New Tilted-Foils Plus beta-NMR Setup at REX-ISOLDE. Polarized Nuclei for Nuclear and Solid-State Physics Experiments.

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and … the collaboration is open

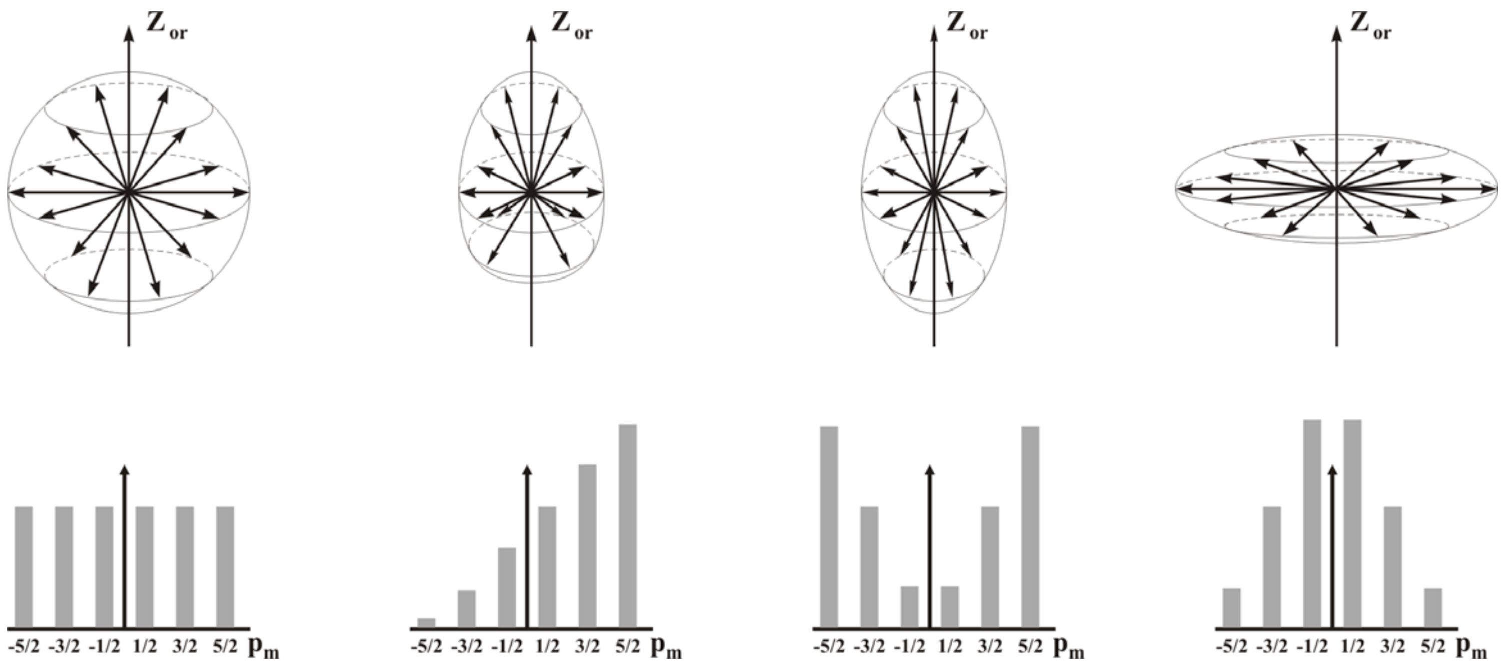
Outline

- Tilted Foil polarization up to now – few examples:
  - Atomic Polarization at Oblique Angles
  - Induced Nuclear Polarization : Multi-foils
  - Nuclear Polarization – Excited States (γ decay)
  - Quadrupole Moments (signs) – Isomeric States
  - Magnetic Moments – Ground States (β decay)
- Advantages of installing TF+β-NMR setup after REX
- Possibilities for Nuclear and Solid-state physics studies

Nuclear orientation – alignment vs. polarization

alignment

isotropic | polarization | prolate | oblate



$p_m = p_{m'}$ $\quad$ $p_m \neq p_{m'}$ $\quad$ $p_m = p_{m'}$

$for\ \forall\ m, m'$ $\quad$ $for\ \forall\ m = -m'$ $\quad$ $for\ \forall\ m = -m'$

→ β - decay

→ γ – ray detection

Atomic Tilted Foil Polarization

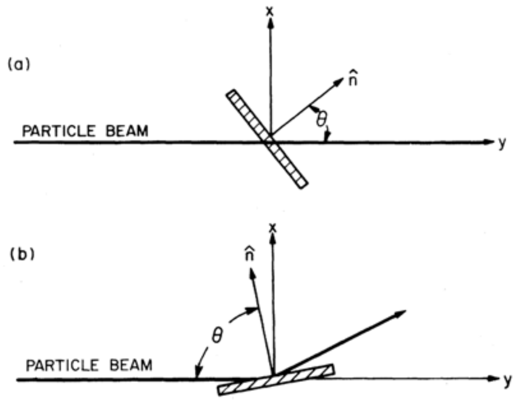


FIG. 1. Schematic illustrations of the experimental configuration: (a) Tilted-foil case. (b) Grazing-incidence case. Photons emitted in the $-z$ direction (out of the page) are detected.

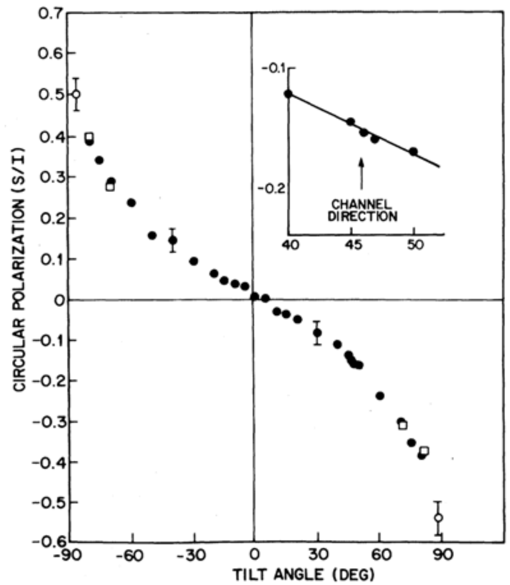


FIG. 2. Circular polarization, S/I, of He^+ ($n=4$ to $n=3$) at 468.6 nm as a function of tilt angle θ at a constant emerging energy of 530 keV for both grazing incidence with a silicon crystal (open circles), and for beam-foil transmission with a silicon crystal (solid circles), and a carbon foil (open squares). The inset shows the tilt-angle dependence of S/I in the vicinity of a low-index channeling direction with channeling critical angle of approximately 0.5°. The channeling direction was indicated by a factor of 5 decrease in backscattered yield.

used in the configuration shown in Fig. 1. The tilt angle θ, defined as the angle between the surface normal and the beam direction, was varied from $-80°$ to $+80°$. The measured polarization is expressed in terms of the three normalized Stokes parameters defined in the following standard way[18]:

$$S/I=(I_{RHC}-I_{LHC})/(I_{RHC}+I_{LHC}),$$
$$M/I=(I_0-I_{90})/(I_0+I_{90}), \qquad (1)$$
$$C/I=(I_{45}-I_{135})/(I_{45}+I_{135}),$$

T. Tolk et al. PRL47, 487 (1981)

Large circular polarization observed

- ~50%

(equivalent to a polarization of the atomic spins)

The polarization identified as a result of the ion-surface interactions (no bulk-effects influences)

Smooth behavior of the polarization, independently on the geometry (transmission or reflection)

From atomic to nuclear polarization

M. Hass et al. / Nuclear polarization 319

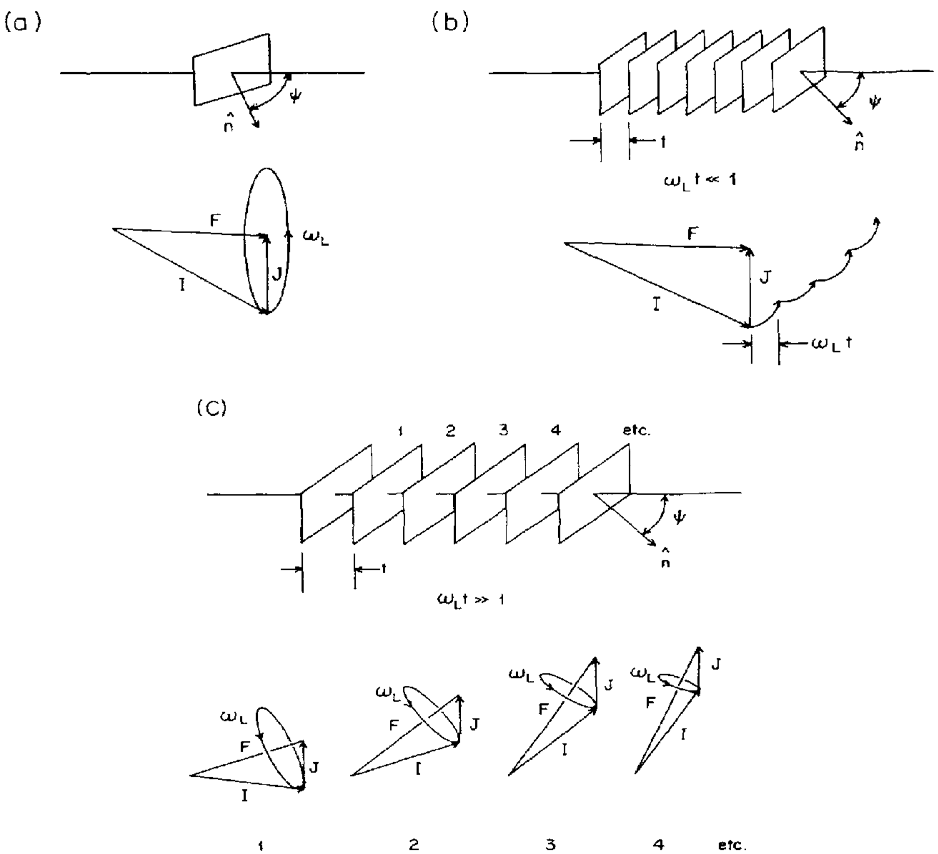


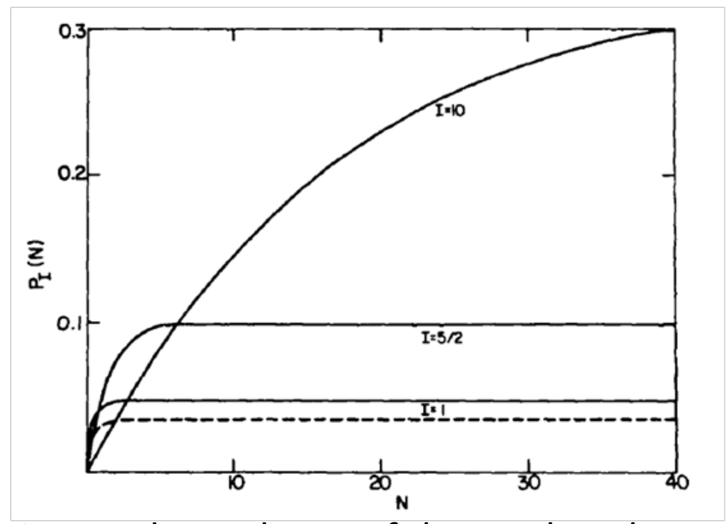
Fig. 1. (a) Hyperfine interaction following recoil from a tilted foil. *J* is shown polarized along the tilt axis at the time of exit from the foil. *I* has a random orientation. ω_L represents an average hyperfine frequency. (b) Cumulative nuclear spin rotation via the interaction with an array of tilted foils. *J* is reoriented along the tilt axis at each foil. (c) Multistep transfer of polarization to *I* by a multifoil array.

M. Hass et al., NPA 414, 316 (84)

- coupling of the electron (J) and the nuclear (I) spins
- interaction of total spin F with the magnetic field of the electrons (ω_L)
- "rotation regime" ($\omega_L\tau$<<1)

PRL 38, 218 (1977)

- "polarization transfer regime" $\omega_L\tau$>>1



Strong dependence of the total nuclear polarization on the nuclear spin I and the number of the foils:

- faster "saturation" at lower I (fewer foils needed)
- higher polarization level at higher I

Nuclear polarization of excited states

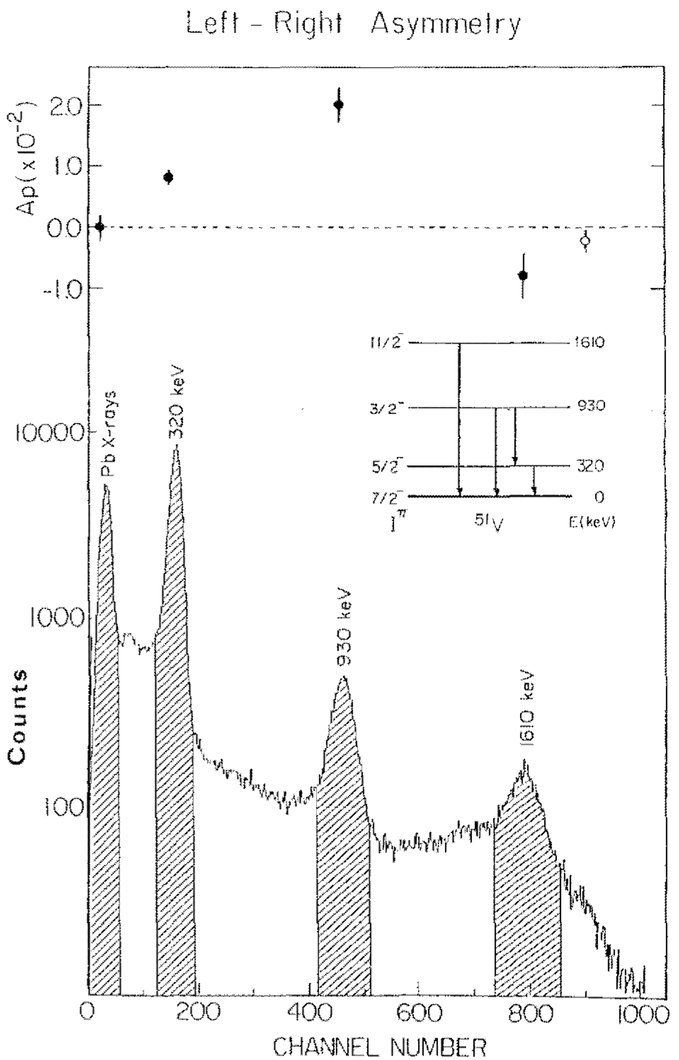


Fig. 3. Left-right asymmetry of the Coulomb excited ^{51}V on ^{208}Pb at 195 MeV for the three main decay γ-rays, Pb x-rays and γ-particle random coincidences (open circle)

J. Bendahan *et al.*, ZPA 331, 343 (88)

Coulomb excitation of polarized nuclei

^{51}V@50 MeV → TF → ^{51}V ($I^{\pi} = 7/2^{-}$), 13^{+} charge state → 195 MeV - Coulex on Pb

- ^{51}V beam intensity ~ 1 pnA
- left-right asymmetry
- strong velocity dependence of the polarization observed:
  - P_I = 1.2(2)% at β = 6.5%
  - P_I > 10(1) % at β = 4.6%

Quadrupole moments (signs) – isomeric states

- Time Dependent Perturbed Angular Distribution (TDPAD) with quadrupole interaction

$$W(t) = 1 + \sum_{k_1,k_2,q} a^q_{k_1,k_2} \sqrt{2I+1} \rho^q_{k_1} F_{k_2} G^{qq}_{k_1,k_2}(t)$$ → the angular distribution

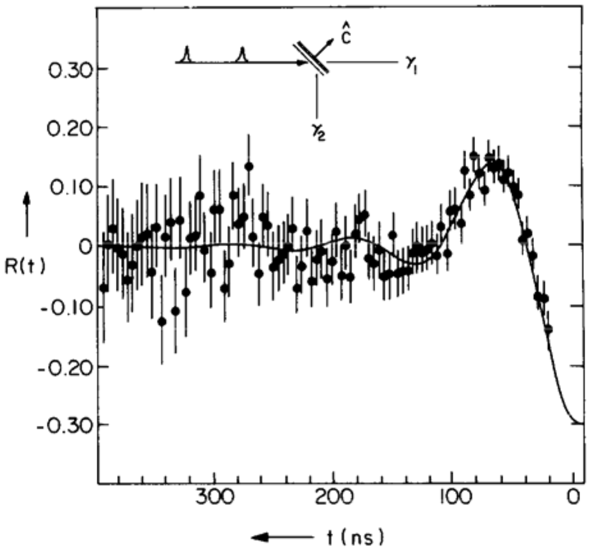
the perturbation factors:

$$G^{qq}_{k_1,k_2} = \begin{cases} \sum_n S^{k_1 k_2}_{nq} \cos(n\omega_0 t) & for\ k_1 + k_2 = even \quad \text{alignment} \\ -i \sum_n S^{k_1 k_2}_{nq} \sin(n\omega_0 t) & for\ k_1 + k_2 = odd \quad \text{polarization} \end{cases}$$

With a polarized ensemble of nuclei one can obtain both the magnitude and the sign of the quadrupole moment

Alignment and polarization Q-TDPAD patterns in Gd isotopes.

E. Dafni et al. / Nuclear polarization

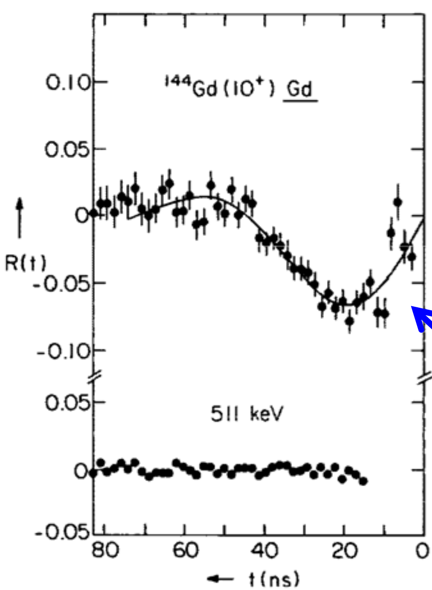


E. Dafni et al., NPA 443 135 (85)

^{144}Gd(10^{+}) - **alignment**

R(t) = maximum at t=0

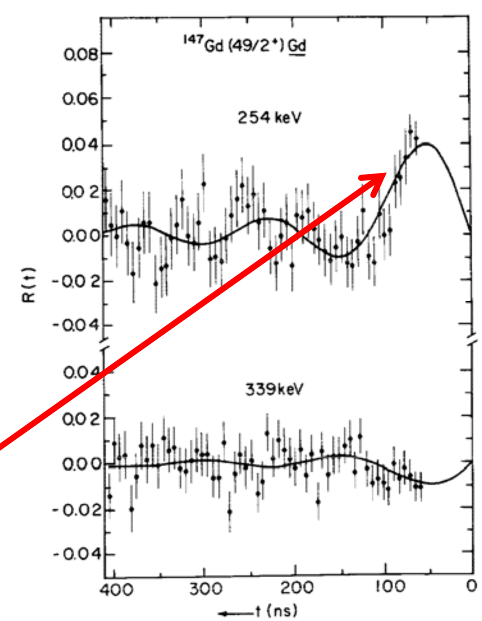
E. Dafni et al. / Nuclear polarization



Polarization

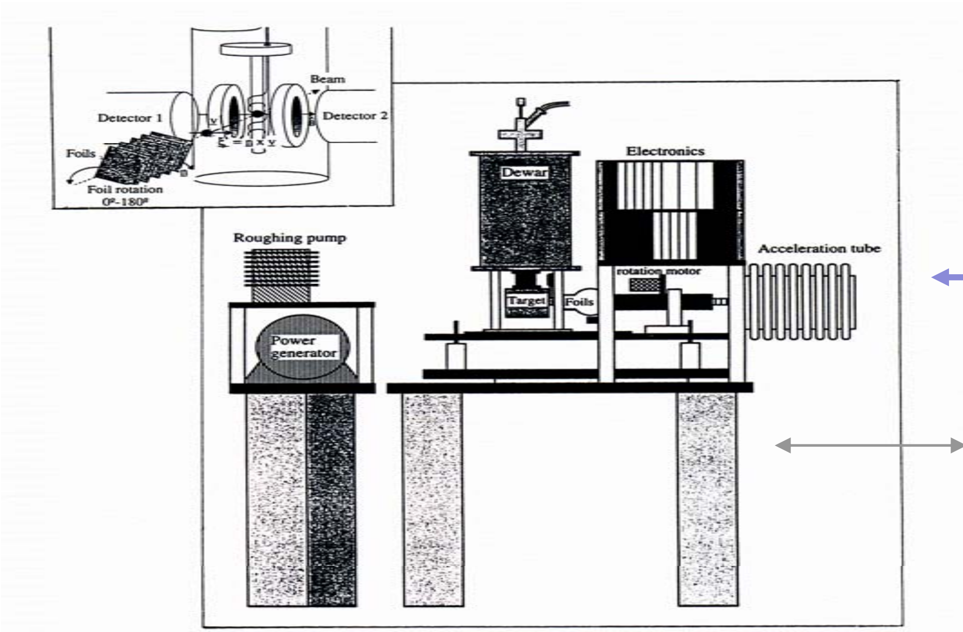
R(t) = 0 at t=0 direction - sign

E. Dafni et al. / Nuclear polarization



Magnetic moments of ground states – ^{23}Mg

- Tilted-foil polarization, β-NMR setup at the HV platform at ISOLDE

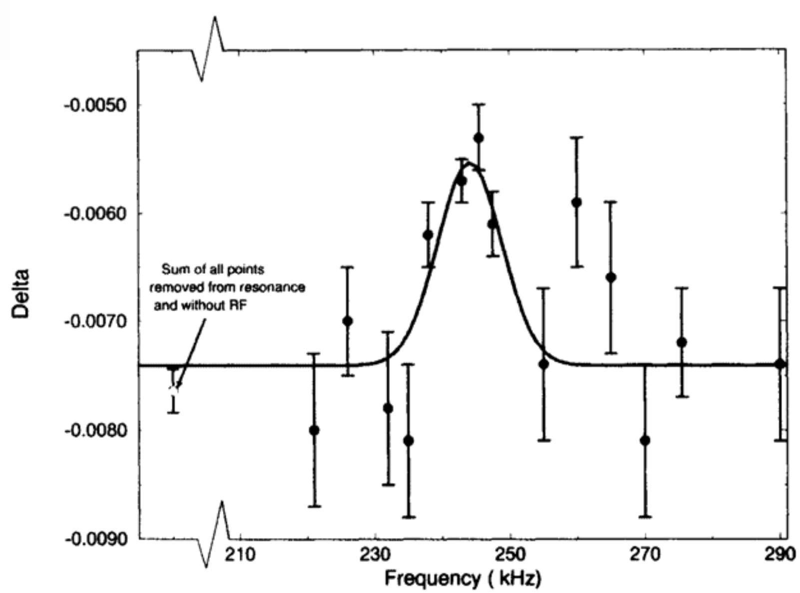


M. Lindroos *et al.*, HI 129, 109 (2000)

ISOLDE BEAM

250 kV

M. Lindroos et al. / Magnetic moments of mirror nuclei



- ^{23}Mg(I^{π}=3/2$^+$, $T_{1/2}$ = 11.3 s), 520 keV energy (2$^+$)
- 3x10^5 ions/s (~50% transm. through the foils)
- host temperature 5-10 K (14 s relaxation time)
- 2 C foils at 75° (3-4 μg/cm^2)
- 0.73(3)% asymmetry

Magnetic moments of ground states – ^{17}Ne

- ^{17}Ne ($I=1/2^{-}$, $T_{1/2}$ = 109 ms)
- ~ 10^5 pps
- 1 C foil at 65° (5-6 μg/cm²)
- 2-3 % polarization

L. Baby *et al.*, JP G30, 519 (2004)

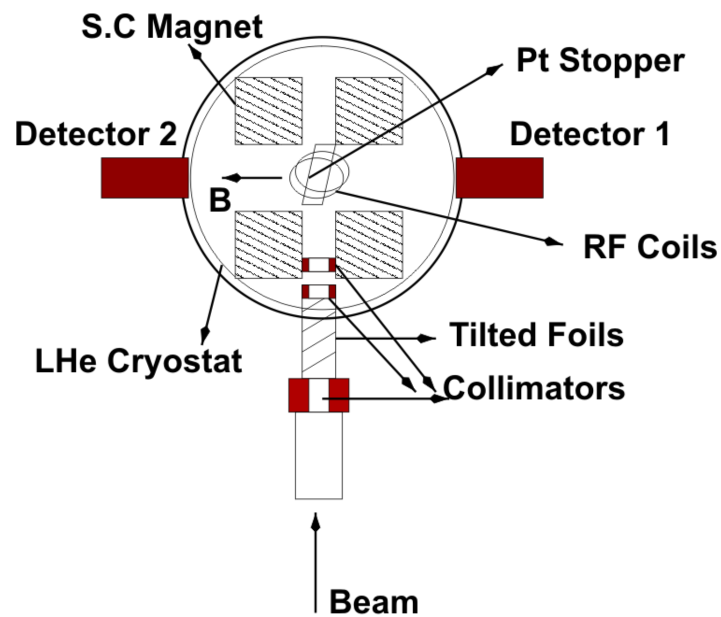


Figure 1. A cross sectional view of the β-NMR setup.

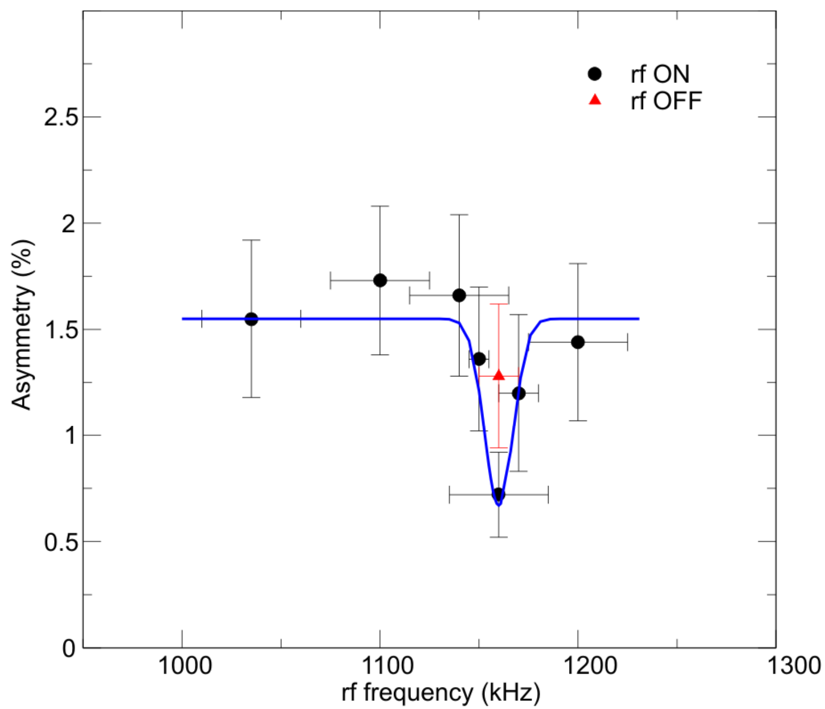


Figure 2. The asymmetry parameter as a function of the rf frequency. The circles represent the asymmetry with rf power 'ON' and the triangle represents the asymmetry obtained with rf power 'OFF'. The solid line is at yielding the value of μ= 0.74 nm.

Advantages of installing TF+β-NMR setup after REX

REX@ HIE ISOLDE ADVANTAGES: Higher energy, higher yields:

Hence:

- Better control of the velocity – "no" multiple scattering in foils.
  - a study of the polarization as a function of the ions velocity is essential
- Variety of charge states, configurations.
  - dependence of the polarization on the atomic configurations
- Ease of operation!!
  - no need to work under high voltage
- More "exotic" nuclei accessible

Necessary detailed studies of the atomic polarization and it transfer to the nuclear spins – REX is the place to do it!

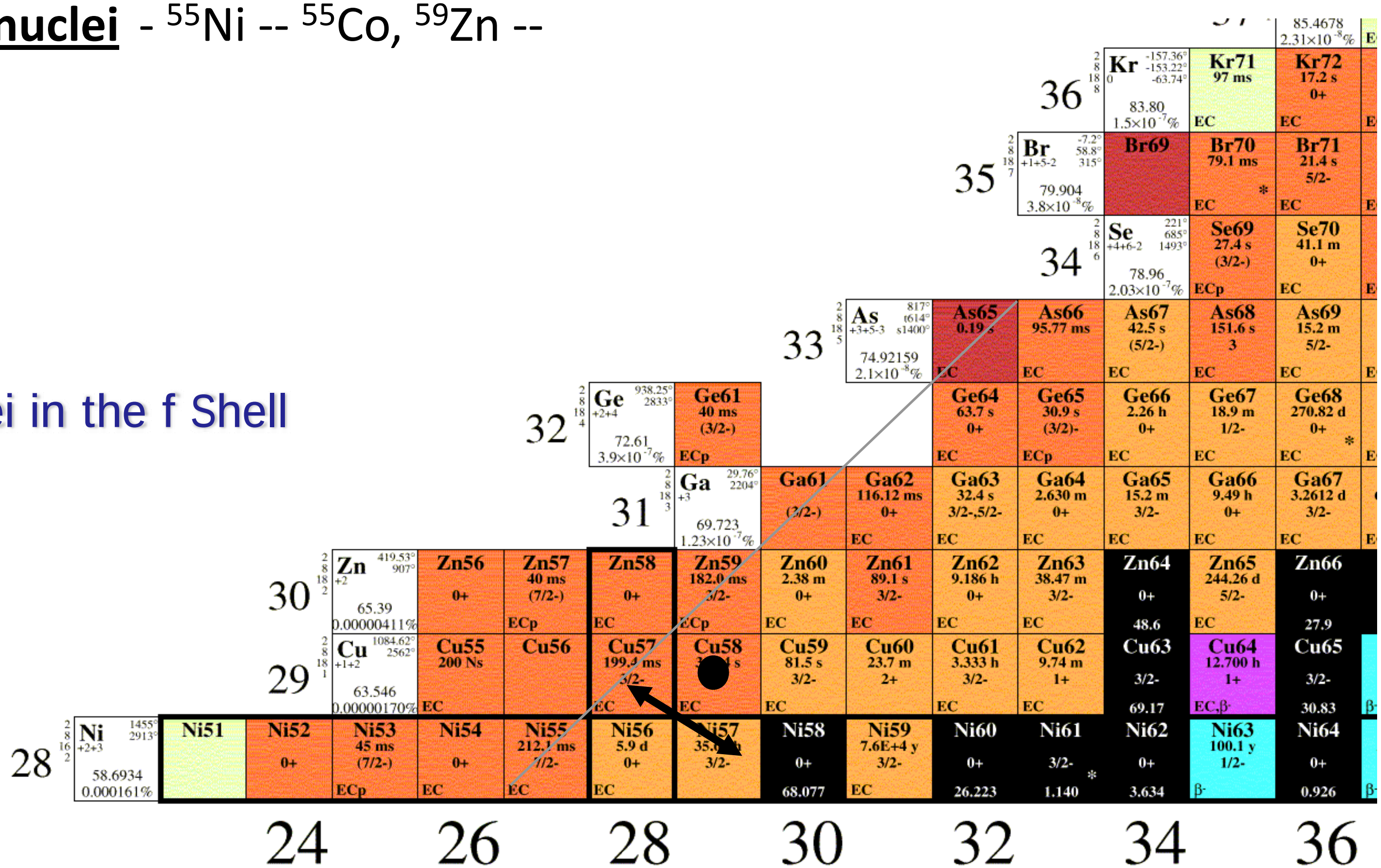
Possibilities for Nuclear physics studies

- Nuclear moment measurements of exotic nuclei

Example – mirror nuclei in the fp shell:

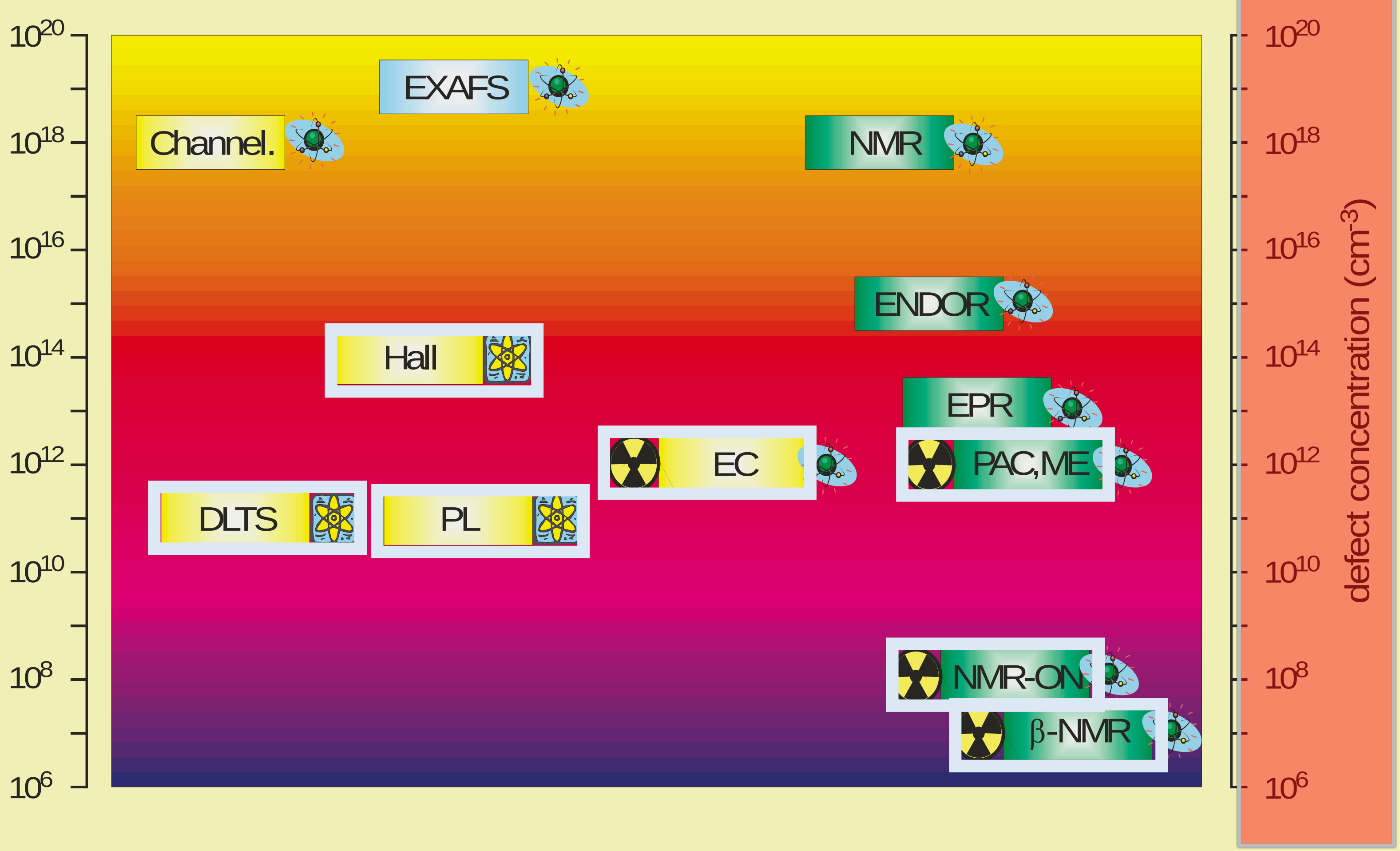
<u>Z=N+1 nuclei</u> - ^{55}Ni -- ^{55}Co, ^{59}Zn --

Mirror Nuclei in the f Shell



Semiconductor Spectroscopy

sensitive to chemical nature or electronic properties
(some require radioactive istopes)



Experimental techniques used with radioactive isotopes at ISOLDE

Beta-NMR: solid state physics aspects

- Very sensitive – 10^9 atoms is enough, compare with 10^{11} for most other nuclear techniques
- An additional local probe of materials, complementing existing techniques

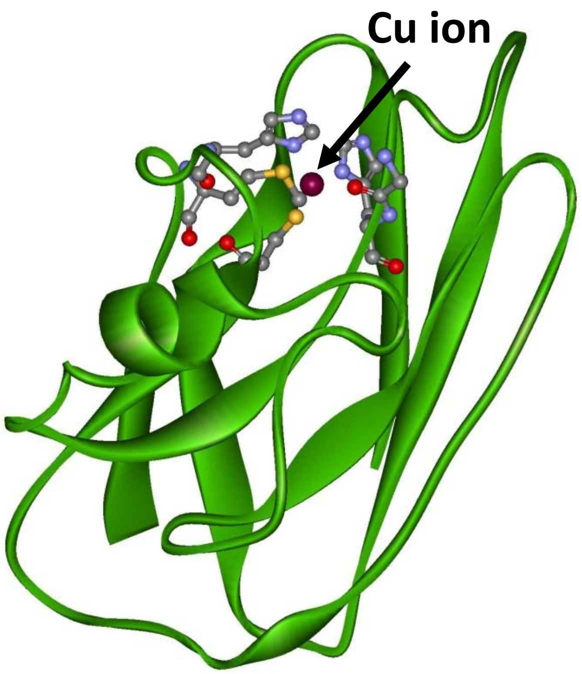
Potential applications in the study of:

- Nanomaterials, the extra sensitivity of β-NMR has advantages over other methods e.g. less damage, fewer atoms needed; e.g. single molecule magnetic systems.
- Can investigate local properties of materials, ranging from semiconductors to biosystems. Doping issues II-VI semiconductors (ZnSe) already studied at ISOLDE using this method: electric field gradient interactions. Current projects could involve ZnO.
- Can be used to study diffusion in materials, e.g. monitoring the spin-lattice relaxation ^{8}Li/β-NMR has been used as a monitor of jump rates in nanocrystalline ceramics.

- Disadvantages, requires relatively high degree of polarization (>10%)
- Experiments done *in-situ* therefore difficult to vary sample parameters, this could be a challenge (though not insurmountable) for biophysics.

β-NMR applied to metal ions in biological systems

- Cu(I)/Cu(II) are essential in many redoxprocesses and electron transport in biology, e.g. in photosynthesis.
- Cu(I) is “invisible” in most (except X-ray and nuclear) spectroscopic techniques because it is a closed shell ion
- Measurements of spectroscopic properties (such as electric field gradients) for Cu(I) in proteins would have considerable impact in bioinorganic chemistry
- Other elements of particular interest: Mn, Fe, Ni, Zn

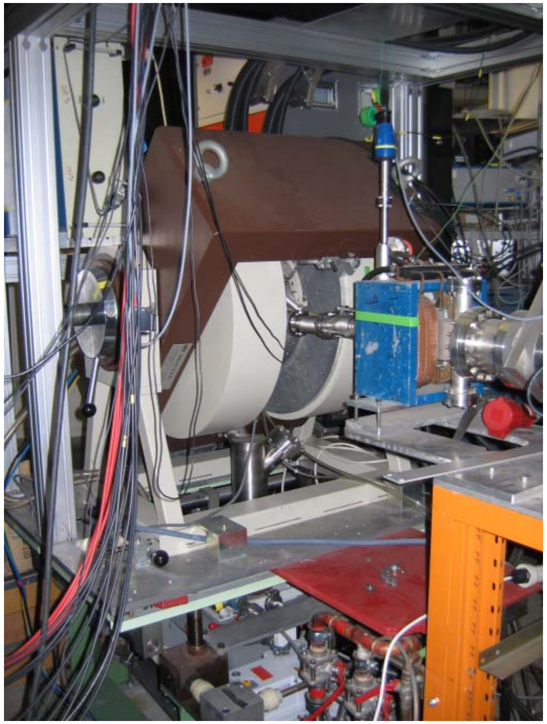


Azurin – an example of a Cu(I)/Cu(II) dependent electron transporting protein

The β-NMR setup moving to ISOLDE

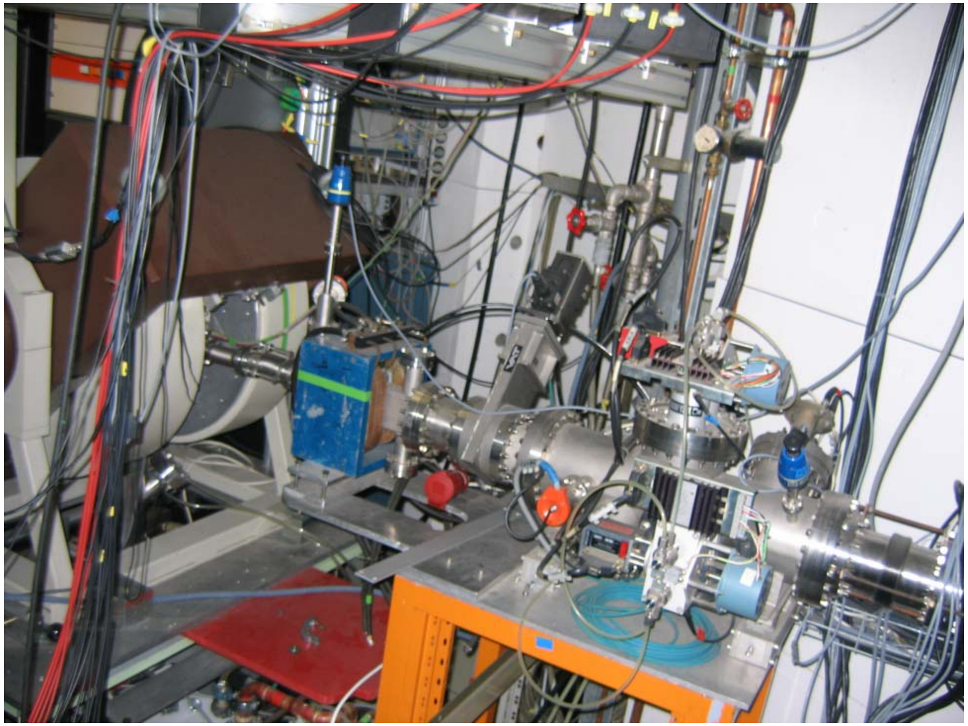
- **From HMI, Berlin – Wolf-Dietrich Zeitz**

What we're not getting



What we are…

Wolf-Dietrich with the electronics



Challenges for ISOLDE:

- Space at REX

Przemek is helping to set things up