中国原子能科学研究院
CHINA INSTITUTE OF ATOMIC ENERGY

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Study of Dependence of Quasi-Particle Alignment on Proton and Neutron Numbers in A= 80 Mass Region through g-factor Measurements

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- **Summary**

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1, Background

g-factor

$$\mu = gI = \frac{1}{\mu_N}\int \Psi^*_{J,J} M_Z \Psi_{J,J}\, dt \qquad g \rightarrow \Psi_{J,J}$$

physical quantity to characterize nuclear properties

very sensitive to nuclear structure

g-factor measurements

provide direct and definite information on nuclear structure

Nuclear structure at high spins

in the mid-weight mass region of A= 80

possesses many interesting features

e.g.

Shape co-existence

Structural softness

Strong dependence on spin & particle numbers

Magnetic rotation

Quasi-particle alignment (QPA) in the $g_{9/2}$ orbit

- **QPA(Quasi-particle alignment (QPA) in the $g_{9/2}$ orbit)**
  a significant feature

- **The g-factor measurement of intra-band states can provide direct & unique information on QPA**

g-factor of high-j (g9/2 orbit) protons

positive and large $g_{\pi} = 1.38$

g-factor of high-j (g9/2 orbit) neutrons

negative and small $g_{\nu} = -0.24$

- **The present work**

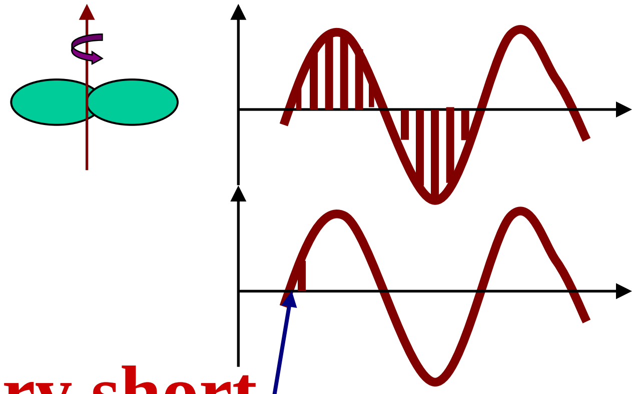
  motivated to measure g-factors of high spin states of ground rotational bands

  in the mass A= 80 region

  in order to study the quasi-particle alignment
- **Experiment performed at HI-13 tandem accelerator in CIAE**

2, Experimental details

- **Requirements**
  in measuring g-factor of high spin states
- **TMF-IMPAD method**
- **Population of high spin states**
- **Data Analysis**



Difficult to measure

g-factors of high spin states:

- **Lifetimes of high spin states are very short usually in the range of sub-ps~ps**

  (Only a very small part of precession can be measured experimentally)

- **Nuclear states of interest are populated by fusion evaporation reactions nuclear precession transfer from higher feeding states to lower states needs to be carefully considered**

  (very complicated)

g-factor measurements of high spin states with short lifetimes requirements:

- Very high magnetic field: ~10^3 T (TMF)
- Knowledge of kinematics from the production of recoil nucleus to its leaving the magnetic foil
- Very precise measurement of precession angle

  $g = 0.31$, $B = 3.68 \times 10^3$ T, tr = 0.25 ps

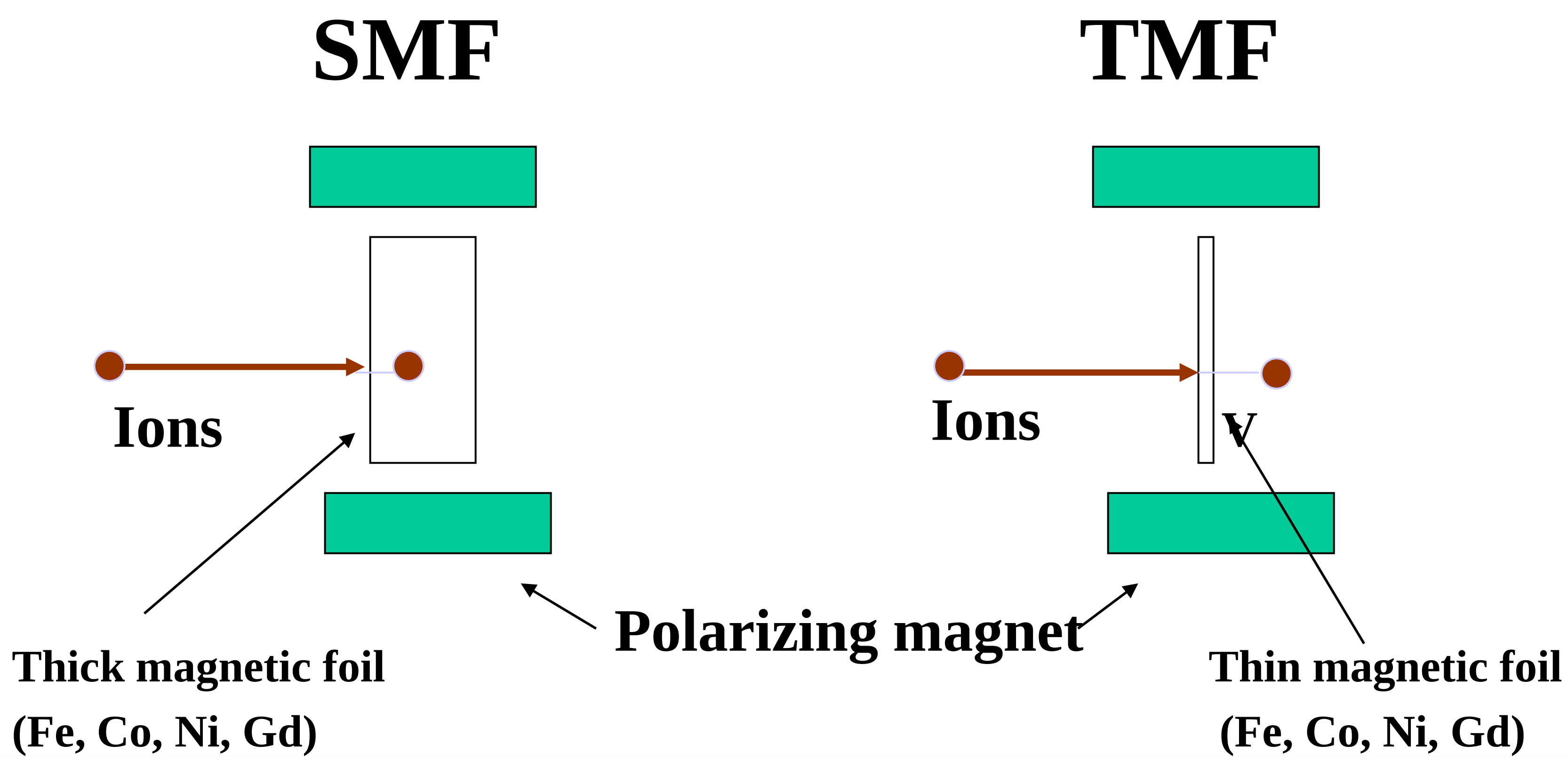
  $\Delta\theta = \omega_L t = 1.63^o$
- Very high resolution γ ray detection due to complicated g ray spectra
- Delicate multi-layer target assembly

Magnetic fields avialable

Type of magnets	Magnetic strength /T	Minimum applicable lifetime/sec
Electro-magnet	~2.5	$\sim 1.0\times 10^{-9}$
Super-conducting magnet	~9	$\sim 2.3\times 10^{-10}$
Static magnetic field（SMF）	~20	$\sim 1.0\times 10^{-10}$
Transient magnetic field（TMF）	~3500	$\sim 6.0\times 10^{-13}$

$g = 0.3$ 和 $\Delta\theta = 1.72^{o}$ used in calculation

T (Tesla) = 10^4 G (gauss)



TMF combined with the time integral perturbed angular distribution (PAD) method is a unique way to measure g-factors of high spin states with short lifetimes

TMF-IMPAD used to measure g-factors of intra-band states of ground rotational bands

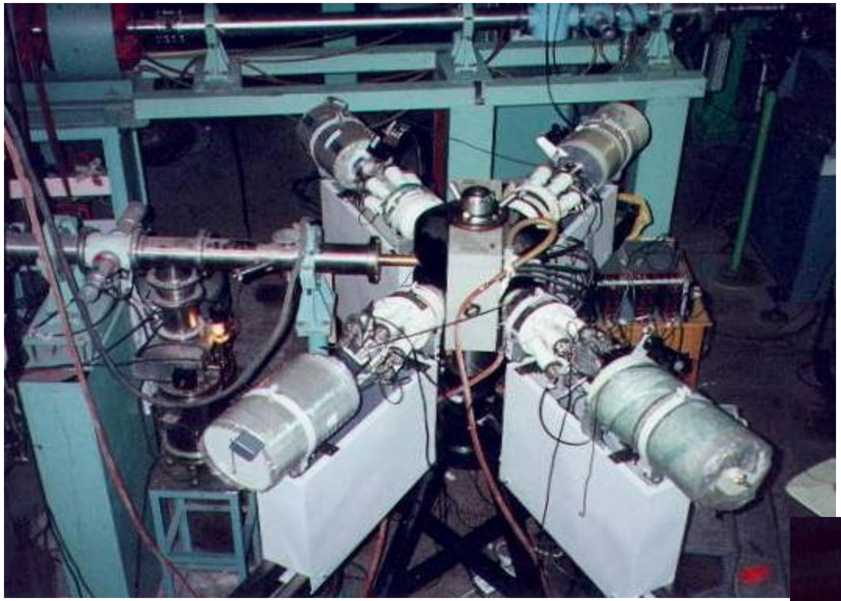
which can precisely determine precession angle $\Delta\theta$

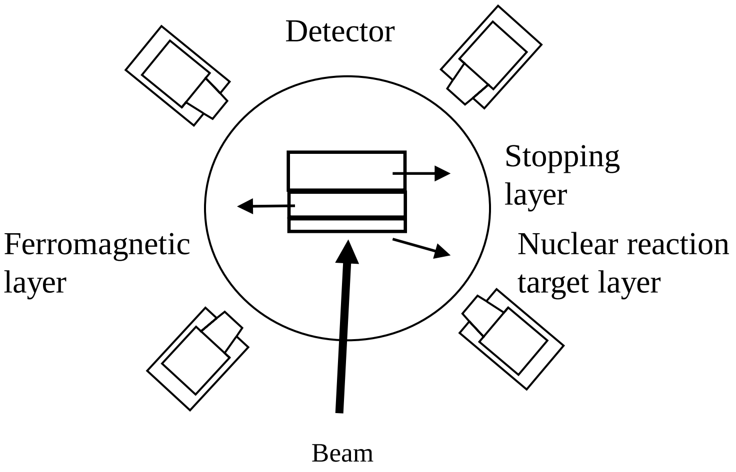
Then g-factor can be deduced through

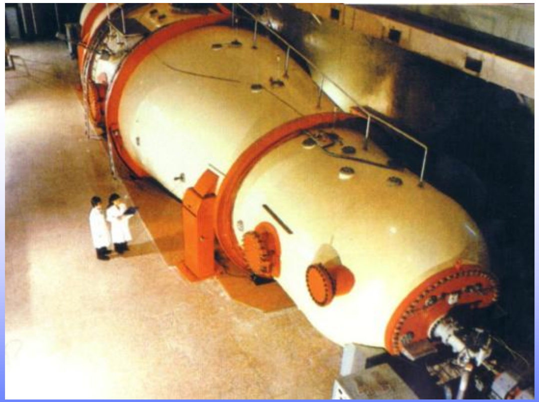
$$g = (\Delta\theta)\,\hbar / B_{TMF}\, t\, \mu_N$$

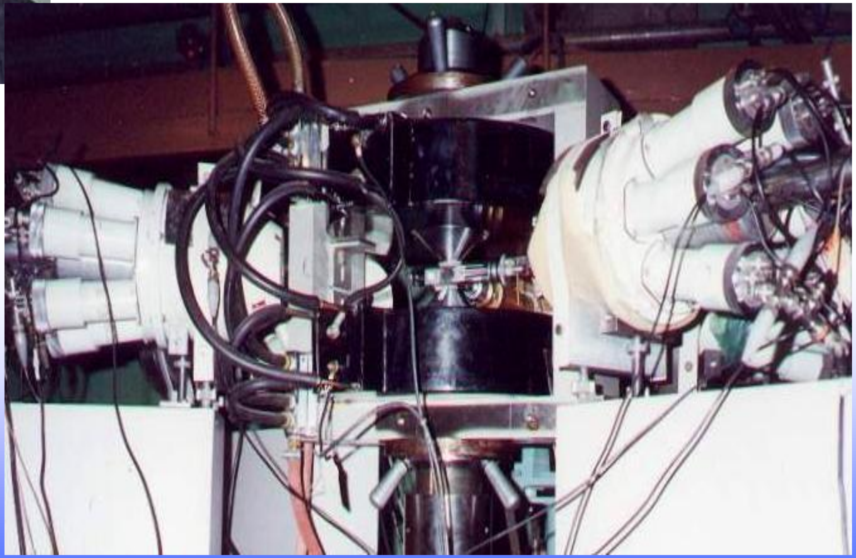
(t precession time)

View of TMF-IMPAD set up at HI-13 tandem



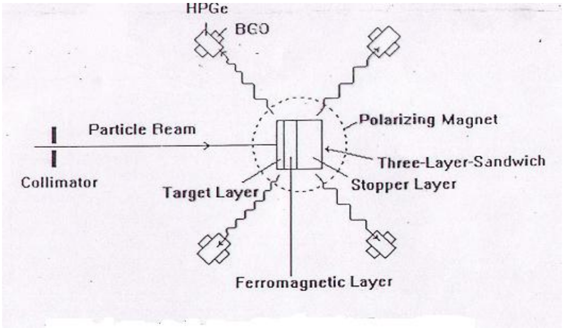


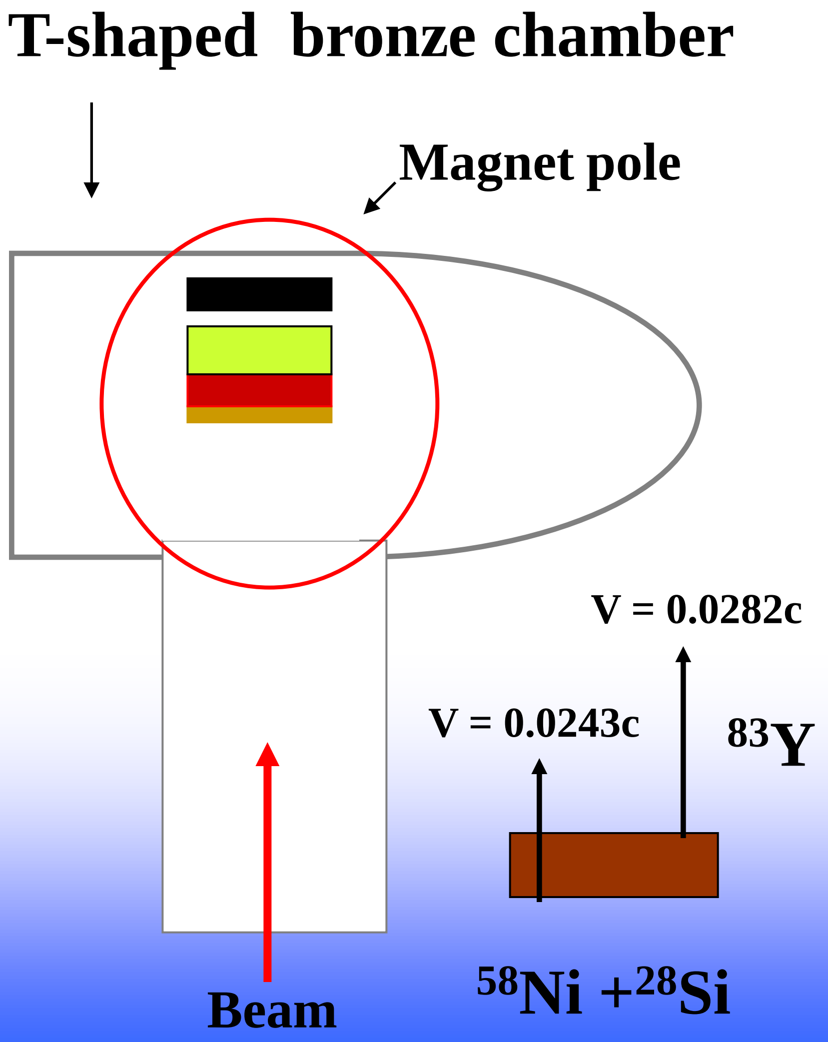




Multi-layer target

- 3-layer target used
- 0.4 mg cm^{-2} target foil enriched to 99.8%
- Ferro-magnetic Fe foil 1.575 mg cm^{-2}
- Cu stopper 12 mg cm^{-2}
- Ta beam catcher 800 mg cm^{-2}





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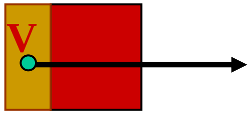
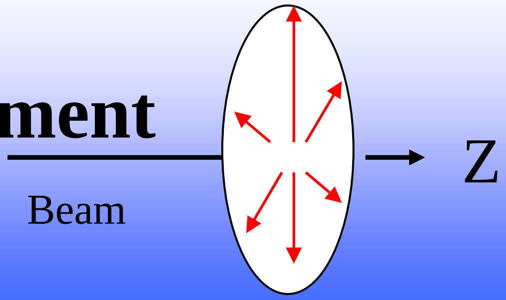
Population of high spin states by fusion evaporation reactions

- **Large nuclear reaction cross section**
- **Many nuclides simultaneously produced**
- **Populating all high spin states of interest**



- **High velocity of recoil nuclides**
- **Large angular momentum transfer**

& high degree of nuclear alignment important for TMF-IMPAD measurement



The high spin states

of the ground rotational band

in ^{82}Sr, ^{83}Y, ^{84}Zr, ^{85}Nb, ^{85}Zr and ^{86}Zr

were populated by the fusion-evaporation reactions with the heavy ion beams

from the HI-13 tandem accelerator at CIAE

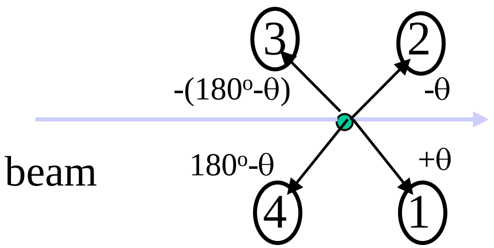
- ^{58}Ni(^{28}Si,3p)^{83}Y E_{Si}= 98 MeV σ~ 230 mb
- ^{58}Ni(^{28}Si,4p)^{82}Sr E_{Si}=110MeV σ~103 mb
- ^{58}Ni(^{28}Si,p2n)^{85}Nb E_{Si}=110MeV σ~ 50 mb
- ^{60}Ni(^{28}Si,2pn)^{85}Zr E_{Si}= 98MeV σ~ 160 mb
- ^{58}Ni(^{28}Si,2p)^{84}Zr E_{Si}= 98 MeV σ~ 40 mb
- ^{58}Ni(^{32}S,4p)^{86}Zr E_{S} = 110 MeV σ~ 125 mb

projectile energies and reaction cross sections calculated by a Cascade program and a PACE4 program

Data Analysis

Double ratio constructed from the field up & down counts to infer the nuclear precession of a state

$$\rho = \frac{\rho_{12}}{\rho_{34}}$$



$$\rho_{12} = \frac{N_1^{\uparrow}}{N_1^{\downarrow}} \frac{N_2^{\downarrow}}{N_2^{\uparrow}} \qquad \rho_{34} = \frac{N_4^{\uparrow}}{N_4^{\downarrow}} \frac{N_3^{\downarrow}}{N_3^{\uparrow}}$$

ρ_{12} and ρ_{34} single ratios formed with the counts $N^{\uparrow}$and $N^{\downarrow}$ of ±θ detector pair and ±(180º-θ) detector pair for an interested transition

The average precession angle Δθ deduced from

$$\Delta\theta = \varepsilon / S(\theta) \qquad \varepsilon = \frac{\rho - 1}{\rho + 1} \qquad S(\theta) = \frac{1}{W(\theta)}\frac{dW(\theta)}{d\theta}$$

g-factor obtained from the precession Δθ and transient field B_{TMF}

$$g = \frac{-\Delta\theta\,\hbar}{\mu_N \int_{in}^{out} B_{TMF}(t) e^{-t/\tau} dt}$$

$$B_{TMF}(v) = 96.7(v/v_0)^{0.45} Z^{1.1} \mu_B N_p$$

μ_N the nuclear magneton, τ the mean lifetime of nuclear stat, S(θ) logarithmic slope of γ-ray angular distribution, the integration runs over the recoiling ion entry to exit times of the ferromagnetic Fe layer. The parameterization of transient magnetic field B_{TMF}(t) given by Shu et al (Phys.Rev., C21 (1980) 1828)

the Bohr velocity, the velocity of the recoiling nuclei that depends on time.

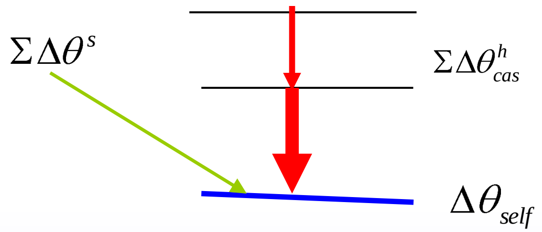
B_{TMF} interpreted as electron polarization transfer from Fe to the s orbit electron of passing ion

B_{TMF} Fe:Co:Ni:Gd = 1.0:0.8:0.3:1.2, Gd needs low temperature.

Precession transfer correction

- **The precession of a lower state also reflects the precessions of the higher spin states in a cascade transition and the side feeding states**
- **The measured precession of an interested state is an algebraic sum of the precession of itself and the precessions of all states that feed it**

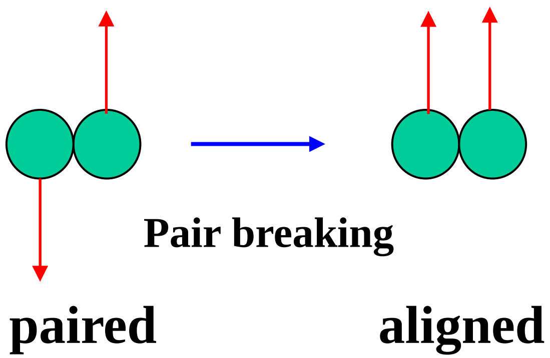
$$\Delta\theta_m = \Sigma\Delta\theta_{cas}^h + \Sigma\Delta\theta^s + \Delta\theta_{self}$$



- **To get the net precession of a certain state a computer program was used to follow the time evolution of the recoiling nucleus from its production in the target to its exit from the Fe foil**

3, Results and discussion

- **Quasi-particle alignment (QPA)**



Dependence of QPA on spin

Dependence of QPA on proton number

Dependence of QPA on neutron number

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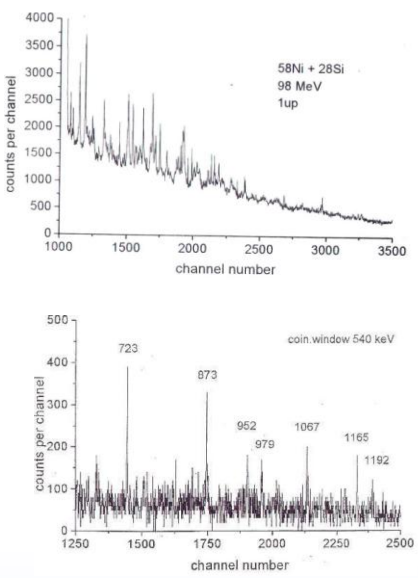
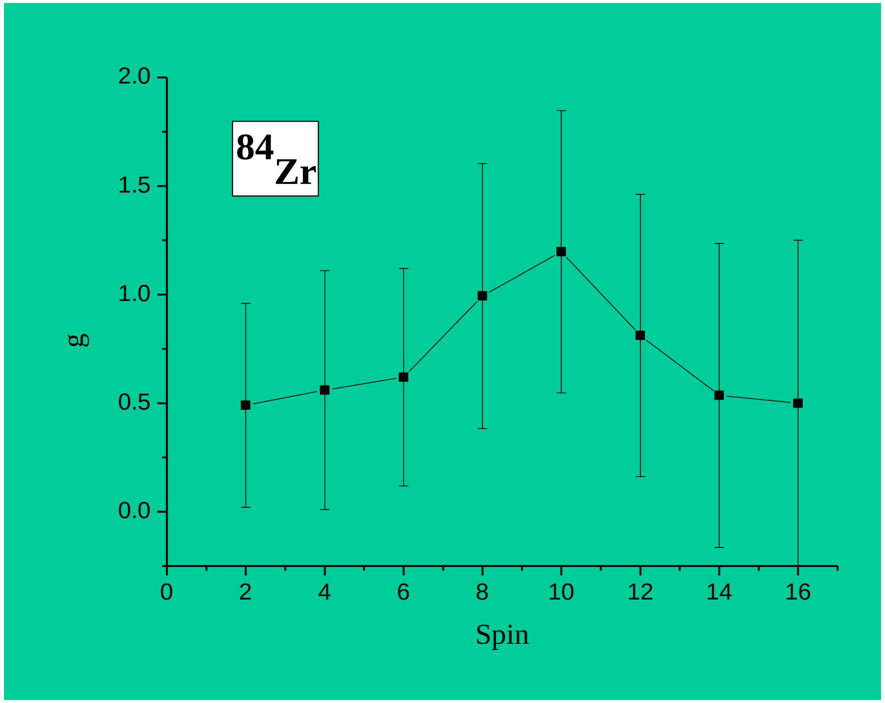
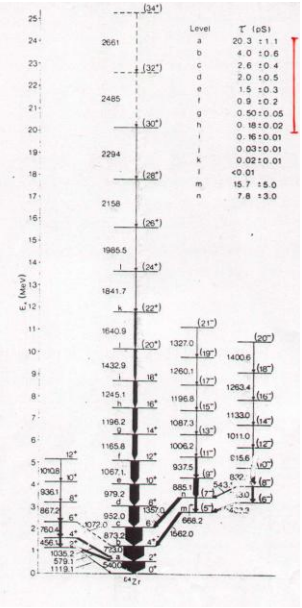
Dependence of quasi particle alignment on spin

^{84}Zr



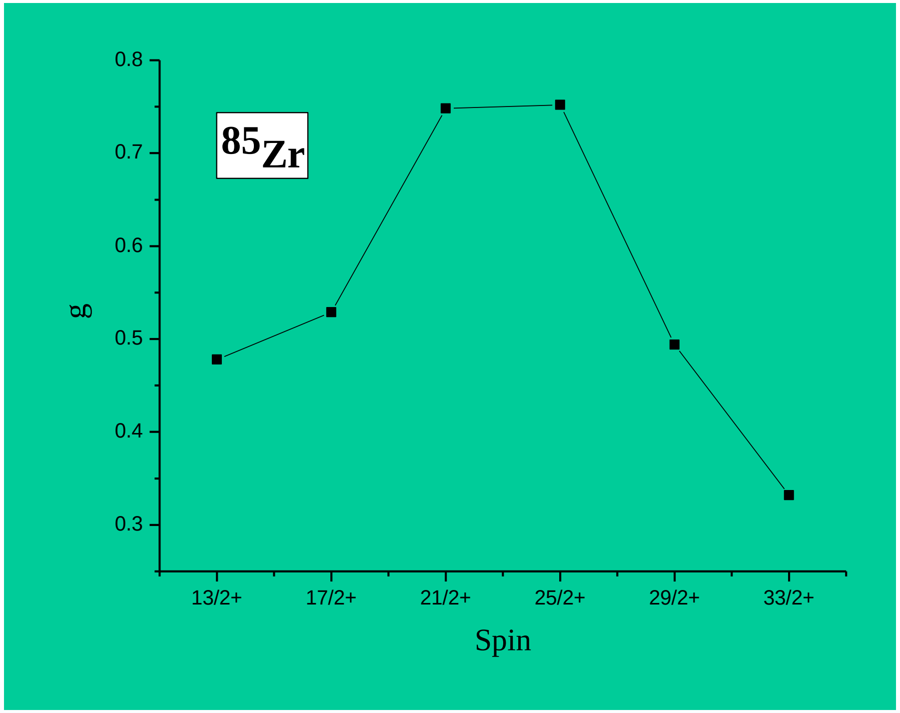


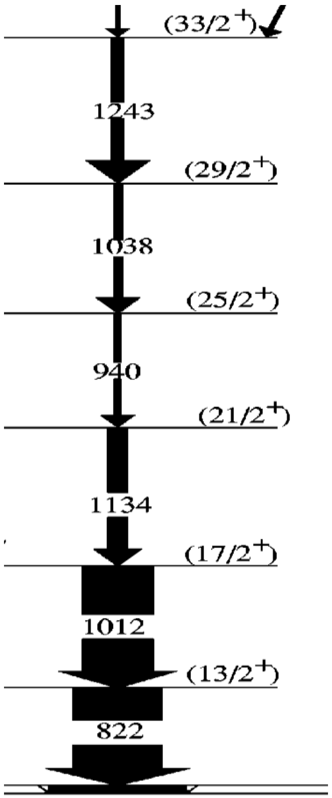


$g_{9/2}$ proton alignment first

then followed by $g_{9/2}$ neutron alignment

^{85}Zr

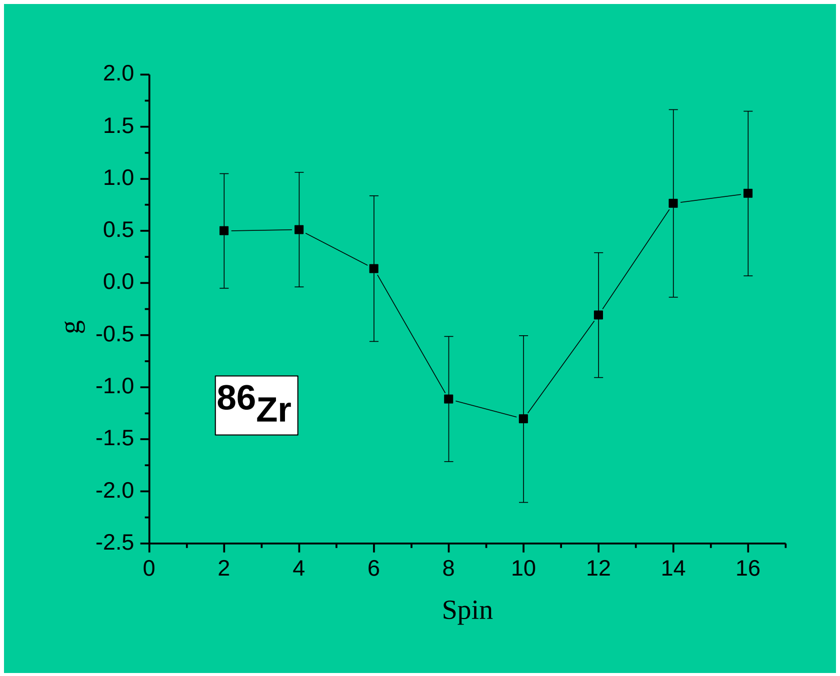




$g_{9/2}$ proton alignment first

then followed by $g_{9/2}$ neutron alignment

^{86}Zr



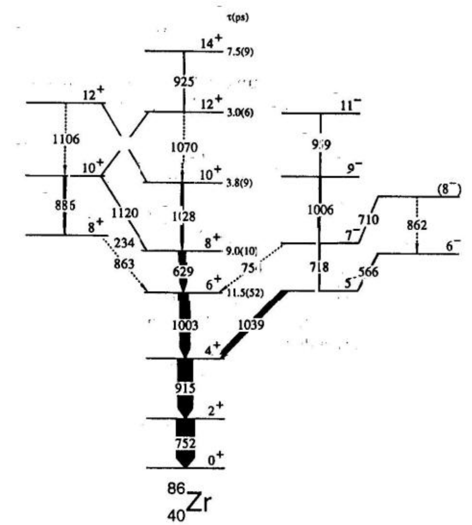
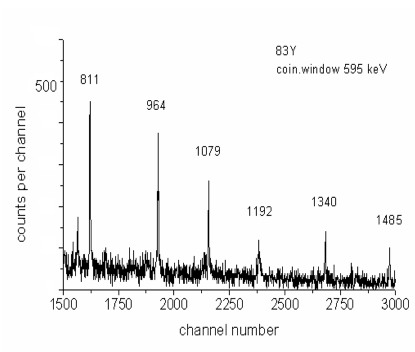


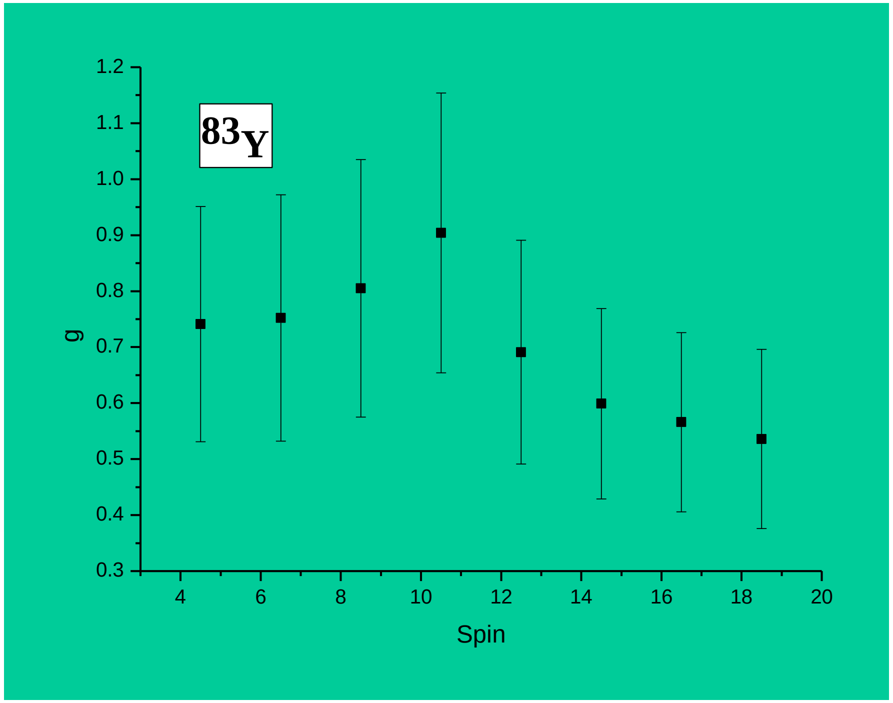
FIG. 1. ^{86}Zr energy levels observed in the $^{12}C(^{77}Se,3n)^{86}Zr$ reaction at 260 MeV. Transition energies are in keV. The transitions indicated by dotted lines were either doublets, contaminations or very weakly observed.

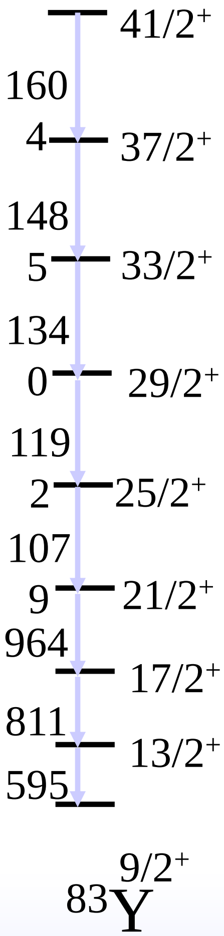
$g_{9/2}$ neutron alignment first

then followed by $g_{9/2}$ proton alignment

^{83}Y



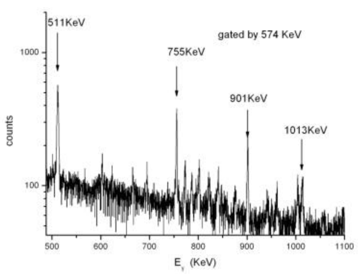


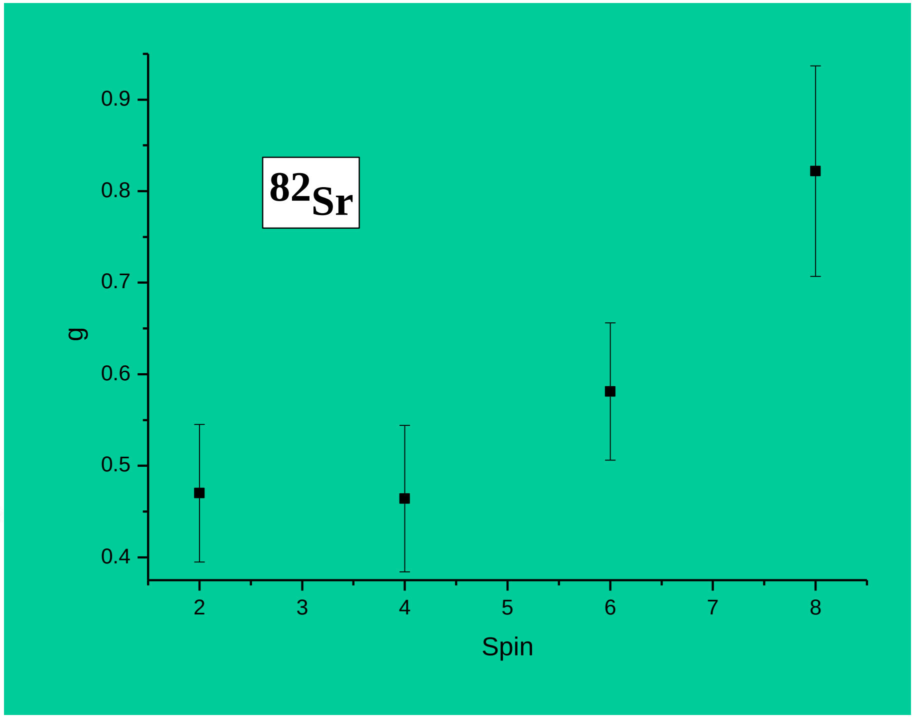


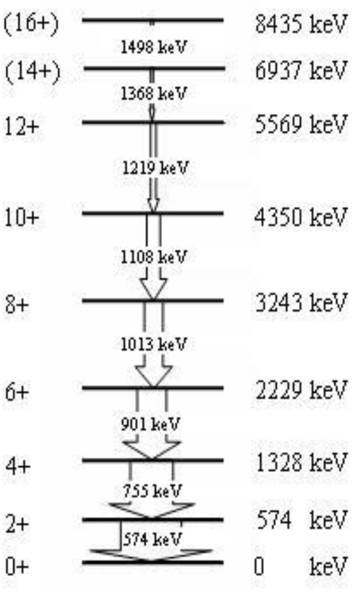
$g_{9/2}$ proton alignment first

then followed by $g_{9/2}$ neutron alignment

^{82}Sr

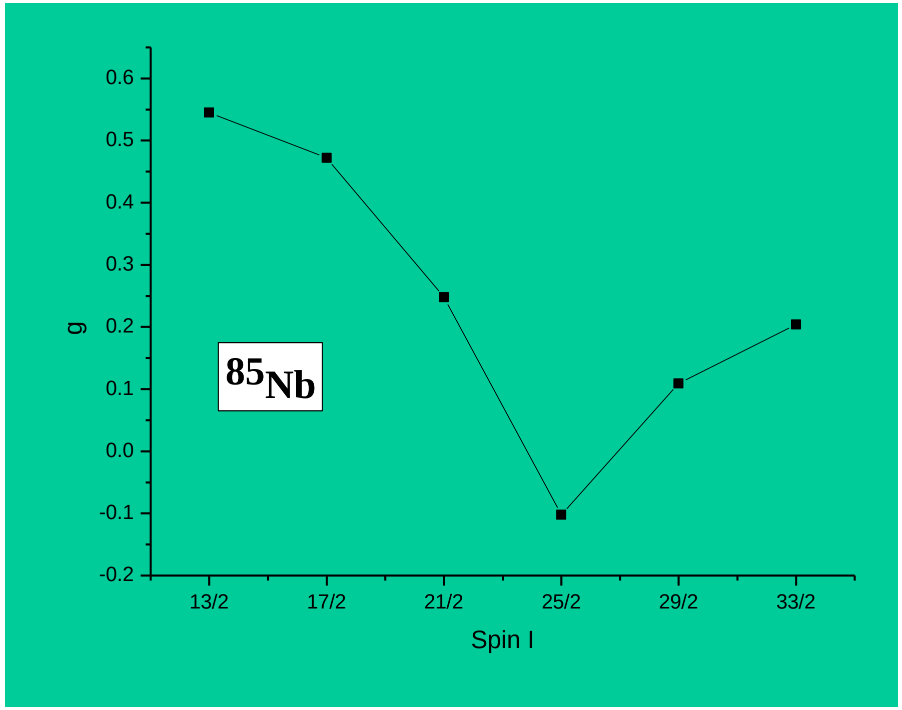


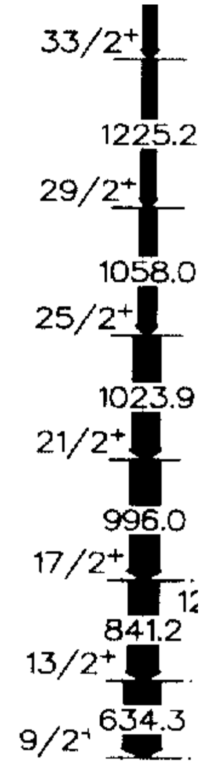




$g_{9/2}$ proton alignment only

^{85}Nb





$g_{9/2}$ neutron alignment first

then followed by $g_{9/2}$ proton alignment

Rotor Plus three particle model

g-factor calculation

- **Empirical formula**

  based on Cranking shell model

$$g(\omega) = g_g + (g_{jp} - g_g)\frac{i_p(\omega)}{I_x(\omega)} + (g_{jn} - g_g)\frac{i_n(\omega)}{I_x(\omega)}$$

i_p (ω) : proton aligned angular momentum
i_n (ω) : neutron aligned angular momentum
I_x (ω) : total aligned angular momentum
g_{jp}: g-factors for the aligned protons
g_{jn}: g-factors for the aligned neutrons
g_g: g-factor close to g_R (~Z/A)
for the collective rotation

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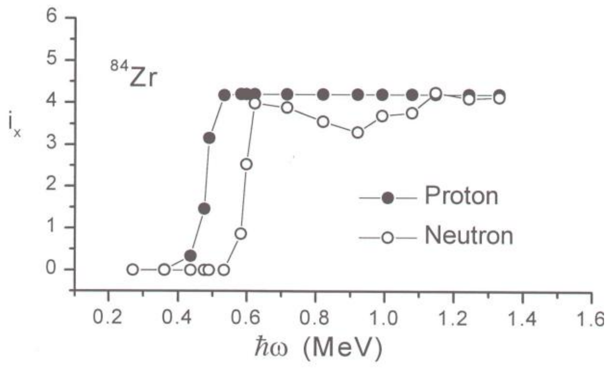
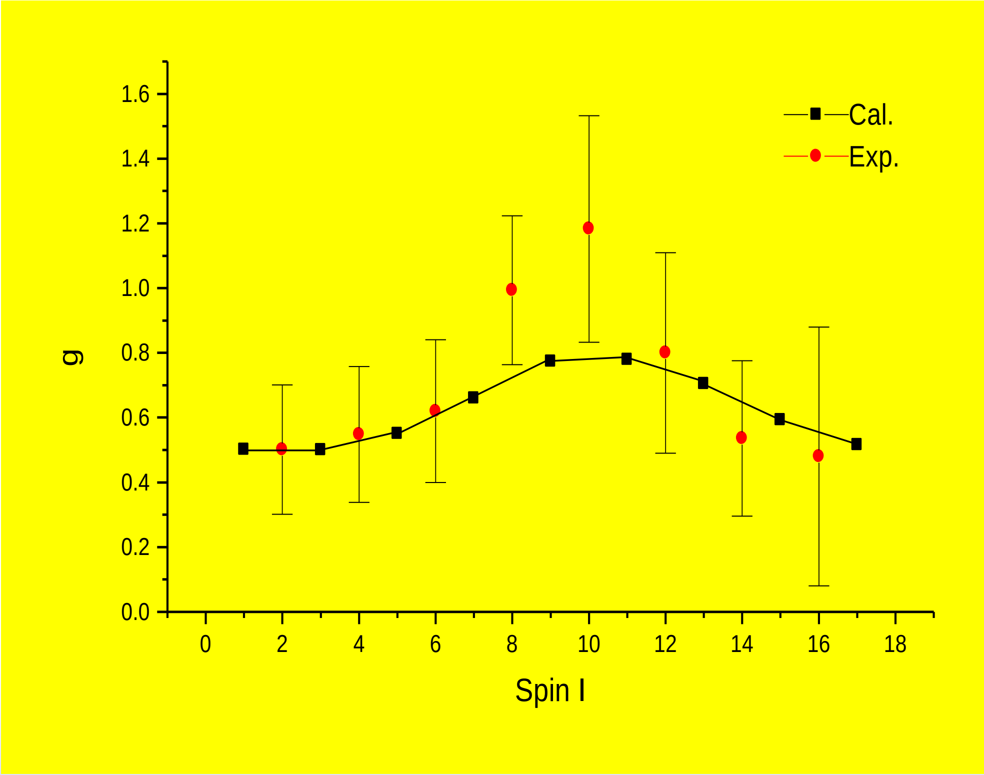
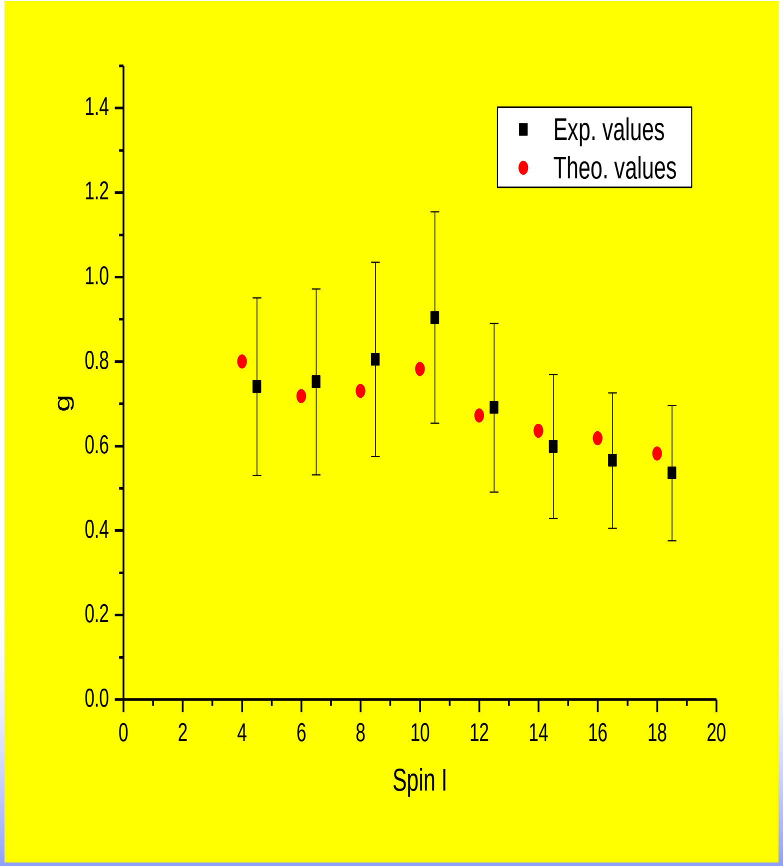
Calculated and measured g-factors for ^{84}Zr





Due to soft to hard structure transition
the calculated g-factors near the peak are lower

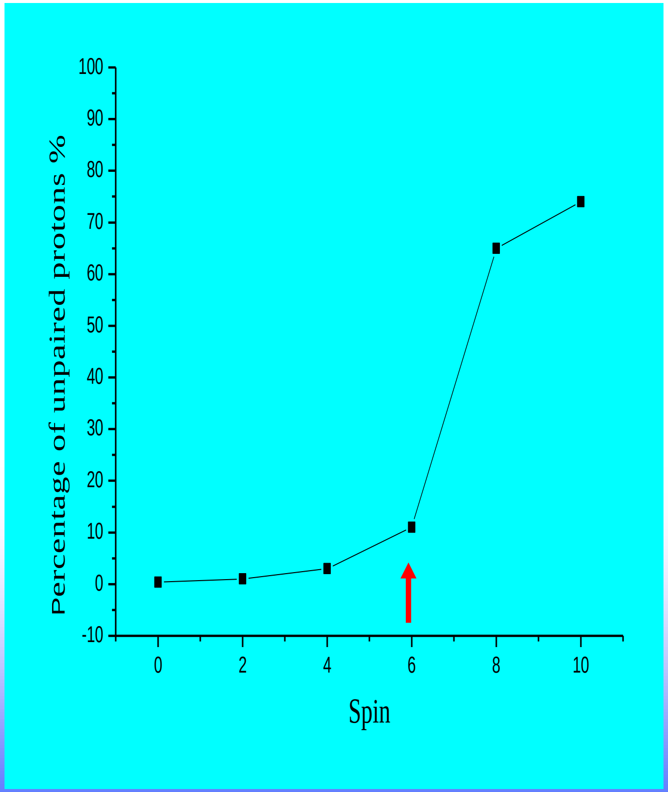
Calculated and measured g-factors for ^{83}Y

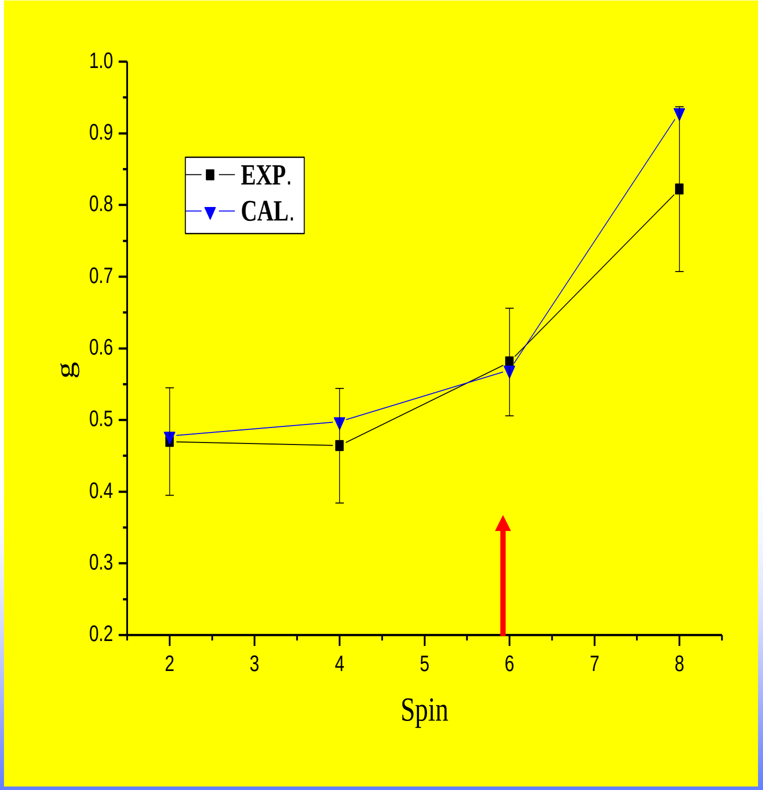


A rotor plus two-particle model (PRM) for ^{82}Sr

^{80}kr even-even core as a rotor

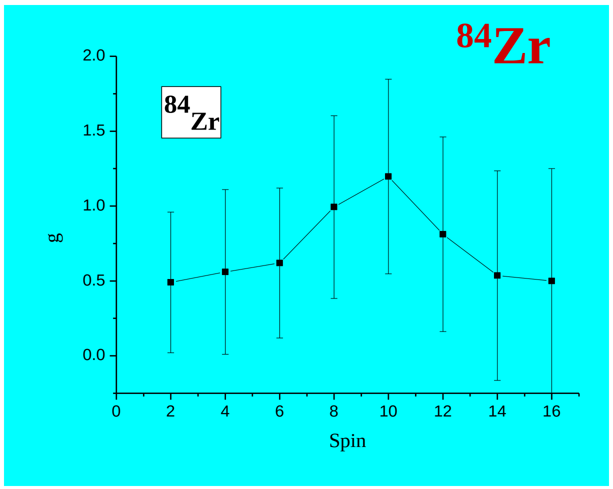
two valence protons outside the core as two particles

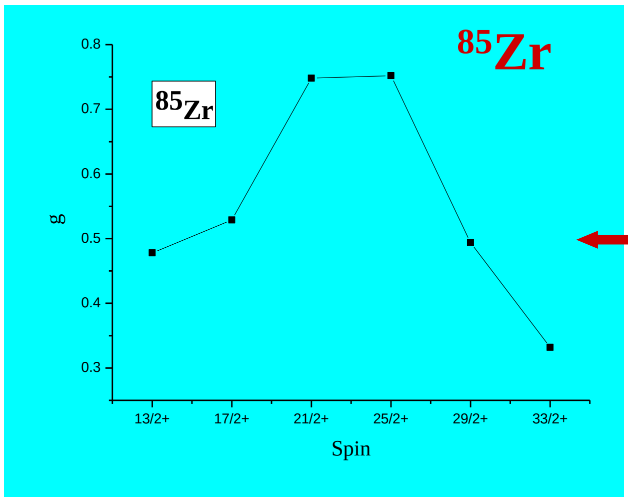


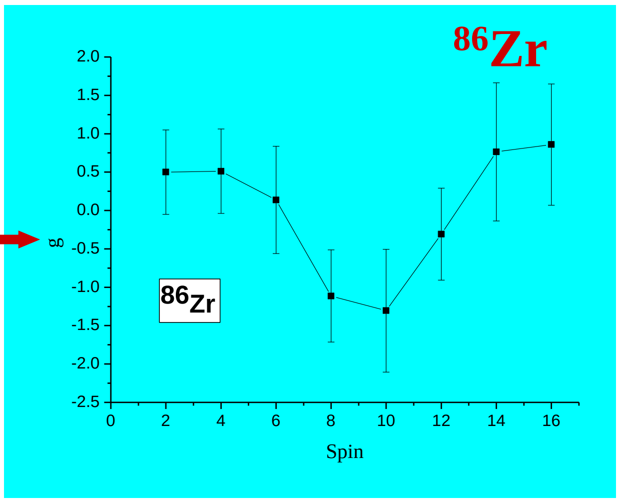


- **Dependence of QPA on neutron number**

Z=40：^{84}Zr、^{85}Zr、^{86}Zr







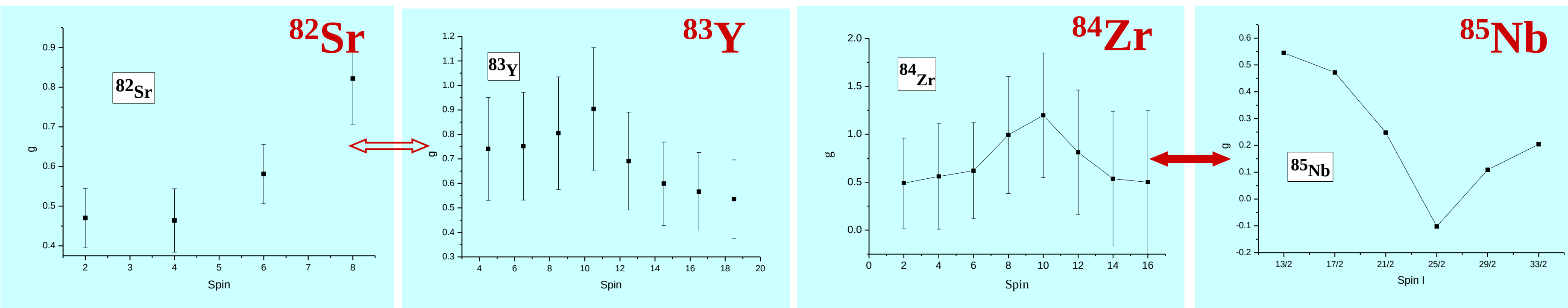
N=44
Proton alignment followed by neutron alignment

N=45
Proton alignment followed by neutron alignment

N=46
neutron alignment followed by proton alignment

- **Dependence of QPA on proton number**

N=44 ^{82}Sr(38)、^{83}Y(39)、^{84}Zr(40)、 ^{85}Nb(41)



Z=38
Proton alignment only

Z=39
Proton alignment followed by neutron alignment

Z=40
Proton alignment followed by neutron alignment

Z=41
Neutron alignment followed by proton alignment

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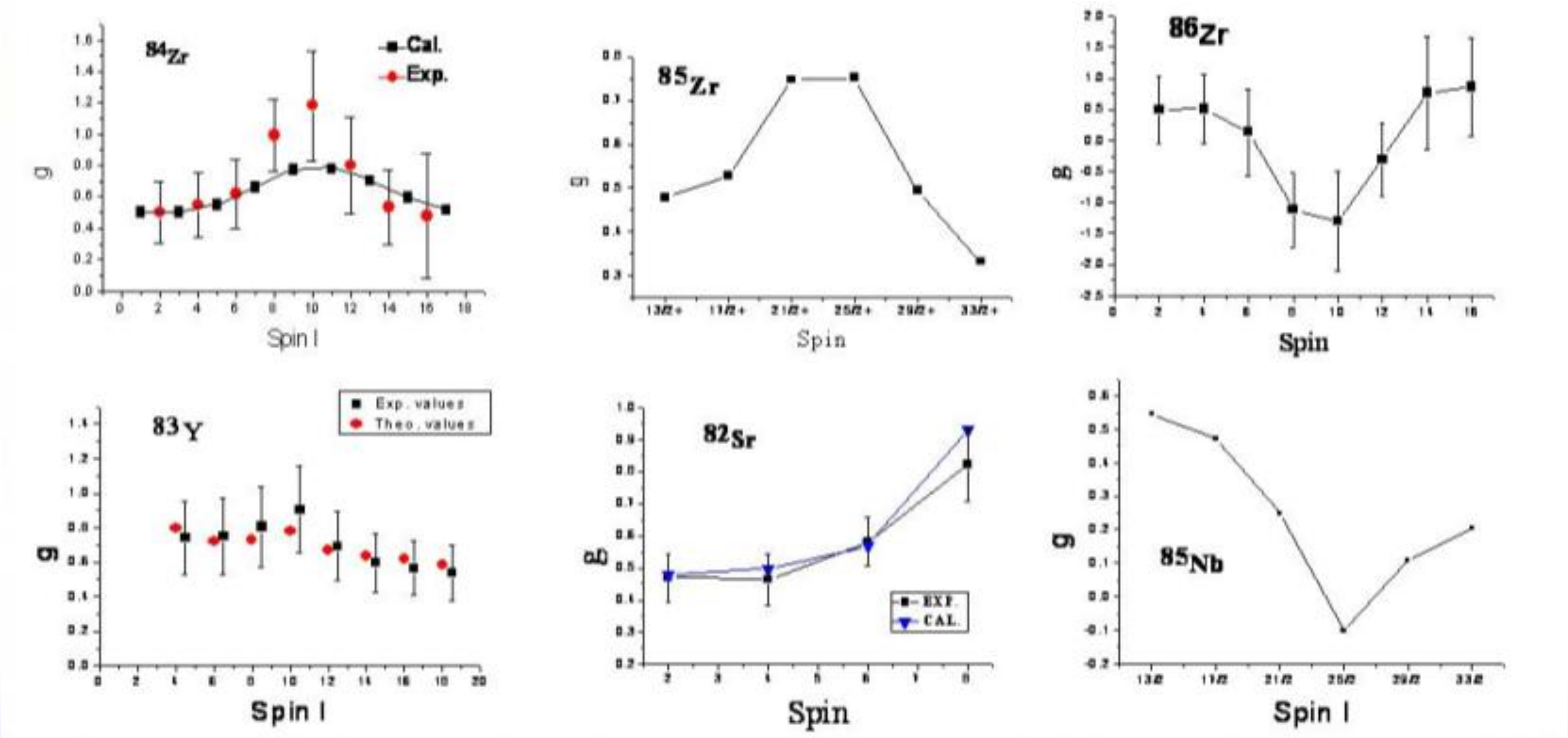

Summary of the results

Quasi-particle alignments to large extent depend on

Spin

proton number

neutron number

Quasi-particle alignments lead to different patterns of variation of g factor with spin

4, Summary

- **The g-factor is a good probe to study QPA**
- **The QPA was well investigated for ^{82}Sr, ^{83}Y, ^{84}Zr, ^{85}Nb, ^{85}Zr and ^{86}Zr through g-factor measurements**
- **The quasi-particle alignments lead to different patterns of variation of g factor with spin**
- **The alignments depend on the quasi-particle number**

① For the nuclides with Z=40 the proton alignment is followed by the neutron alignment in ^{84}Zr and ^{85}Zr, while the neutron alignment is followed by the proton alignment in ^{86}Zr

②For the nuclides with N=44 the proton aligns only in ^{82}Sr, the proton aligns first and then the neutron starts to align at higher spins in ^{83}Y and ^{84}Zr and the neutron alignment is followed by the proton alignment in ^{85}Nb

Thank You !