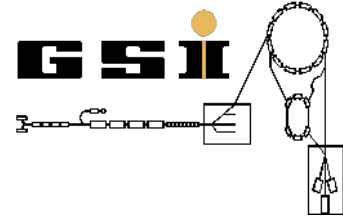


# Polarized Nuclear Physics Program at FAIR

HELMHOLTZ

RESEARCH FOR GRAND CHALLENGES

Yuri A. Litvinov



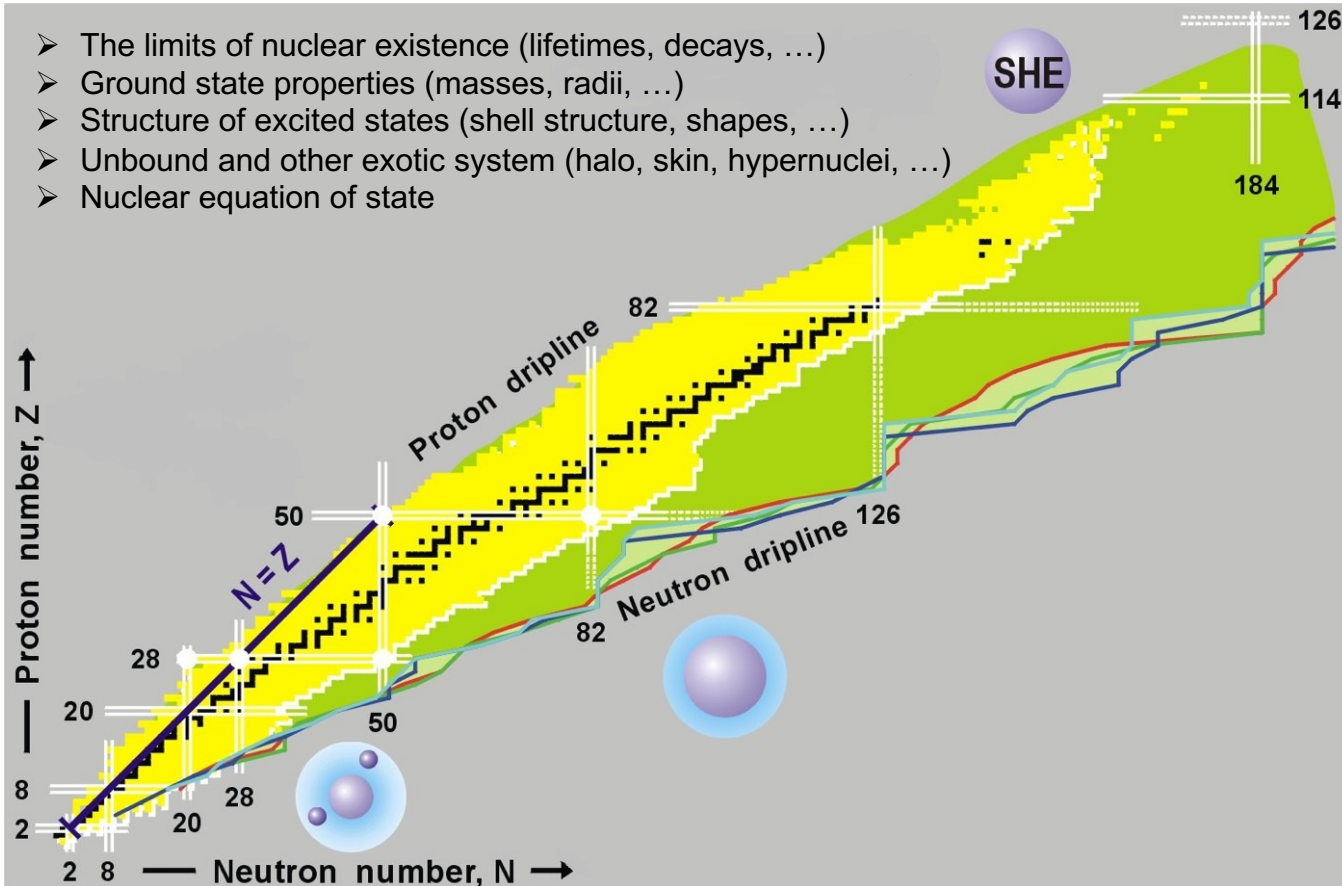
2<sup>nd</sup> PBT2026

Huizhou, China



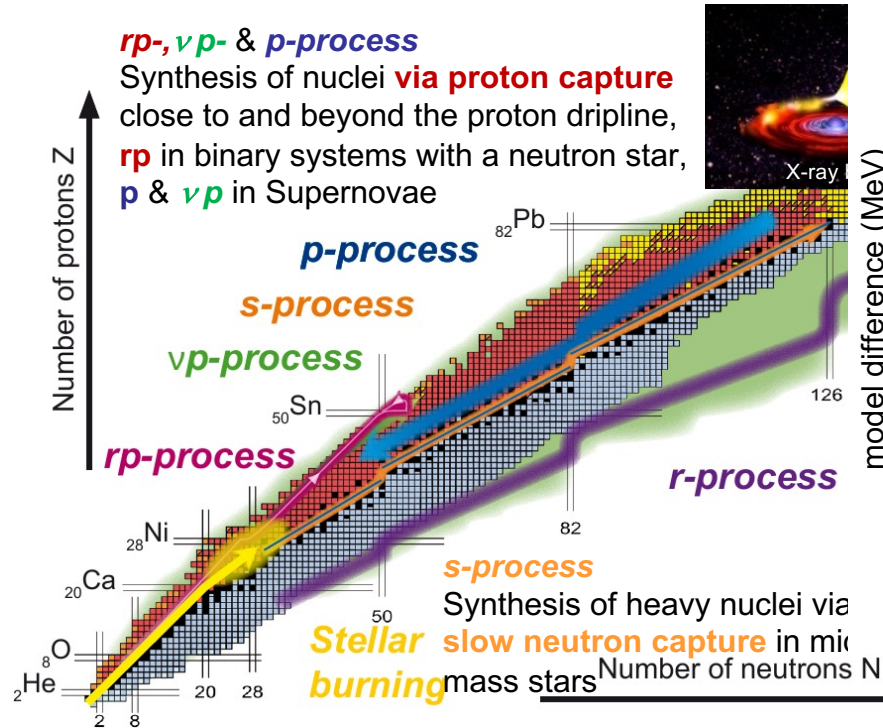
**2<sup>nd</sup> Workshop on Polarized Beam and Target – Physics and Applications**  
Institute of Modern Physics, Chinese Academy of Sciences, Huizhou Campus, China  
30 March – 3 April 2026

- The limits of nuclear existence (lifetimes, decays, ...)
- Ground state properties (masses, radii, ...)
- Structure of excited states (shell structure, shapes, ...)
- Unbound and other exotic system (halo, skin, hypernuclei, ...)
- Nuclear equation of state

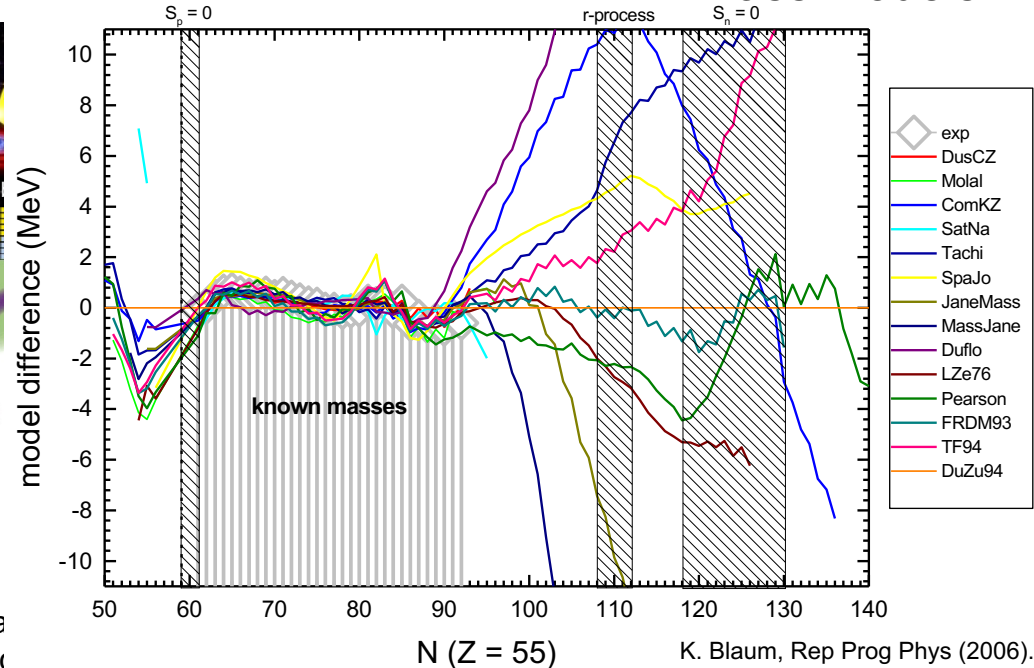


# Nuclear astrophysics: The origin of elements

Measurements in the laboratory: Mass, lifetime, decay channels, structure of very rare (neutron- or proton-rich) nuclei far from the valley of stability



## Mass models



# NUSTAR - The Experiments/sub-collaborations

<b>Super-FRS</b>	Production, separation, and identification of radioactive ion beams (RIB)
<b>HISPEC/ DESPEC</b>	In-beam $\gamma$ -spectroscopy at low and intermediate energy, high-resolution $\gamma$ -, $\beta$ -, $\alpha$ -, p- spectroscopy and n-decays
<b>MATS</b>	In-trap mass measurements and decay studies
<b>LaSpec</b>	Laser spectroscopy
<b>R<sup>3</sup>B</b>	Kinematically complete reactions with relativistic radioactive beams
<b>ILIMA</b>	Large-scale scans of mass and lifetimes of nuclei in ground and isomeric states and in highly charged ions
<b>Super-FRS EC</b>	High-resolution spectrometer experiments at the border line of nuclear, atomic and hadron physics
<b>SHE</b>	Synthesis and study of super-heavy elements
<b>ELISE(*)</b>	Elastic, inelastic, and quasi-free e <sup>-</sup> -A scattering
<b>EXL(*)</b>	Light-ion scattering reactions in inverse kinematics (dissolved and merged into ILIMA)

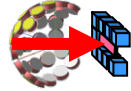
(\*) formally “beyond” MSV, but limited “operation” possible at **ESR/CR/HESR** within MSV

# Complementarity of NUSTAR experiments

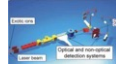
Super-FRS EC



HISPEC/DESPEC



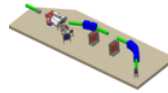
LASPEC



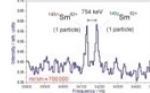
MATS



R3B



ILIMA



SHE



ELISE

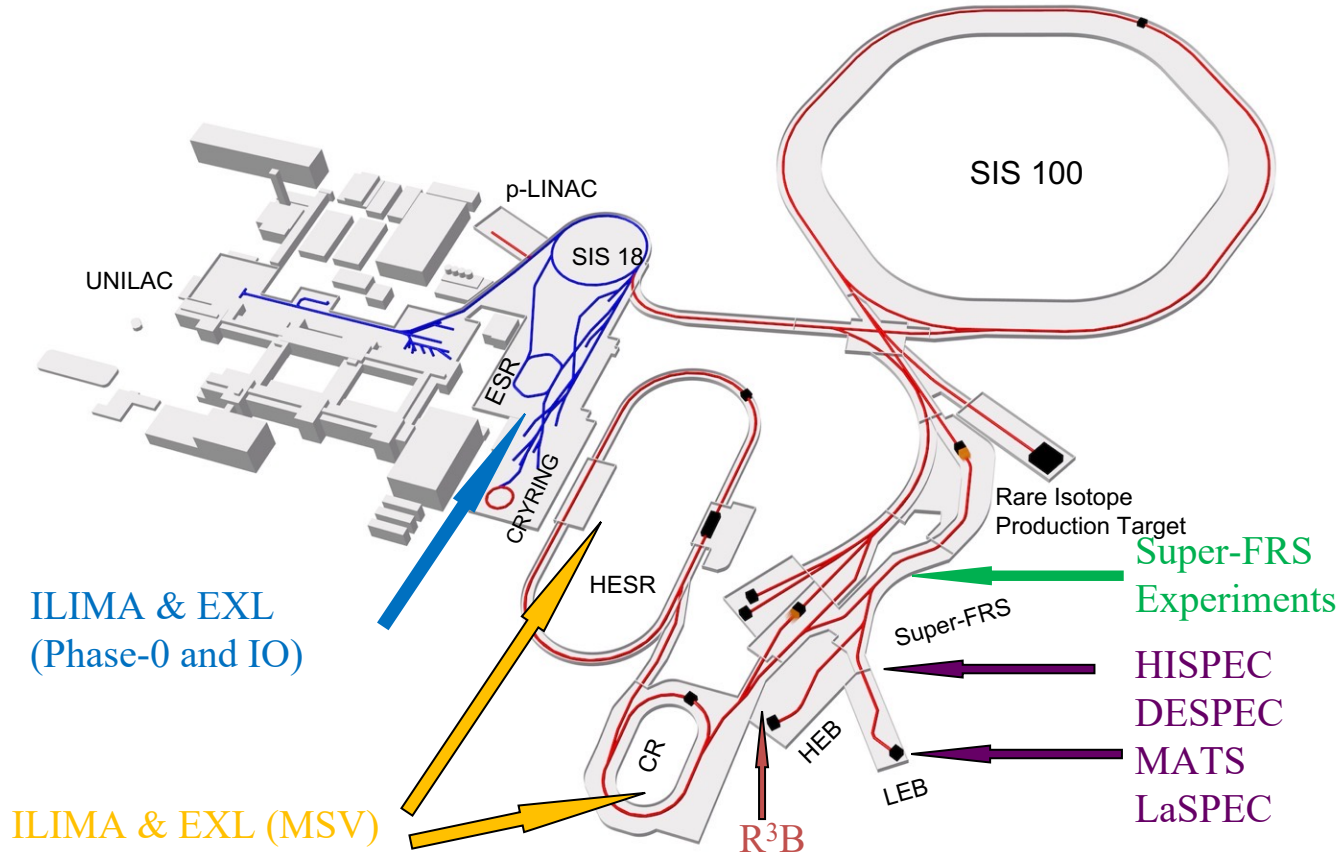


EXL

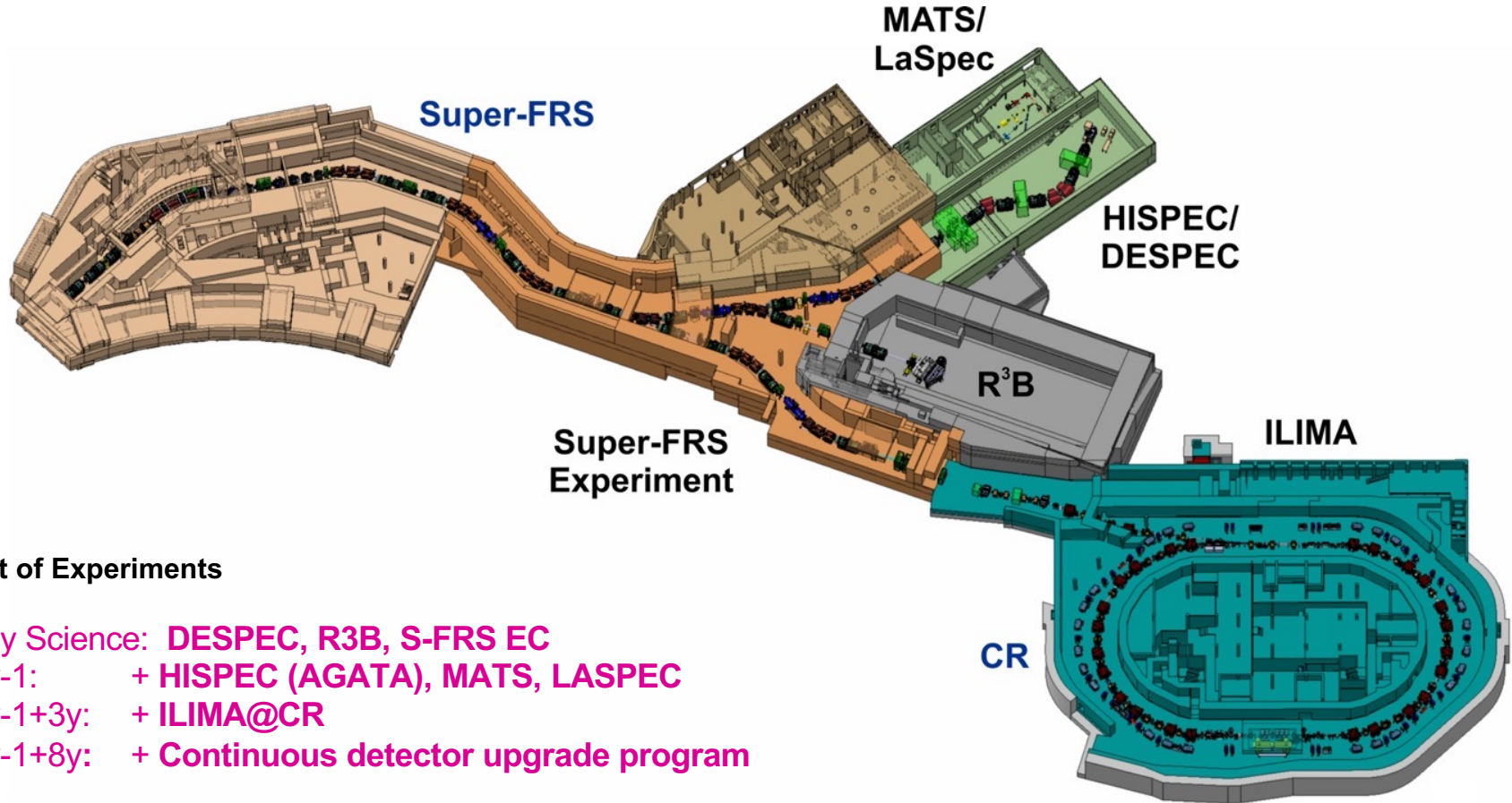


	Super-FRS EC	HISPEC/DESPEC	LASPEC	MATS	R3B	ILIMA	SHE	ELISE	EXL
<b>Masses</b>		Q-values, isomers		dressed ions, highest precision	unbound nuclei	bare ions, mapping study	precision mass of SHEs		
<b>Half-lives</b>	ps...ns-range	ground state and isomers $\mu$ s...s			resonance width, decay up to 100ns	bare ions, ms...years	$\mu$ s...days		
<b>Matter radii</b>	interaction x-section				interaction cross sections				matter density distribution
<b>Charge radii</b>	charge-changing cross sections		mean square radii		charge-changing cross sections			charge density distribution	
<b>Single-particle structure</b>	high resolution, angular momentum	high-resolution particle and $\gamma$ -ray spectroscopy	magnetic moments, nucl. spins	evolution of shell str., pairing int., valence nucl.	quasi-free knockout, short-range & tensor correlations	evolution of shell closures, pairing corr.	shell structure of SHEs		low momentum transfers
<b>Collective behavior</b>		electromagnetic transition strength	quadrupole moments	halo structure	dipole response, fission	changes in deformation		electromagnetic transition strength	monopole resonance
<b>EoS</b>					polarizability, neutron skin			neutron skin	neutron skin, compressibility
<b>Exotic Systems</b>	bound mesons, hypernuclei, nucleon resonances	rare and exotic e.m. and particle decays			n-rich hypernuclei	exotic decay modes			

# Implementation of the NUSTAR experiments



# The Super-FRS facility for NUSTAR@FAIR



## Start of Experiments

Early Science: **DESPEC, R3B, S-FRS EC**

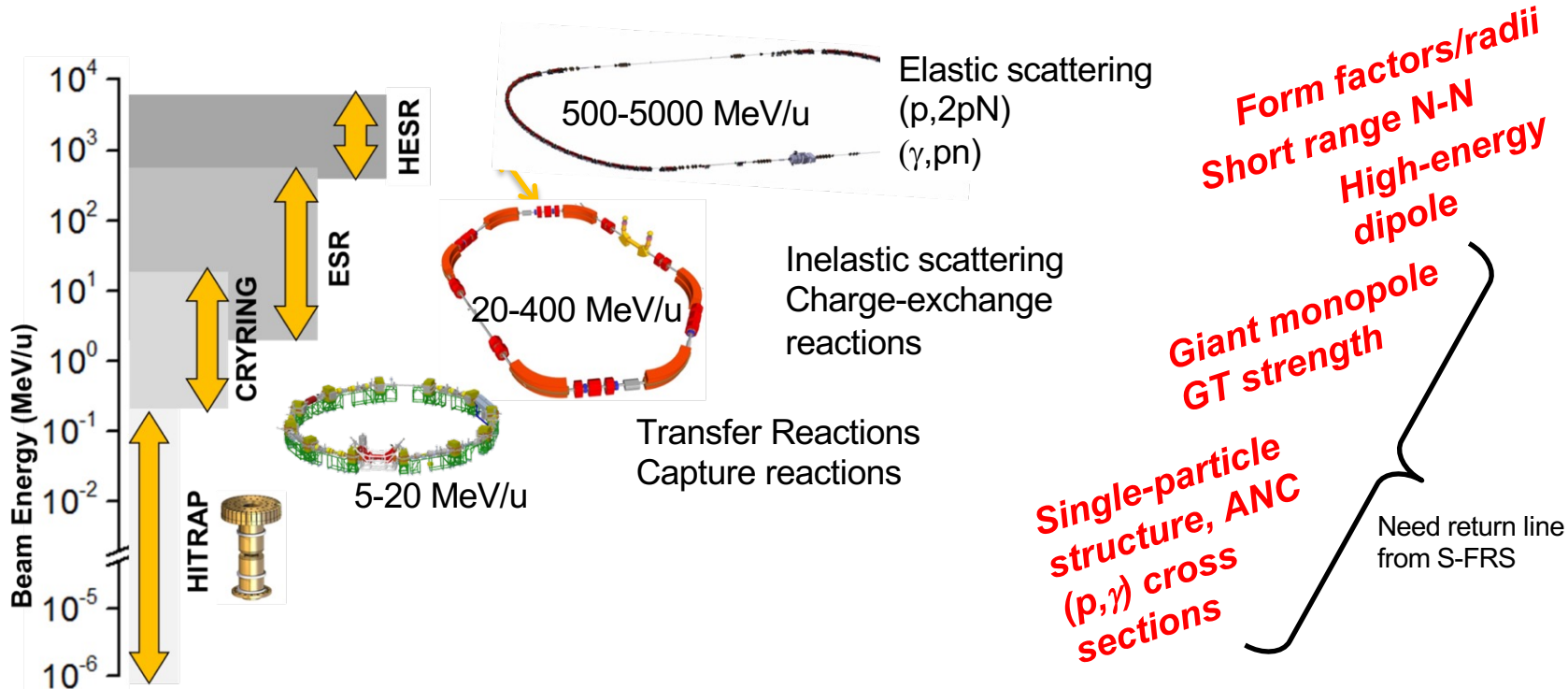
Day-1: + **HISPEC (AGATA), MATS, LASPEC**

Day-1+3y: + **ILIMA@CR**

Day-1+8y: + **Continuous detector upgrade program**

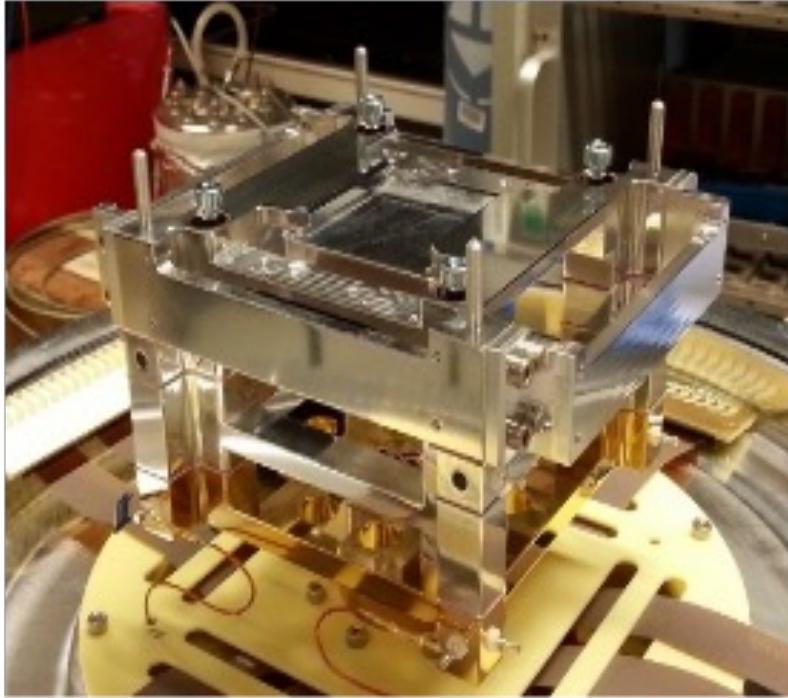
# Experiments with exotic nuclei using storage rings will broaden the physics program

FAIR uniqueness is largely based on storage rings



- Research at GSI storage and trapping facilities (bridge between SPARC and NUSTAR)

# Support of research inherited from FZJ (fusion, polarized targets, ...)

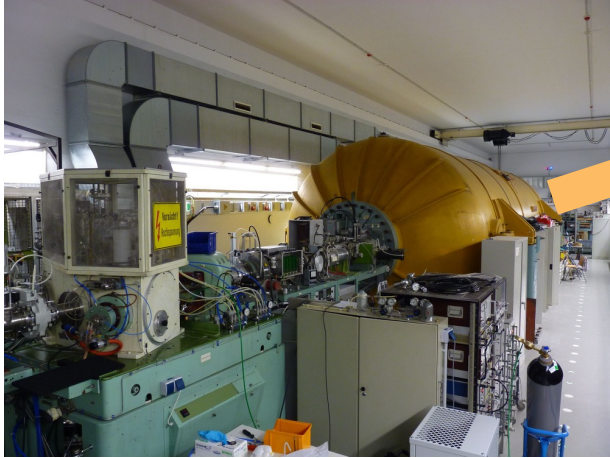


Semiconductor detectors

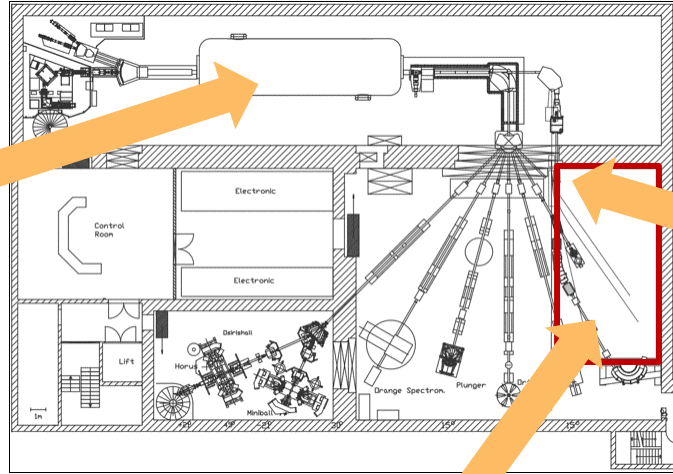


Polarized atomic targets

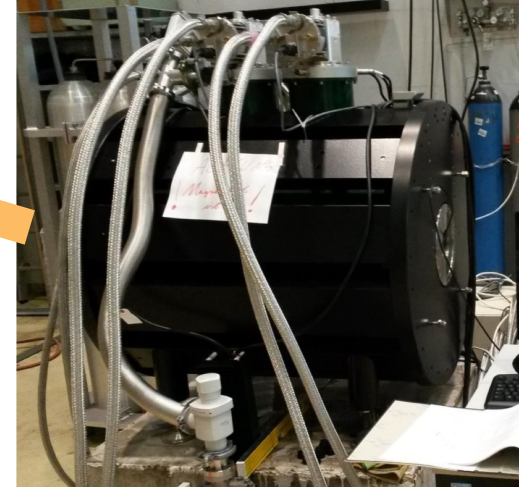
# Experiments at 10 MV Tandem at the University of Cologne



10 MV tandem at Uni Cologne



FFP experiment station

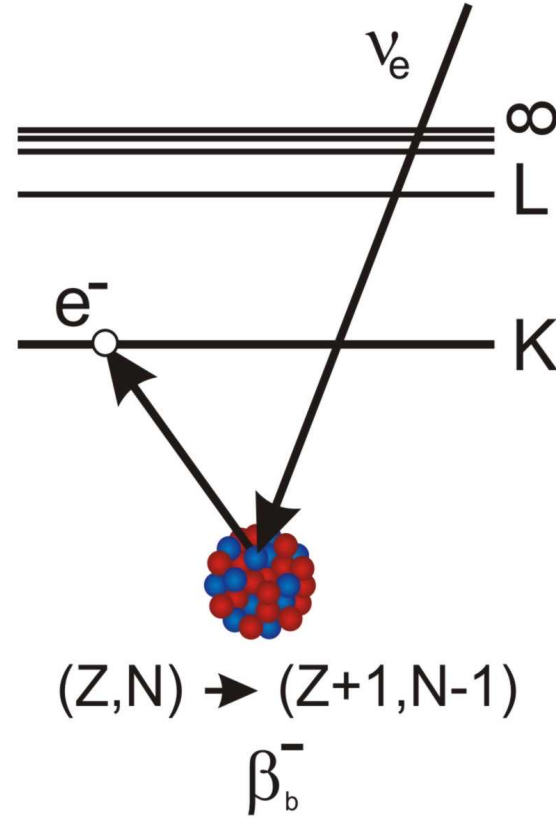
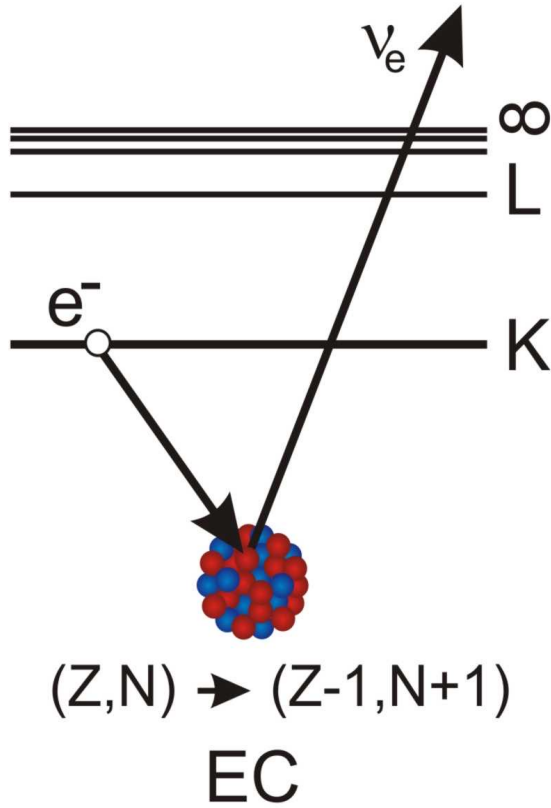


Superconducting solenoid

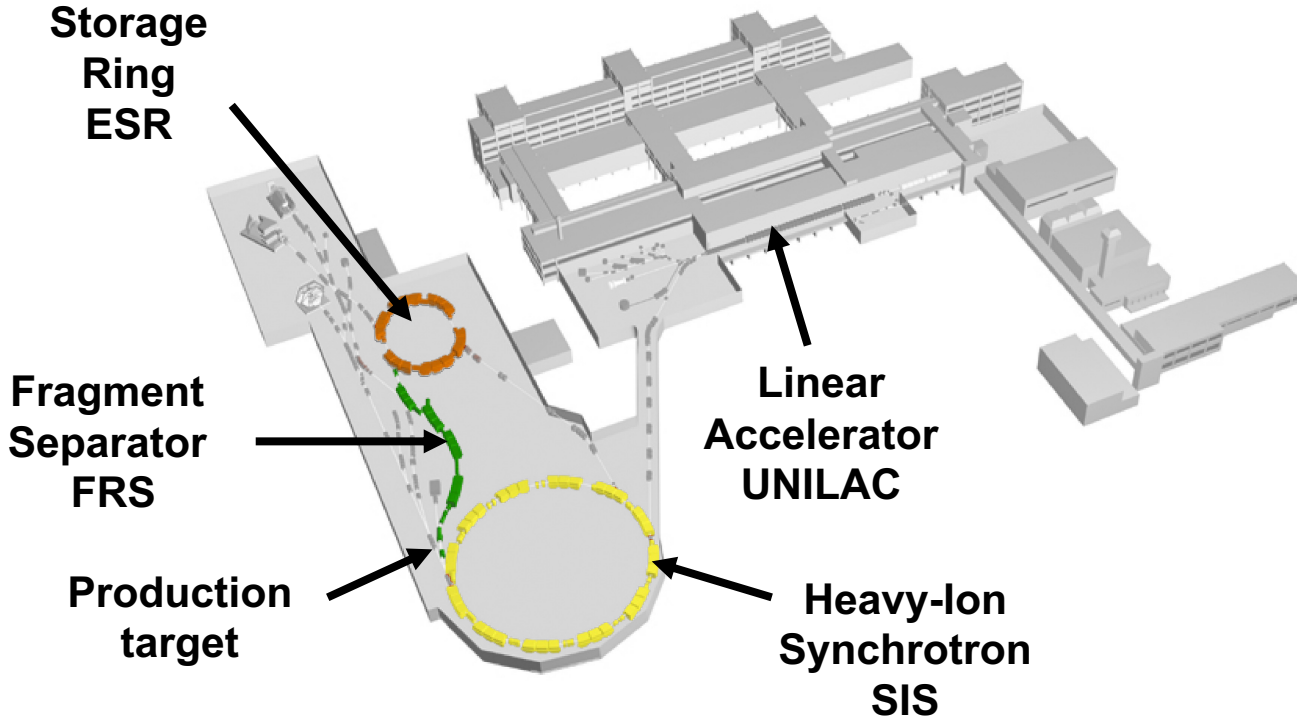
NUCLEAR INSTRUMENTS AND METHODS 150 (1978) 407-416 , © NORTH-HOLLAND PUBLISHING CO

**THE LAMB SHIFT POLARIZED ION SOURCE AT THE FN TANDEM  
VAN DE GRAAFF ACCELERATOR OF THE UNIVERSITY OF COLOGNE**

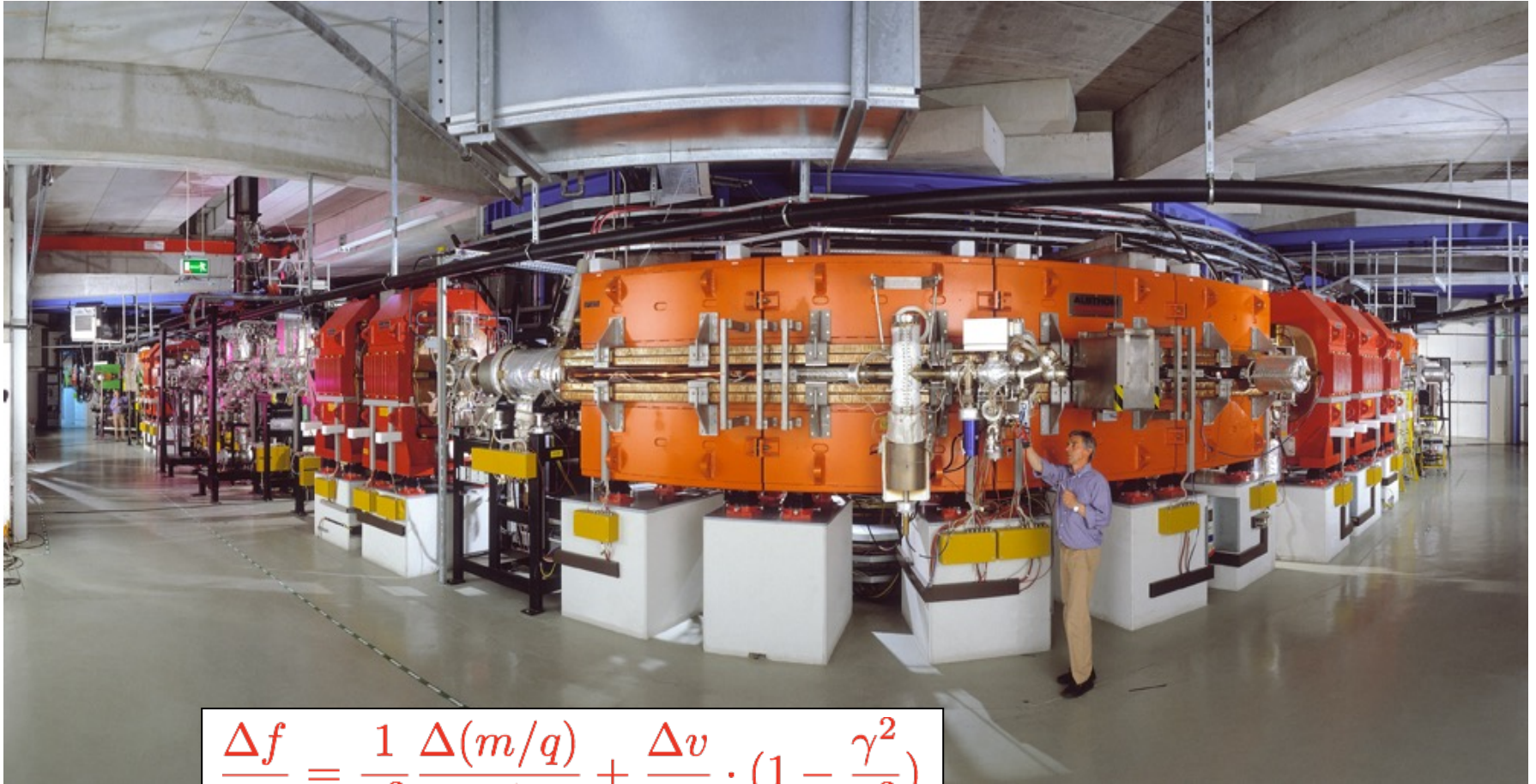
# Two-Body Beta Decay



# Secondary Beams of Short-Lived Nuclei



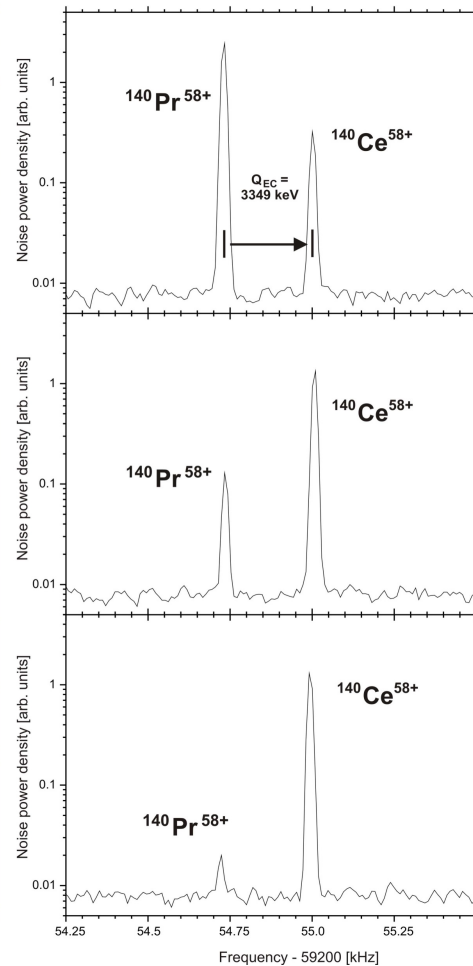
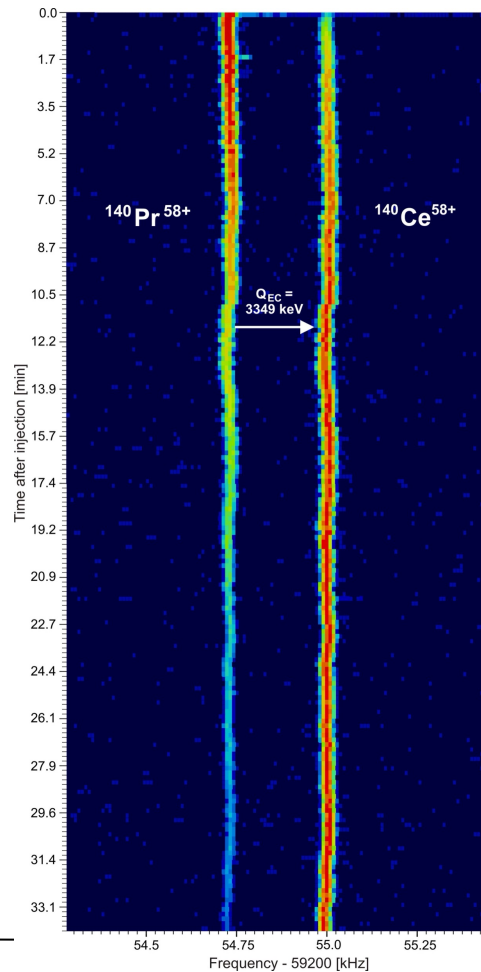
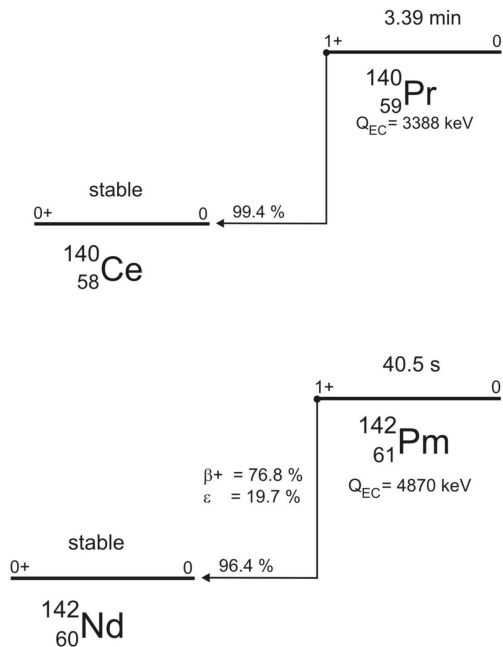
# ESR: The experimental Storage Ring



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

# Orbital Electron Capture Decay of Few-Electron Ions

## Allowed Gamow-Teller Transitions



# 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:

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

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

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

**Conclusion:**

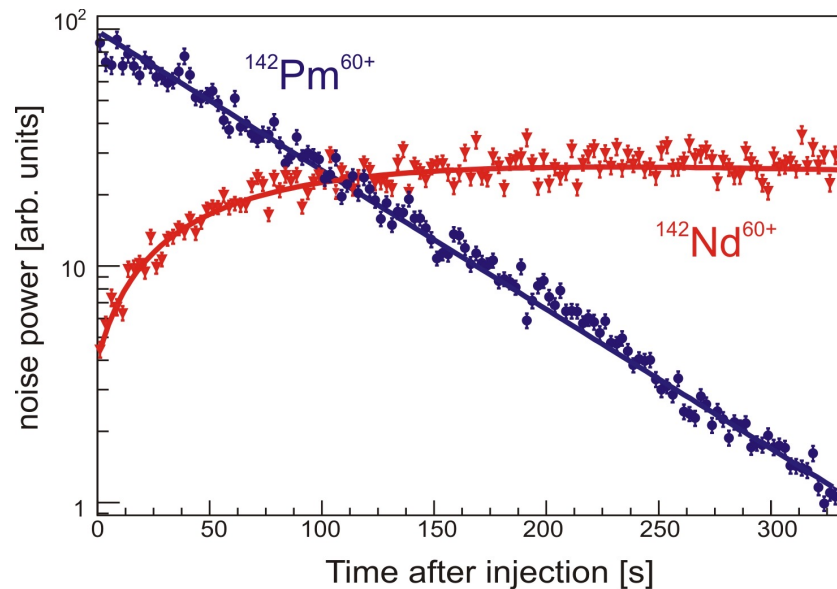
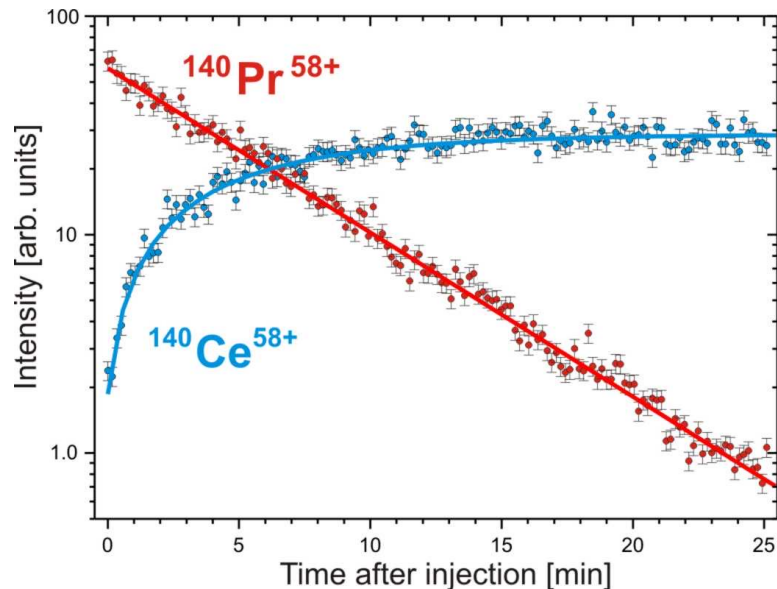
**H-Like ion should have 41%  
longer half-life**

$$\lambda_{EC}(\text{H-like})/\lambda_{EC}(\text{He-like}) \approx 0.5$$

# Orbital Electron Capture Decay of Few-Electron Ions

Expectations:

$$\lambda_{\text{EC}}(\text{H-like})/\lambda_{\text{EC}}(\text{He-like}) \approx 0.5$$



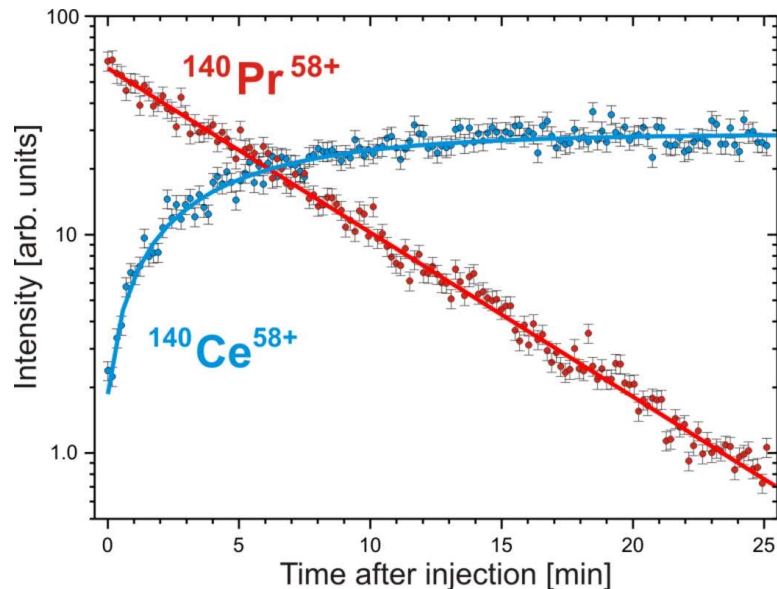
Yu.A. Litvinov et al., Phys. Rev. Lett. 99 (2007) 262501

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

# Orbital Electron Capture Decay of Few-Electron Ions

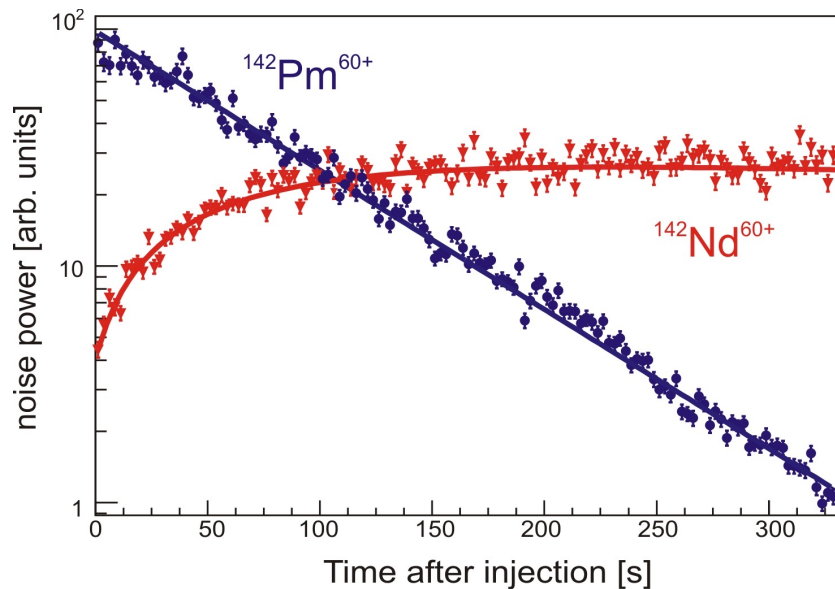
Expectations:

$$\lambda_{\text{EC}}(\text{H-like})/\lambda_{\text{EC}}(\text{He-like}) \approx 0.5$$



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

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

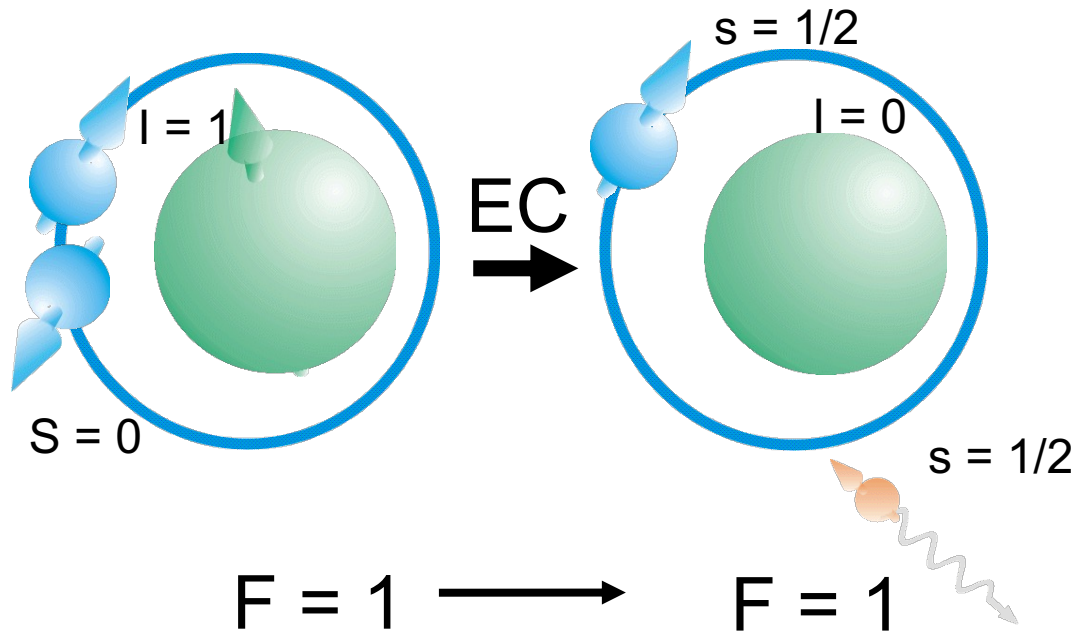
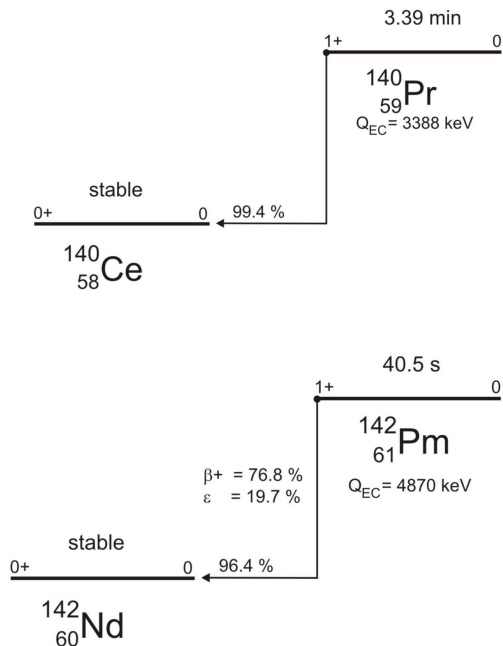


$$\lambda_{\text{EC}}(\text{H-like})/\lambda_{\text{EC}}(\text{He-like}) = 1.44(6)$$

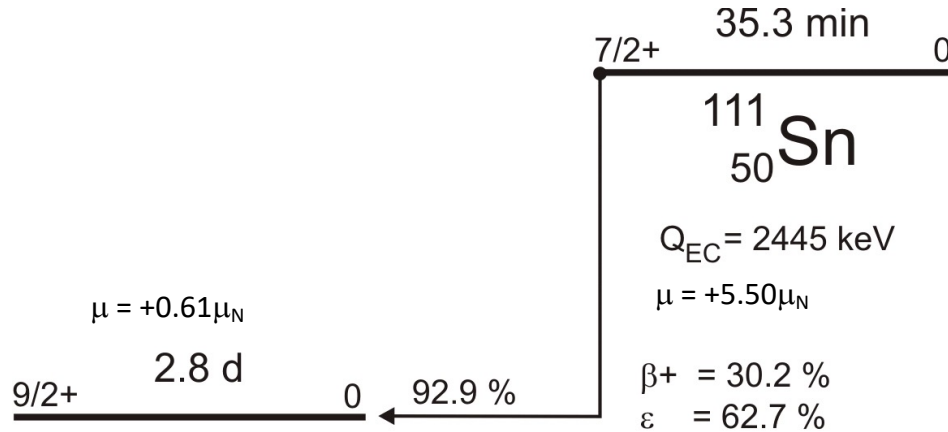
N. Winckler et al., Phys. Lett. B579 (2009) 36

# Orbital Electron Capture Decay of Few-Electron Ions

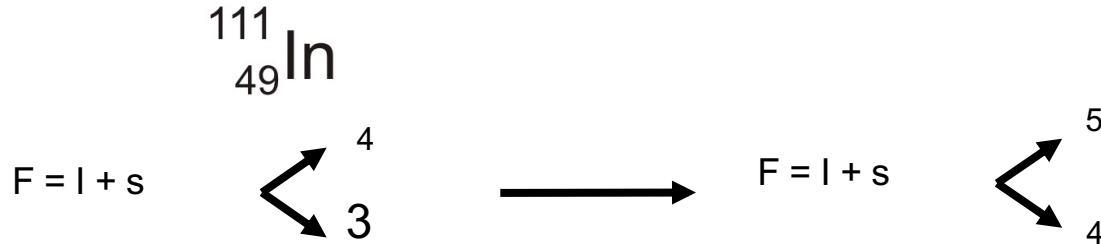
## Allowed Gamow-Teller Transitions



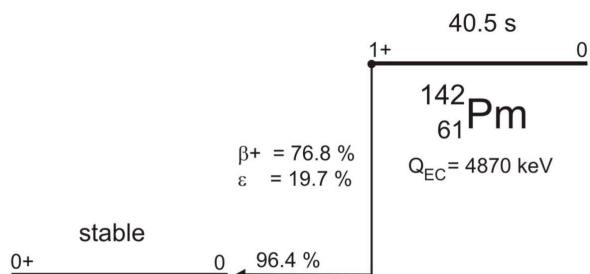
# What happens in $^{111}\text{Sn}$ ?



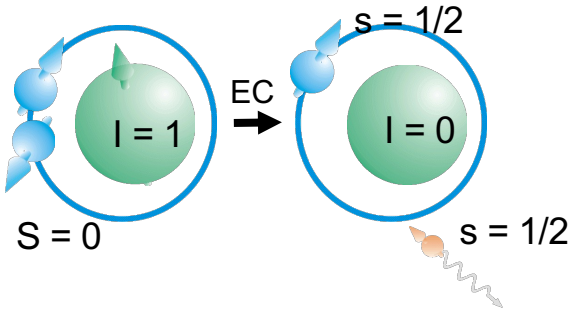
Electron screening in beta decay



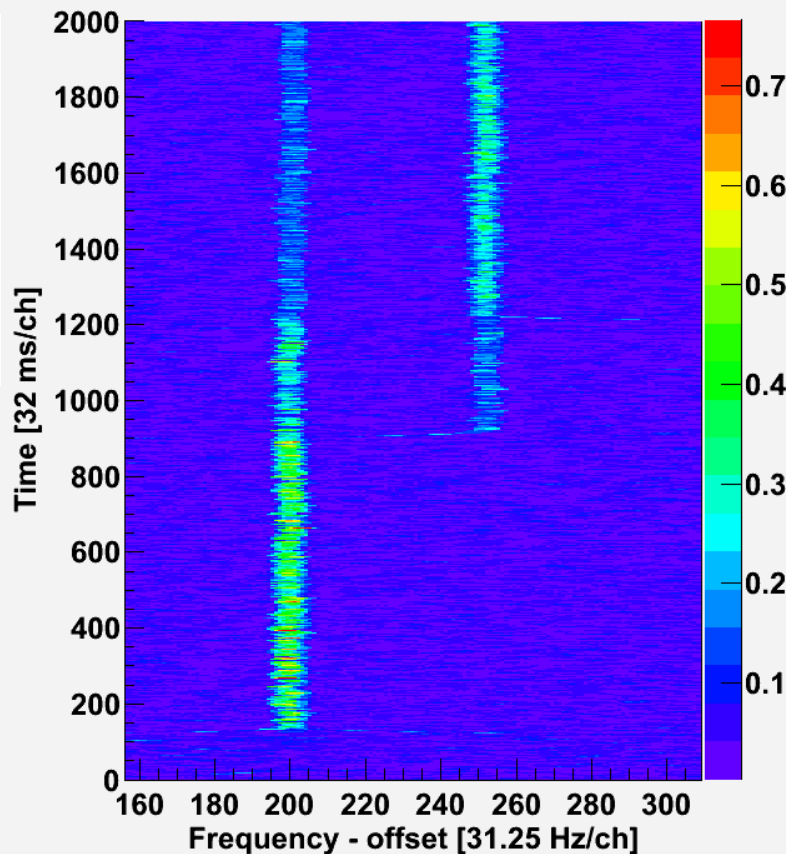
# Three Parent He-Like $^{142}\text{Pm}$ Ions



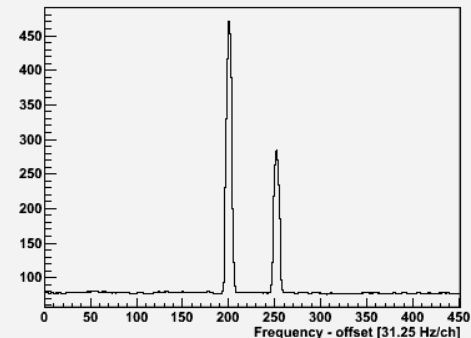
$^{142}_{60}\text{Nd}$



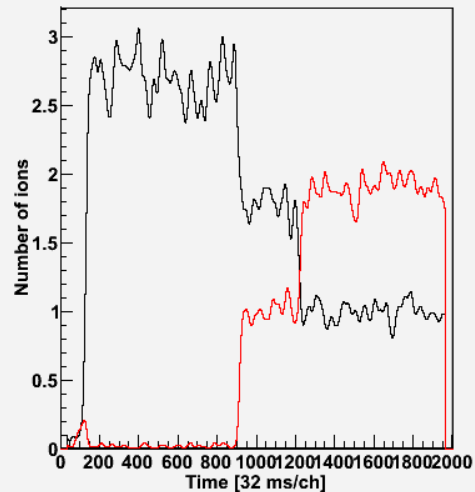
Time-resolved Schotky Spectrum



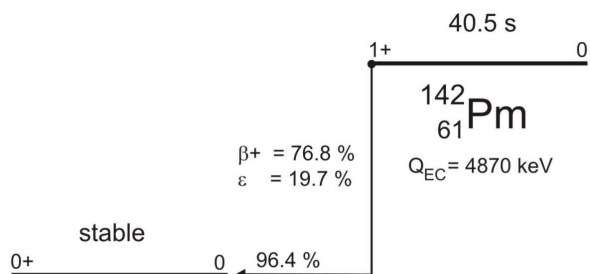
Projection



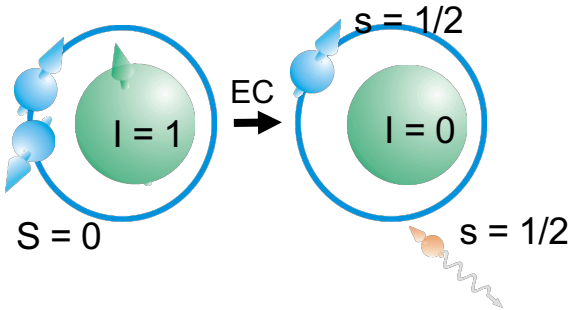
Number of parent and daughter ions



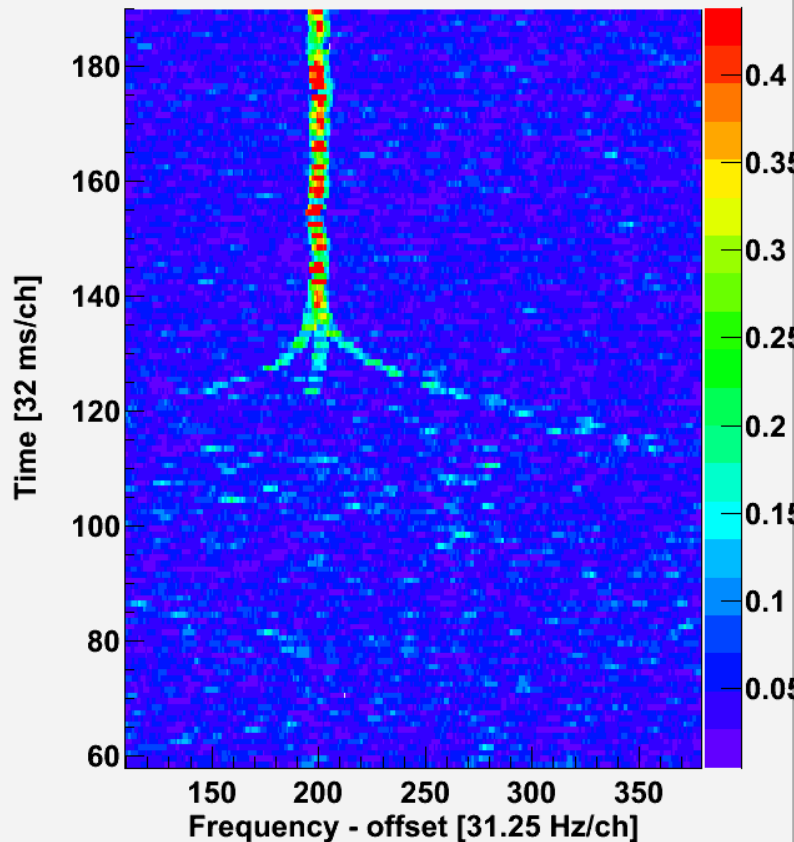
# Three Parent He-Like $^{142}\text{Pm}$ Ions



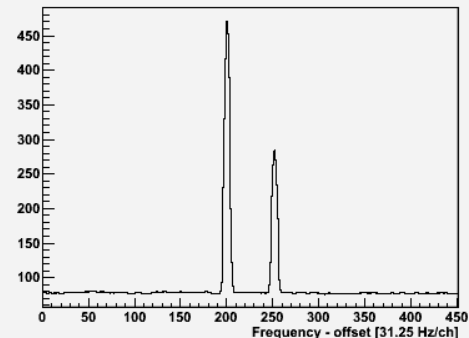
$^{142}_{60}\text{Nd}$



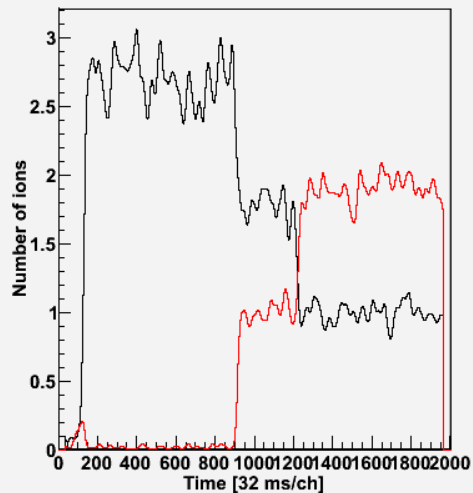
Time-resolved Schotky Spectrum



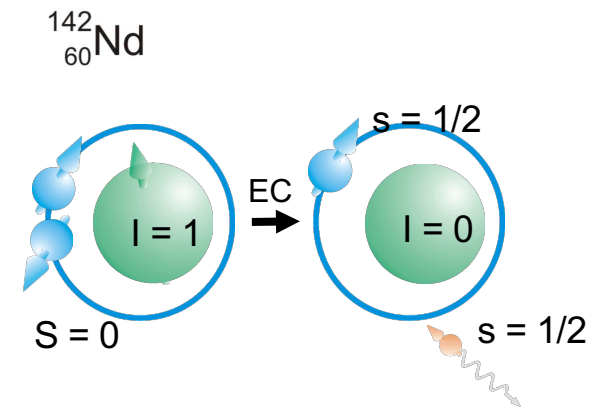
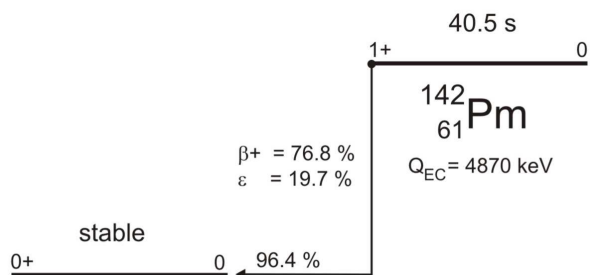
Projection



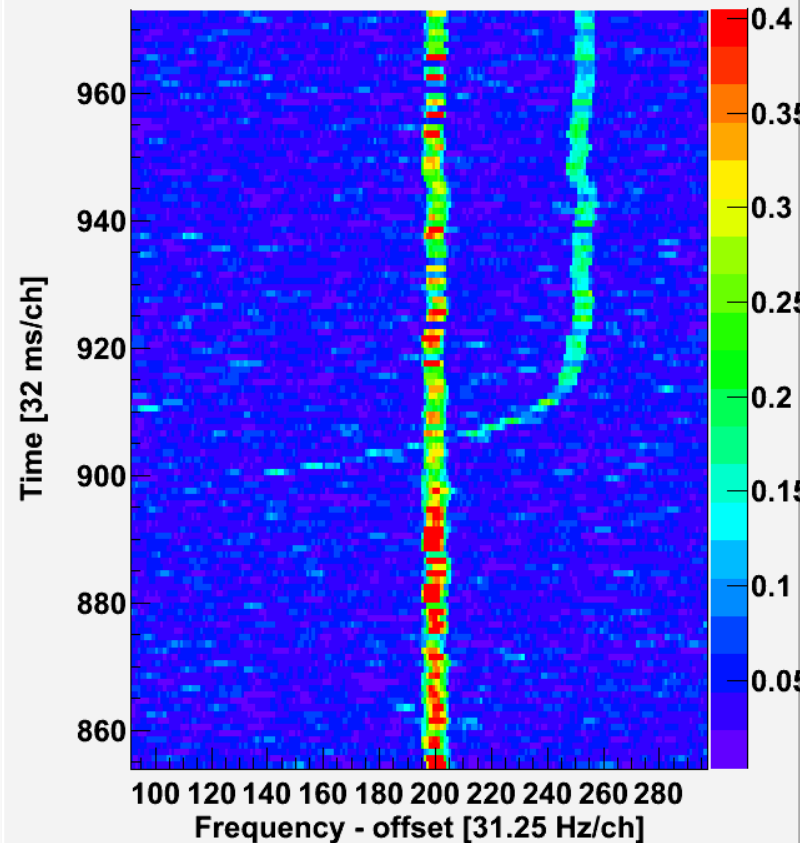
Number of parent and daughter ions



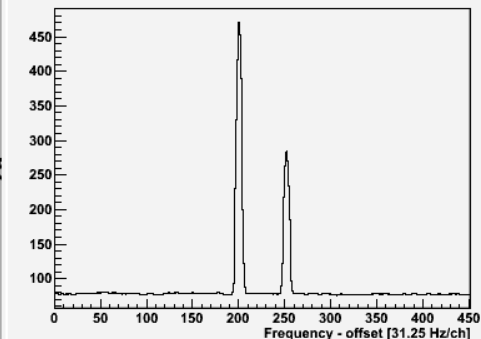
# Three Parent He-Like $^{142}\text{Pm}$ Ions



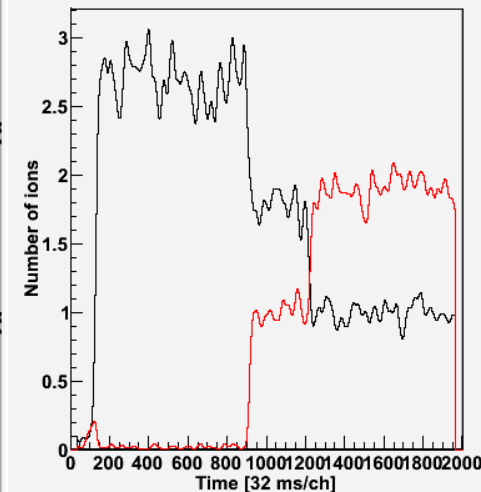
Time-resolved Schotky Spectrum



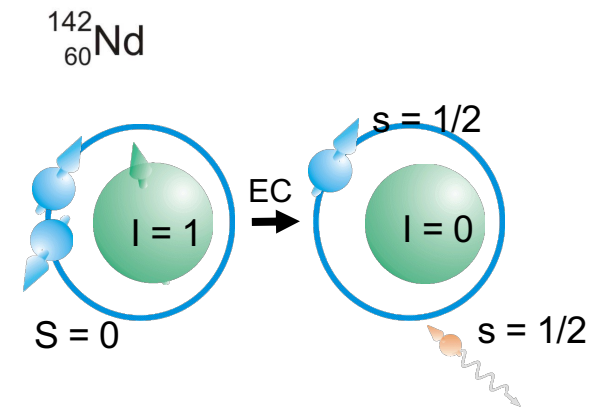
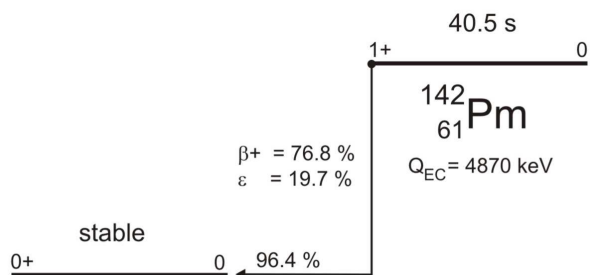
Projection



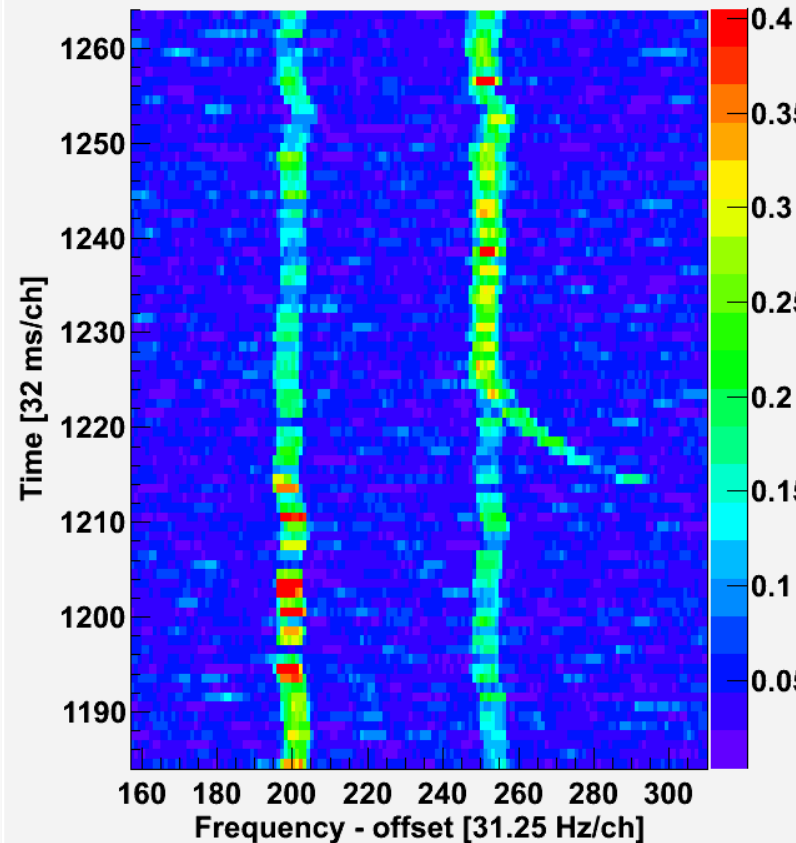
Number of parent and daughter ions



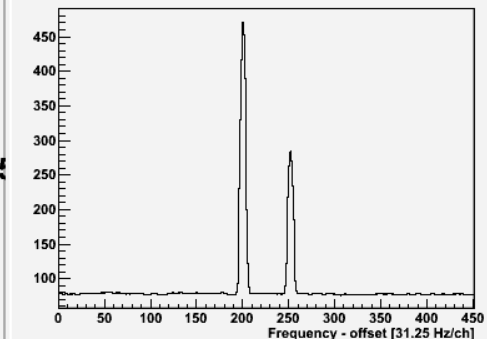
# Three Parent He-Like $^{142}\text{Pm}$ Ions



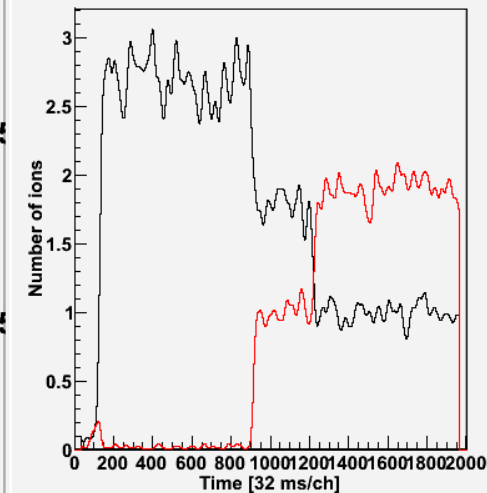
Time-resolved Schotky Spectrum



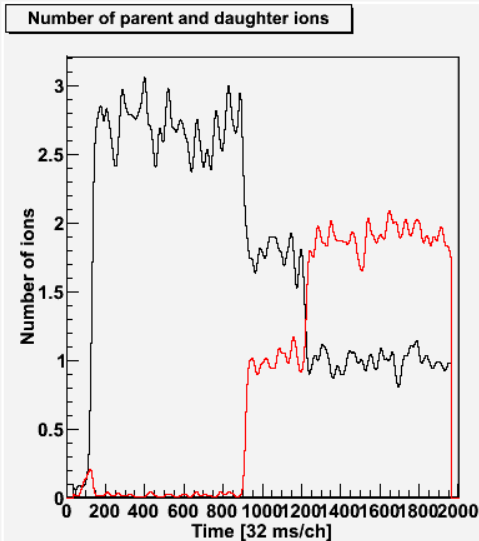
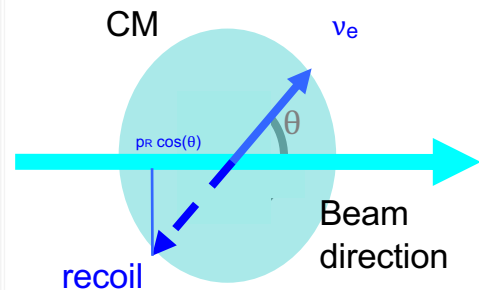
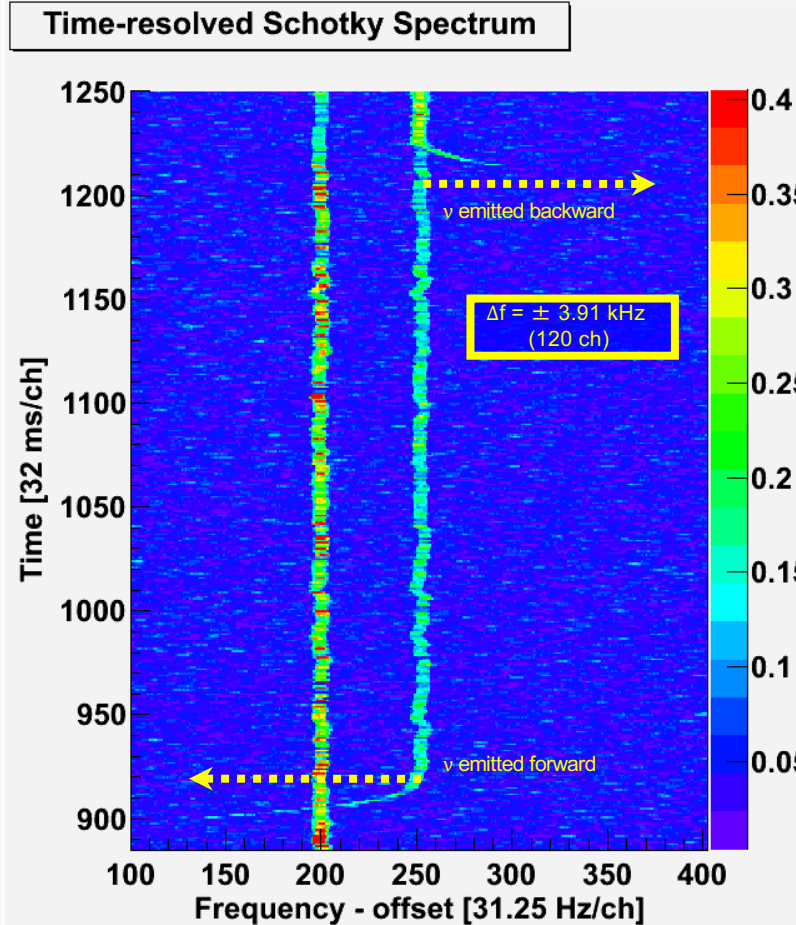
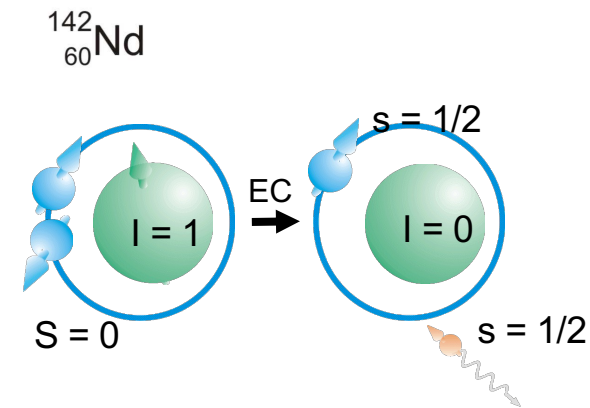
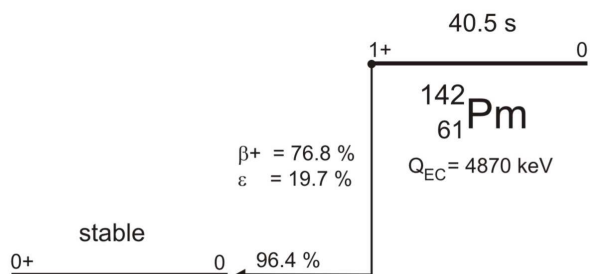
Projection



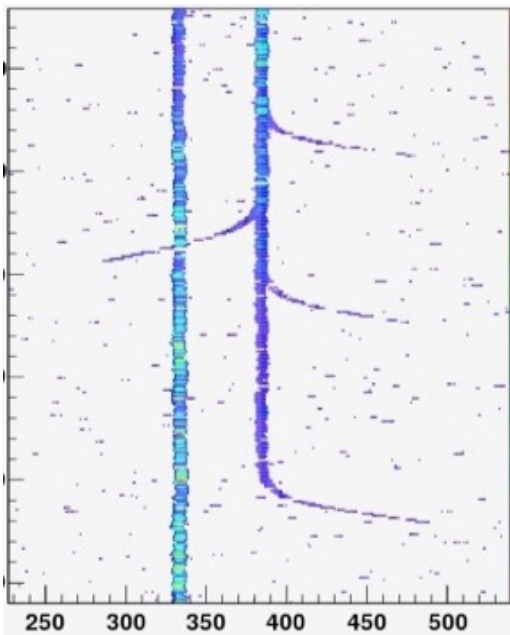
Number of parent and daughter ions



# Three Parent He-Like $^{142}\text{Pm}$ Ions

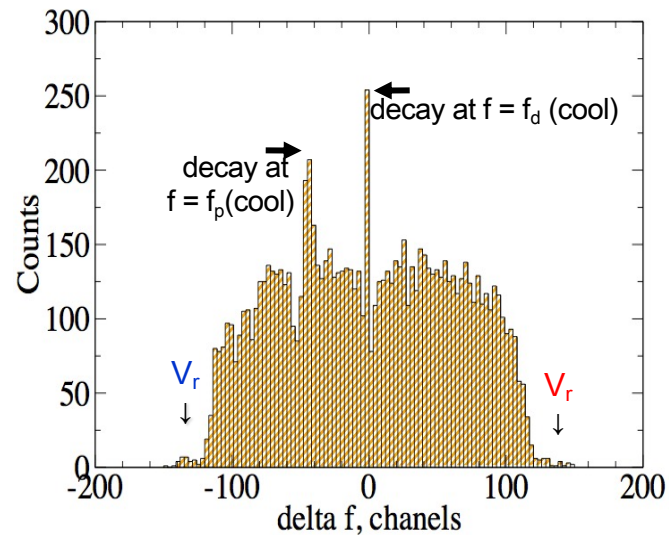


# Revolution-frequency difference $\delta f$ of the recoils just after decay



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

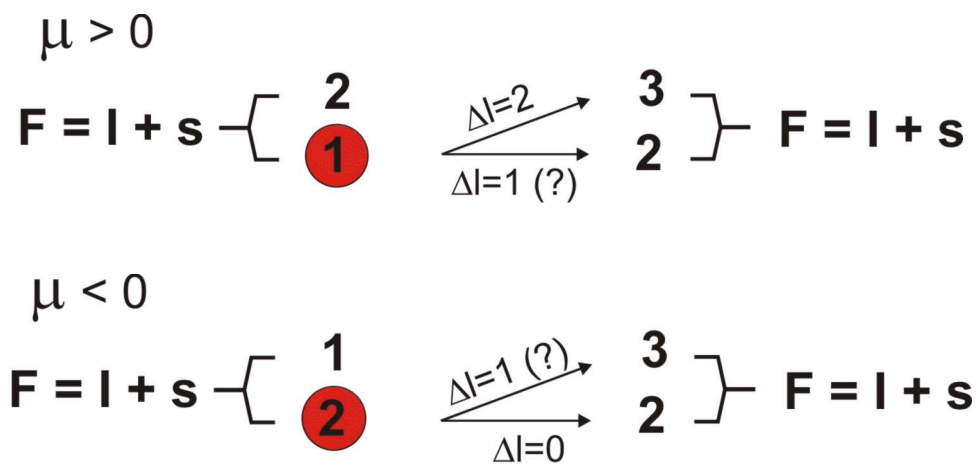
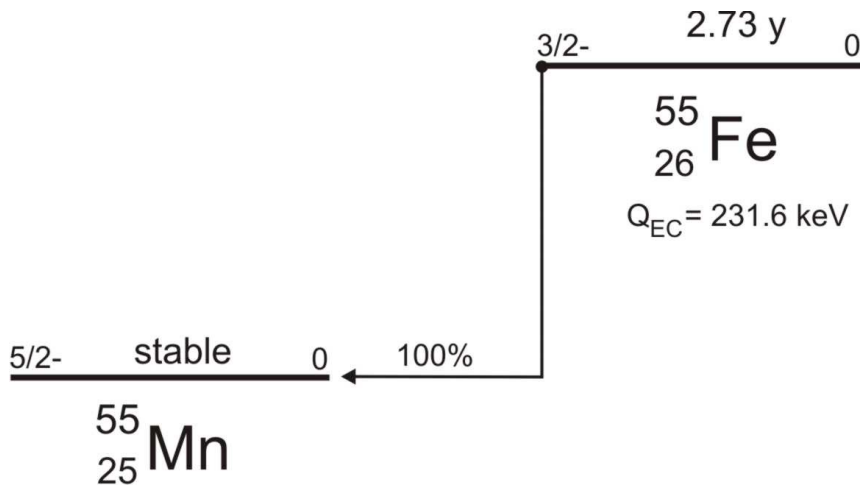
For a (steadily controlled) polarized beam the distribution would provide the helicity of the neutrino



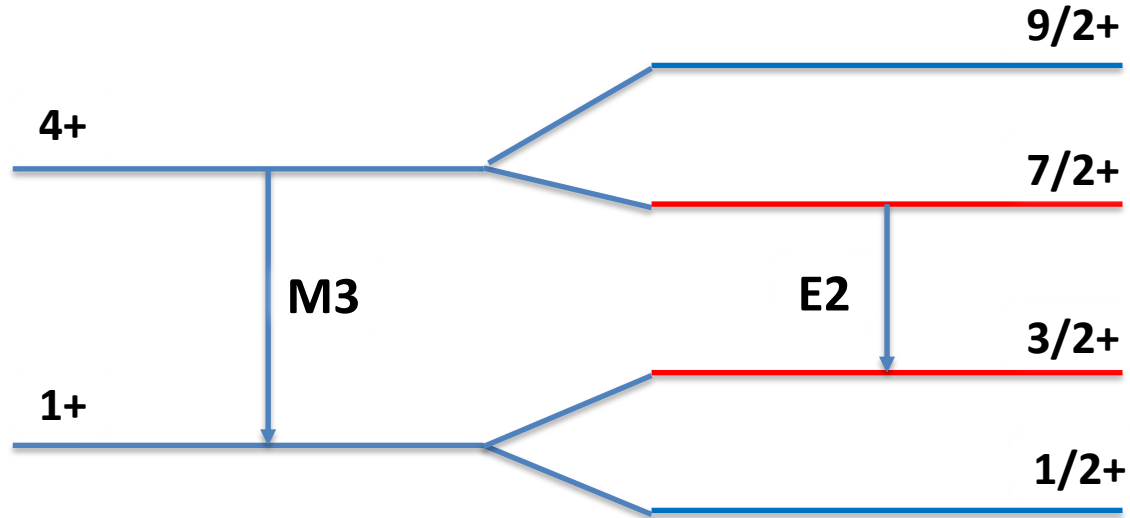
From  $v_r$  and  $m_r$  one gets the momentum of the (monochromatic) neutrino:  $(pc)_d = m_d cv_d = (pc)_v$

From  $m_p$  and  $m_d$  one gets its energy:  $E_v = (m_p - m_d) c^2$   
and then  $\beta_v = E_v / (pc)_v$

# What happens in hydrogen-like $^{55}\text{Fe}$ ?



# Electromagnetic Transitions in Highly-Charged Ions



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

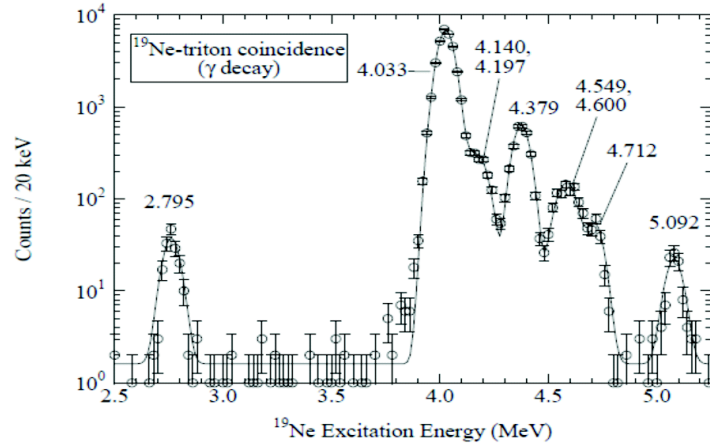


Figure 2: taken from Figure 7 in [10] which shows the selective population of the key resonance at 4.033 MeV excitation energy in  $^{19}\text{Ne}$  using the  $^{21}\text{Ne}(p,t)$  reaction.

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

Measure g and a branching ratio

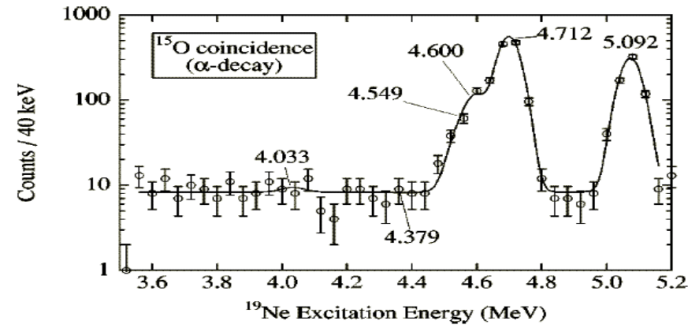
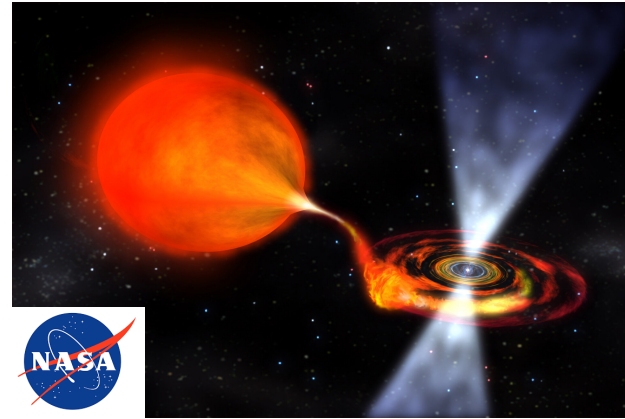
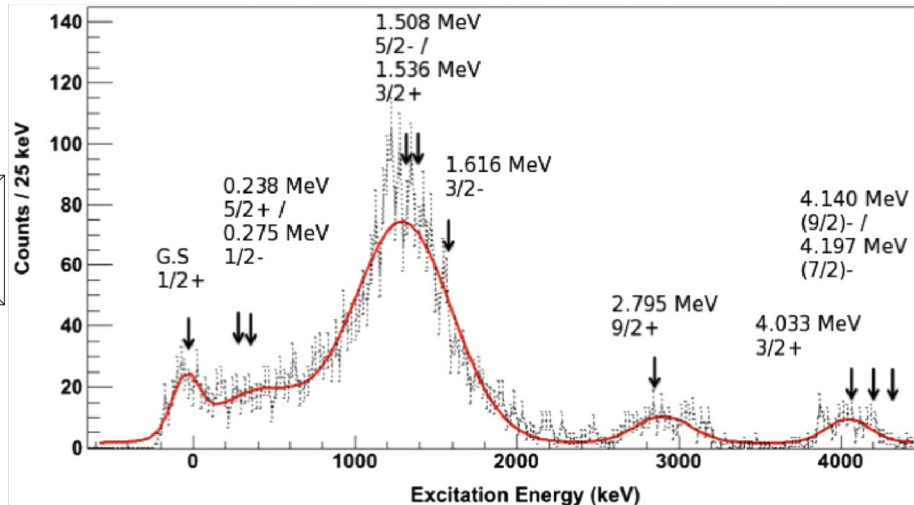
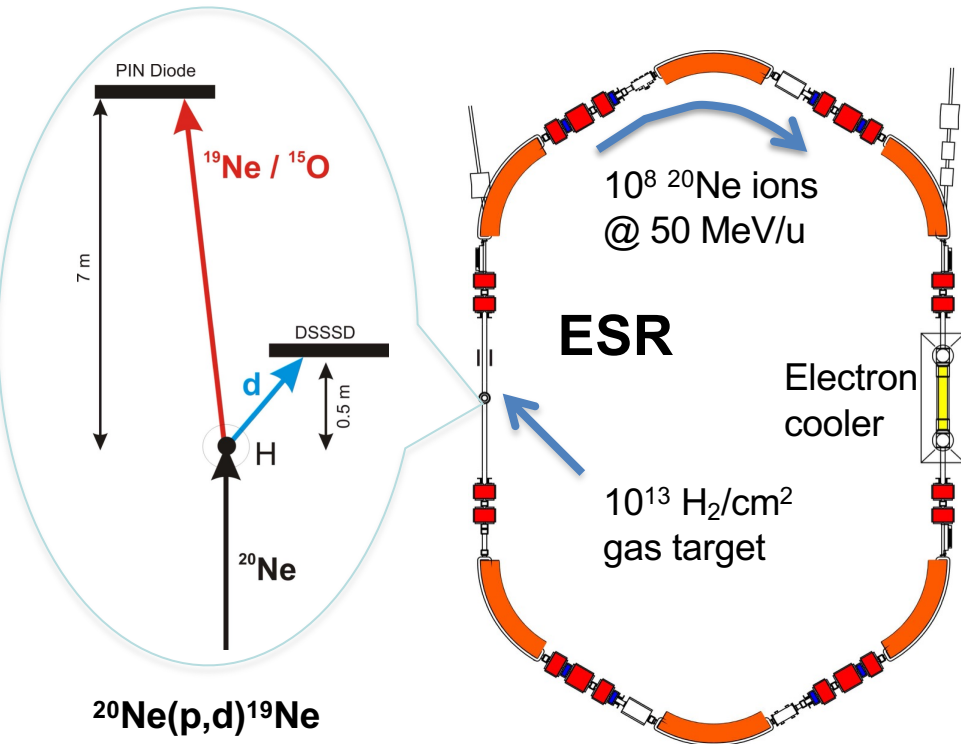


Figure 1: taken from Figure 9 of [10] showing the events corresponding to  $\alpha$ -decaying resonances in  $^{19}\text{Ne}$ . Note the flat background associated with fragmentation reactions on C atoms in the  $(\text{CH}_2)_n$  target.

# First transfer reaction measurement at the ESR



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: Enhancement/reduction due to the relative spin orientation;  
Addressing selected reaction channels