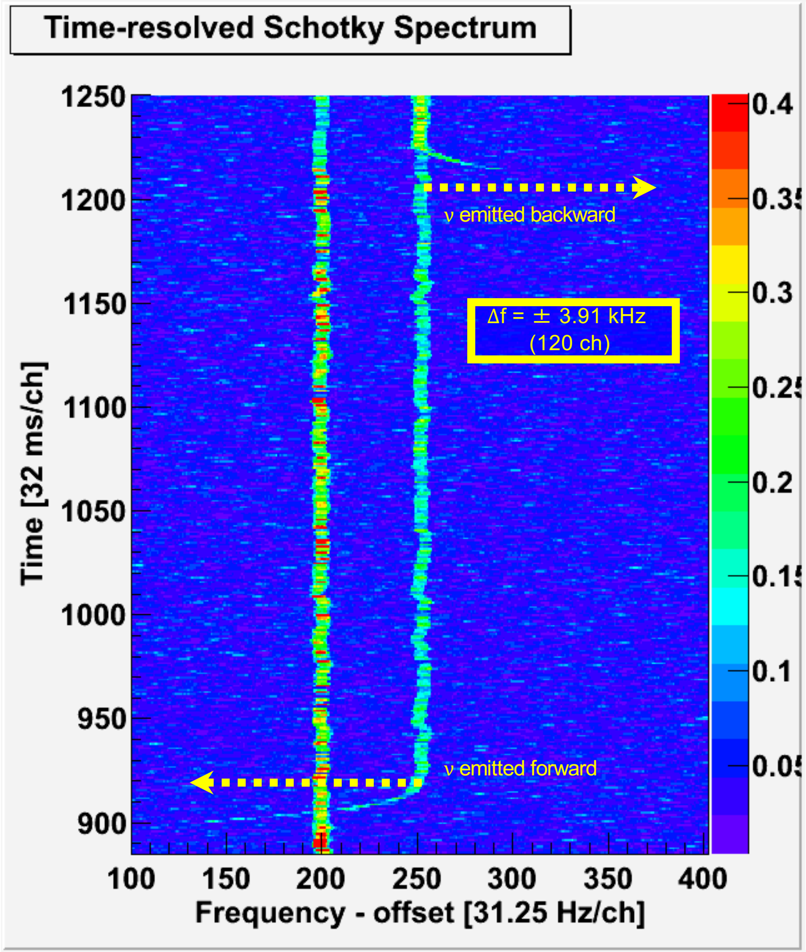
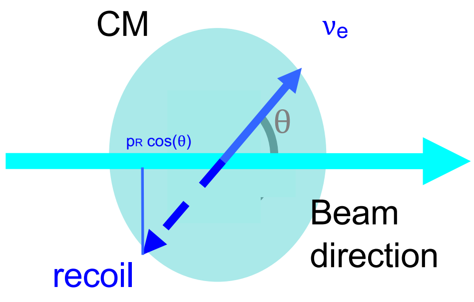
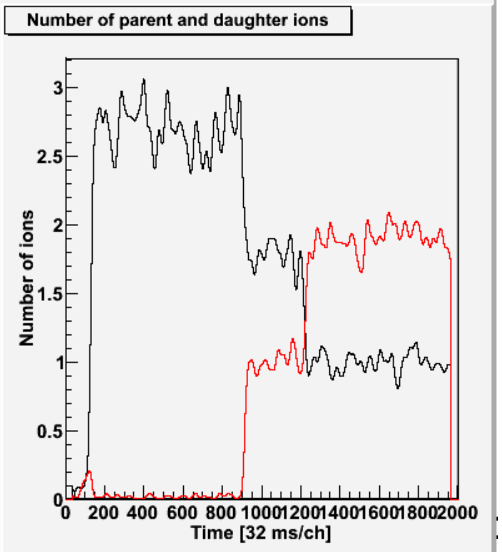


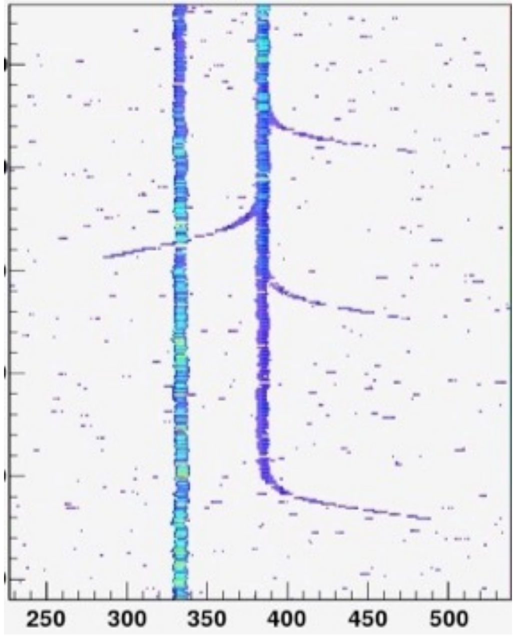


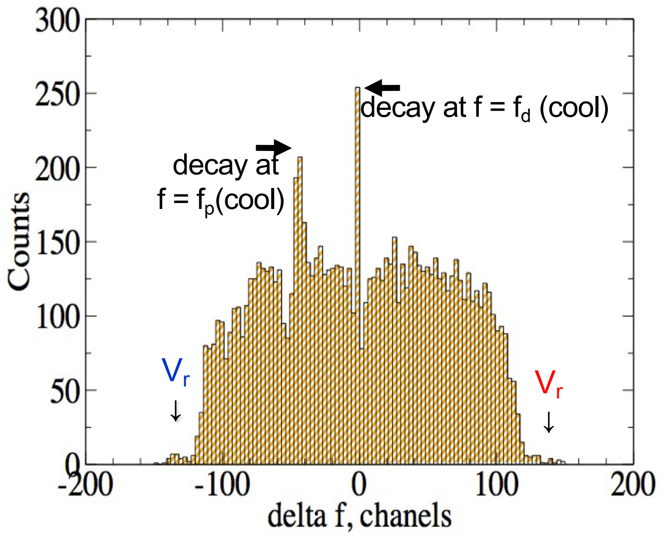






Revolution-frequency difference δf of the recoils just after decay





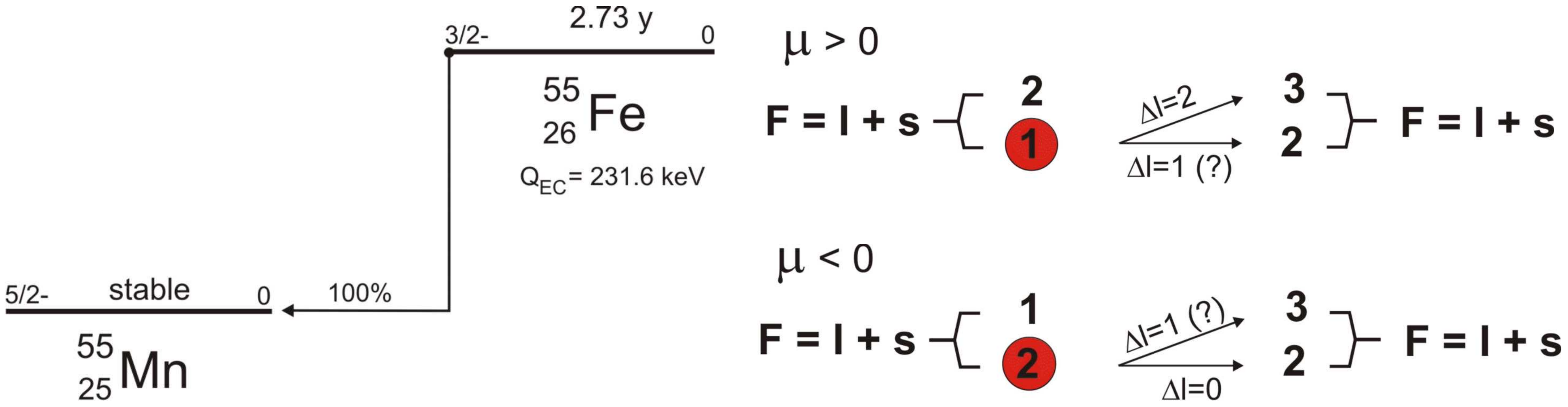
For a (longitudinally) unpolarized beam the distribution should have a rectangular shape

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

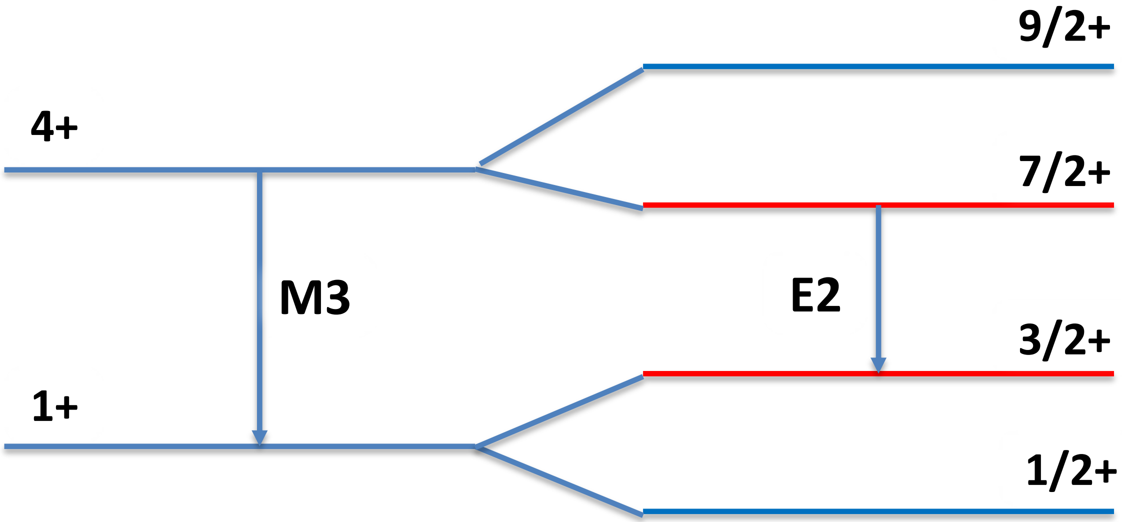
From v_r and m_r one gets the momentum of the (monochromatic) neutrino: $(pc)_d = m_d\, cv_d = (pc)_\nu$

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

What happens in hydrogen-like ^{55}Fe ?



Electromagnetic Transitions in Highly-Charged Ions



^{15}O(a,g)^{19}Ne reaction for the rp-process

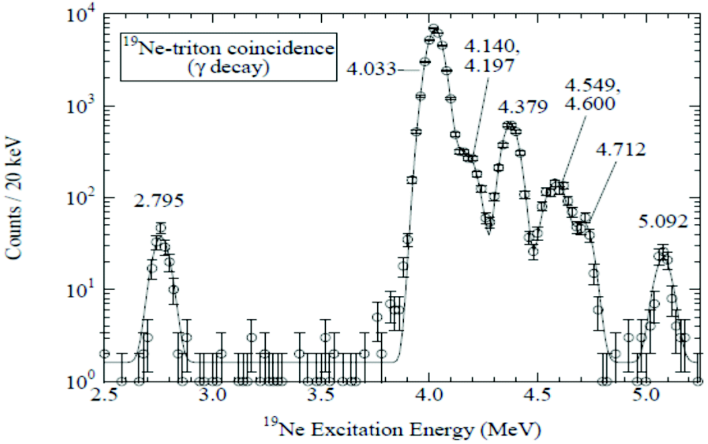
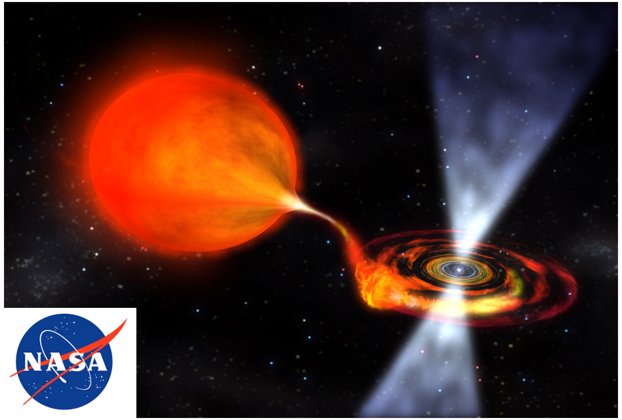


Figure 2: taken from Figure 7 in [10] which shows the selective population of the key resonance at 4.033 MeV excitation energy in ^{19}Ne using the ^{21}Ne(p,t) reaction.

Population of 4.033 MeV level in ^{19}Ne via (p,t) reaction on ^{21}Ne

Measure g and a branching ratio



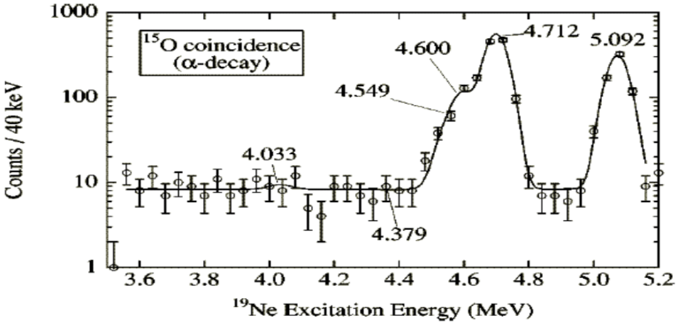
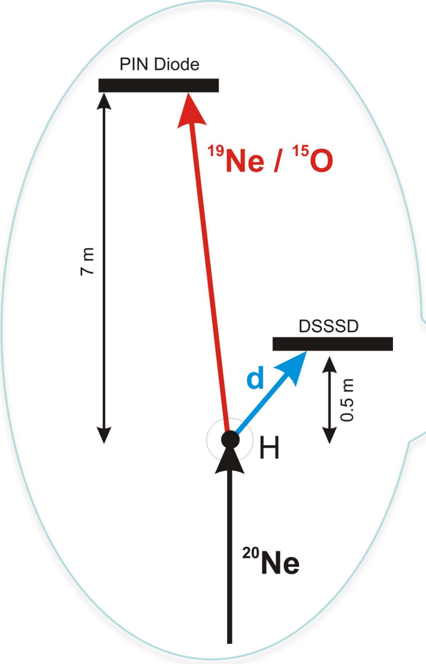
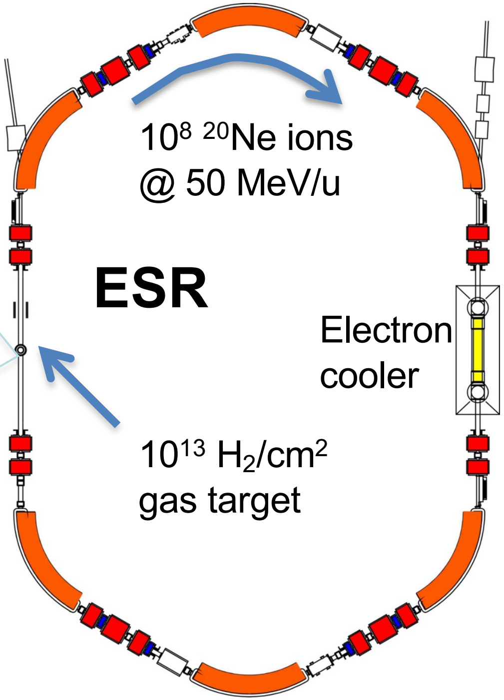


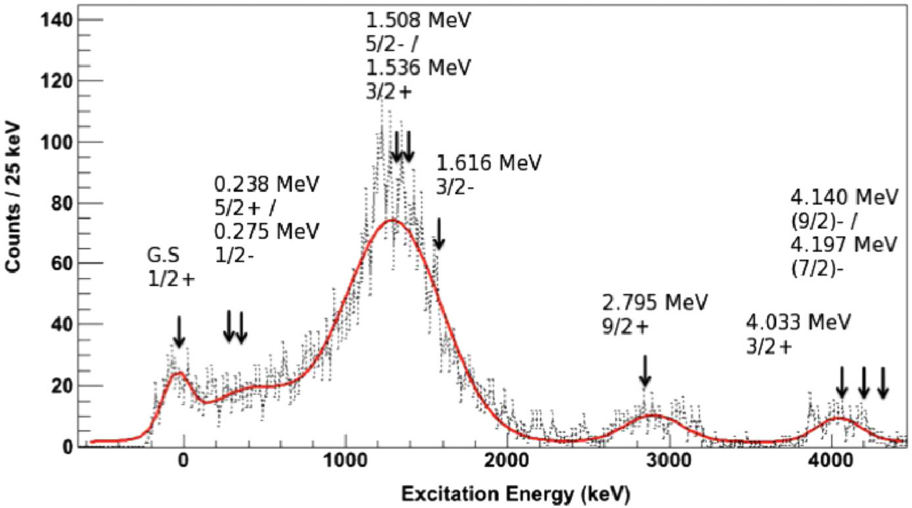
Figure 1: taken from Figure 9 of [10] showing the events corresponding to α-decaying resonances in ^{19}Ne. Note the flat background associated with fragmentation reactions on C atoms in the $(CH_2)_n$ target.

First transfer reaction measurement at the ESR



$^{20}Ne(p,d)^{19}Ne$ reaction





D. Doherty et al., Phys. Scr. T166 (2015) 014007

Experiment: 08-14 October 2012

Summary and Outlook

Electron capture decay can be employed to detection of spin orientation of a stored beam

Polarisation degree of freedom in radioactive decays of highly charged ions is largely unexplored

- **? Conservation of angular momentum / parity**
- **? Helicity of electron (anti)neutrino**
- **? Selection rules in electromagnetic transitions**

Vortex beams: Is there a time-dependent decay-rate?

Nuclear reaction rates: Enchancement/reduction due to the relative spin orientation; Addressing selected reaction channels