Table of contents:

Basic principles to measure nuclear moments

The nuclear moments can be measured by investigating their interaction with the electromagnetic fields in their immediate environment

→ the magnetic moment interacts with magnetic fields (static or dynamic)

measure the magnetic interaction frequency $\nu_B = g\mu_N B/h$

→ the quadrupole moment interacts with the gradient of an electric field ($\partial^2 V / \partial z \partial z$)

measure the quadrupole interaction frequency $\nu_Q = eQV_{zz}/h$

The nuclear properties (detected radiation, lifetime, spin, production method, ...) **determine which method can/needs to be used to measure it's nuclear moments**

→ **many methods have been developed (more than 25 for radioactive nuclei !)**

distinguish two main categories, depending on the origin of the electromagnetic field

The electromagnetic fields can be induced by two means:

→ **By the electron cloud in free atoms** (atoms or ions in a beam)

measure the hyperfine structure of atoms/ions via **laser spectroscopy methods**
(lecture R. Neugart, Les Houches, 2002)

→ **By implantation in a solid** : crystal-induced electromagnetic fields occur and also external magnetic fields are applied.

The interaction of these fields with the nuclear spin causes a perturbation of the nuclear spin-orientation, which is reflected in the angular distribution of the radiation.

measure the perturbation of the angular distribution of the radioactive decay by **hyperfine interaction methods**

I will concentrate on these types of experiments !

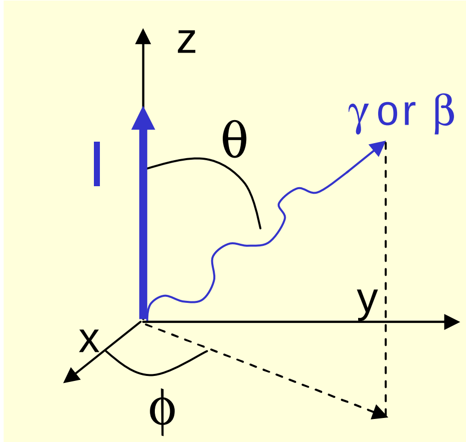
Requirements:

1. The **lifetime of the nuclear state** is longer than the interaction time, such that the interaction can cause a significant perturbation of the nuclear spin orientation before the nucleus decays. $(\tau > 1/\omega_i)$

2. The **ensemble of nuclear spins needs to be oriented** (anisotropic distribution) in order to allow measuring a change in the anisotropy induced by the applied interactions.

Angular distribution of radiation

The direction in which the radiation, emitted by a radioactive nucleus, is emitted, depends on the direction of its nuclear spin.
This is formally described by the 'angular distribution' function:



$$W(\theta,\phi,t) = \sum_{k,n} \frac{\sqrt{4\pi}}{2k+1} \; A_k \; B_k^n(t) \; Y_k^n(\theta,\phi)$$

A_k = radiation parameter → properties of detected radiation

B_k^n = orientation tensor → describes the orientation of the spin ensemble

unperturbed: $B_k^n(t=0)$ (at time of implantation)

perturbed: $B_k^n(t) = \sum_{k',n'} G_{kk'}^{nn'}(t) \, B_k^n(t=0)$

→ Perturbation factor

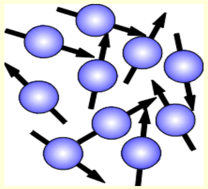
Y_k^n = spherical tensors

Measuring the angular distribution, for γ-decay or β-decaying nuclei, allows to deduce information about the interaction of their nuclear spins with their environment → nuclear moments

Orientation of an ensemble of nuclear spins

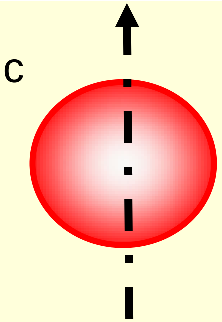
Definitions

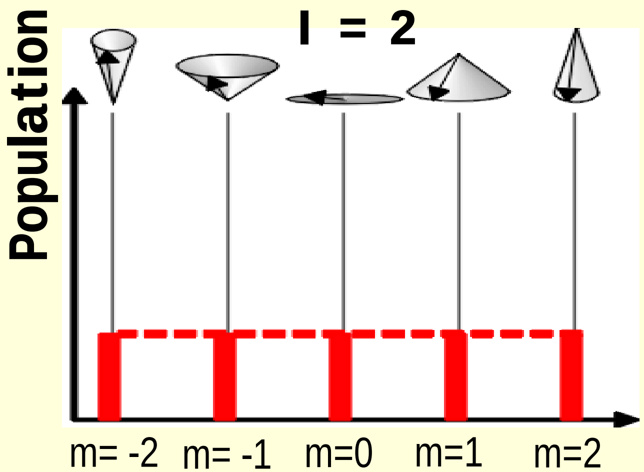
An ensemble of spins is said to be **isotropic**, if all spins are pointing in random directions.



Classical :
spherical symmetric distribution
of the nuclear spins

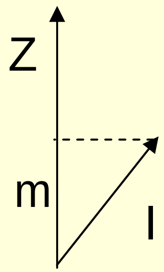
Spherical symmetric
radiation pattern



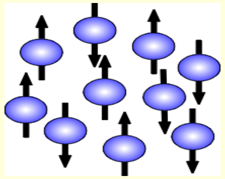


Quantum mechanical:
All spin projected states (m-quantum states)
are equally populated:

p(m) equal $\forall$ m

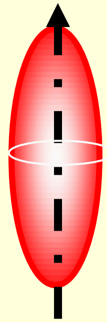


An ensemble of spins is said to be **aligned,**
if all spins are preferentially along a certain direction (axial symmetry)

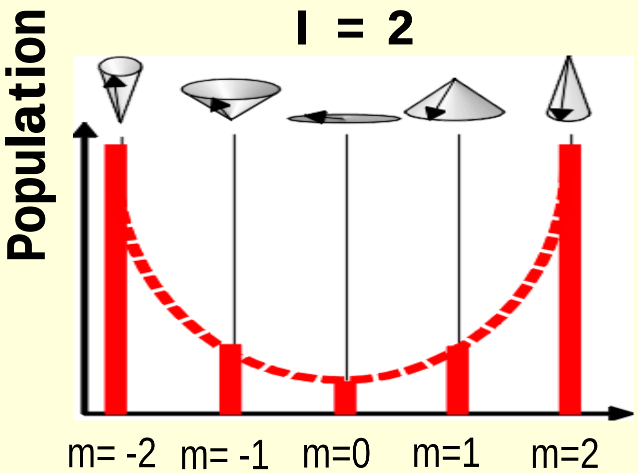


Classical :
equal amount of spins are
pointing up and down

Aligned radiation pattern
(up/down symmetry
along the axial symmetry axis)



N(0°)=N(180°)
and
no dependence on ϕ
Measure N(0)/N(90)



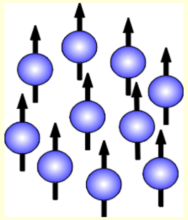
Quantum mechanical:
Equal amount of spins with +/-m :

p(m) = p(-m)
+ axial symmetry around Z

An ensemble of spins is said to be **polarized,**

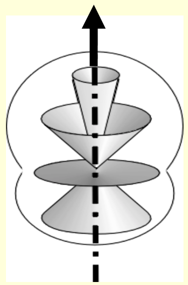
if all spins are preferentially along a certain direction (axial symmetry)

and if the UP/DOWN symmetry is broken



Classical :
all spin point in the same preferential direction

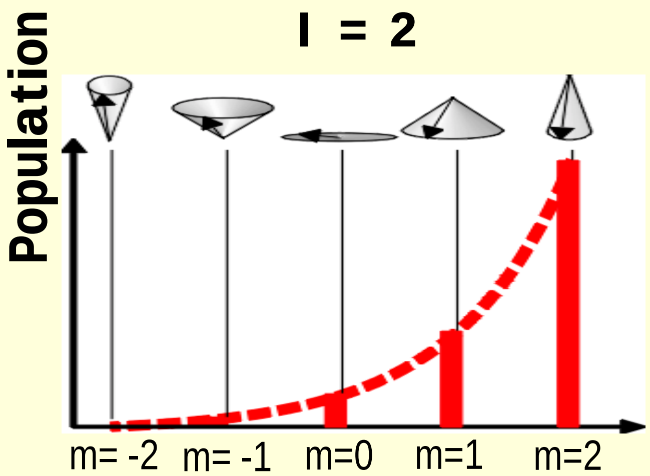
Polarized radiation pattern
(up/down symmetry is broken)



$N(0°) \neq N(180°)$

and

no dependence on ϕ



Quantum mechanical:
Different amount of spins with +/-m :

$p(m) \neq p(-m)$

+ axial symmetry around Z

Methods to Orient Nuclear Spins

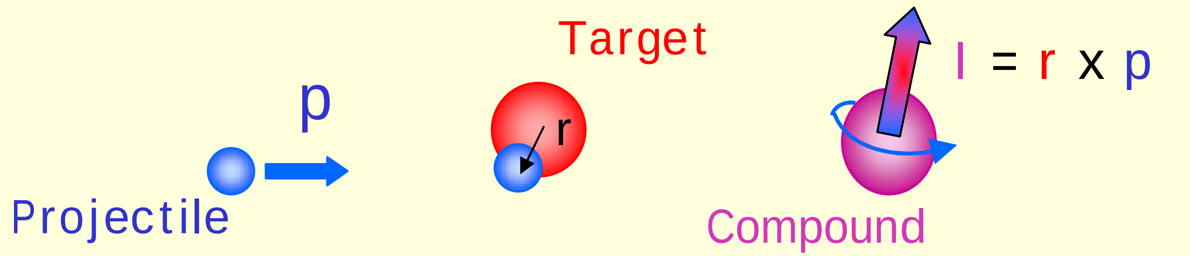
Direct methods → spin-orientation given by the production process

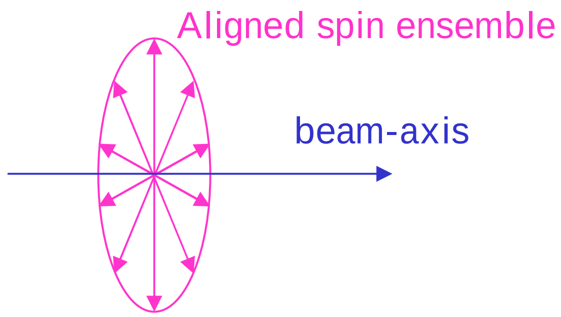
- the nuclear reaction produces spin-oriented reaction products
- the spin-orientation is maintained until implantation into a host material

examples: fusion-evaporation
projectile fragmentation
coulomb excitation
….

<u>Fusion evaporation:</u> nearly complete alignment

Principle: transfer of momentum from projectile to target





Fusion evaporation: pro's and contra's

Experiments:

(1) in-beam (mostly)

- production + recoil into the target → **very high orientation !**

only neutron deficient nuclei

not always target = host possible !

- with recoil-implantation → avoid air gaps between target and host foil

(loss of orientation due to hyperfine interaction between randomly oriented electron spin and nuclear spin during the flight in vacuum)

Problems for experiments on exotic nuclei:

- in-beam is no longer possible (need selection)
- need a selection method that maintains orientation !

(2) after recoil mass separation (in-flight)

inverse kinematics + recoil separation !

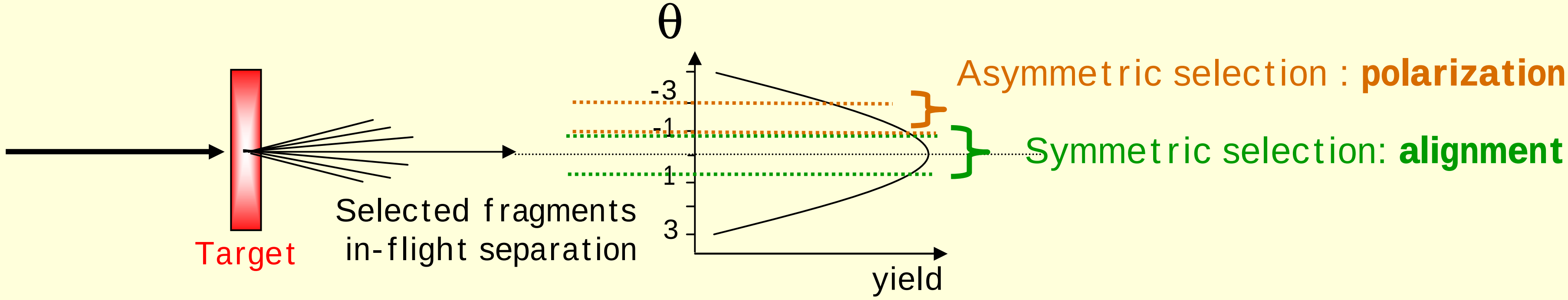
→ select isomers in noble-gas charge state

proof of principle : E. Dafni and M. Satteson, Phys. Rev. C38 (1988) 2949

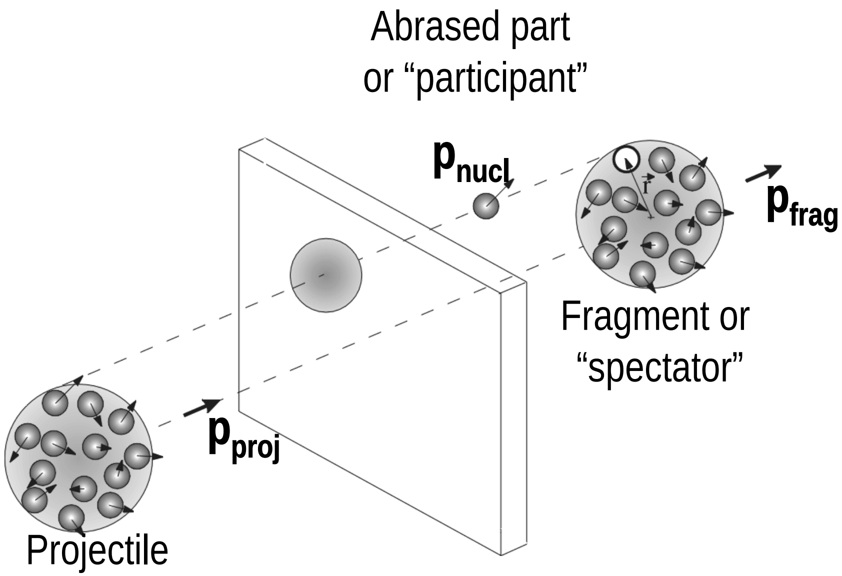
(only) 15% of initial alignment is maintained !

Projectile fragmentation: rather low orientation (5-30%)

Principle: transfer of momentum via nucleon removal in the projectile



the participant spectator model: peripheral collisions



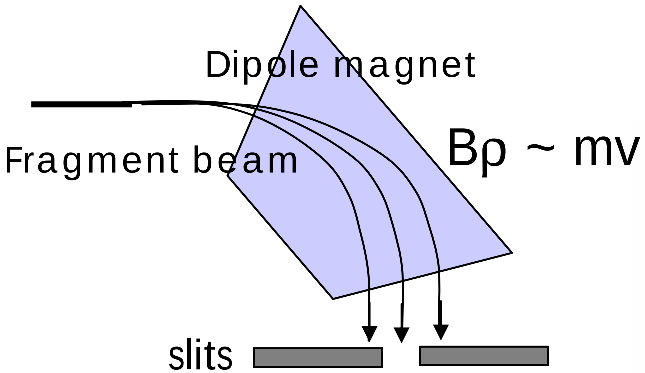
Spin-orientation from projectile fragmentation: still under investigation !

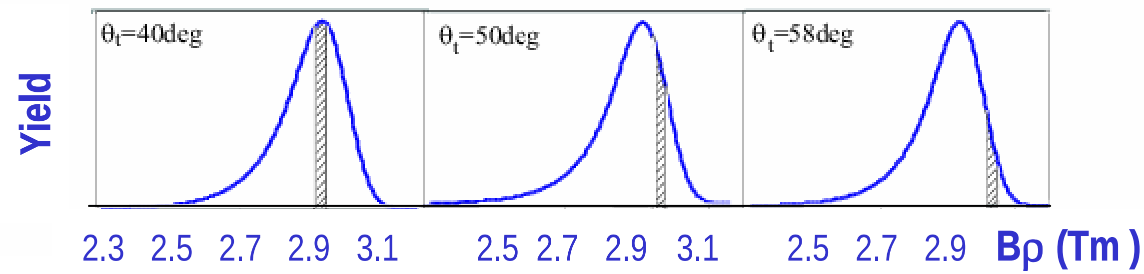
It depends on

- the energy of the projectile beam
- the Z of the target , the thickness of the target
- the Z (and N ?) of the selected fragment
- the selected energy of the fragment beam (longitudinal momentum)
- the selected angle of the fragment beam (transverse momentum)

Projectile fragmentation: dependence on fragment energy

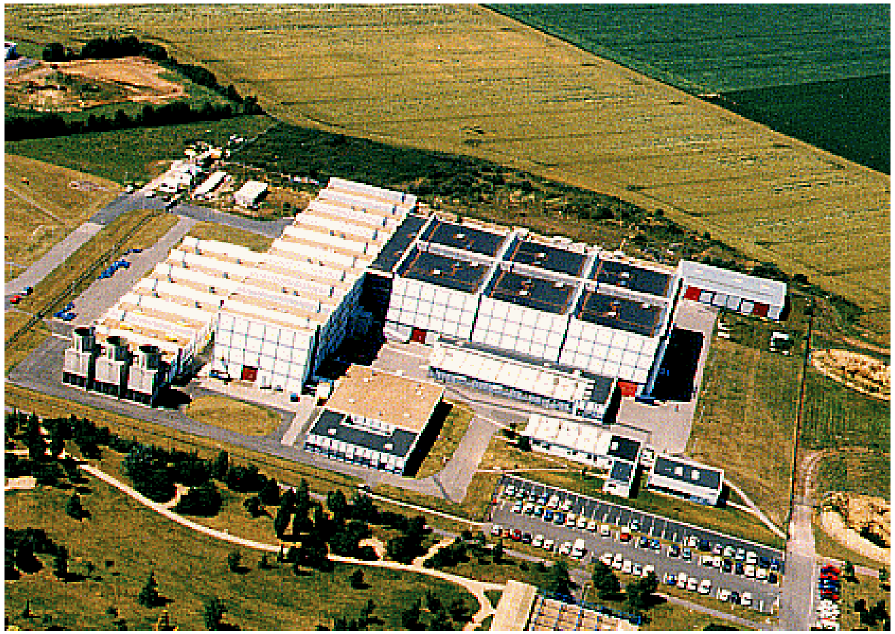
A fragment separator has a certain **momentum acceptance**
→ selection of the fragment momentum (energy) by slits





Examples of fragment separators:
LISE at GANIL
A1200 at MSU
RIPS at RIKEN
FRS at GSI

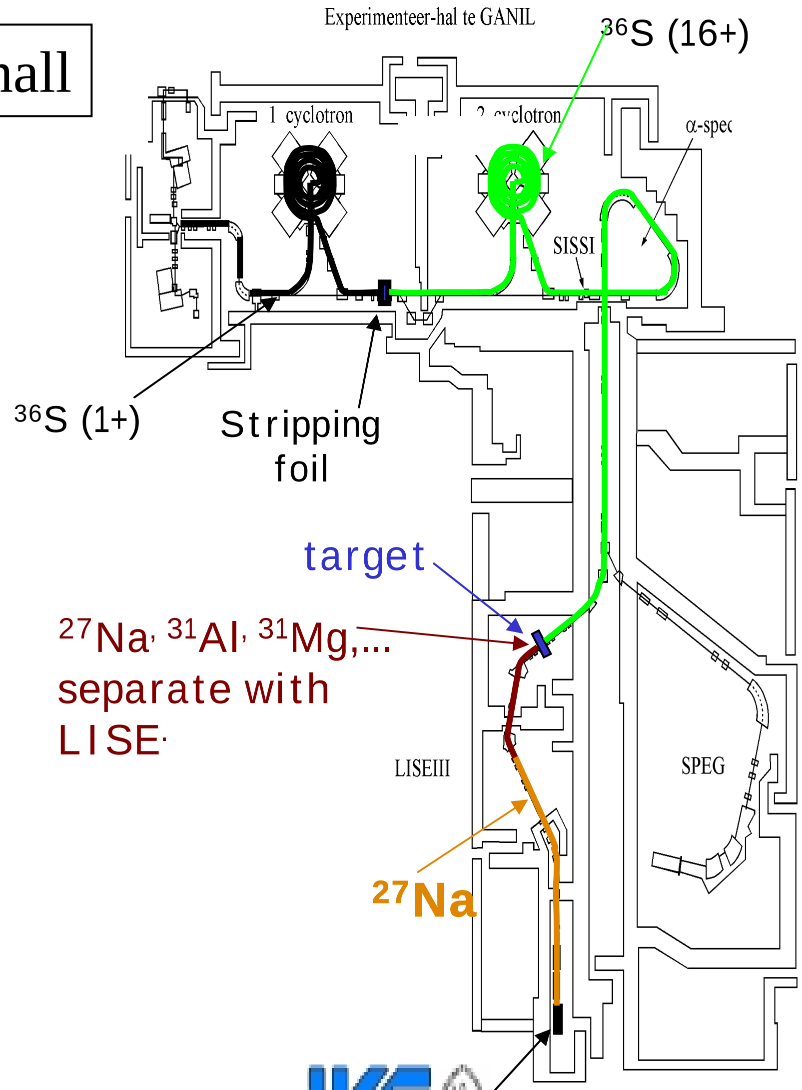
GANIL
GRAND ACCELERATEUR NATIONAL D'IONS LOURDS



Projectile fragmentation: dependence on fragment energy

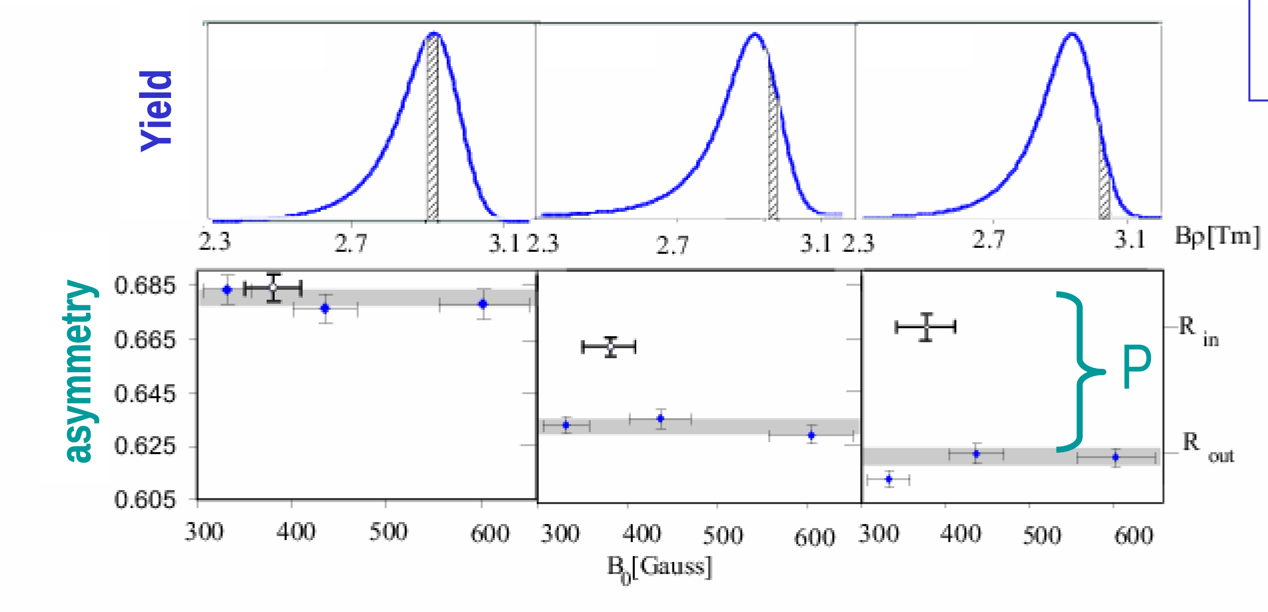
Experiment @ GANIL: **^{36}S (77 MeV/A) + ^{9}Be**

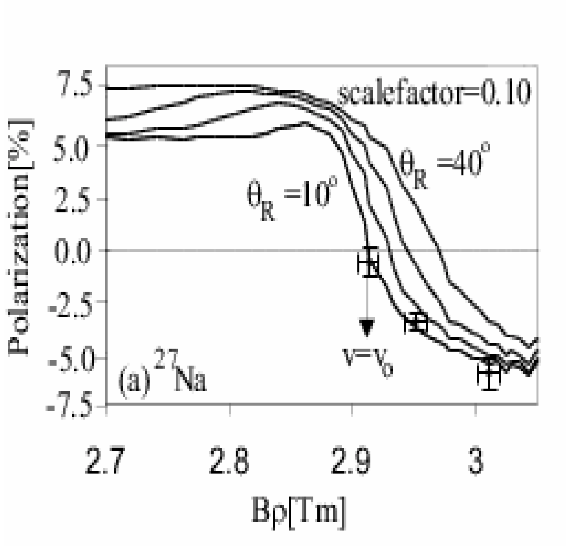
Experimental hall



Projectile fragmentation: dependence on fragment energy

Experiment @ GANIL:
36S (77 MeV/A) + 9Be





Polarization is maximal in wing of momentum distribution (lowest yield) (for reaction on a low-Z target).

Model : H. Okuno, K. Asahi et al., PL B335 (1994) 29

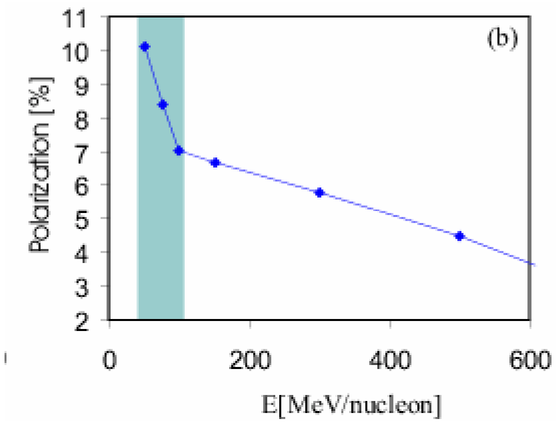
Ref: D. Borremans, PRC 66 (2002) 054601

Projectile fragmentation: dependence on beam energy

Prediction by the kinematical model:

strong reduction of polarization with increasing beam energy

(in combination with strong forward peaked yield)



Experimental results:

At GANIL energies (50-80 MeV/A)

A = 10 - 15%   P = 3 - 10%

High GSI energies (> 500 MeV)

A = 15-30%   P < 1%

Ref.: PLB 393 (97) 36   PRC 66 (2003) 054601   Z.Phys. A350 (94) 215   PRC 57(98)2205

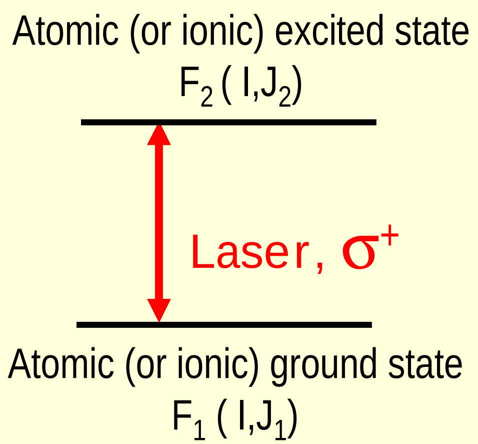
Methods to Orient Nuclear Spins

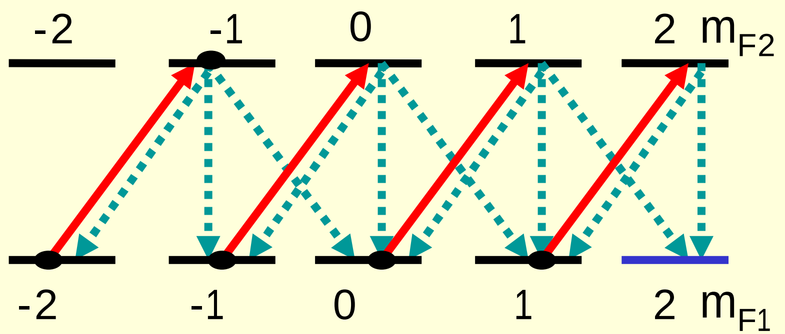
Indirect methods → spin-orientation produced after the production reaction (a requirement for ISOL-beams !)

examples: optical pumping with a collinear laser beam
tilted foils polarization
low temperature orientation (T ~ 20 mK, B ~ 10 T)

<u>Optical pumping</u>: interaction of a radioactive beam and a laser beam
(dedicated set-up: COLLAPS – ISOLDE) only one worldwide ?

Principle: polarize the atom (or ion) by resonant excitation with a polarized laser beam





Total atomic spin F gets polarized through pumping !
Consequence: **nuclear spin polarization**
(via the hyperfine interaction)

Formal description of the orientation of an ensemble of nuclear spins:

from	**density matrix**	$\rho_{mm'}$	(population of m-levels)
to	**density tensor**	ρ_k^n	(easy to rotate)
to	**orientation tensor**	B_k^n	(used in ang. Distr.)

The **density matrix** describes the population and coherences between m-quantum states of an ensemble of nuclear spins:

$$\rho_{mm} = \langle m|\rho|m\rangle = p(m)$$ population of level | Im>

$$\rho_{mm'} = \langle m|\rho|m'\rangle \; (m \neq m')$$ coherence between level m and m'

In case of axial symmetry → only p(m) exists, non-diagonal terms are zero

The **density tensor for ensemble of spins (I)** is obtained by projection on the spherical tensor basis:

$$\rho_k^n = \langle U_k^n|\rho\rangle$$

$$= \sqrt{2k+1} \sum_{m,m'} (-1)^{I+m} \begin{pmatrix} I & I & k \\ -m & m' & n \end{pmatrix} \rho_{mm'}$$

In case of axial symmetry → only ρ_k^0 exists, terms with $n \neq 0$ are zero

The **orientation tensor** is defined as: $B_k^n = \sqrt{2I+1} \; \rho_k^{n*}$

Properties of alignment and polarization

An isotropic ensemble has $B_0 = 1$, all other components are zero

An aligned ensemble has B_k^0 components for k=even,

n≠0 components are zero

odd tensors are zero

B_2 , B_4 ~ amount of alignment A

$$A = \sum_m \frac{[3m^2 - I(I+1)]\, p(m)}{I(I+1)} \qquad \text{(integer } I\text{)}$$

A polarized ensemble has B_k^0 components for k=odd and k=even !

n≠0 components are zero

B_1 ~ amount of polarization P

$$P = \sum_m \frac{m\, p(m)}{I}$$

Simplifications in the angular distribution function

Table of contents:

The angular distribution for γ- and β-decay: simplifications !

In most cases:

→ γ-detection: A_k only for k=even → detect alignment

$$W(\theta,\phi,t) = 1 + \frac{\sqrt{4\pi}}{5} \sum_n A_2 \; B_2^n(t) \; Y_2^n(\theta,\phi) + \ldots \qquad .$$

→ β-detection: A_k only for k=1 → detect polarization
+ detection along the polarization axis (n=0)

$$W(\theta,\phi,t) = 1 + A_1 \; B_1^0(t) \; \cos\theta$$

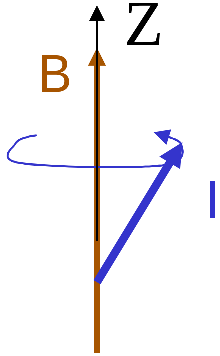
$$B_1^0(t) = \sum_{k,n} G_{1k}^{0n}(t) \; B_k^n(t=0)$$

Consequence: for study of isomers: need aligned beam !
for study of ground states: need polarized beam !

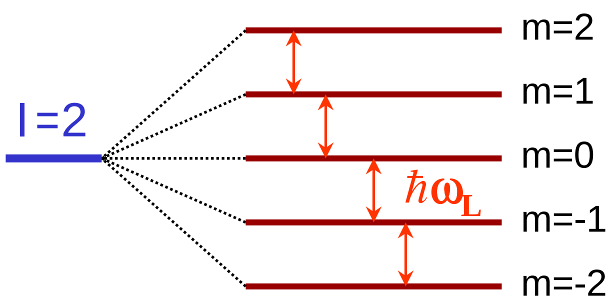
Static Magnetic and Quadrupole Interaction

Nucleus in static magnetic field B

$$H_B = -\bar{\mu} \cdot \bar{B}$$



$$E_m = -\hbar\omega_L\, m$$



Zeeman splitting

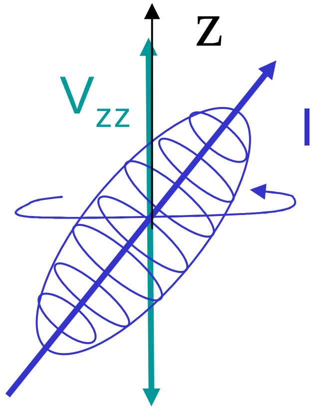
1 frequency ν_L

Larmor frequency $\nu_L = g\mu_N B/h$

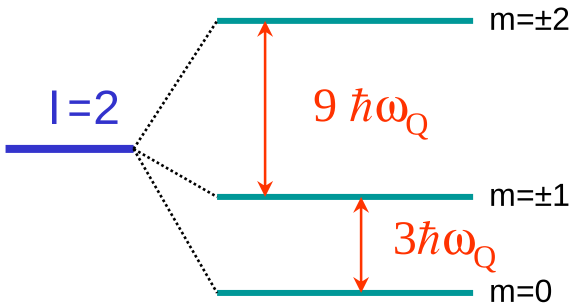
Coupling constant: $\omega_L = 2\pi\nu_L$

Nucleus in electric field gradient V_{zz}

$$H_Q = \frac{\hbar}{\omega_Q}\,(3\bar{I}_z^{\,2} - \bar{I}^2)$$



$$E_m = \hbar\omega_Q[(3m^2 - I(I+1)]$$



Quadrupole splitting

I (or I-1/2) frequencies $\nu_Q(n) \sim \nu_0$

Quadrupole frequency $\nu_0 = eQV_{zz}/h$

Coupling constant: $\omega_Q = \nu_0\, 2\pi/4I(2I-1)$

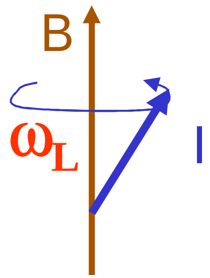
Experimental techniques to measure moments

Measure as a function of time (= time differential methods)

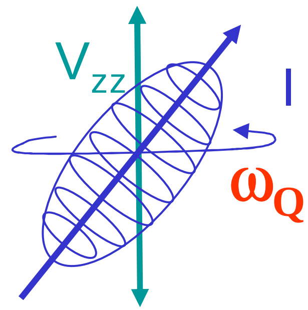
Measure the **change in anisotropy as a function time**

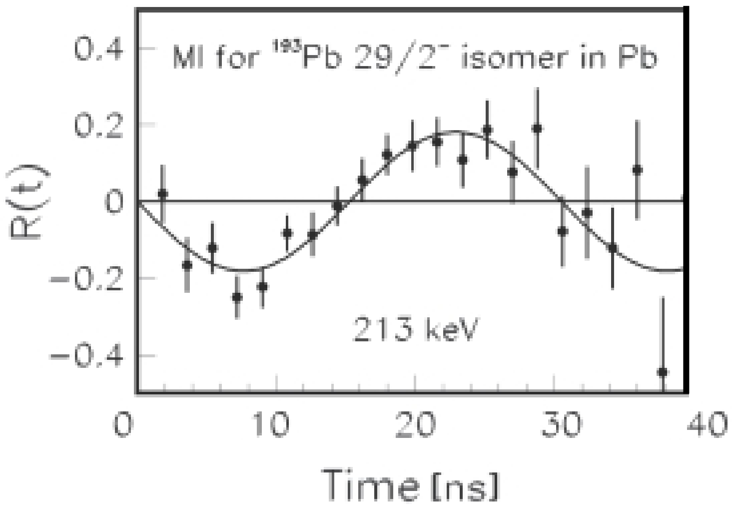
→ Time Differential Perturbed Angular Distribution (TDPAD) methods

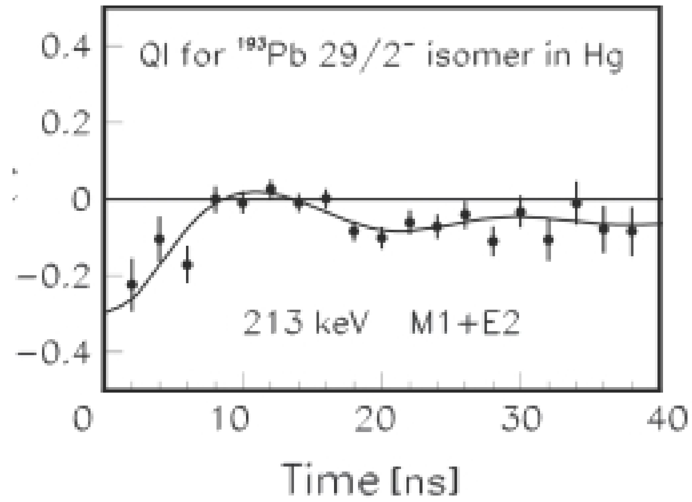
Measure the **larmor precession** of an oriented ensemble submitted to a static field B



Measure the **quadrupole precession** of an oriented ensemble submitted to an EFG

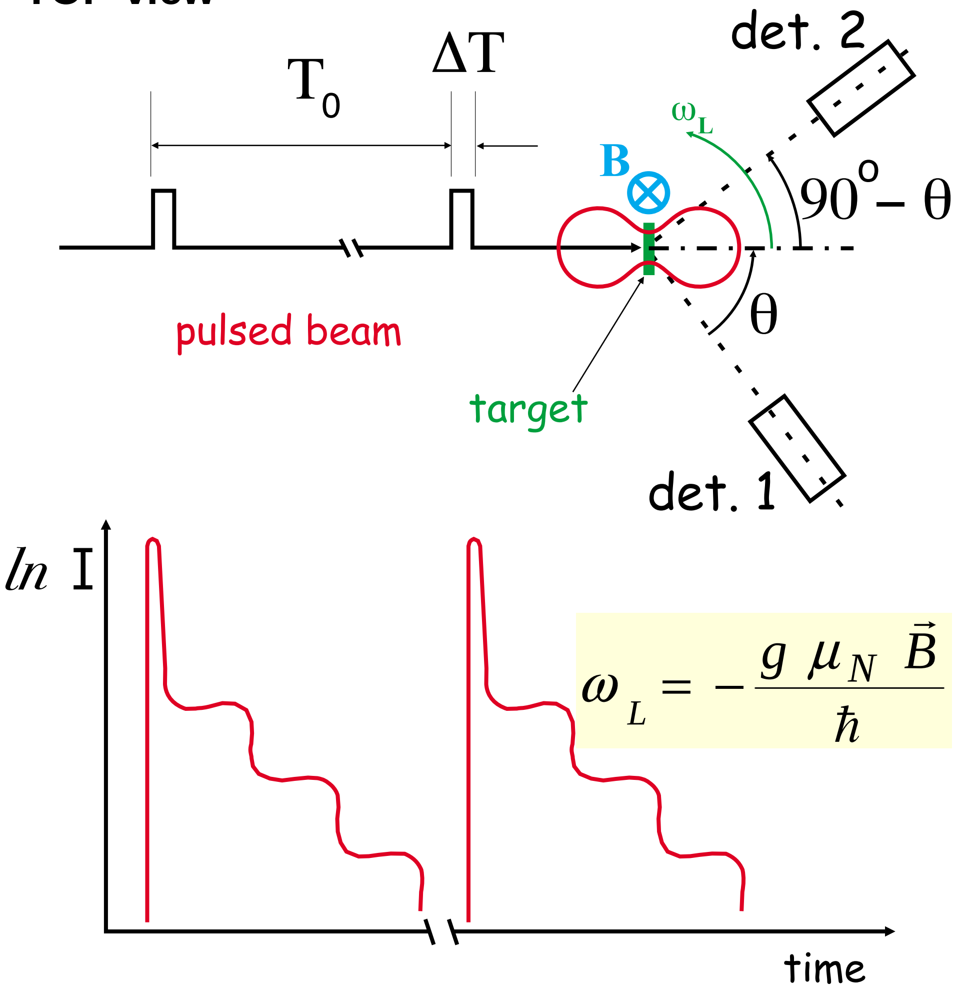






TDPAD (Time Differential Perturbed Angular Distribution)

TOP view



$$\omega_L = -\frac{g\,\mu_N\,\vec{B}}{\hbar}$$

Pulsed beam needed:

$T_0 > 3\tau$ $\Delta T << \tau$ (duty cycle)

Detection : γ-detectors (HPGe)

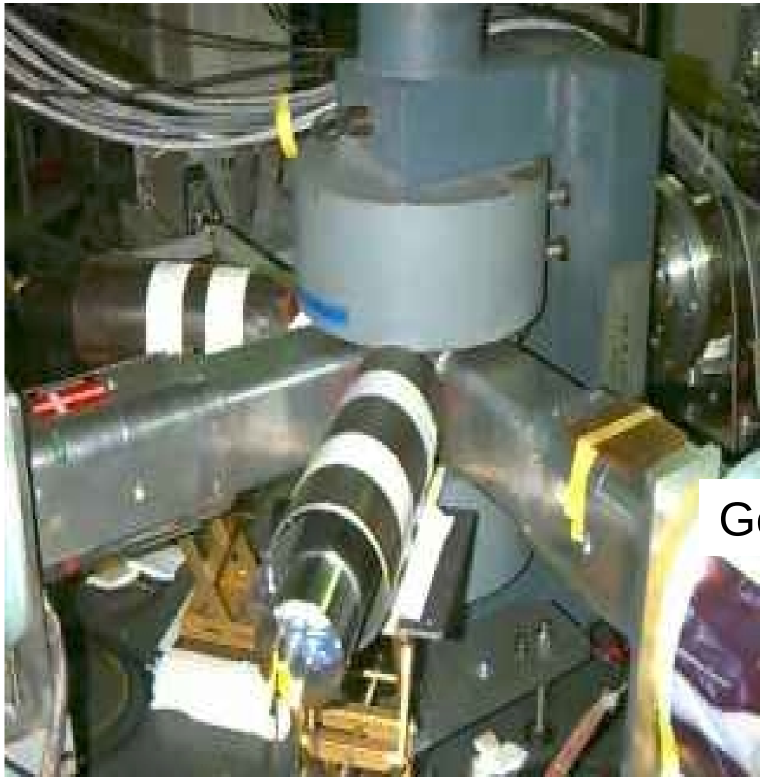
At 90° wrt each other
In the plane of the orientation symmetry axis
Perpendicular to the static field

Registered signal:

γ-intensity as function of time
start = puls from beam
or ion arrival time
stop = detection of a γ

$$R(t) = \frac{N(0)-N(90)}{N(0)+N(90)}$$

TDPAD setup at GANIL



Experimental techniques to measure moments

time differential methods (TDPAD)

for short lifetimes only
(spin-spin relaxation time ~ 10-100 μs)

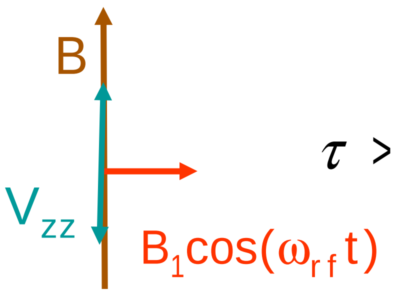
Measure time integrated (= time integrated methods)

Measure the **change in anisotropy as a function of an external variable**

spin-lattice relaxation is longer (ms – sec)

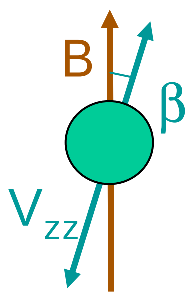
→ Nuclear Magnetic Resonance (NMR) method
→ Nuclear Quadrupole Resonance (NQR) method
→ Level Mixing Resonance (LMR) method

A **radiofrequency (rf) magnetic field** induces a perturbation of the population of the quantum levels.
external variable = **applied rf-frequency**



$\tau > 1/\omega_1(rf) > 100\ \mu s$

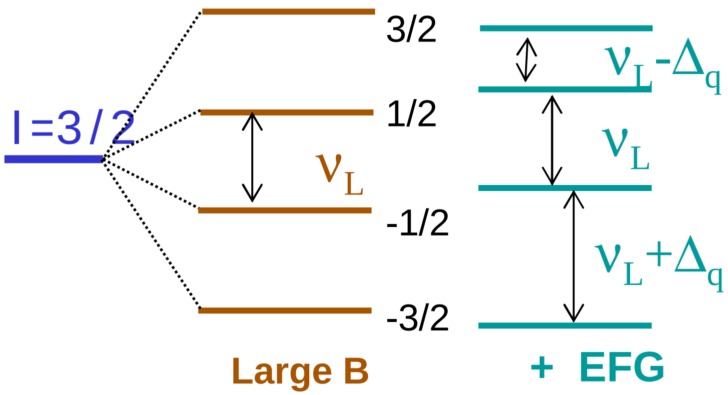
The **misalignment of two static interactions** induces a perturbation of the population of the quantum levels.
external variable = **static field strength**

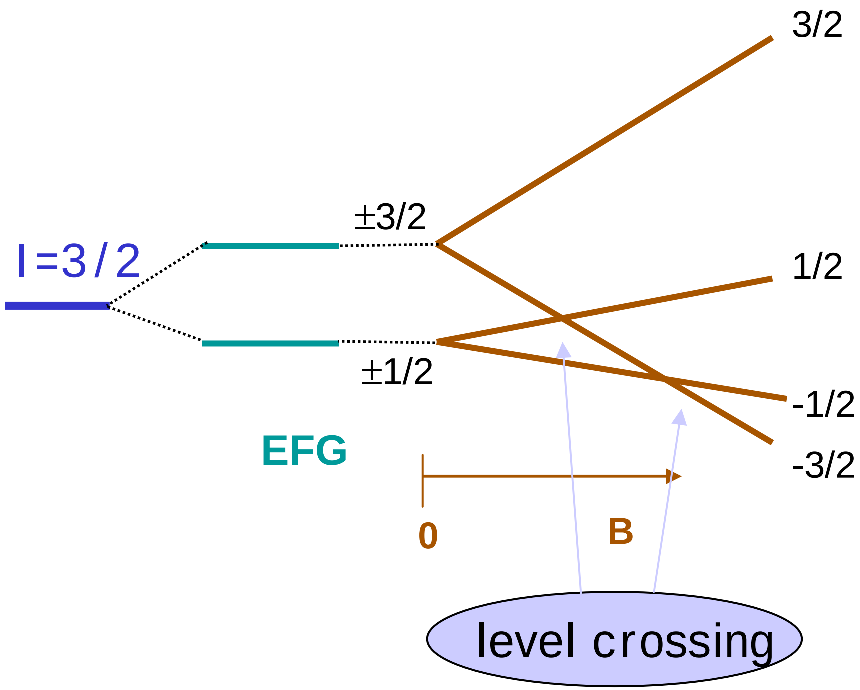


$\tau > 1/\omega_1(\beta) > 1\ \mu s$

Combined interactions: magnetic dipole + electric quadrupole

Crystal c-axis parallel to magnetic field

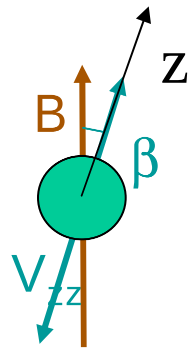


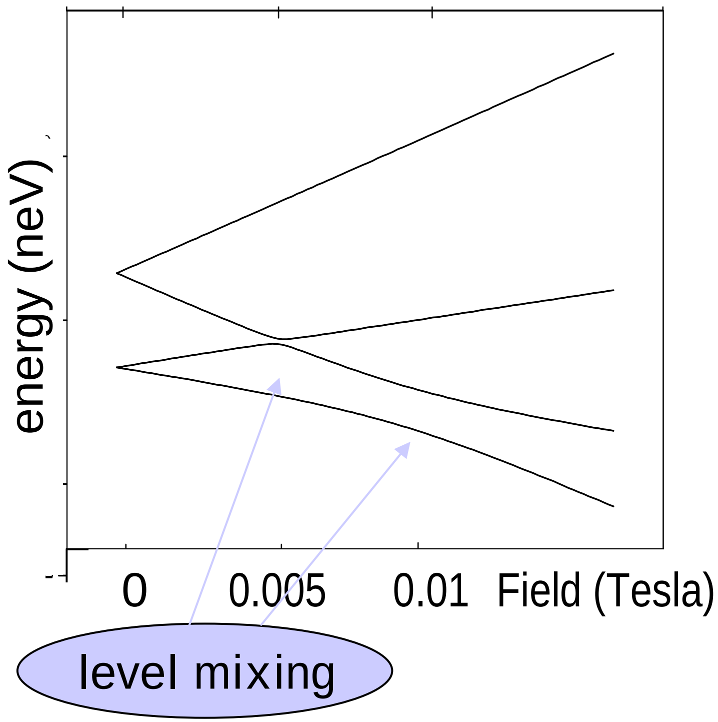


Crystal c-axis makes angle β with B

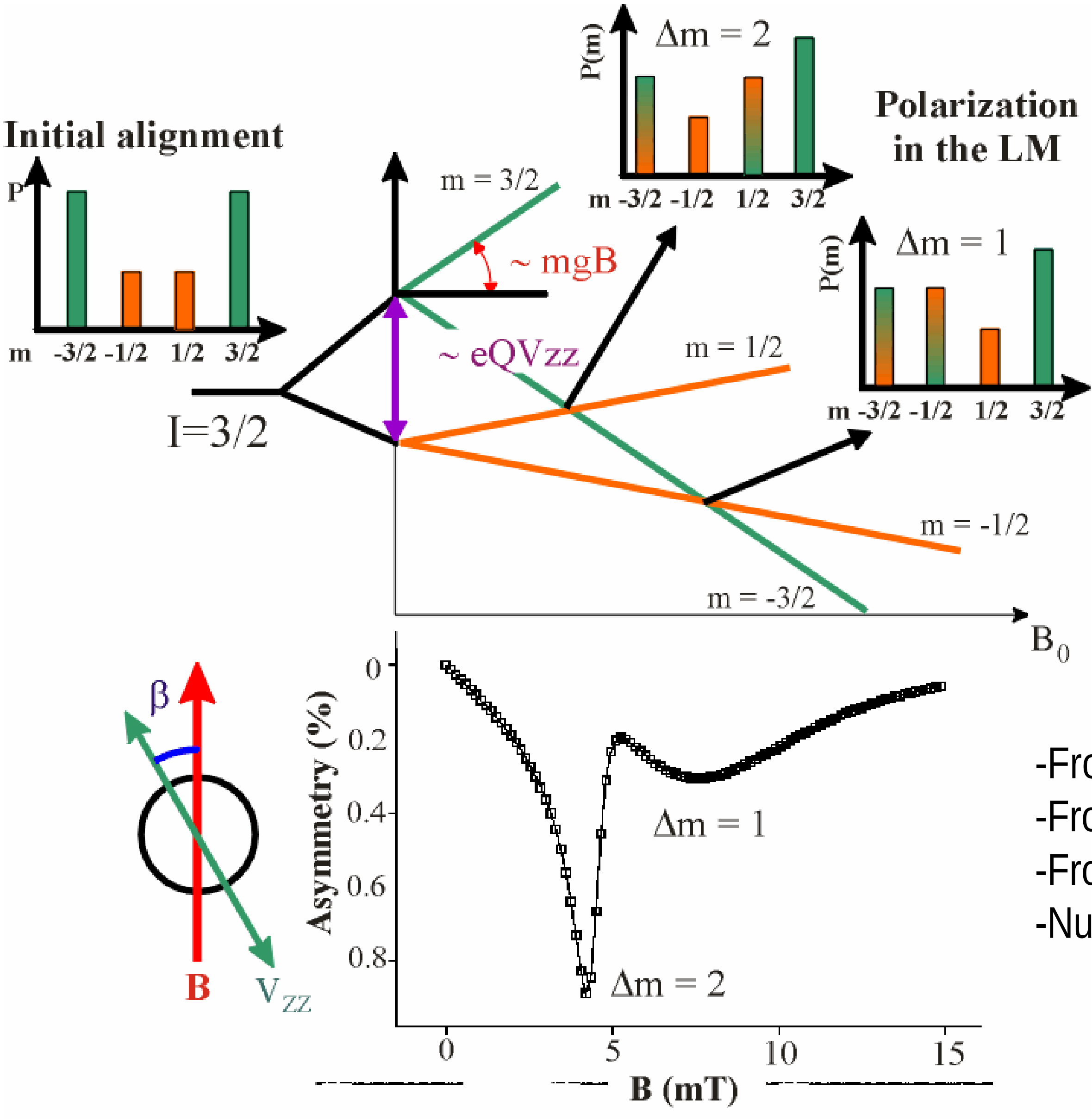
$$H = -\bar{\mu}_z \bar{B}_z + \bar{\mu}_x \bar{B}_x + \frac{\hbar}{\omega_Q}(3\bar{I}_z^2 - \bar{I}^2)$$

$$E_m = \hbar\omega_Q[(3m^2 - I(I+1)] - \hbar\omega_L\, m \cos\beta + \hbar\omega_L\, m \sin\beta$$





β–LMR (Level Mixing Resonance)



Transfer of alignment into polarization

-From the position	ν_Q/μ
-From the amplitude	orientation
-From the width	angle β
-Number of resonances	spin I

<u>at crossing field:</u> $E_{m1} = E_{m2}$

If angle β occurs between V_{zz} and B → breaking of axial symmetry (small)

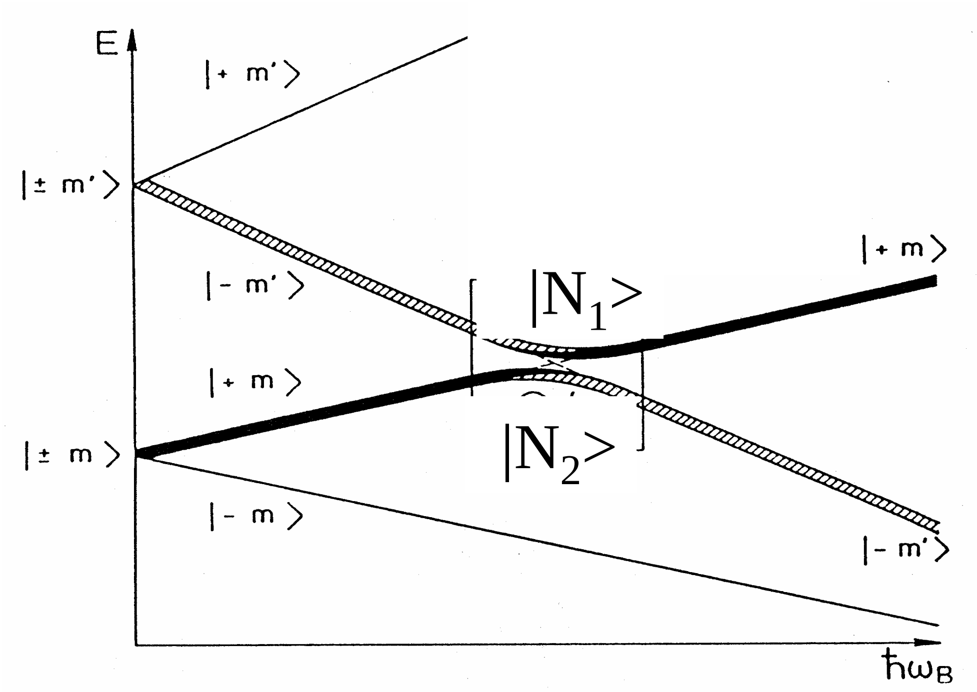
Make a two-level approximation, apply perturbation theory

$$|N_1\rangle = \frac{1}{\sqrt{2}}\{|m_1\rangle - |m_2\rangle\}$$

$$|N_2\rangle = \frac{1}{\sqrt{2}}\{|m_1\rangle + |m_2\rangle\}$$

⇒ $p(N_1) = p(N_2)$

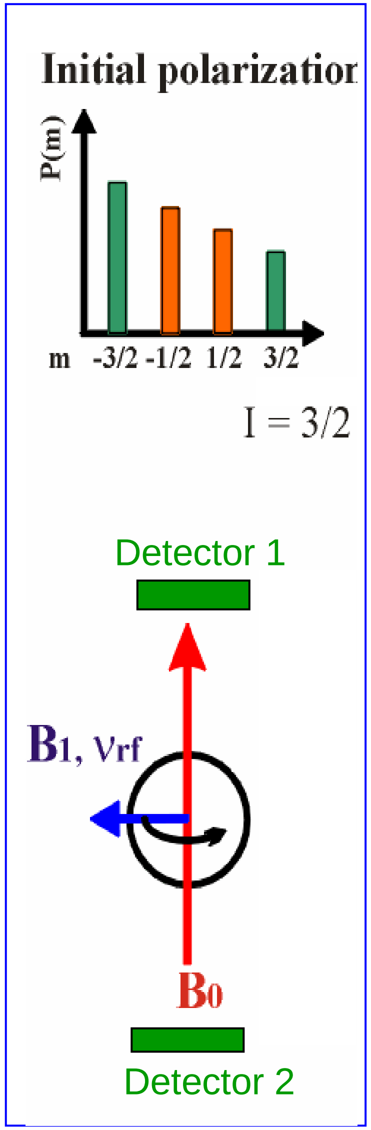
⇓



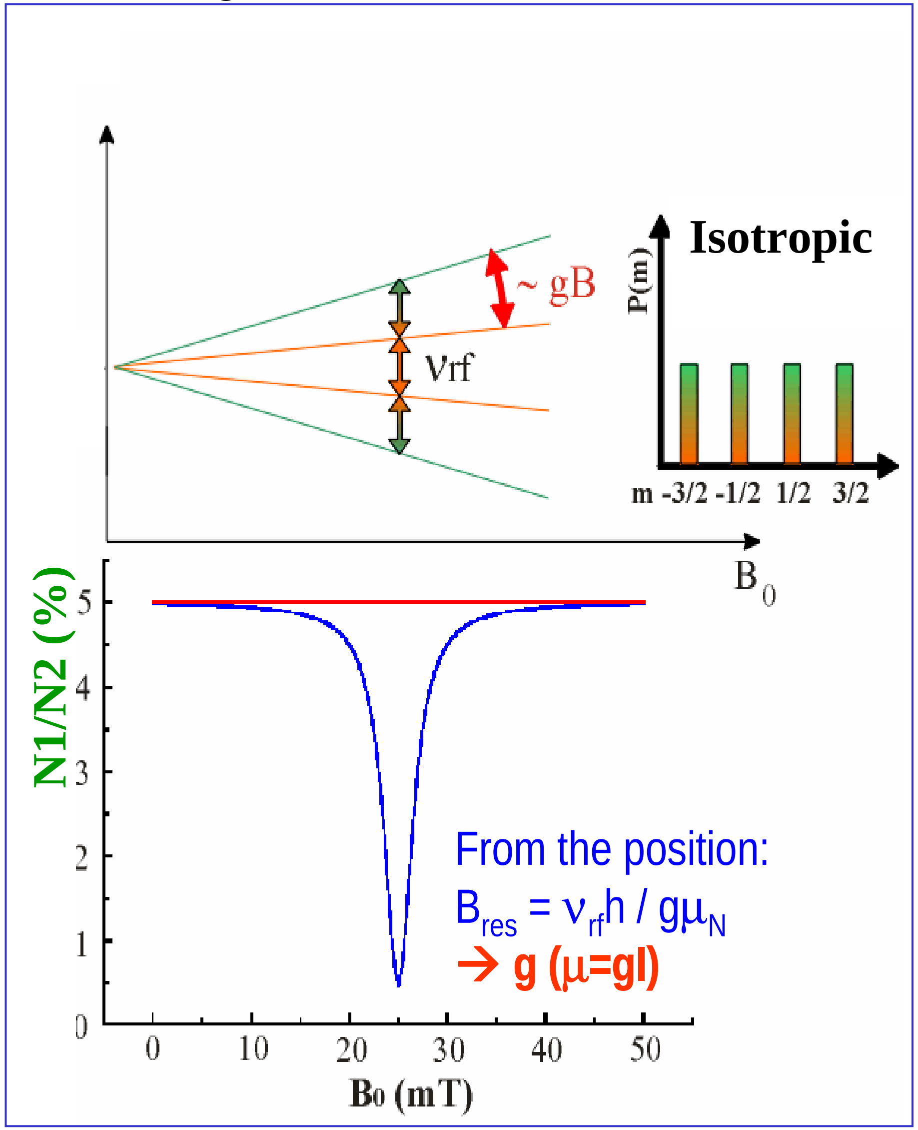
Conclusion: **change in orientation**

Visible as a resonance in the asymmetry of β-decay

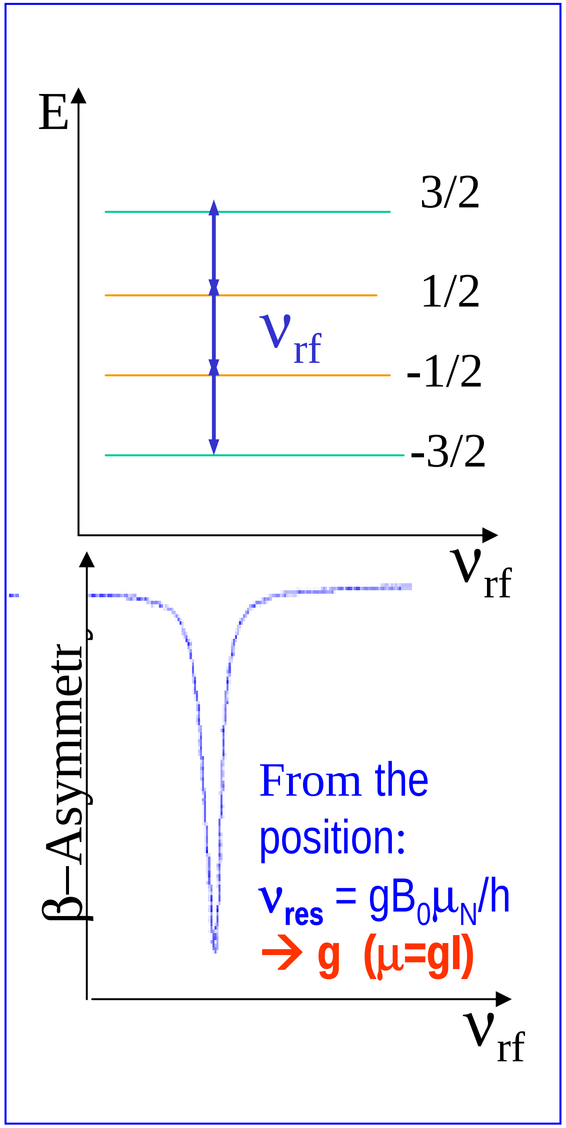
β–NMR (Nuclear Magnetic Resonance)



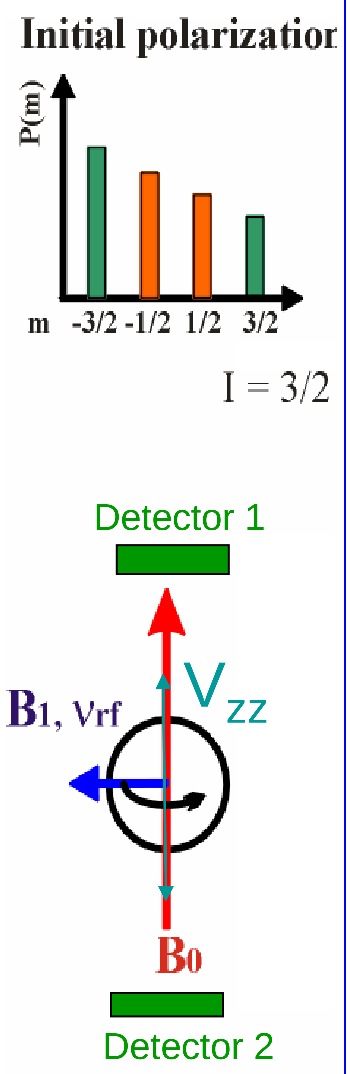
Magnetic field as variable



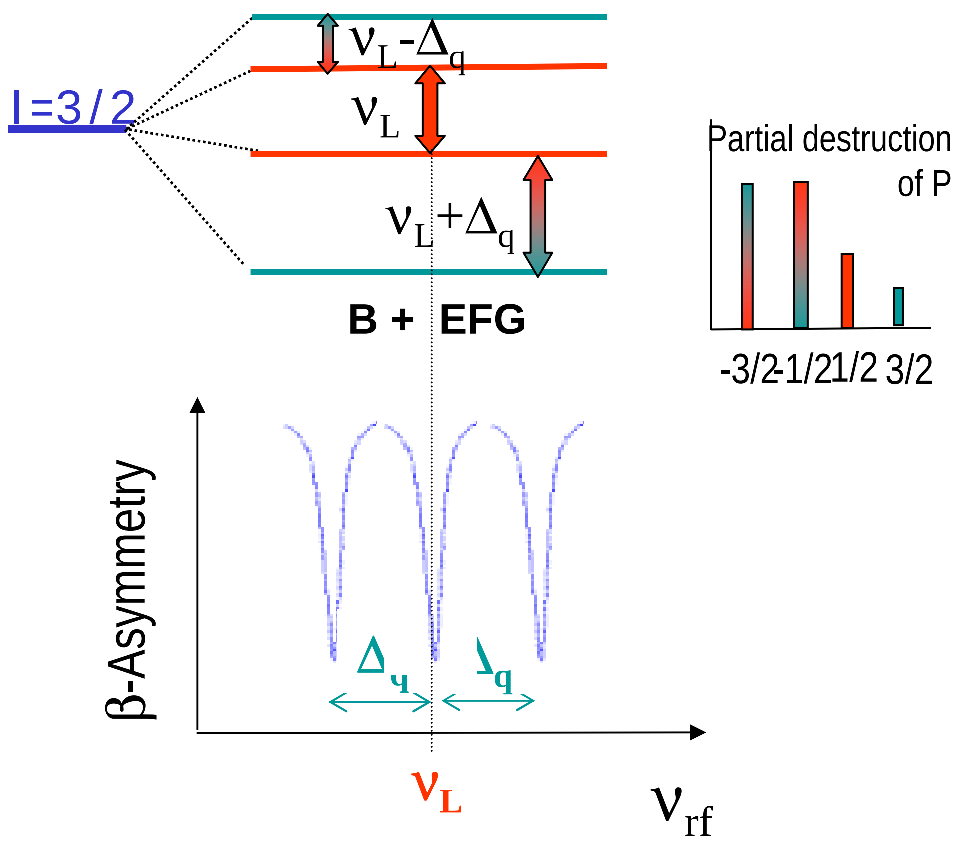
Rf-Frequency as variable



β–NQR (Nuclear Quadrupole Resonance)



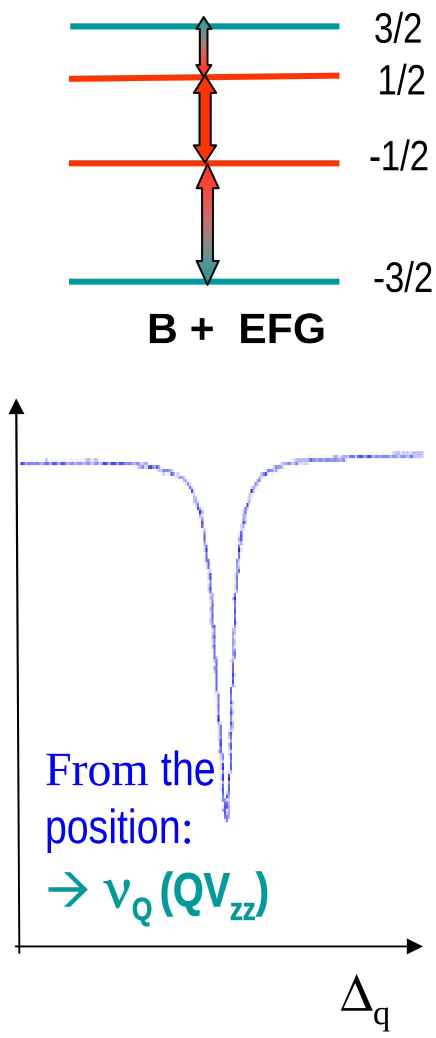
Rf-Frequency as variable



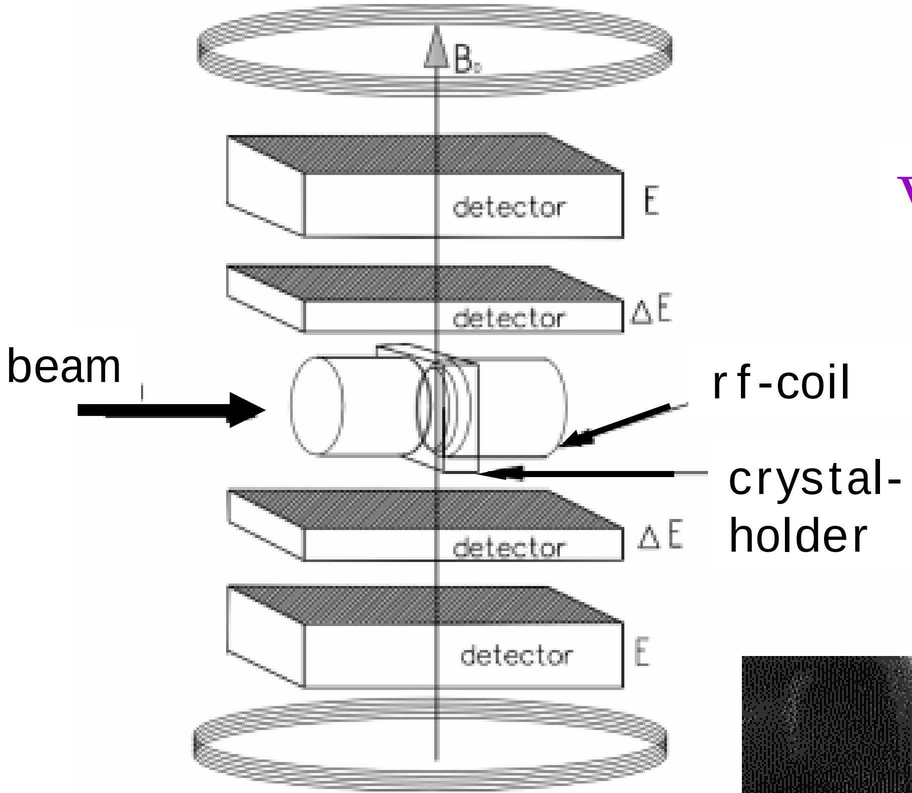
From the positions:

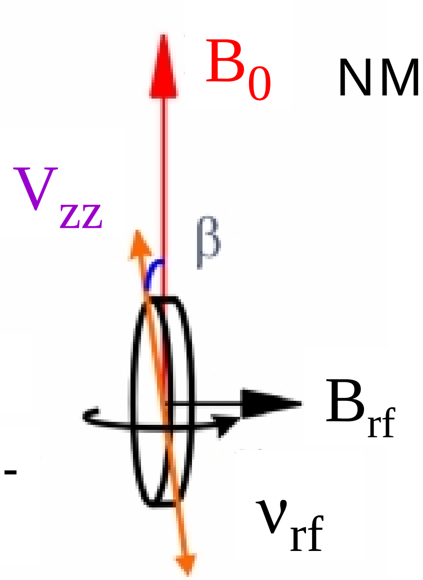
$\nu_L \rightarrow$ **g (μ=gI)** $\quad \Delta_q = \frac{1}{2}\nu_Q \rightarrow$ **Q,V_{zz}**

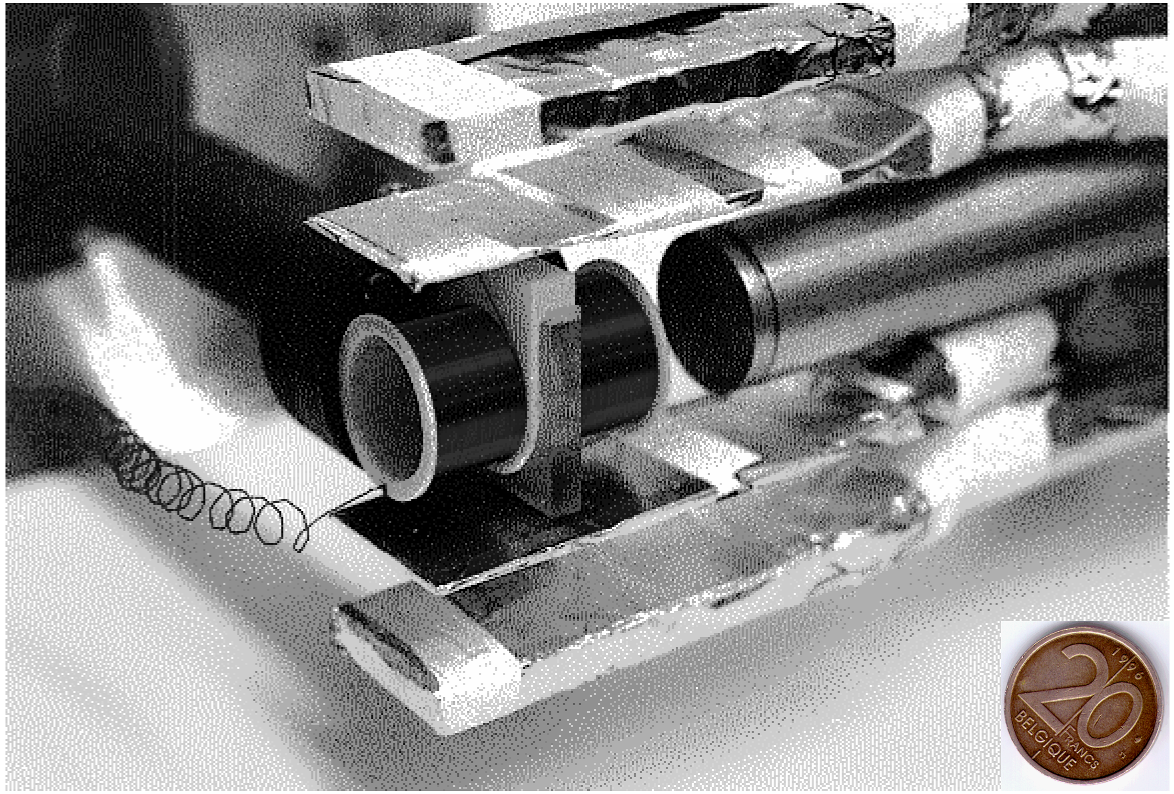
3 rf simultaneously



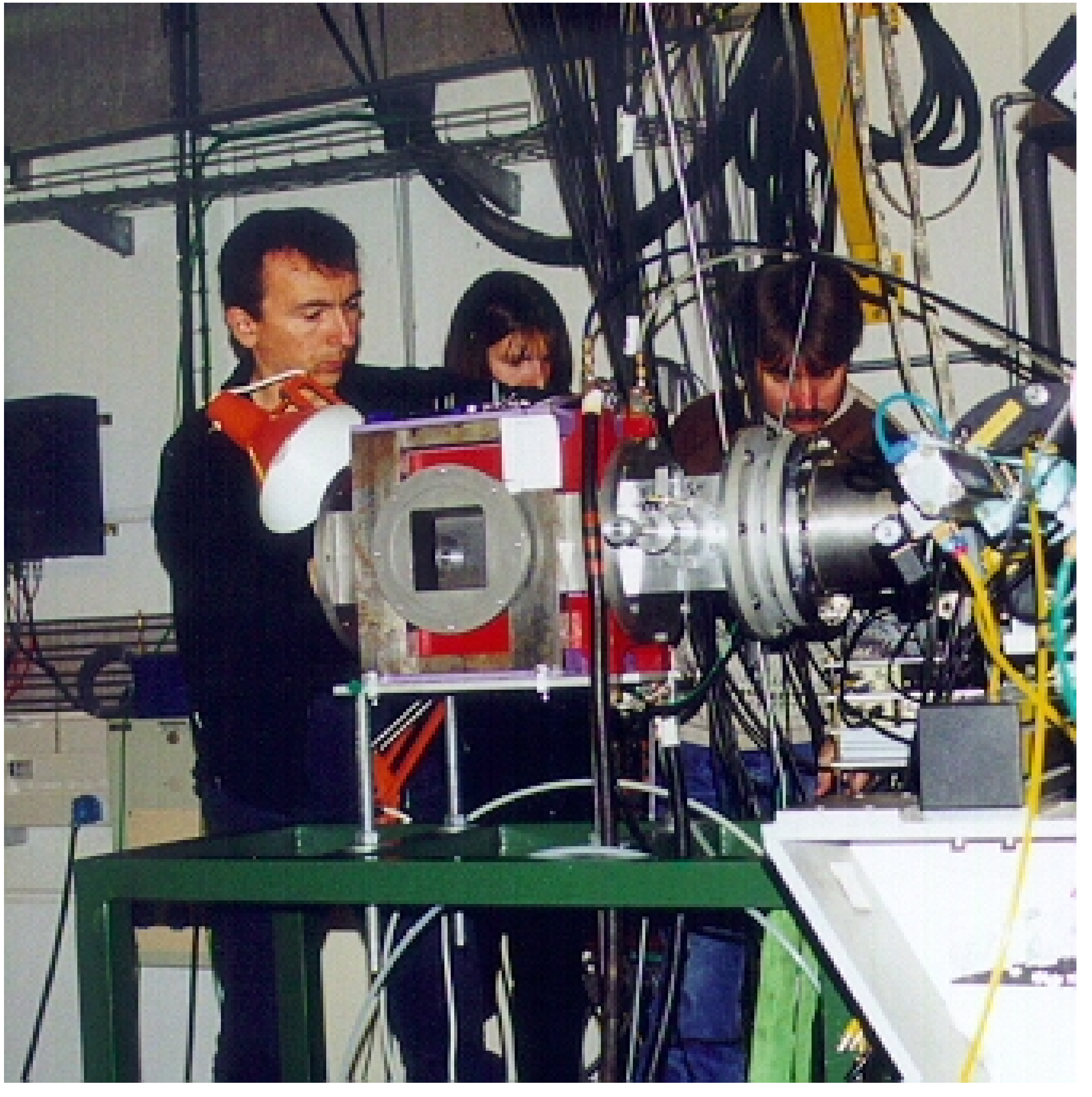
NMR-LMR setup at GANIL







Sideview set-up



NMR-LMR setup at GANIL