Experimental nuclear spectroscopy :Trieste IAEA April 2005

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Lecture 1 : Content

Books

Energies and lifetimes

Observables & quantum numbers

Example : quantum numbers in ^{124}Xe

Nuclear shapes : soft or rigid?

Shape parameters beta and gamma vs $q_2$and q_3

Shape parameters from restricted data : examples

Books: **Experimental nuclear spectroscopy** is a broad subject. A few excellent books:

R. F. Casten: Nuclear Structure

A. Bohr and B. R. Mottelson: Nuclear structure

H. Ejiri, M. J. A. de Voigt Nuclear Spectroscopy

H. Morinaga and T. Yamazaki. Gamma spectroscopy

D. N. Poenaru and W. Greiner: Experimental techniques

R. Bock: Heavy ion collisions Vol 1-3

Introduction: States, energies, widths, electromagnetic (em) transitions , quantum numbers

Example: levels in ^{124}Xe vs IBA

States : energies, widths lifetimes and electromagnetic (em) transitions. A quasistationary state $\Psi_0(t)$ - i.e. an excited nuclear state - has a complex energy :

$$\epsilon_0 = \quad E_0 - (i/2)\Gamma_0$$

where E_0 is the energy of the state and Γ_0 is the width of the state. This width is related to the lifetime of the state by the relation :

$$\tau_0 = (h/2\pi)/\Gamma_0$$

The energy of the state can be measured most directly from the mass of the state e.g. in an ion trap. In reactions we generally measure not the energies but energy differences. The lifetime τ_0 can be obtained from the exponential decay of the state

$$| \Psi_0(t) |^2 = A * exp(-t/\tau_0)$$

From the lifetime τ_0 or from partial lifetimes τ_{0k} respectively one obtains the electromagnetic transition probabilities $B(E, M,\lambda)$, which are crucial observables. Of course the partial lifetimes are obtained from the total life time by considering the branched decay.

PS: Some of you may protest. They say Hamiltonians are Hermitean, eigenenergies are real so they don't like the complex energy

$$\epsilon_0 \; = \quad E_0 - (i/2)\Gamma_0$$

Indeed for particle bound states :

$$Re\ \varepsilon_0 = E_0 \gg \Gamma_0.$$

So the energies are nearly real but not "really real". Excited states decay; we can measure their life time very well; so real energies are an approximation.

Observables, Quantum numbers:

Besides the the Hamiltonian H and the energy E_0, there are a number of other important observables and corresponding quantum numbers as e.g

$$H \ , \ I^2 \ , I_z \ , \ \sigma^2 \ , \ T_z$$

$$E \ , \ I(I+1) \ , M \ , \ S(S+1), \ 1/2(N-Z))$$

$$P \ , \ T^2 \ , \ K \ = I_3 \ , \ F^2$$

$$\pi \ , \ T(T+1) \ , K \ , \ F(F+1)$$

here the observables and the corresponding quantum numbers in the second row are approximate ones .

A crucial question in spectroscopy is whether state Ψ_0 characterized by its measured energy E_0 has other good quantum numbers e.g the parity π. The answer is yes if the following assumptions are true

1) $[H, P] = 0$,

2) Ψ_0 is not degenerate.

i.e 1) : the Hamiltonian commutes with the operator of the quantum

number : here the parity operator P i.e. : 1) $[H, P] = 0$,

2) : The dimension of space of the eigenvectors with energy E_0 is one

1) $[H, P] = 0$,

2) Ψ_0 is not degenerate.

Then one finds that $H\Psi_0 = E_0 * \Psi_0$ and $HP\Psi_0 =.PH\Psi_0 = E_0 * P\Psi_0$. Thus $\Psi_0\ and\ P\Psi_0$are degenerate states with the same energy E_0 and are due to assumption 2) identical states i.e. $P\Psi_0 = \lambda\Psi_0$. This point is a little tricky if one considers that the various magnetic sub-states are degenerate in energy for $B = 0$. Summing up we find many good or approximately good quantum numbers in nuclear spectroscopy.

It is an aim of nuclear spectroscopy to measure besides the energies and the partial lifetimes these additional quantum numbers for many nuclear state. The data groups represented at this workshop have then to make a critical evaluation and to compile them and to make this information easily accessible.

Example : levels in ^{124}Xe vs the Interacting Boson Model (IBM)

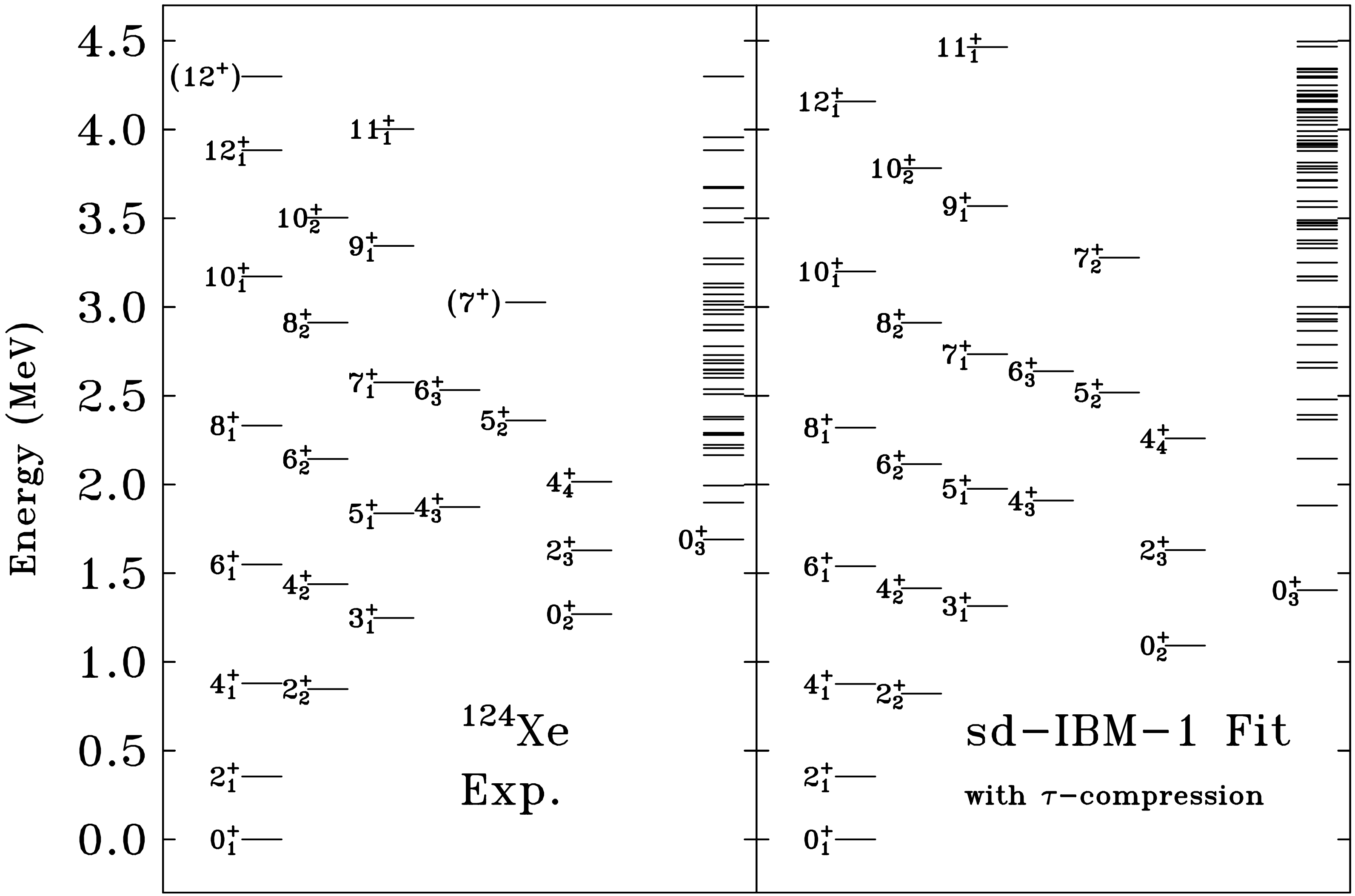
The shown level scheme is from the Koeln group. The experiments observed a rather "complete " low spin level scheme. It shows many spin multiplets e.g. there are four 4^{+}states. Such data allow a very stringent test of theoretical models in this case the IBM-1 proposed by Arima and Iacchello.

A problem with phenomenological theories e.g. the IBM but also the shell model is that they have a few free parameters . Of course there is a convincing solution to this : multitudes of relevant data. A typical example of such approach - multitudes of relevant data - is a description of the nucleus

^{124}Xe in the frame of the Interacting Boson Model IBM1 which is given in the next figure.

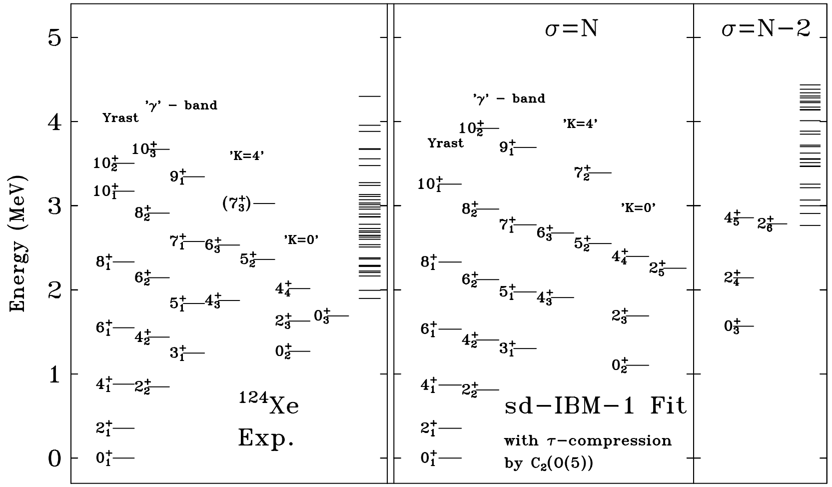
This data comes from the OSIRIS spectrometer in Koeln. V. Werner et al. N . P. A 692 (2001), 451.

Of these data 7 collective positive parity bands with about 20 levels and 30 B(E2) ratios and 5 lifetimes are described by the IBM1 with 6 parameters. Of course one can do even better by looking at a set of data of several neighboring nuclei.



Energy (MeV)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
^{124}Xe
Exp.
sd−IBM−1 Fit
with τ−compression
(12^+)
12_1^+
10_2^+
11_1^+
9_1^+
10_1^+
(7^+)
8_2^+
7_1^+
6_3^+
5_2^+
8_1^+
6_2^+
4_4^+
5_1^+
4_3^+
0_3^+
2_3^+
6_1^+
4_2^+
3_1^+
0_2^+
4_1^+
2_2^+
2_1^+
0_1^+
7_2^+

^{124}Xe



$$\mathbf{H}_{\tau-\mathbf{ECQF}} = \epsilon \mathbf{n_d} + \lambda \mathbf{LL} + \kappa \mathbf{Q}^{\chi}\mathbf{Q}^{\chi} + \beta \mathbf{C_2}(\mathbf{O}(\mathbf{5}))$$

$$= \kappa \left(\frac{\epsilon}{\kappa}\mathbf{n_d} + \frac{\tilde{\lambda}}{\kappa}\mathbf{LL} + \mathbf{Q}^{\chi}\mathbf{Q}^{\chi} + \mathbf{4}\frac{\beta}{\kappa}\mathbf{T}^{(\mathbf{3})}\mathbf{T}^{(\mathbf{3})} \right)$$

$$\epsilon/\kappa = -20.9\ ,\ \chi = -0.257\ ,\ \beta/\kappa = 0.563\ ,\ \lambda/\kappa = -0.284$$
$$\kappa = -34.91 keV\ ,\ e_b = 0.14224 e^2 b^2$$

V. Werner et al., Nucl. Phys. A 693 (2001) 451.

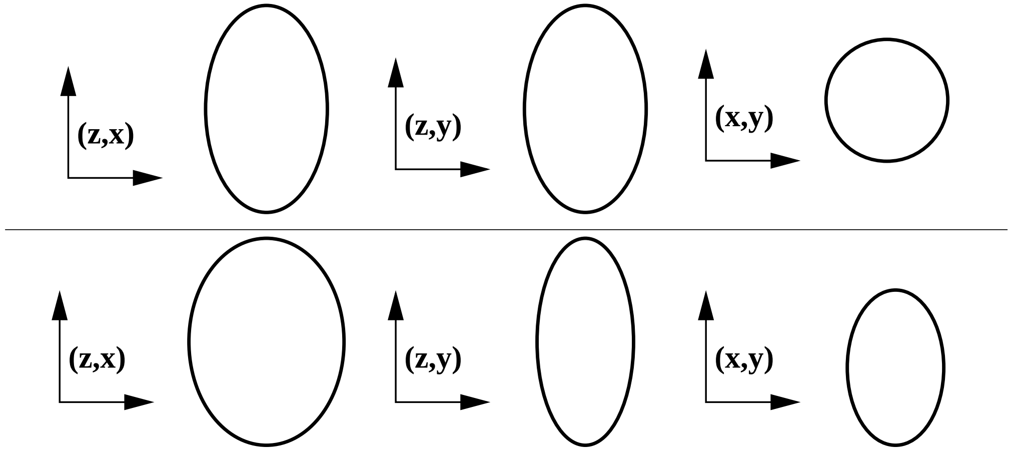
A useful point of the figure is that it gives the full Hamiltonian with the used parameters so people can check. Useful are also the “extra” experimental levels, some of which have unknown spins and parities. Also the theoretical levels not used in the comparison are given. This is very useful information and should be given always . Often theoretical papers show only the levels corresponding to the observed experimental levels which fit . The authors seem not to realize how much of the “testing” value of their figure is lost in such “comparisons”.

Shape parameters for the nucleus

A) Shape parameters beta and gamma for nuclei which have a rigid shape in the intrinsic system

B) Shape parameters beta(eff) and gamma(eff) for nuclei which have a soft (vibrating) shape in the intrinsic system

Investigation of nuclear deformation

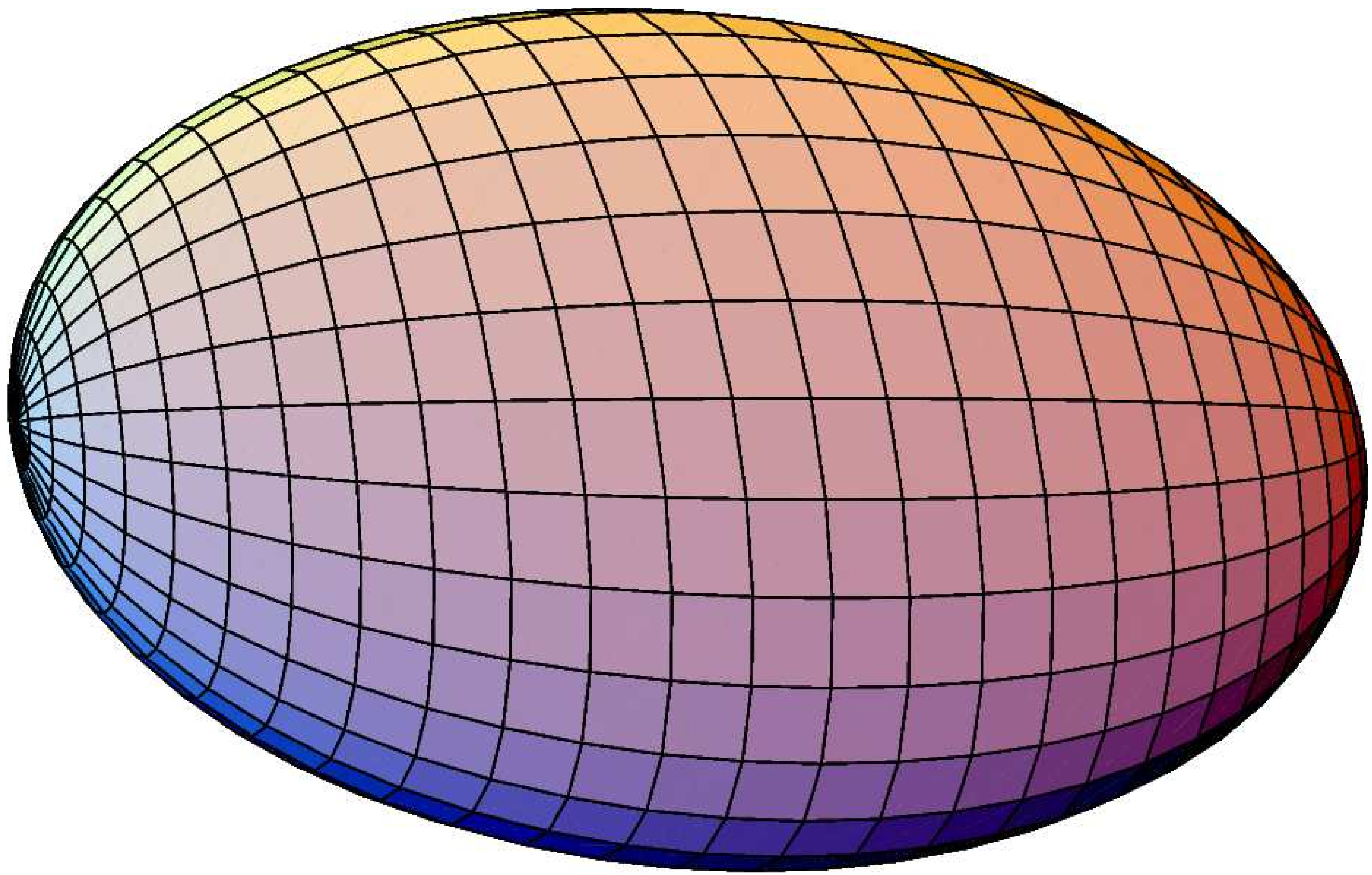


$$\mathbf{R}_\lambda = R\left(1+\beta\sqrt{\frac{5}{4\pi}}cos\left(\gamma-\frac{2\pi}{3}\lambda\right)\right) \qquad \lambda = 1,2,3$$

$$\mathbf{Q_0} = \frac{3ZR^2\beta}{\sqrt{5\pi}}$$

$$\mathrm{R} = \mathrm{R_0}\cdot\sqrt[3]{A}$$

Davydov & Filippov, Nucl. Phys. 8 (1958) 237−249



Nuclear shapes rigid or soft?

Crucial and fundamental parameters of the nucleus are the radius R_0 and the Bohr parameters β and γ, which describe the quadrupole shape of the nuclear surface. Of course these parameters are to some extent model dependent. The most used simple model is the rigid axial rotor model of Bohr and Mottelson and its generalization to to a triaxial shape by Davidov and Fillipov. This is given in the next transparencies.

The shape parameters β and γ are are widely used . There is a problem. Many nuclei have even in the "body fixed" reference system- whatever that means for soft nuclei - no fixed values of γ and even of β.

Thus the values of β and γ found in the literature are really effective parameters β_{eff} and γ_{eff} although few authors, who give them admit it. The shape parameters β_{eff} and γ_{eff} are model dependent parameters. A rather clean way to introduce effective shape parameters which are observables has been suggested by K. Kumar and Doug Cline using the concept of Q-invariants or Q shape parameters . Relative Q-invariants called K- shape parameters were used by the Koeln-Dubna group. A problem with these shape parameters is that they are defined by sum rules. Thus we have to do some extrapolation from the data which can be done however safely by suitable nuclear models as e.g. the Interacting Boson model 1 introduced by Arima and Iacchello or the proton Neutron version of the Interacting Boson Model IBM-2 which was introduced by Iacchello , Arima , Otsuka and Talmi.

Triaxiality in nuclei. A very active topic @ Gamma Sphere, Euroball & Co @ Argonne , Berkeley, Legnaro, Strasbourgh & Co.

1) Wobbling mode in strongly deformed triaxial odd nuclei e.g. ^{163}Lu, ^{165}Lu. Experiment : e.g. G. B. Hagemann et al. Kopenhagen, Bonn ..., Theory: I. Hamamoto Kopenhagen - Lund

2) Chiral - twin bands in odd odd triaxial nuclei e.g. ^{130}Pr -^{134}Pr . Experiment : e.g. K. Starosta , T. Koike, D. B. Fossan et al., Stony Brook et al. Theory : S. Frauendorf, Notre Dame

3) Near maximum triaxiality e.g. in odd ^{125}Xe, ^{127}Xe et al. Experiment and analysis with particle rotor model e.g. : I. Wiedenhoever, A. Gade, A. Gelberg et al. , Koeln

Triaxiality and the quadratic and cubic

Q invariants (Q shape parameters) q_2 and q_3 .

A basic property of the nucleus is its geometric shape. Parameterizing the nuclear shape, one usually turns to the well known geometric deformation parameters β and γ.

But this approach incorporates a major problem. In many nuclei e.g. in vibrating nuclei the shape parameters β and γ do not have fixed values. As a partial solution K. Kumar introduced and Doug Cline used very much the quadrupole shape invariants (parameters) q_n. K. Kumar, Phys. Rev. Lett. **28** (1972) 249 ; D. Cline Nucl. Phys. A 557 (1993) 615.

The quadrupole shape invariants (parameters) q_n. K. Kumar, Phys. Rev. Lett. **28** (1972) 249 are the expectation values of the products of the E2 transition operator eQ.

$$q_2 = \qquad e^2 < 0_1^+|(Q.Q)|0_1^+ > , \qquad (1)$$

$$q_3 = \sqrt{\frac{35}{2}} \quad e^3 < 0_1^+|[QQQ]^{(0)}|0_1^+ > , \qquad (2)$$

$$q_4 = \qquad e^4 < 0_1^+|(Q.Q)\ (Q.Q)|0_1^+ > , \qquad (3)$$

dot: scalar product; brackets: tensorial coupling ; Q

quadrupole operator; e elementary electric charge.

For the rigid triaxial rotor the parameters q_2 and q_3 are directly related to the deformation parameters β and $\gamma$and the nuclear radius R_0:

$$\mathbf{q_2 = e^2 Q_0^2 \beta^2, where \quad Q_0 = 3ZR_0^2/(4\pi)} \tag{4}$$

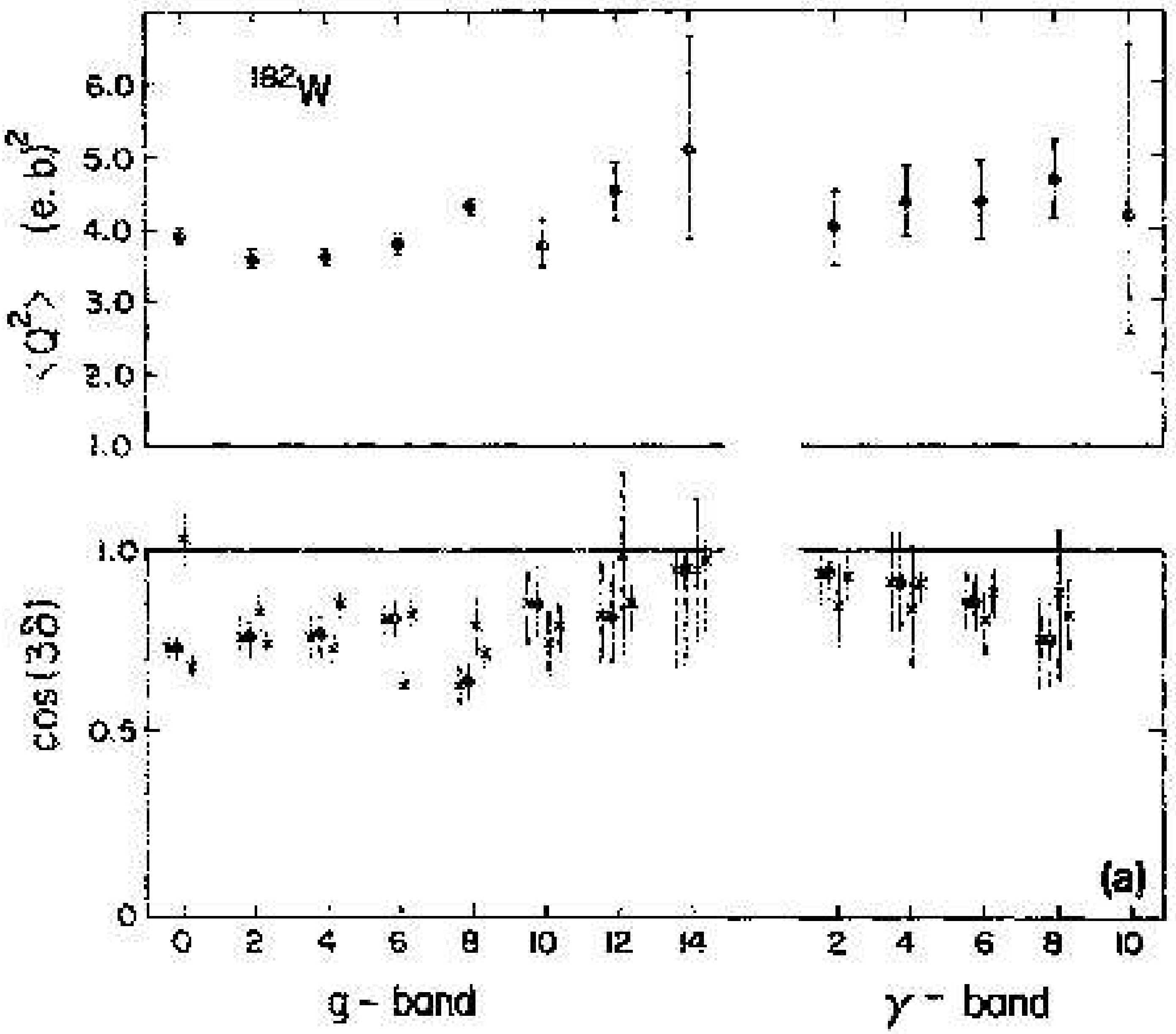
$$\mathbf{q_3 = e^3 Q_0^3 \beta^3 \cos(3\gamma) = q_2^{3/2} \cos(3\gamma)} \tag{5}$$

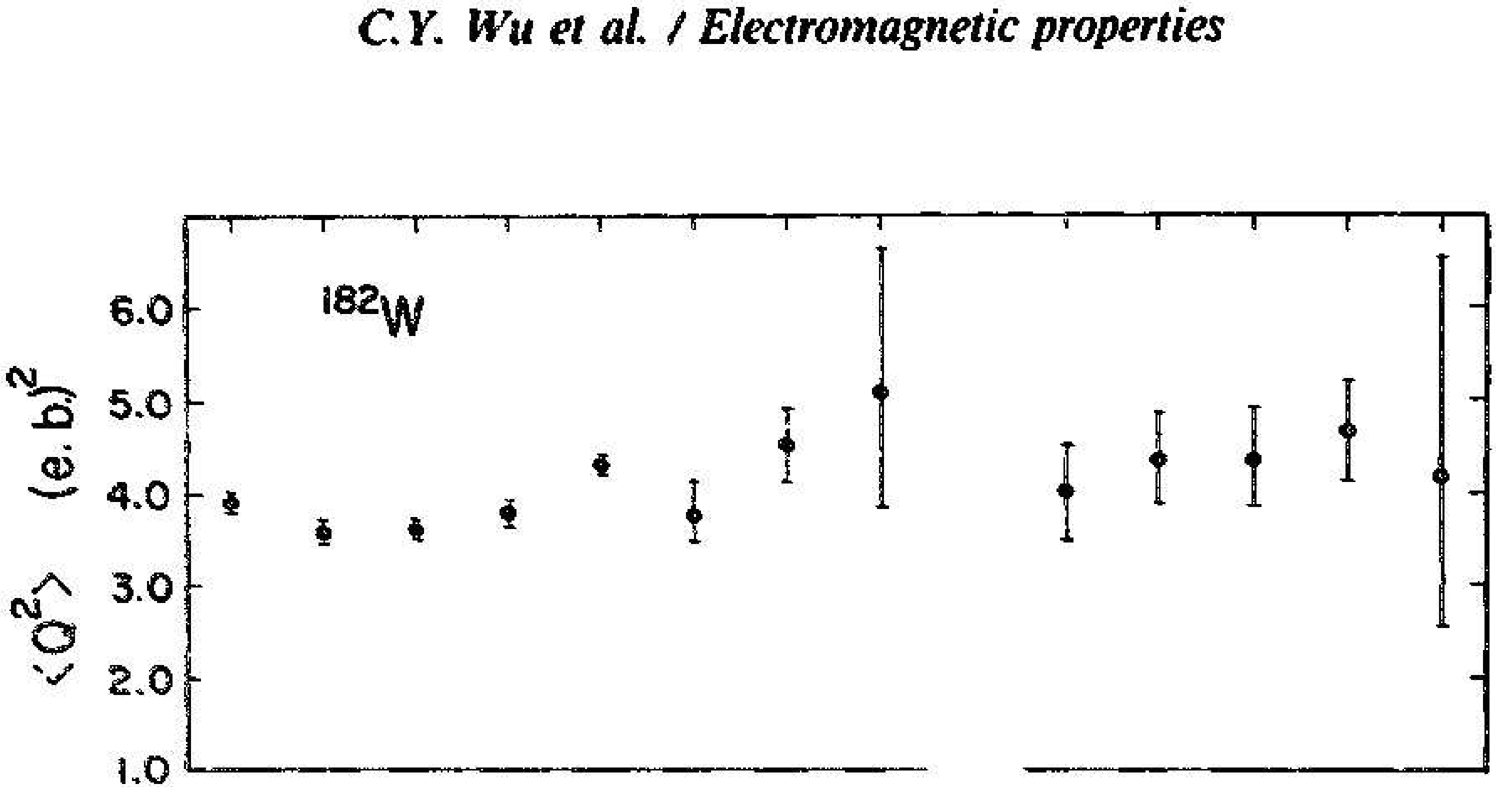
The quantities q_2 and q_3 are obtained directly from data by multiple sums of E2 matrix elements:

$$\mathbf{q_2} = \quad \mathbf{e^2 \sum_i < 0_1^+ ||Q|| 2_i^+ >< 2_i^+ ||Q|| 0_1^+ >}, \tag{6}$$

$$\mathbf{q_3} = \sqrt{\frac{7}{10}} \quad \mathbf{e^3 \sum_{i,j} < 0_1^+ ||Q|| 2_i^+ >< 2_i^+ ||Q|| 2_j^+ >< 2_j^+ ||Q|| 0_1^+ >} \tag{7}$$

These relations are called the Cline Flaum sum rule. No doubt the geometrical parameters β and γ are more intuitive. But the parameters q_2 and q_3 can be directly “measured” from the above (truncated) sum rule.


^{182}W
$\langle Q^2 \rangle$ (e. b)^2
6.0
5.0
4.0
3.0
2.0
1.0
cos (3δ)
1.0
0.5
0
(a)
0 2 4 6 8 10 12 14
2 4 6 8 10
g - band
γ - band



An evaluation of q_2 and q_3 by the Cline Flaum sum rule using E(2) transition matrix elements from multiple Coulomb excitation has been done for some nuclei by D. Cline and Co-workers, An evaluation of q_2 and q_3 by the Cline Flaum sum rule using extensive sets of experimental quadrupole transition matrix elements from multiple Coulomb excitation has been done for some nuclei by D. Cline and Co-workers,

e.g .C.Y. Wu, D. Cline, T. Czosnyka, A. Backlin, C. Baktash, R.M. Diamond, G.D. Dracoulis, L. Hasselgren, H. Kluge, B. Kotlinski, J.R. Leigh, J.O. Newton, W.R. Phillips, S.H. Sie, J. Srebrny and F.S. Stephens, Nucl. Phys. A **607** (1996) 178.

Of course, there is great interest to obtain the shape invariants q_2 and q_3 from relations involving restricted sets of data. These relations are obtained by suitable truncation of the sums. A further crucial point is to establish the accuracy of these approximate relations in the various collective models. In second order one obtains for q_2 and q_3 the following relations:

$$\mathbf{q_2 \approx q_2^{(1)} = e^2 < 2_1^+||Q||0_1^+ >^2 = B(E2; 0_1^+ \to 2_1^+)} \tag{8}$$

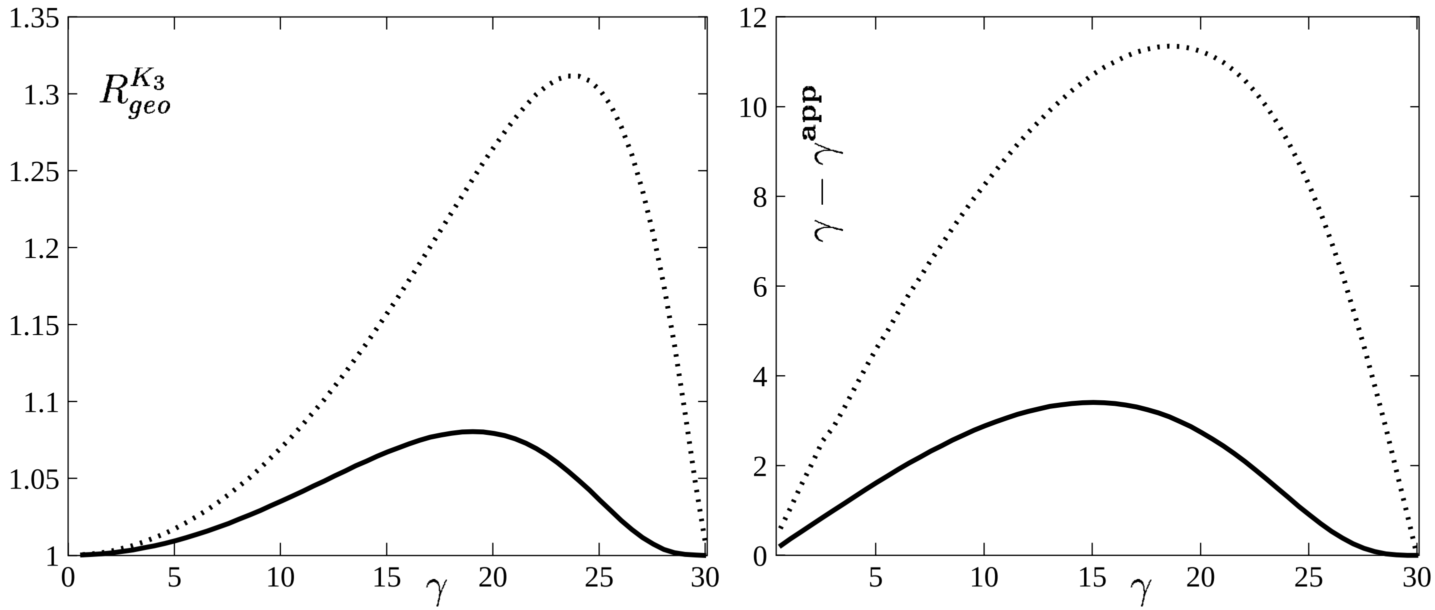
$$|\sqrt{\frac{10}{7}}(\mathbf{q_3/q_2^{3/2}})^{\mathbf{approx}}| = \sqrt{\frac{10}{7}}|\mathbf{K_3^{appr.}}| = \tag{9}$$

$$|\sqrt{\frac{B(E2;2_1^+ \to 2_1^+)}{B(E2;2_1^+ \to 0_1^+)}} - 2 * \frac{\sqrt{\mathbf{B(E2;2_2^+ \to 0_1^+) \cdot B(E2;2_2^+ \to 2_1^+)}}}{\mathbf{B(E2;2_1^+ \to 0_1^+)}}|, \tag{10}$$

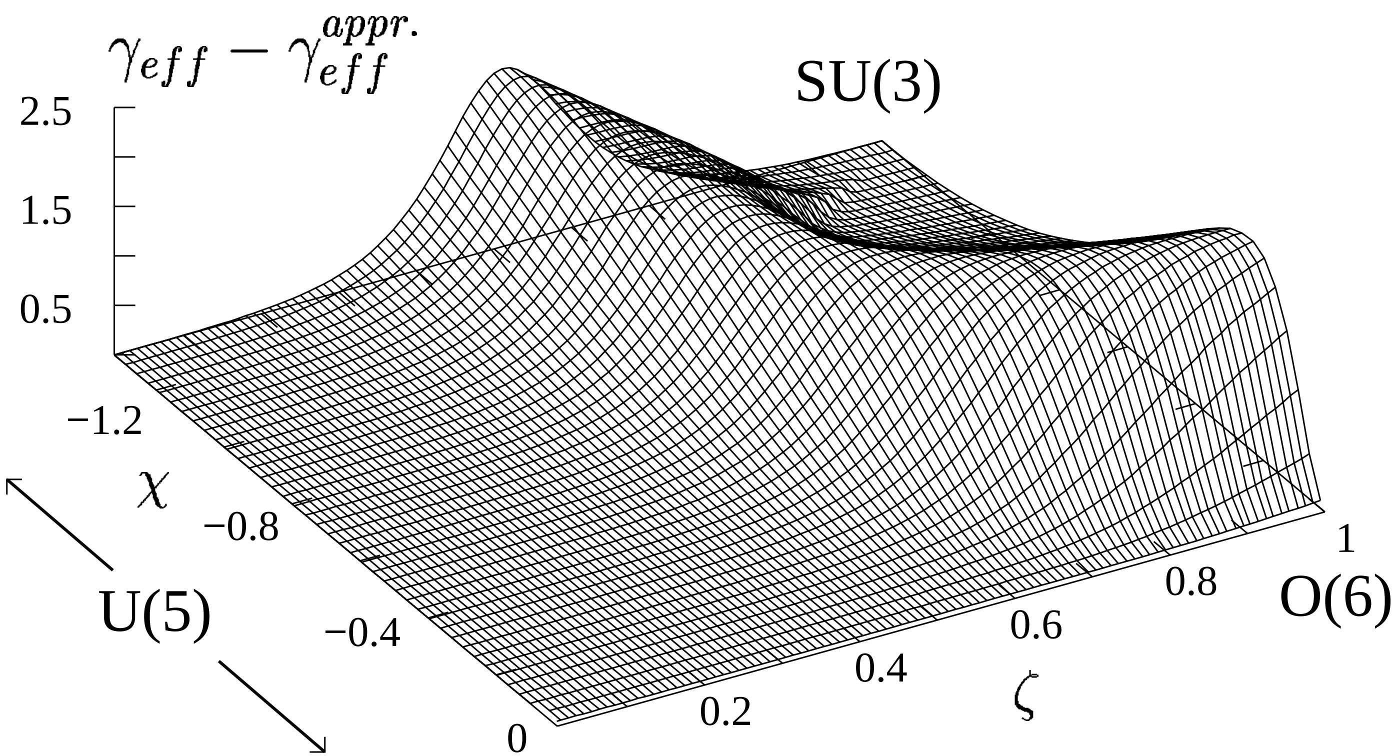
where we again write the squared quadrupole moment in form of a B(E2)

$$\mathbf{B(E2;2_1^+ \to 2_1^+) = (35/32 * \pi) * Q(2_1^+)^2} \ .$$

Differences of the approximate and exact values of K_3 and γ in the Triaxial Rigid Rotor Model. Black line second order expression from 4 BE2 . Dotted line first order from 2 B(E2) . $R^{K_3} = 1$and $\gamma - \gamma^{appr} = 0$ means approximation is exact. Maximum difference of $2^{nd} order$ approximation : $\gamma - \gamma^{appr} < 3 degree$



V. Werner, C. Scholl, P. von Brentano. Koeln-Yale PRC 2004.



$\gamma_{eff} - \gamma_{eff}^{appr.}$
2.5
1.5
0.5
SU(3)
−1.2
χ
−0.8
−0.4
U(5)
0
0.2
0.4
ζ
0.6
0.8
1
O(6)

Determination of γ_{appr} from $K_3^{appr.}$ i.e. from 4 B(E2)`s and from the sign of the quadrupole moment of the 2_1^+state .

$$(q_3/q_2^{3/2})^{approx} = K_3^{appr.} =< \beta^3 cos(3\gamma.) > / < \beta^2 >^{3/2}$$

$152Sm$	154Gd	156Gd	158Gd	160Gd	188Os	
6(1)	**7(2)**	**7(2)**	**6(2)**	**5(2)**	**17(3)**	$\gamma.$
0.307	0.310	0.339	0.349	0.351	0.185	β
192Os	194Pt	196Pt	106Pd*	112Cd*	114Cd*	
25(2)	**41(2)**	**42(2)**	**19(2)***	**22(2)***	**25.8(7)***	$\gamma.$
0.167	0.143	0.129	0.230	0.181	0.184)	β

* β soft nucleus; $\beta$and $\gamma$are correlated.

Quartic shape parameter $q_4 = e^4 < QQ.QQ >$as a measure of beta rigidity

$$q_4 = (q_2^2) * < \beta^4 > / < \beta^2 >^2$$

$< \beta^4 > / < \beta^2 >^2 = 1$ for $\beta-$rigid nucleus.

Quartic shape parameter q_4 from two absolute B(E2)'s

$$q_4 = q_2^2 * (7/10) * B(E2, 4_1^+ \to 2_1^+)/B(E2, 2_1^+ \to 0_1^+)$$

What do we learn for β and γ from q_2 , q_3, q_4 if the nucleus is rigid or $\beta rigid$ and gammasoft ?

$$K_3 = q_3/(q_2)^{3/2} =< \beta^3 cos(3\gamma)/ < \beta^2 >^{3/2}$$

$$K_4 = q_4/(q_2)^2 =< \beta^4 >< \beta^2 >^2$$

Quartic shape parameter q_4 from two absolute B(E2)'s

$$q_4 = q_2^2 * (7/10) * B(E2, 4_1^+ \rightarrow 2_1^+)/B(E2, 2_1^+ \rightarrow 0_1^+)$$

β	γ		K_3	K_4	
rigid	0	SU(3)	1	1	
rigid	rigid	Triax Rot	$cos(3\gamma)$	1	
rigid	soft	0(6)	$< cos(3\gamma) >$	1	

Summing up: there is an approach to extract physics from data by looking at approximate relations between observables with no free parameters at all.

These approximate relations are obtained from truncated sum rules and their accuracies have been established in various collective models as the rigid triaxial rotor and the IBA . Examples of such relations are :

Cubic shape parameter q_3 from four observables and triaxiality

The Three B(E2) Relation

Spin Dependent Generalized Grodzins Relation

Thanks: V. Werner (now Yale), R. Jolos (Dubna), N. Pietralla (Stony Brook) , C. Scholl(Cologne) R. Casten, A. Dewald

The Three B(E2) Relation

V. Werner, P. von Brentano R.V. Jolos PL B **521** (2001)146

I. M. Naqib J. Phys G1 (1975) L19

Phenomenological models are crucial in the analysis of data. Particularly interesting are (approximate) relations between observables without free parameters. An example is the Three B(E2) Relation, which occasionally allows to get a quadrupole moment from B(E2) data.:

$$\mathbf{B(E2;\, 2_1^+ \rightarrow 2_1^+)} =$$

$$= \mathbf{B(E2;\, 4_1^+ \rightarrow 2_1^+)} - \mathbf{B(E2;\, 2_2^+ \rightarrow 2_1^+)}$$

$$\mathbf{B(E2;\, 2_1^+ \rightarrow 2_1^+)} = \frac{35}{32\pi}\, \mathbf{Q(2_1^+)^2} \;.\bullet$$

Three B(E2) Relation :

For the three dynamical symmetries of the IBM :

$$\mathbf{B(E2;4_1^+ \to 2_1^+) \;=\; B(E2;2_2^+ \to 2_1^+) \;+\; B(E2;2_1^+ \to 2_1^+)}$$

Rotor	**SU(3)**	$B(E2;2_2^+ \to 2_1^+) = 0$
γ **– unstable – Rotor**	**O(6)**	$B(E2;2_1^+ \to 2_1^+) = 0$
Vibrator	**U(5)**	$B(E2;2_1^+ \to 2_1^+) = 0$

$$\mathbf{B(E2;2_1^+ \to 2_1^+) = (35/32 * \pi) * Q(2_1^+)^2} \;.$$

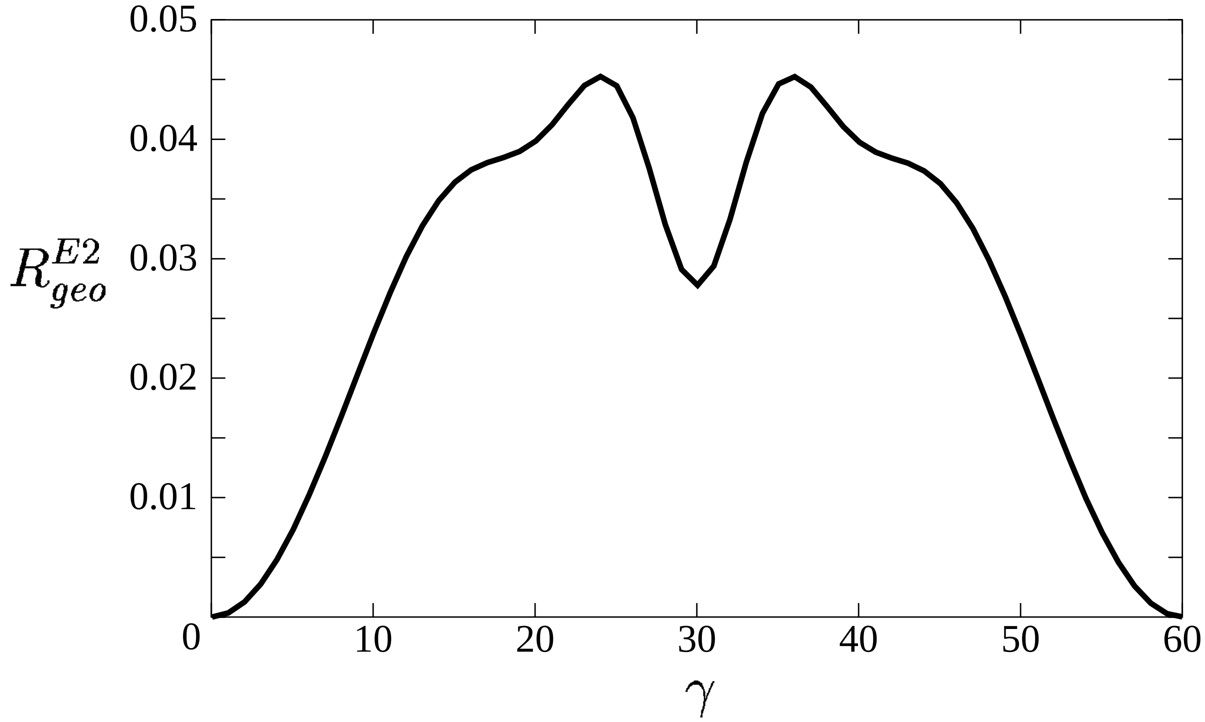
The Three B(E2) Relation connects the squared electric

quadrupole moment of the 2_1^+ state $Q(2_1^+)^2$ with the absolute lifetimes of the 4_1^+ and the 2_2^+ states.. It gives a new way to approximately determine $Q(2_1^+)^2$, which is usually not easy to access experimentally and which may be of interest for RIB experiments:

$$\mathbf{Q(2_1^+)^2 = 32\pi/35 * [B(E2; 4_1^+ \rightarrow 2_1^+) \quad - \quad B(E2; 2_2^+ \rightarrow 2_1^+)]}$$

This (approximate) relation was checked successfully for the triaxial rotor and in the parameter space of the Casten triangle of the IBM.

Test of the Three B(E2) Relation in the Triaxial Rigid Rotor Model. R = 0 means relation is fulfilled. Maximum deviation 5% ; independent of β.



$$R^{E2} = 1 - \frac{B(E2; 4_1^+ \to 2_1^+)}{B(E2; 2_1^+ \to 2_1^+) + B(E2; 2_2^+ \to 2_1^+)} \qquad (11)$$

Good agreement between γ^{appr} from 4 B(E2) and γ for rigid triaxial rotor . $\beta = 0.3$ agrees also.

$\langle 2_1^+ \Vert Q \Vert 0_1^+ \rangle$	$\langle 2_1^+ \Vert Q \Vert 2_1^+ \rangle$	$\langle 2_2^+ \Vert Q \Vert 2_1^+ \rangle$	$\langle 2_2^+ \Vert Q \Vert 0_1^+ >$	K_3^{app}	γ_{app}	γ
6.394	-7.643	0.000	0.000	-1.00	0.02	0
6.176	-6.619	3.821	1.655	-0.62	17.25	20
6.394	0.000	7.643	0.000	0.00	30.00	30
6.176	6.619	-3.821	1.655	0.62	42.75	40
6.394	7.643	-0.001	0.001	1.00	59.98	60

Test of three B(E2) relation vs data

	$B(E2; 2_1^+ \to 2_1^+)$ $[e^2b^2]$	$B(E2; 2_2^+ \to 2_1^+)$ $[e^2b^2]$	$(1) + (2)$ $[e^2b^2]$	$B(E2; 4_1^+ \to 2_1^+)$ $[e^2b^2]$
^{156}Gd	1.296(54)	0.017(1)	1.314(54)	1.312(25)
^{160}Gd	1.51(6)	0.030(2)	1.54(6)	1.47(2)
^{164}Dy	1.43(28)	0.043(4)	1.48(28)	1.45(7)
^{186}Os	0.61^{+9}_{-15}	0.16^{+2}_{-1}	0.77^{+9}_{-15}	0.85^{+4}_{-4}
^{196}Pt	0.08(6)	0.32(2)	0.40(6)	0.41(6)
^{106}Pd	0.10(2)	0.12(1)	0.22(2)	0.21(2)
^{114}Cd	0.05(2)	0.093(6)	0.14(2)	0.20(2)

Test of $Q(2_1^+)^2$ from Three B(E2) Relation vs $Q(2_1^+)^2_{exp}$

$$\mathbf{Q(2_1^+)^2 = 32\pi/35 * [(B(E2; 4_1^+ \rightarrow 2_1^+)\text{ - }B(E2; 2_2^+ \rightarrow 2_1^+))}$$

156Gd	158Gd	160Gd	188Os	190Os	e^2b^2
3.79(11)	**4.19(11)**	**4.20(10)**	$\mathbf{1.80^{+7}_{-21}}$	$\mathbf{1.14^{+14}_{-30}}$	B(E2)Rel
3,72(15)	**4.04(16)**	**4.33(17)**	$\mathbf{1.72^{+10}_{-38}}$	$\mathbf{0.90^{+19}_{-32}}$	$Q(2_1^+)^2_{exp}$
192Os	194Pt	196Pt	112Cd	114Cd	e^2b^2
$\mathbf{0.56^{+6}_{-19}}$	$\mathbf{-0.13^{+5}_{-18}}$	$\mathbf{0.26(9)}$	**0.43(6)**	**0.31(4)**	B(E2)Rel
$\mathbf{0.84^{+24}_{-8}}$	$\mathbf{0.20^{+2}_{-7}}$	**0.24(18)**	**0.14(3)**	**0.13(6)**	$Q(2_1^+)^2_{exp}$

end lecture 1

Experimental nuclear spectroscopy 2

Trieste IAEA April 2005

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Lecture 2:

N**uclear spectroscopy** is a broad subject. Excellent books are e.g.:

R. F. Casten: Nuclear Structure

A. Bohr and B. R. Mottelson: Nuclear structure

H. Ejiri, M. J. A. de Voigt Nuclear Spectroscopy

H. Morinaga and T. Yamazaki. Gamma spectroscopy

D. N. Poenaru and W. Greiner: Experimental techniques

R. Bock: Heavy ion collisions Vol 1-3

Second lecture:

Lifetimes from Doppler shifted Spectra from RDDS (recoil distance Doppler shifted) data from fusion evaporation reactions. Examples ^{158}Er and $Xenon$ isotopes

K- parameters, Q invariants. Rigid or soft shape of nuclei.

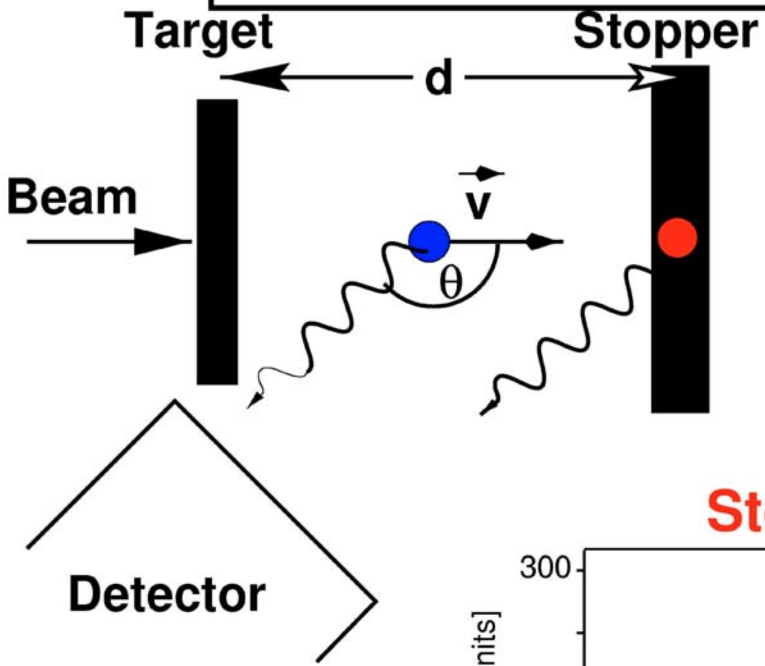
Spin Dependent Generalized Grodzins Relation

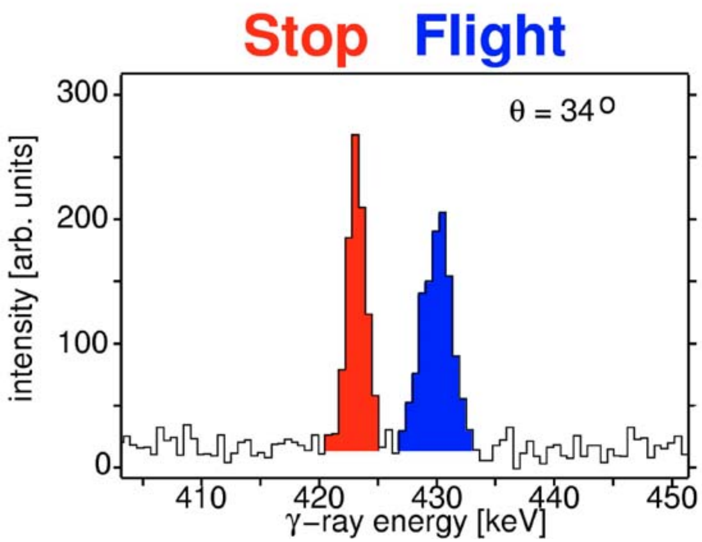
In the measurements of lifetimes of nuclear states great progress has been made. In particular the problem of unknown side feeding in fusion reactions has been solved by the use of γ, γ coincidence Doppler shifted data and by novel analysis methods such as the variants of the DDCM method. Here I mention in particular the work of the Dewald group in Koeln. Thus reliable lifetimes are now available not only from Coulomb excitation - as shown in the work of Doug Cline and D. Schwalm - but also from fusion reactions e.g. in the work of the Dewald group; which allow to determine the shapes of collective excitations in nuclei. These developments will be reviewed by examples

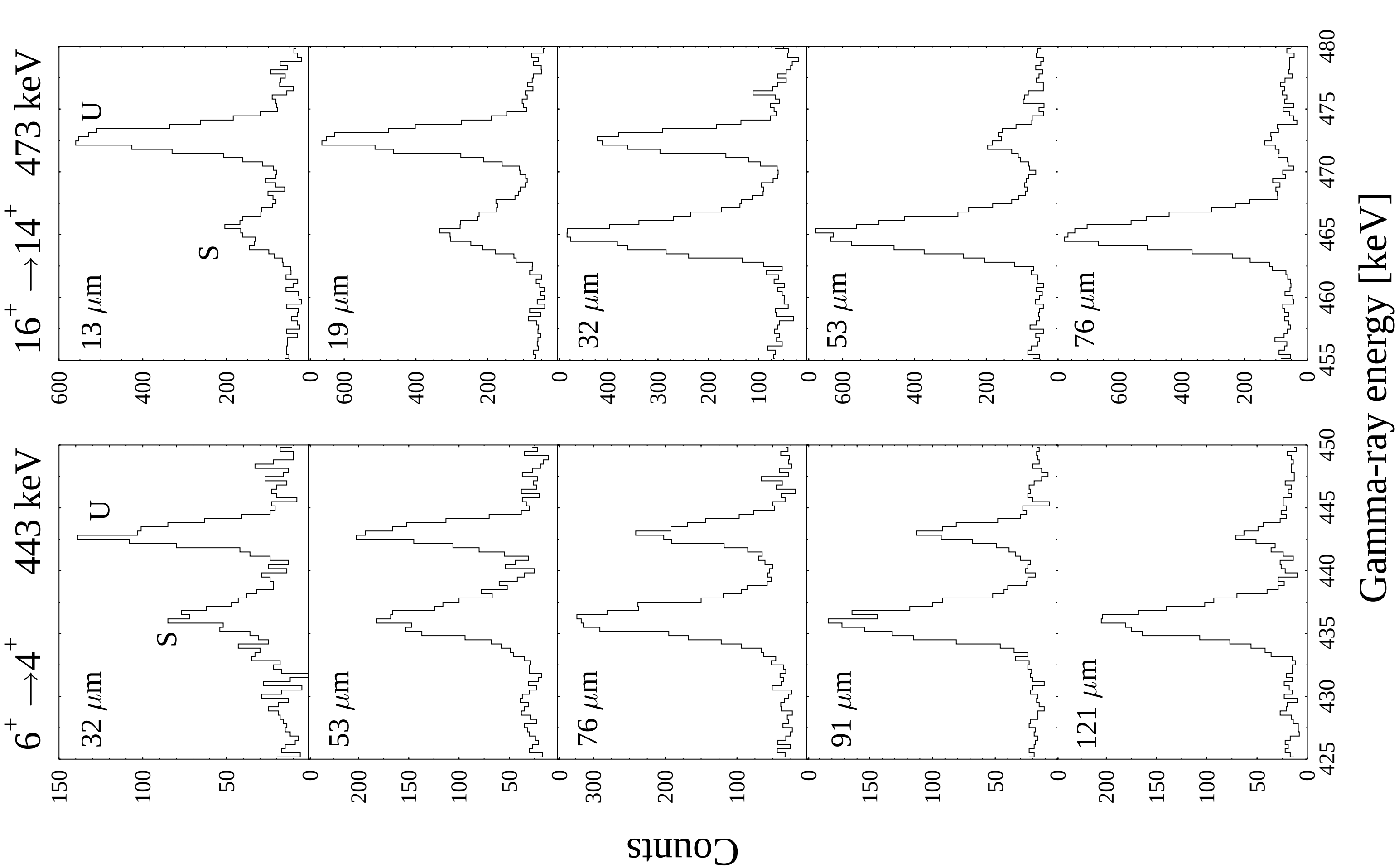
The RDDS Method

Recoil **D**istance **D**oppler-**S**hift
→ lifetimes in the ps-range

$$\boxed{E_{Flight} \approx E_{Stop}\left(1 + \frac{v}{c}\cos\theta\right)}$$







6+ →4+ 443 keV
16+ →14+ 473 keV
32 μm
53 μm
76 μm
91 μm
121 μm
13 μm
19 μm
32 μm
53 μm
76 μm
S
U
Counts
Gamma-ray energy [keV]

Problems in RDDS lifetimes . Single RDDS

a) unobserved side-feedings of unknown lifetimes

b)de-orientation: angular distribution changes with time.

c) complicated (observed) cascading in decay scheme

d)target heated by beam develops bubble.

Remedies: d) reduce beam current . Singles lifetime RDDS data are reliable only if a-d are discussed in paper.

(γ, γ)coincidence RDDS data with DDCM analysis eliminates the 3 problems a,b,c. Implies statistics problem : need GASP, Euroball,

Gamma Sphere & Co.

Lifetimes from Doppler shifted Spectra from (γ, γ)coincidence RDDS (recoil distance Doppler shifted) data.

Quantitative analysis : DDCM by Dewald Köln group :

Method and example of ^{158}Er

Refs e.g. and refs contained therein:

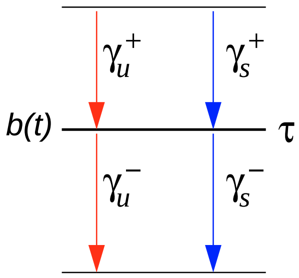
1989De38 Z.Phys. A334, 163 (1989) A.Dewald, S.Harissopulos, P.von Brentano The Differential Plunger and the Differential Decay Curve Method for the Analysis of Recoil Distance Doppler-Shift Data .

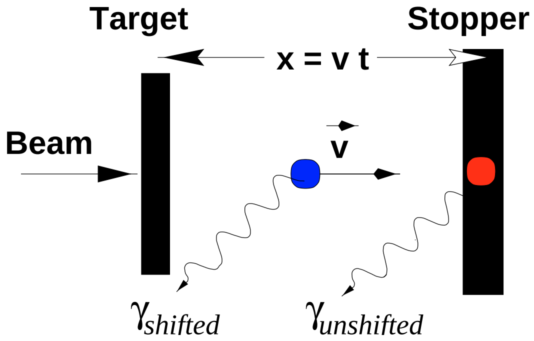
2001PE02 Nucl.Instrum.Methods . A457, 527 (2001) P.Petkov, A.Dewald, P.von Brentano Gating on the Feeding or on the Depopulating Transition in Coincidence Recoil-Distance Doppler-Shift Lifetime Measurements

2002Kl02 Phys.Lett. 524B, 252 (2002) T.Klug, A.Dewald, R.V.Jolos, B.Saha, P.von Brentano, J.Jolie Supersymmetry of Identical Bands in 171,172Yb Supported by Lifetime Data

2002Kr09 Phys.Rev.Lett. 88, 232501 (2002) R.Krucken, B.Albanna, C.Bialik, R.F.Casten, J.R.Cooper, A.Dewald, N.V.Zamfir, C.J.Barton, C.W.Beausang, M.A.Caprio, A.A.Hecht, T.Klug, J.R.Novak, N.Pietralla, P.von Brentano B(E2) Values in 150Nd and the Critical Point Symmetry X(5

Recoil Distance Doppler Shift Data





$$\#\gamma_u^+(t)\Big|_t^\infty = B_u^+(t),$$

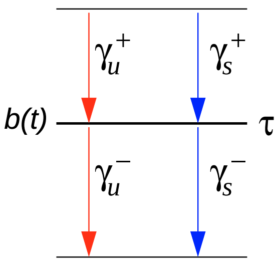
$$\#\gamma_u^-(t)\Big|_t^\infty = B_u^-(t)$$

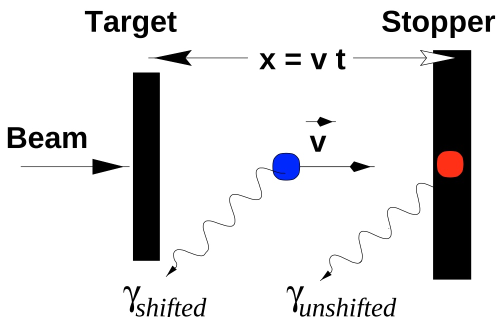
$$B_u^+(t) + b(t) = B_u^-(t)$$

$$B_u^-(t) = \int_t^\infty \frac{1}{\tau}\, b(t)dt \quad \Rightarrow \quad \dot{B}_u^-(t) = -\frac{1}{\tau}\, b(t)$$

$$\Rightarrow \qquad \boxed{\dot{B}_u^- = -\tfrac{1}{\tau}\left(B_u^- - B_u^+\right)}$$

Lifetimes from $\gamma\gamma$-coincidences





$\{\gamma_1, \gamma_2\} := \#\gamma_2$ in coincidence with γ_1

$$B_u^+ = \{\gamma_u^+, \gamma_{u+s}^-\} = \{\gamma_u^+, \gamma_u^-\} + \underbrace{\{\gamma_u^+, \gamma_s^-\}}_{=0}$$

$$B_u^- = \{\gamma_{u+s}^+, \gamma_u^-\} = \{\gamma_u^+, \gamma_u^-\} + \{\gamma_s^+, \gamma_u^-\}$$

$$\{\gamma_{u+s}^+, \gamma_{u+s}^-\}^\bullet = 0 \qquad \Rightarrow \qquad \dot{B}_u^- = -\{\gamma_s^+, \gamma_s^-\}^\bullet$$

$$\dot{B}_u^- = -\frac{1}{\tau}\left(B_u^- - B_u^+\right) \quad \Rightarrow \boxed{\{\gamma_s^+, \gamma_s^-\}^\bullet = \frac{1}{\tau}\{\gamma_s^+, \gamma_u^-\}}$$

The lifetime tau is thus obtained by a very intuitive relation:

$$d/dt \quad (s^{+},\ s^{-})_t \ = \ (1/\tau) * (s^{+},\ u^{-})_t$$

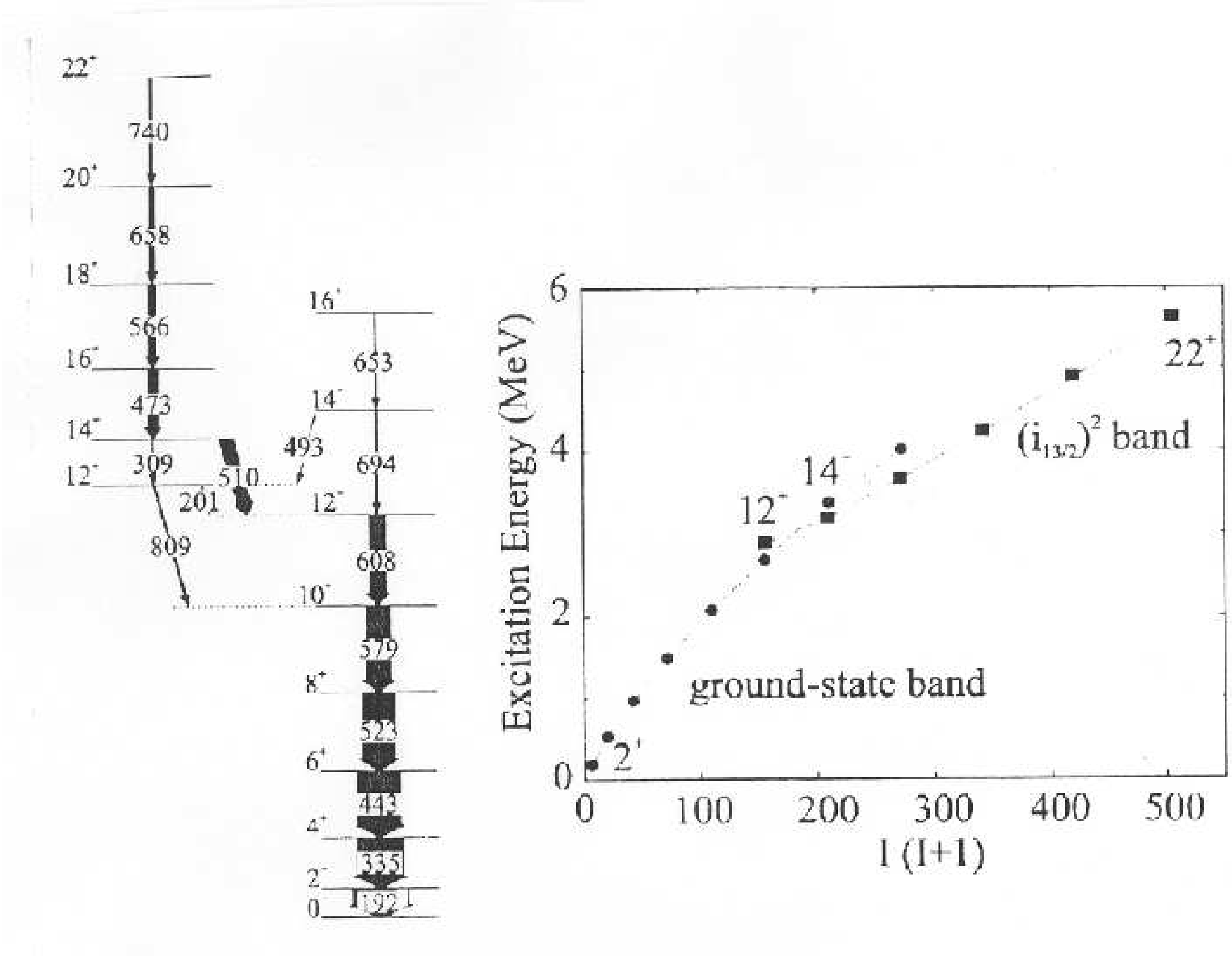
Here $(s^{+},\ s^{-})_t$ is the number of s^{-} in the gate on s^{+}

and $(s^{+},\ u^{-})_t$ is the number of u^{-} in the gate on s^{+}

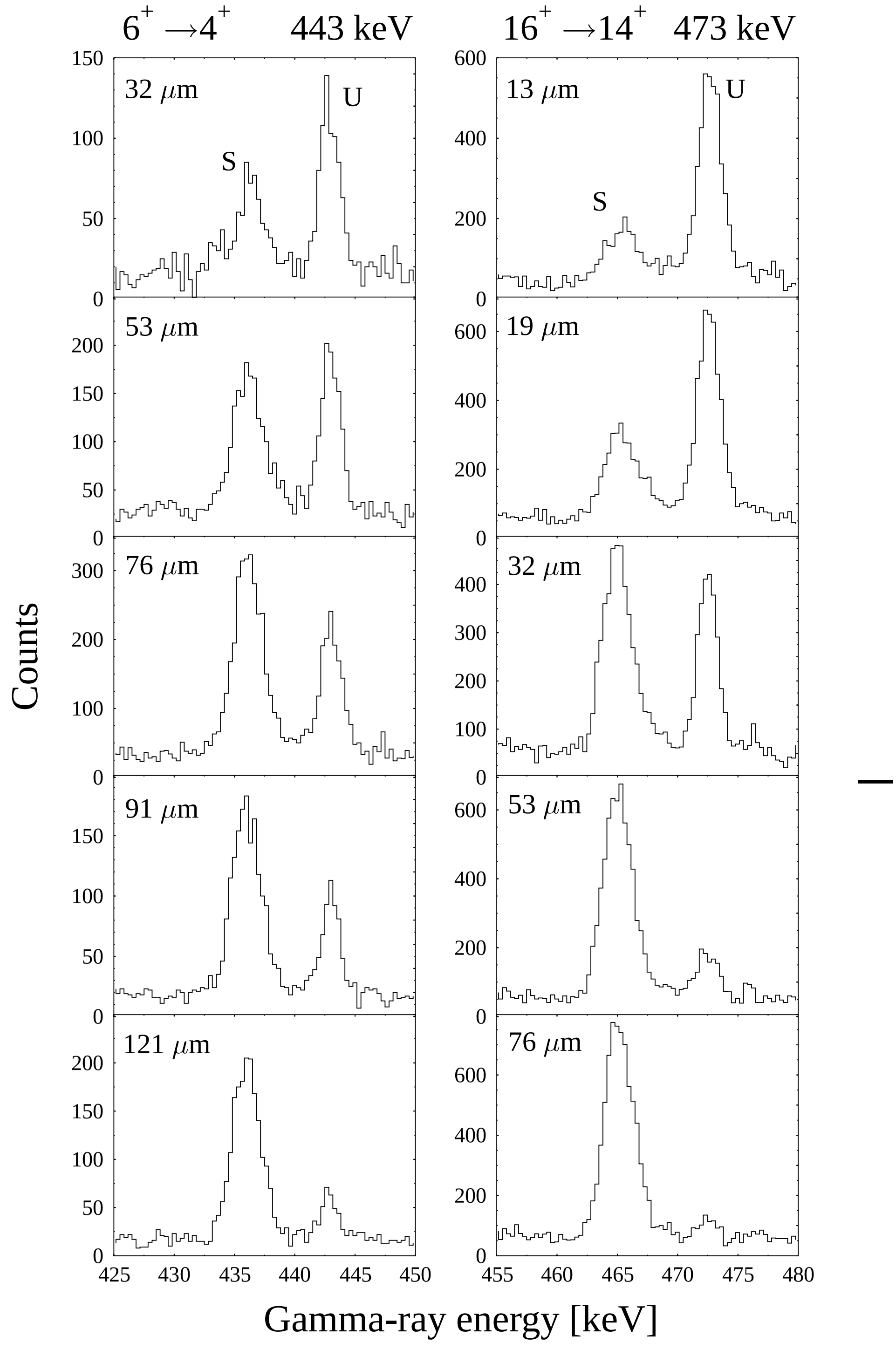
and d/dt is the time derivative of the function$(s^{+},\ s^{-})_t$.

One notes that the absolute normalizations cancel out. This is still some work.

In the next figure we show the decay scheme of ^{158}Er which serves as an exemple. The data are from Gammasphere at Berkeley and are from a Liverpool , Daresbury , Koeln ++.... collaboration.



Rotational bands in ^{158}Er.



6+ →4+ 443 keV
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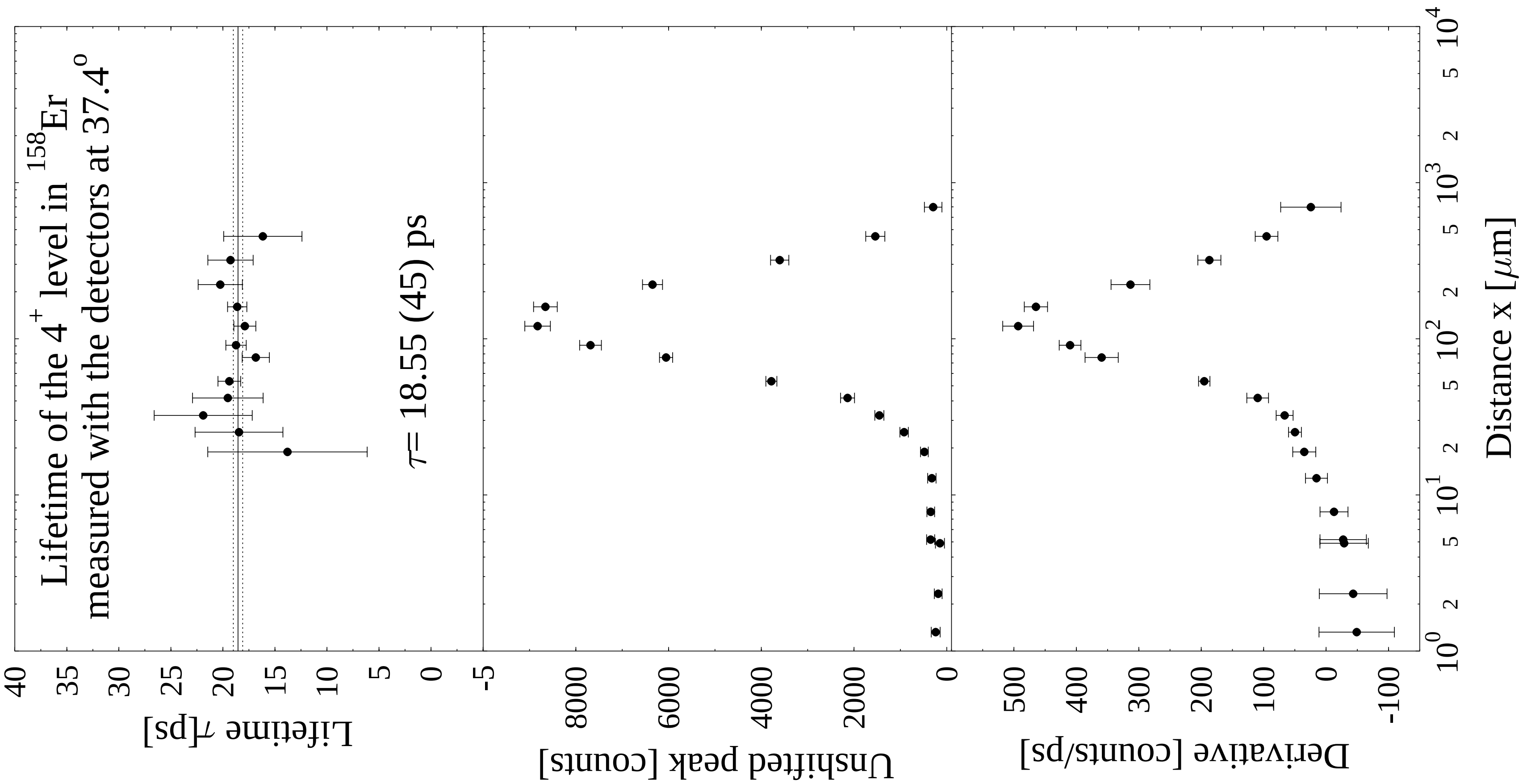
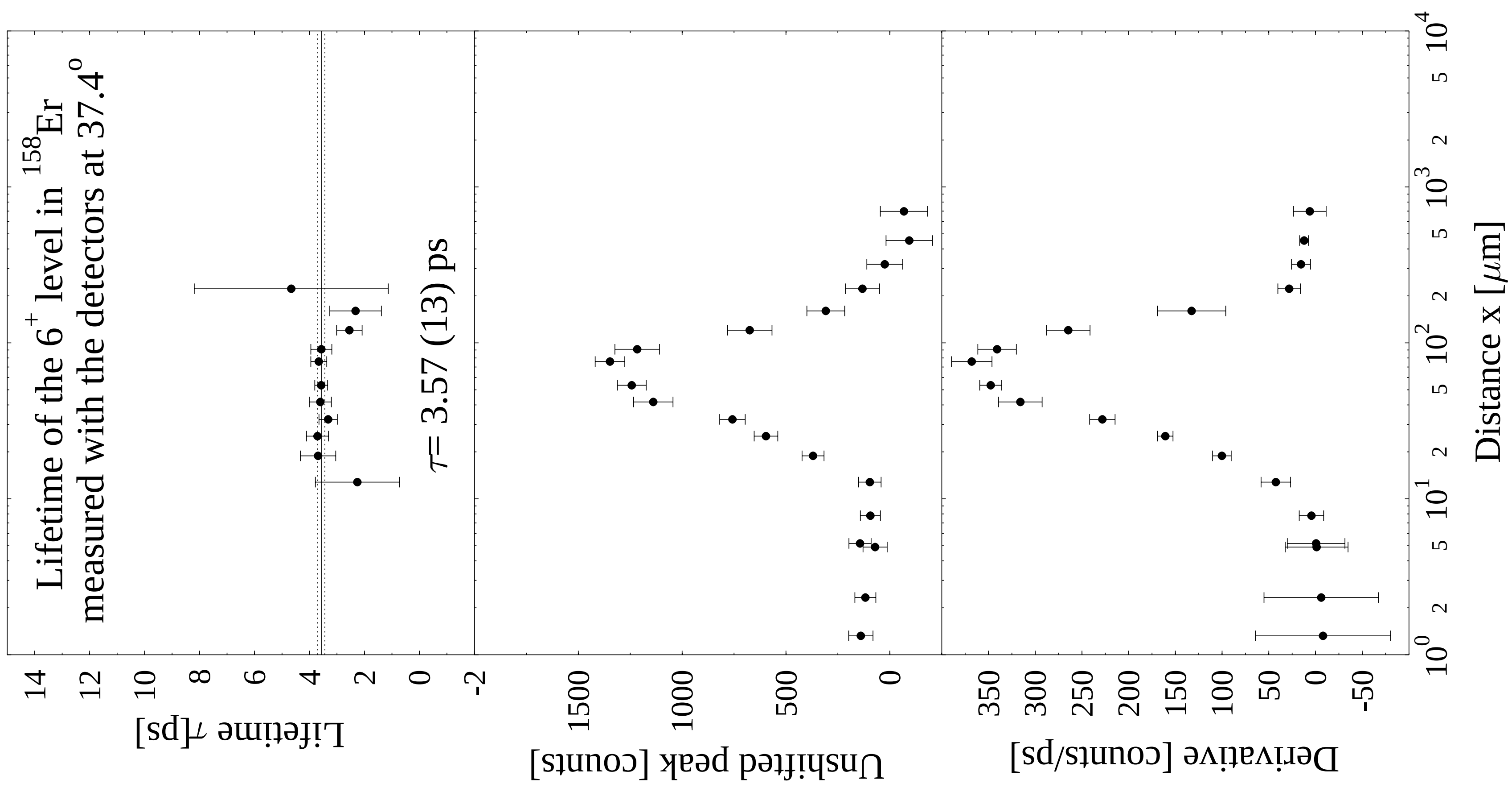
32 μm
53 μm
76 μm
91 μm
121 μm
13 μm
19 μm
32 μm
53 μm
76 μm
S
U
Counts
Gamma-ray energy [keV]

2002Sh09 Phys.Rev. C65, 034320 (2002) S.L.Shepherd, J.Simpson, A.Dewald, P.Petkov, P.J.Nolan, M.A.Riley, A.J.Boston, T.B.Brown, R.M.Clark, P.Fallon, D.J.Hartley, S.Kasemann, R.Krucken, P.von Brentano, R.W.Laird, E.S.Paul, R.Peusquens High Precision Quadrupole Moment Measurements of States up to I = (h-bar) in the Yrast Band of 158Er



Lifetime of the 4^+ level in ^{158}Er
measured with the detectors at 37.4°
τ= 18.55 (45) ps
Lifetime τ[ps]
Unshifted peak [counts]
Derivative [counts/ps]
Distance x [μm]



Lifetime of the 6^+ level in ^{158}Er
measured with the detectors at 37.4^o
τ= 3.57 (13) ps
Lifetime τ[ps]
Unshifted peak [counts]
Derivative [counts/ps]
Distance x [μm]

"Transition quadrupole moment" $Q_t(I)$ for soft rotors:

For the rigid rotor one finds

$$B(E2; I+2 \to I) = \left(C^{I0}_{I+2020}\right)^2 Q_0^2 \tag{1}$$

For the diagonal matrixelements one finds:

$$\langle I \parallel Q_2 \parallel I \rangle = \sqrt{2I+1} C^{I0}_{I020} Q_0 \tag{2}$$

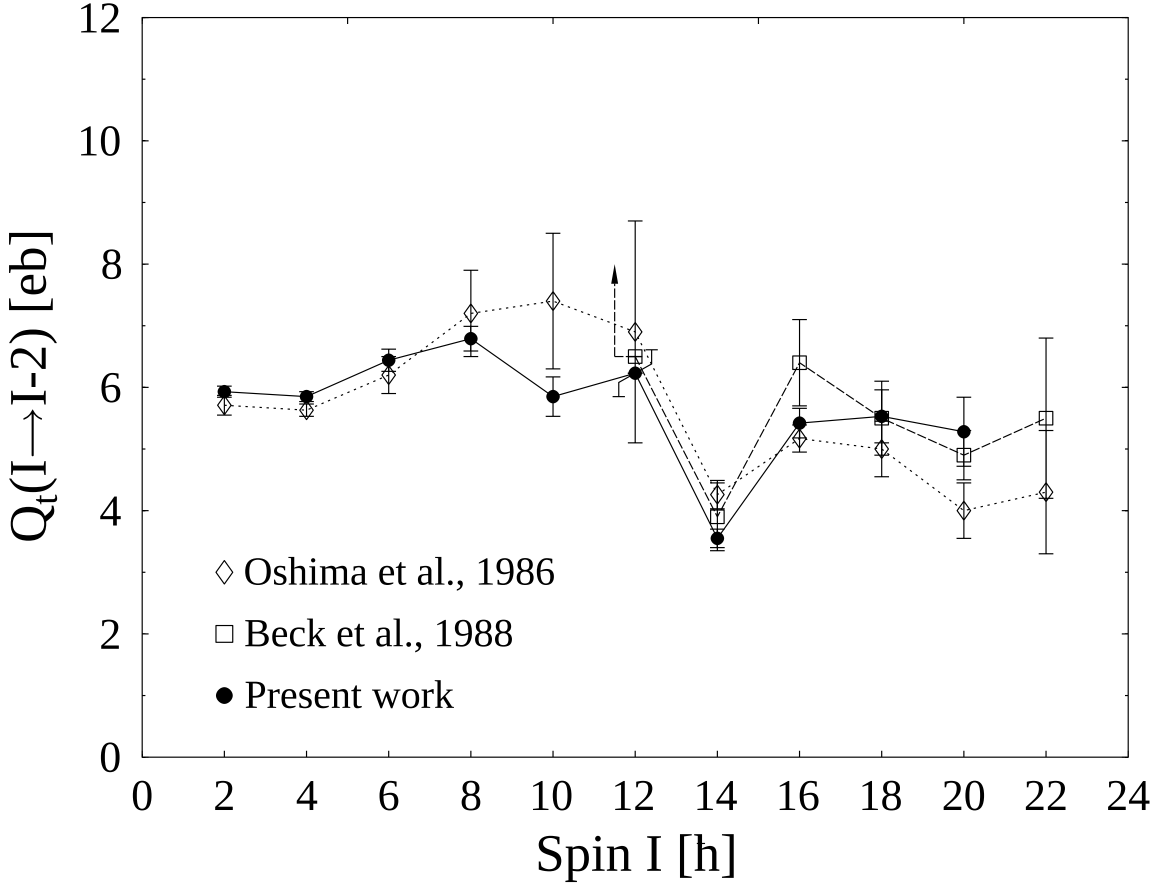
where Q_0 is a constant equal to the intrinsic quadrupole moment Q_0 of the nucleus.

In the case that the nucleus is not a rigid but a soft rotor the intrinsic quadrupole moment $Q_0(I)$ is a function of the angular momentum . In this case one introduces following Emling and Schwalm a spindependent

“transition quadrupole moment” $Q_t(I)$ and writes:

$$B(E2; I+2 \rightarrow I) = \left(C^{I0}_{I+2020}\right)^2 Q(I)^2_t \tag{3}$$

The constant Q_0^2 is replaced by a spindependent function $Q_t^2(I)$. In this case one finds a slightly different $Q_t(I)$ for the diagonal moment. The advantage of introducing the “transition quadrupole moment” $Q_t(I)$ is that its spin dependence is only due to the deviations from the rigid rotor.

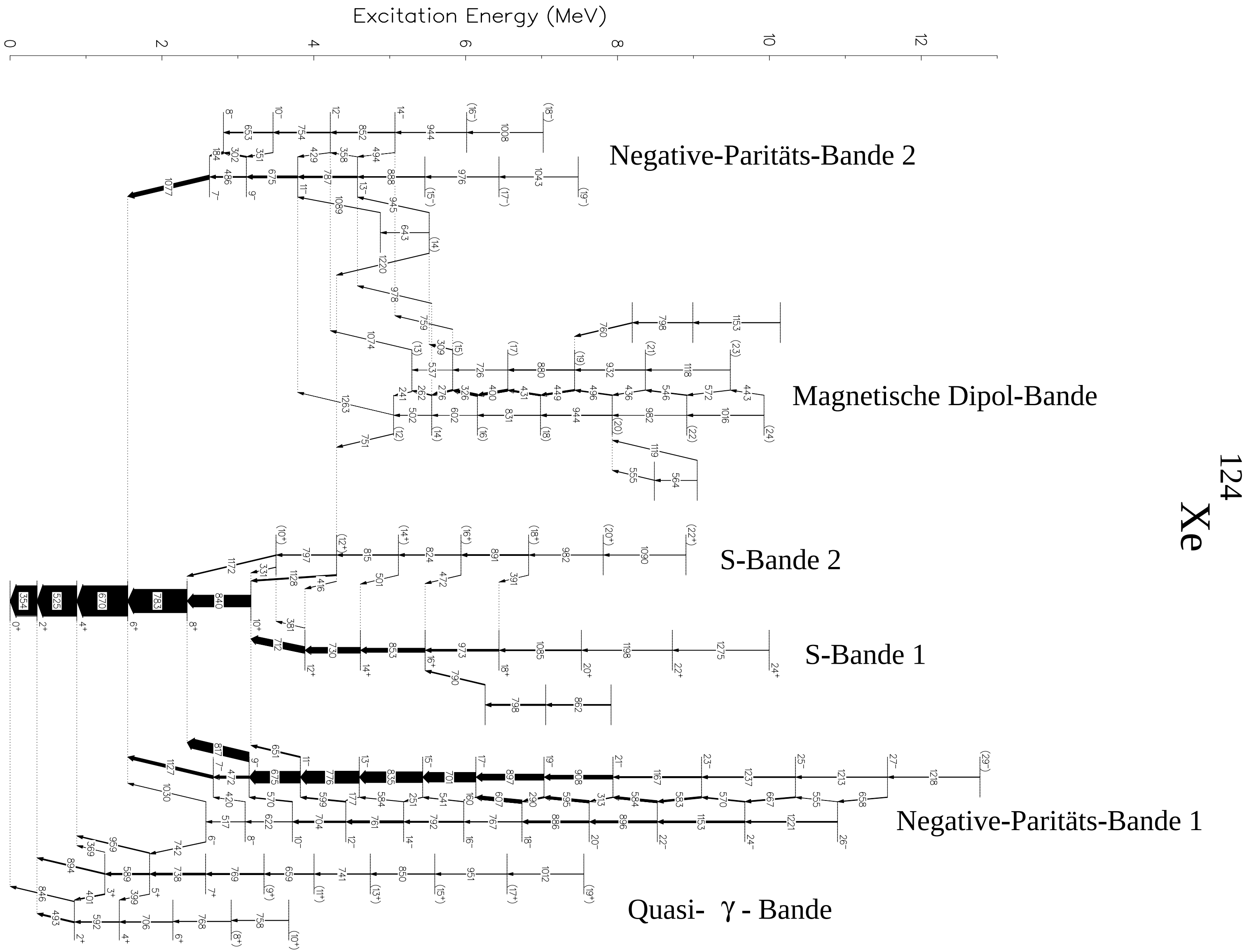


12
10
8
6
4
2
0
0
2
4
6
8
10
12
14
16
18
20
22
24
$Q_t(I\rightarrow I\text{-}2)$ [eb]
Spin I [ħ]
◊ Oshima et al., 1986
□ Beck et al., 1988
● Present work

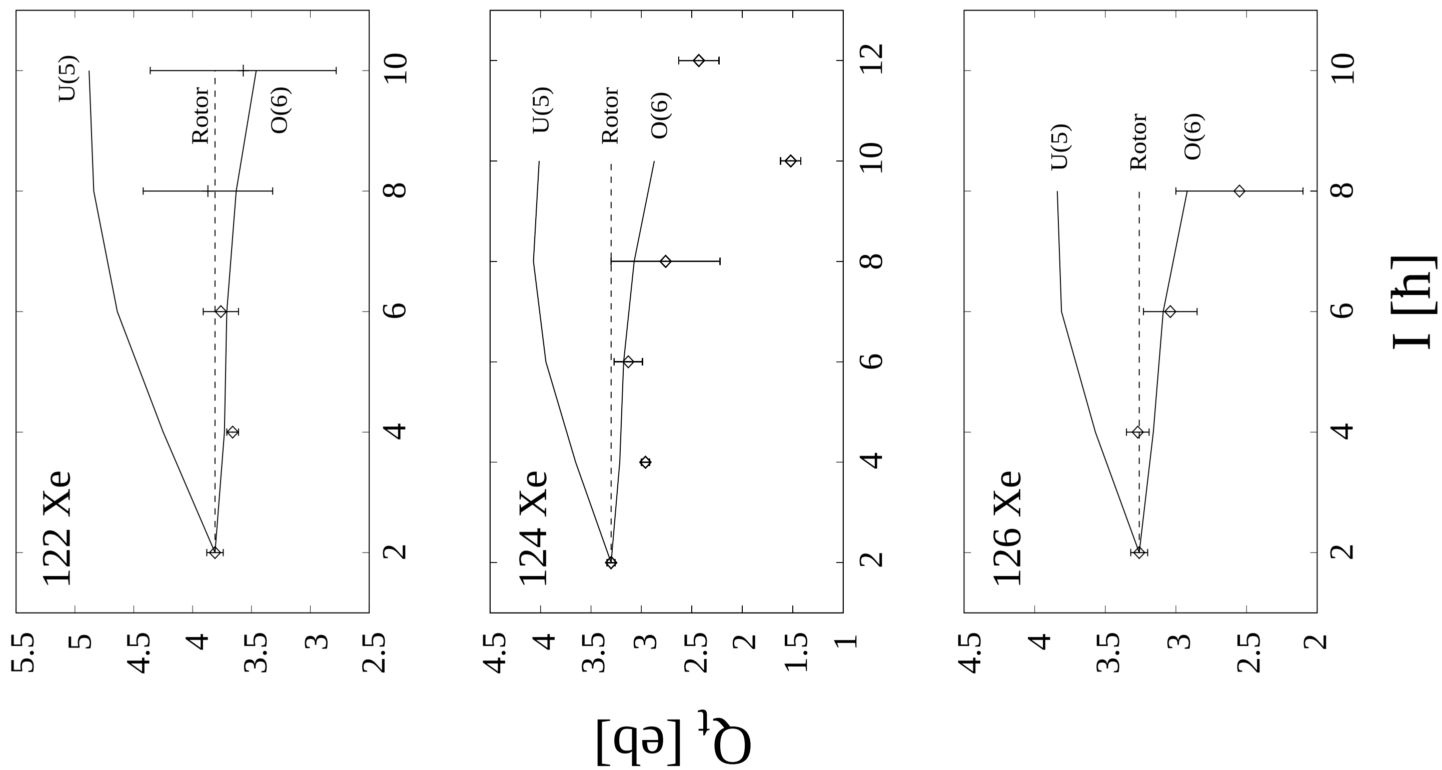
Lifetimes from RDDS

(recoil distance Doppler shifted) data.

Results for $Xenon\ isotopes$



124 Xe
Negative-Paritäts-Bande 2
Magnetische Dipol-Bande
S-Bande 2
S-Bande 1
Negative-Paritäts-Bande 1
Quasi- γ - Bande
Excitation Energy (MeV)


122 Xe
124 Xe
126 Xe
U(5)
Rotor
O(6)
Q_t [eb]
I [ħ]

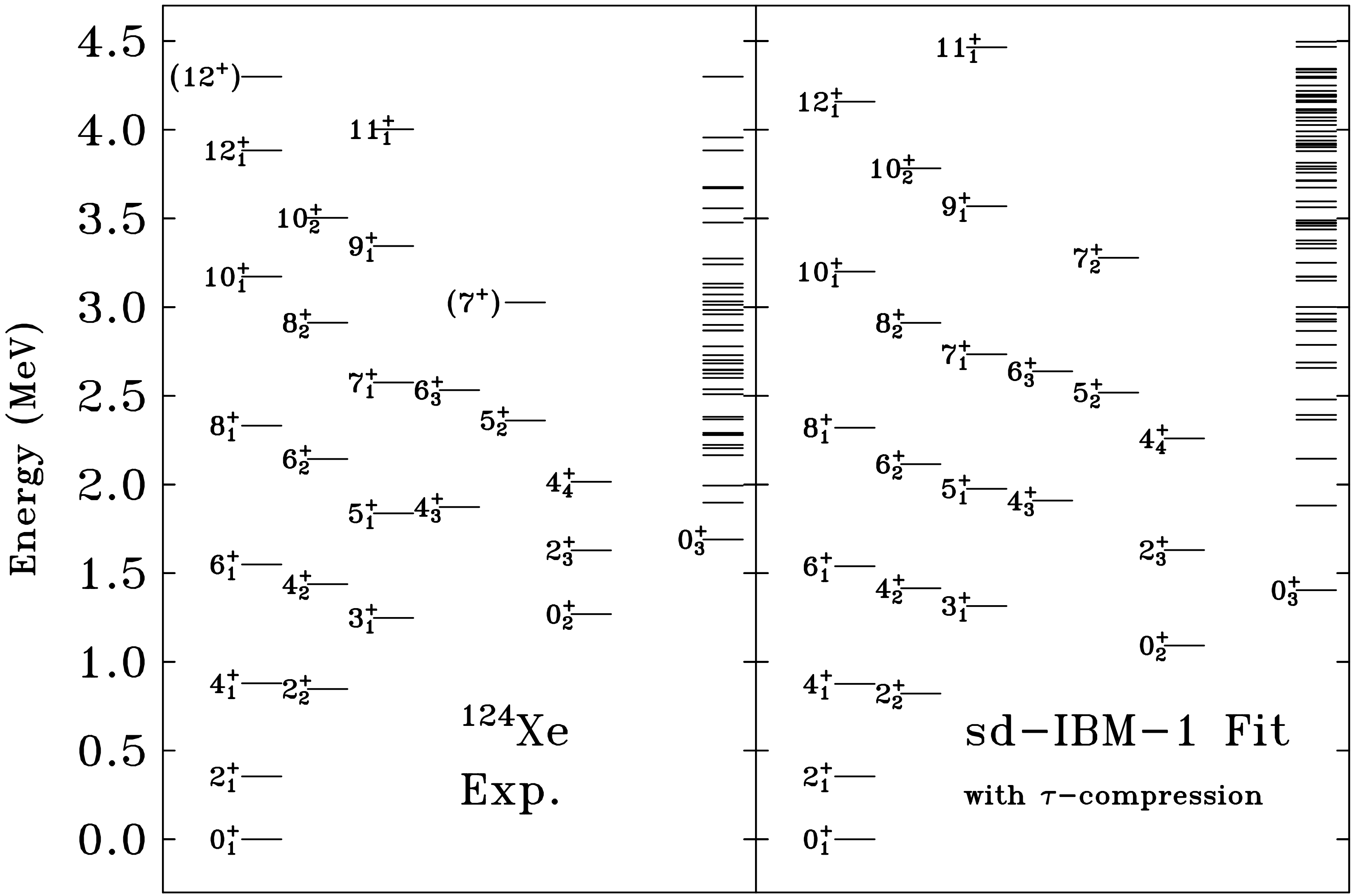
A problem with phenomenological theories is that they have a few free parameters . Of course there is a convincing solution: multitudes of relevant data. A typical example of such approach - multitudes of relevant data - is a description of the nucleus

^{124}Xe in the frame of the Interacting Boson Model IBM1 which is given in the next figure.

This data comes from the OSIRIS spectrometer in Koeln. V. Werner et al. N . P. A 692 (2001), 451.

Of these data 7 collective positive parity bands with about 20 levels and 30 B(E2) ratios and 5 lifetimes are described by the IBM1 with 6 parameters.

Of course one can do even better by looking at a set of neighboring nuclei.


Energy (MeV)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
(12$^+$)
12_1^+
11_1^+
10_2^+
9_1^+
10_1^+
(7$^+$)
8_2^+
7_1^+
6_3^+
5_2^+
8_1^+
6_2^+
4_4^+
5_1^+
4_3^+
0_3^+
2_3^+
6_1^+
4_2^+
3_1^+
0_2^+
4_1^+
2_2^+
^{124}Xe
Exp.
2_1^+
0_1^+
11_1^+
12_1^+
10_2^+
9_1^+
7_2^+
10_1^+
8_2^+
7_1^+
6_3^+
5_2^+
8_1^+
4_4^+
6_2^+
5_1^+
4_3^+
2_3^+
6_1^+
4_2^+
0_3^+
3_1^+
0_2^+
4_1^+
2_2^+
sd−IBM−1 Fit
2_1^+
with τ−compression
0_1^+

sd - IBA - 1 parameters

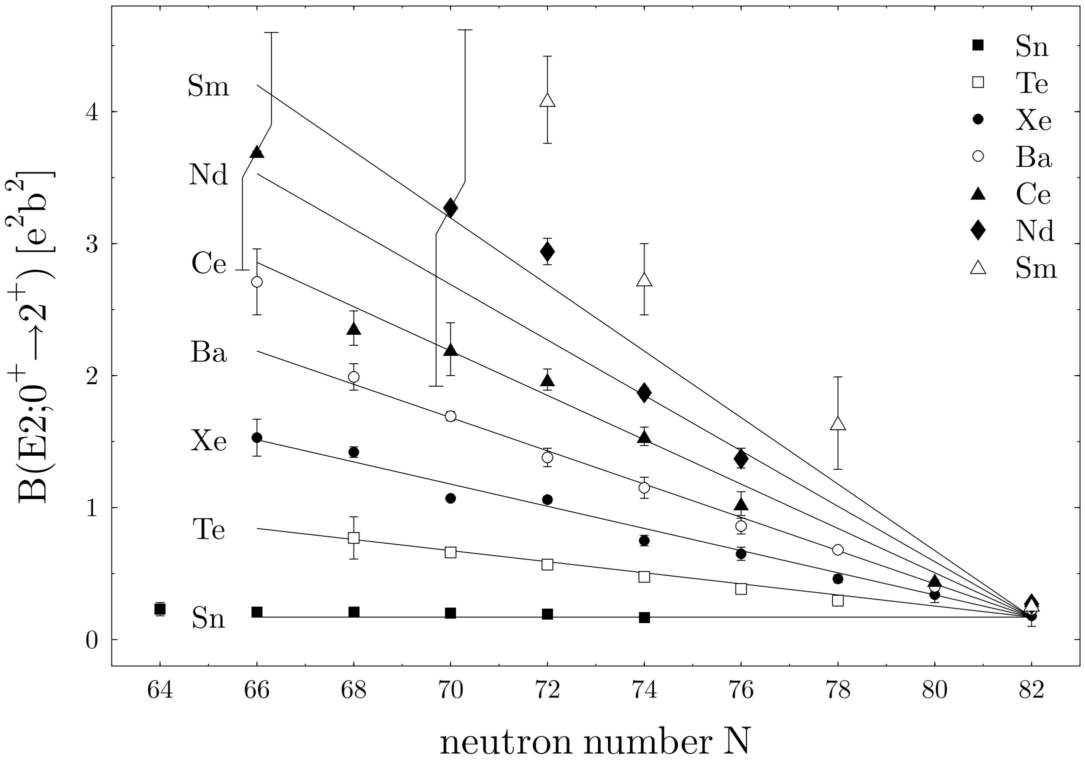
$$\mathbf{H_{CQF}} = \kappa \mathbf{Q}^{\chi} \cdot \mathbf{Q}^{\chi}$$

$\Longrightarrow$ **1 structure parameter** χ

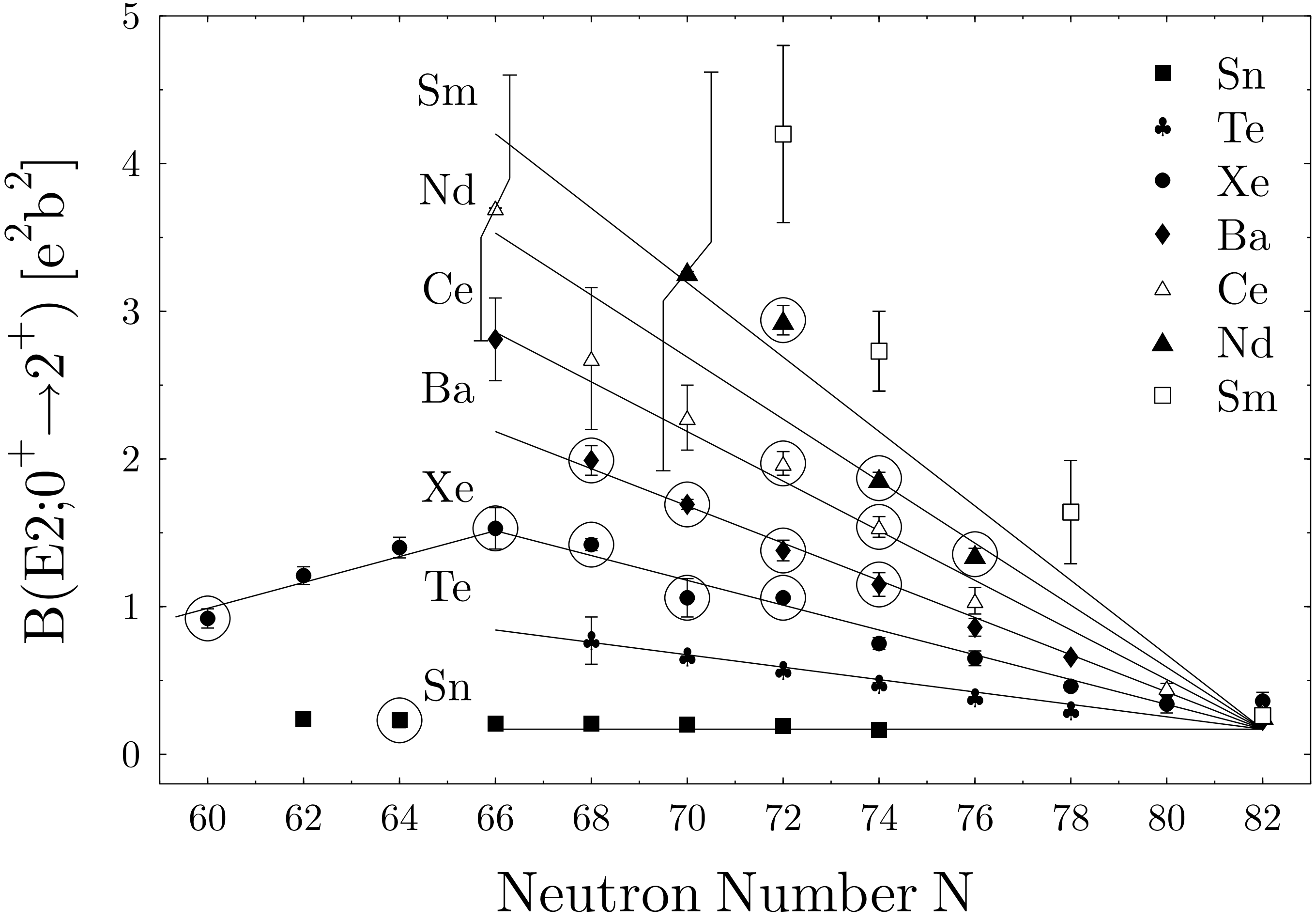
$$\begin{aligned} \mathbf{H_{ECQF}} &= \varepsilon \mathbf{n_d} + \kappa \mathbf{Q}^{\chi} \cdot \mathbf{Q}^{\chi} \\ &= \kappa \left(\frac{\varepsilon}{\kappa} \mathbf{n_d} + \mathbf{Q}^{\chi} \cdot \mathbf{Q}^{\chi} \right) \end{aligned}$$

$\Longrightarrow$ **2 structure parameters** $(\varepsilon/\kappa, \chi)$

	SU(3)	O(6)	U(5)
ε/κ	0	0	$-\infty$
χ	$-\sqrt{7}/2$	0	0



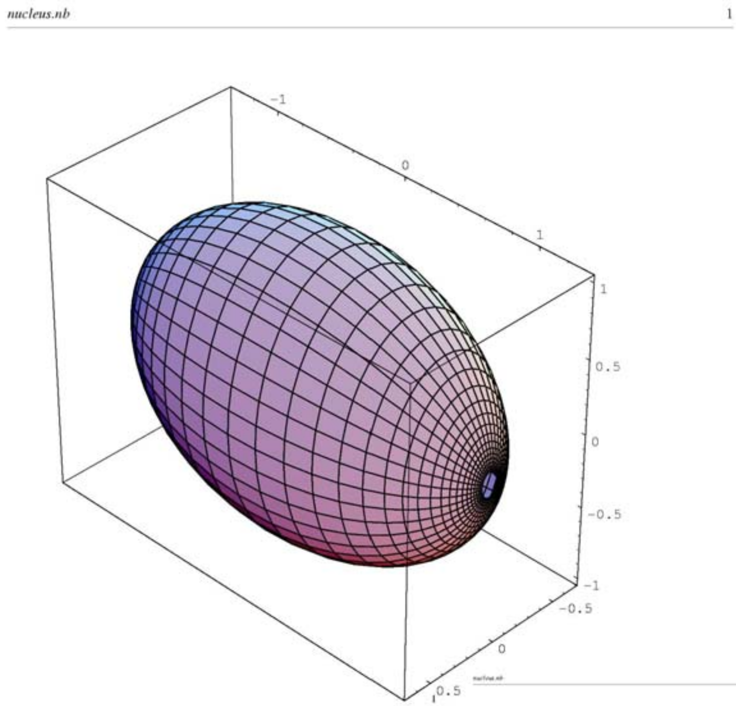
Sm
Nd
Ce
Ba
Xe
Te
Sn
Sn
Te
Xe
Ba
Ce
Nd
Sm
0
1
2
3
4
64
66
68
70
72
74
76
78
80
82
$B(E2;0^+ \to 2^+)$ $[e^2b^2]$
neutron number N

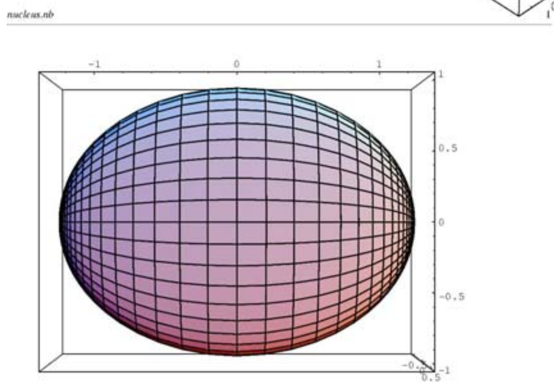


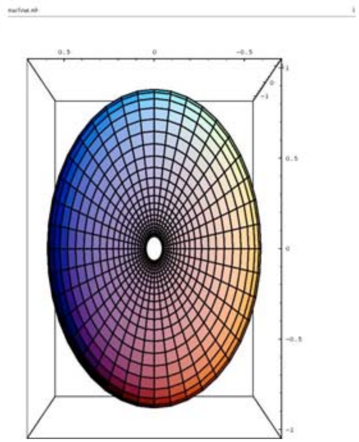
B(E2;0⁺→2⁺) [e²b²]
Neutron Number N
0
1
2
3
4
5
60
62
64
66
68
70
72
74
76
78
80
82
Sm
Nd
Ce
Ba
Xe
Te
Sn
Sn
Te
Xe
Ba
Ce
Nd
Sm

1999Kl11 Phys.Rev. C60, 034301 (1999) T.Klemme, A.Fitzler, A.Dewald, S.Schell, S.Kasemann, R.Kuhn, O.Stuch, H.Tiesler, K.O.Zell, P.von Brentano, D.Bazzacco, F.Brandolini, S.Lunardi, C.M.Petrache, C.Rossi Alvarez, G.De Angelis, P.Petkov, R.Wyss Lifetimes Measurements for 134Nd and Neighboring Nuclei with the Coincidence-Plunger Technique

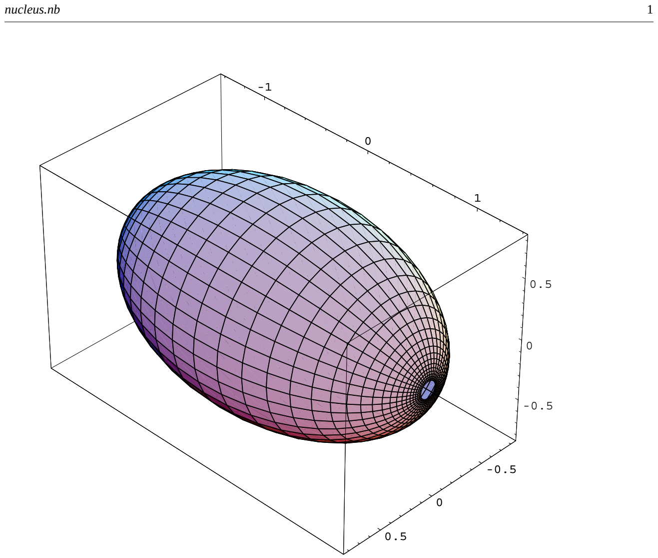
triaxial deformation

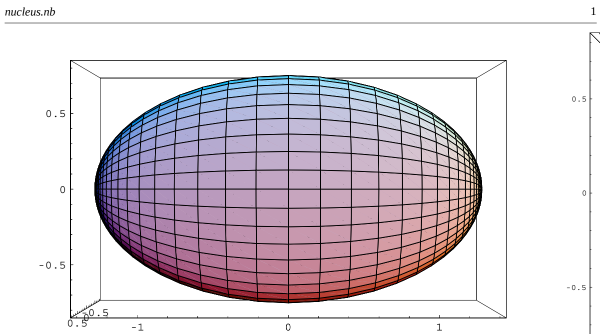


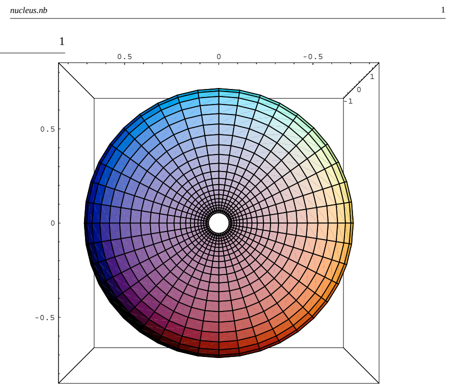




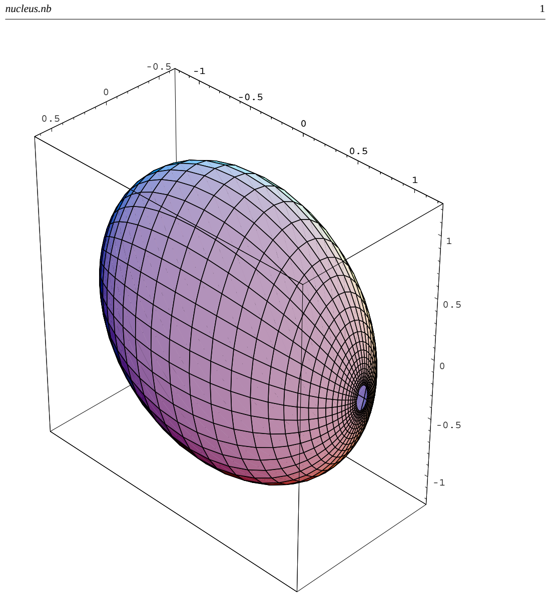
prolate deformation

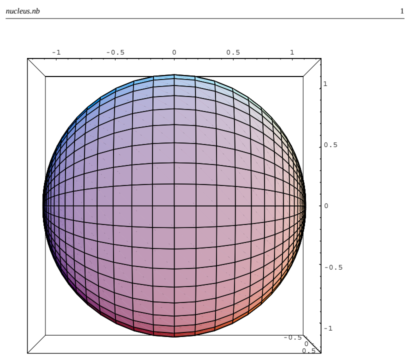


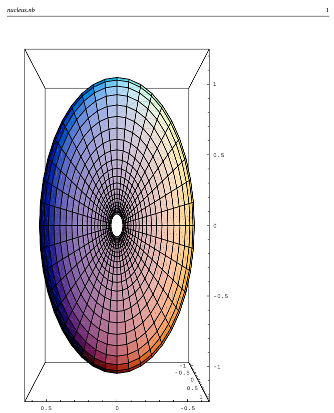




oblate deformation







Z \ N	68	69	70	71	72	73	74	75	76	77	78	79
56	^{124}Ba $\beta = 0.30$ $\gamma = 20.3^o$		^{126}Ba $\beta = 0.28$ $\gamma = 21.8^o$	^{127}Ba $\beta = 0.24$ $\gamma = 21^o$	^{128}Ba $\beta = 0.24$ $\gamma = 22.3^o$	^{129}Ba $\beta = 0.22$ $\gamma = 23^o$	^{130}Ba $\beta = 0.22$ $\gamma = 24.4^o$	^{131}Ba $\beta = 0.20$ $\gamma = 25^o$	^{132}Ba $\beta = 0.19$ $\gamma = 26.4^o$		^{134}Ba $\beta = 0.16$ $\gamma = 28.3^o$	
55			^{125}Cs $\beta = 0.26$ $\gamma = 21^o$		^{127}Cs $\beta = 0.22$ $\gamma = 22^o$		^{129}Cs $\beta = 0.20$ $\gamma = 22^o$					
54	^{122}Xe $\beta = 0.26$ $\gamma = 24.7^o$	^{123}Xe $\beta = 0.22$ $\gamma = 21^o$	^{124}Xe $\beta = 0.25$ $\gamma = 25.5^o$	^{125}Xe $\beta = 0.21$ $\gamma = 24^o$	^{126}Xe $\beta = 0.19$ $\gamma = 27.2^o$	^{127}Xe $\beta = 0.18$ $\gamma = 24^o$	^{128}Xe $\beta = 0.19$ $\gamma = 27.4^o$	^{129}Xe $\beta = 0.18$ $\gamma = 29.0^o$	^{130}Xe $\beta = 0.17$ $\gamma = 28.2^o$	^{131}Xe $\beta = 0.16$ $\gamma = 30^o$	^{132}Xe $\beta = 0.14$ $\gamma = 29.1^o$	^{133}Xe $\beta = 0.13$ $\gamma = 30^o$

Values of the Q invariants and the K- parameters for the dynamical symmetries of the Interacting Boson model .

Comparison to data

calculated shape invariants

^{124}**Xe**

$$\mathbf{F_2} = \frac{\mathbf{B(E2;0_1^+ \to 2_1^+)}}{\mathbf{q_2}} \qquad \mathbf{q_2} = \sum_{\mathbf{j}} \mathbf{B(E2;0 \to 2_j^+)}$$

	τ–ECQF	ECQF	CQF	[1]
q_2	1.542	1.546(5)	1.543	1.541
F_2	0.98	0.97	0.98	0.98
K_3	0.26	0.32(4)	0.22	0.39
K_4	1.031	1.043(13)	1.000	1.107
K_5	0.29	0.36(5)	0.22	0.51
K_6	0.35	0.39(3)	0.30	0.53
β_{eff}	0.269	0.269(1)	0.269	0.269
γ_{eff}	25.0°	23.9(9)°	25.7°	22.3°
σ_4	0.031	0.043(13)	0.0	0.107
σ_5	0.03	0.04(6)	0.0	0.12
σ_6	0.28	0.29(4)	0.25	0.37

[1] calculated with fit parameters from
W.-T. Chou, N.V. Zamfir, R.F. Casten, PRC56(1997),829

calculated shape invariants in the O(6) - region

$$\mathbf{R_2^{SU(3)}} = \frac{\mathbf{q_2^{fit}}}{\mathbf{q_2(SU(3))}} \qquad \mathbf{R_2^{O(6)}} = \frac{\mathbf{q_2^{fit}}}{\mathbf{q_2(O(6))}} \qquad \mathbf{R_2^{U(5)}} = \frac{\mathbf{q_2^{fit}}}{\mathbf{q_2(U(5))}}$$

	^{124}Xe	^{126}Xe	^{132}Ce	O(6)
N_B	8	7	8	∞
e_B	0.130	0.120	0.150	
q_2	1.542	1.082	2.020	
F_2	0.98	0.98	0.94	1
$R_2^{SU(3)}$	0.60	0.63	0.60	
$R_2^{O(6)}$	0.95	0.98	0.96	
$R_2^{U(5)}$	2.21	2.10	2.23	
K_3	0.258	0.200	0.282	0
K_4	1.031	1.016	1.029	1
K_5	0.285	0.211	0.283	0
K_6	0.345	0.300	0.334	0.32
β_{eff}	0.269	0.223	0.275	
γ_{eff}	25.0°	27.7°	24.5°	30°
σ_4	0.031	0.016	0.029	0
σ_5	0.027	0.091	0.001	0
σ_6	0.278	0.286	0.254	0.32

calculated shape invariants in the O(6) - region

$$\mathrm{R}_2^{\mathrm{SU(3)}} = \frac{\mathrm{q}_2^{\mathrm{fit}}}{\mathrm{q}_2(\mathrm{SU(3)})} \qquad \mathrm{R}_2^{\mathrm{O(6)}} = \frac{\mathrm{q}_2^{\mathrm{fit}}}{\mathrm{q}_2(\mathrm{O(6)})} \qquad \mathrm{R}_2^{\mathrm{U(5)}} = \frac{\mathrm{q}_2^{\mathrm{fit}}}{\mathrm{q}_2(\mathrm{U(5)})}$$

	^{124}Xe	^{126}Xe	^{132}Ce	O(6)
N_B	8	7	8	∞
e_B	0.130	0.120	0.150	
q_2	1.542	1.082	2.020	
F_2	0.98	0.98	0.94	1
$R_2^{SU(3)}$	0.60	0.63	0.60	
$R_2^{O(6)}$	0.95	0.98	0.96	
$R_2^{U(5)}$	2.21	2.10	2.23	
K_3	0.258	0.200	0.282	0
K_4	1.031	1.016	1.029	1
K_5	0.285	0.211	0.283	0
K_6	0.345	0.300	0.334	0.32
β_{eff}	0.269	0.223	0.275	
γ_{eff}	25.0°	27.7°	24.5°	30°
σ_4	0.031	0.016	0.029	0
σ_5	0.027	0.091	0.001	0
σ_6	0.278	0.286	0.254	0.32

K- parameters, Q invariants. Rigid or soft shape of nuclei.

We call the nucleus beta rigid if $(QQ)_0$is diagonal for spin zero states.i.e. :

$$< 0_n|QQ|0_1 >= q_2 \, \delta_{1n}$$

In this case one finds

$$q_4 =< 0_1|(QQ)_0(QQ)_0|0_1 > =$$

$$= \Sigma_n < 0_1|(QQ)_0|0_n >< 0_n|(QQ)_0|0_1 > =$$

$$< 0_1|(QQ)_0|0_1 >< 0_1|(QQ)_0|0_1 >$$

$$q_4 \;\; = \;\; q_2 * q_2$$

$$q_4 \;=\; q_2 * q_2$$

This implies

$K_4 = K_2 * K_2$ and

$$\sigma_4 \;=\; K_4 - K_2 * K_2 \;=\; 0$$

That is for a beta rigid nucleus the shape fluctuations σ_4 vanish. This is what one expects of course.

Similar arguments hold for a gamma rigid nucleus for which $\sigma_6 \;=\; 0$.

Discussion of parameters of ^{124}Xe:

q_2 is very well determined

F_2 measures how much E_2 strength is in the 2_1^+ state. As we are near a dynamical symmetry here $0(6)$ F_2 is nearly one. $F_2 \simeq 1$ shows the quality of the Q- phonon model.

K_3 is nearly 0 in accordance with the 0(6) character of ^{124}Xe

K_4 is nearly one. This shows the interesting fact that ^{124}Xe has a fixed value of β. Thus ^{124}Xe is beta rigid.

In correspondence the fluctuations σ_4 =0.031 are small.

The large values of K_6 and of the fluctuation parameter σ_6 =0.28 show the interesting fact that ^{124}Xe has no fixed value of γ. Thus it is γ soft. Of course <γ> can have a mean value : $< \gamma >_{eff} = 25^0$, which is very near to the maximum possible triaxiality of $\gamma = 30$. We have made a long and detailed discussion of the K and σ parameters showing how much physics is in these parameters.

Summary

Shape ^{124}Xe

beta shows no fluctuations

gamma shows strong fluctuations

Nucleus is beta rigid and gamma soft

It is rather good case of =86) dynamical symmetry of IBA

The usual approach to spectroscopy is to compare the individual states and observables to a theoretical model like the Interacting Boson Model or the Shell Model. There is , however, another approach to extract physics from data. This approach uses relations between collective observables with no free parameters at all. Such approach may be better suited to RIB physics, which inherently yields a more restricted set of data.

These - parameter free - approximate relations can be obtained from truncated sum rules and their accuracies can be tested in the various collective models. Examples are:

Cubic shape parameter q_3 and Triaxiality (lecture 1)

Cubic shape parameter q_3 from four observables (lecture 1)

The Three B(E2) Relation (lecture 1)

Spin Dependent Generalized Grodzins Relation (follows)

Spin Dependent Generalized Grodzins Relation,

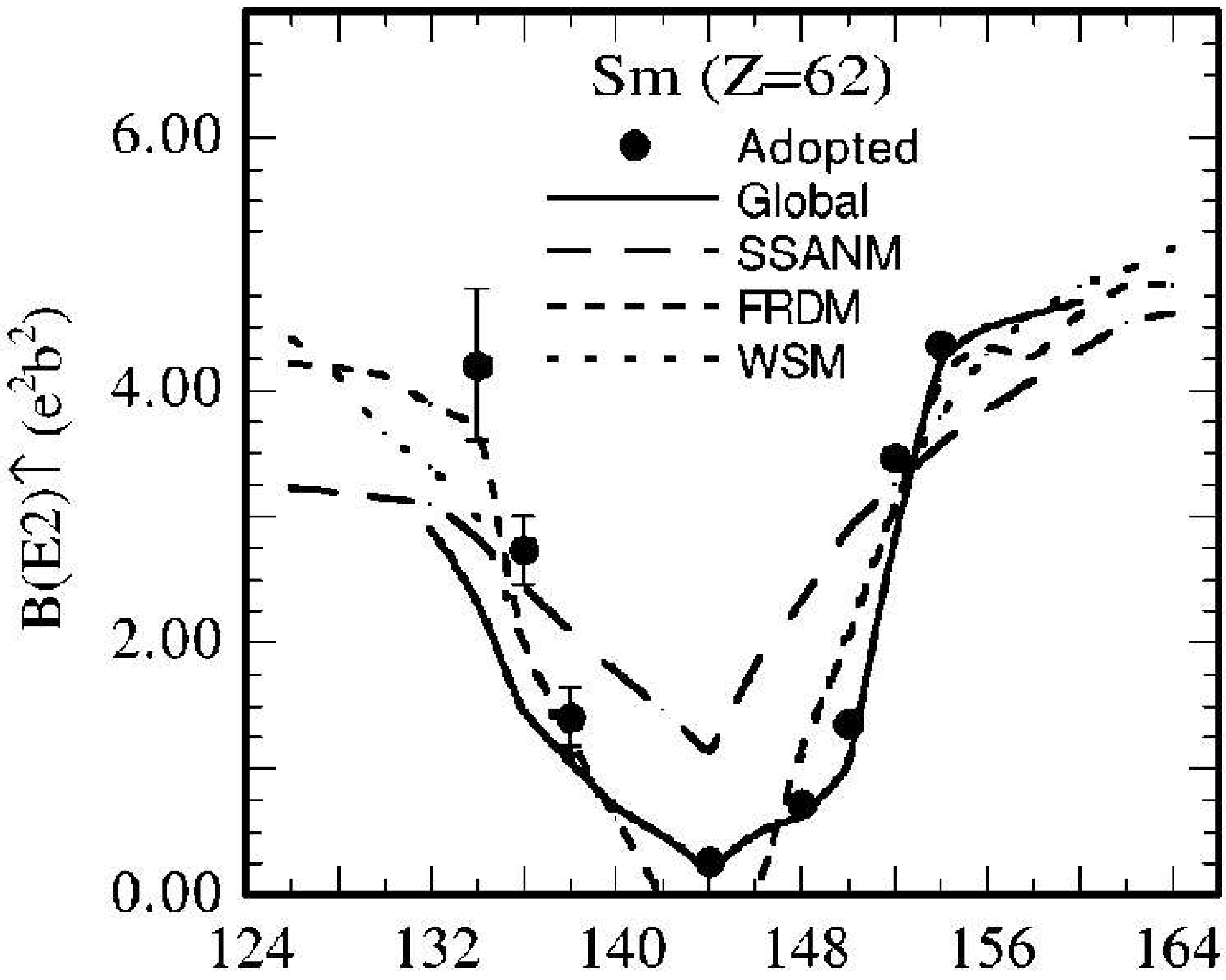
The Grodzins relation : L. Grodzins, PL 2, 88 (1962). S. Raman, ADNDT 78 (2001).and its generalization R.V. Jolos , P. von Brentano and N. Pietralla, Dubna, Koeln, Stony Brook.

$$\mathbf{E(2_1^+) * B(E2; 2 \Rightarrow 0^+) = (0.5 \pm 0.1) * Z^2 * A^{-2/3}}$$

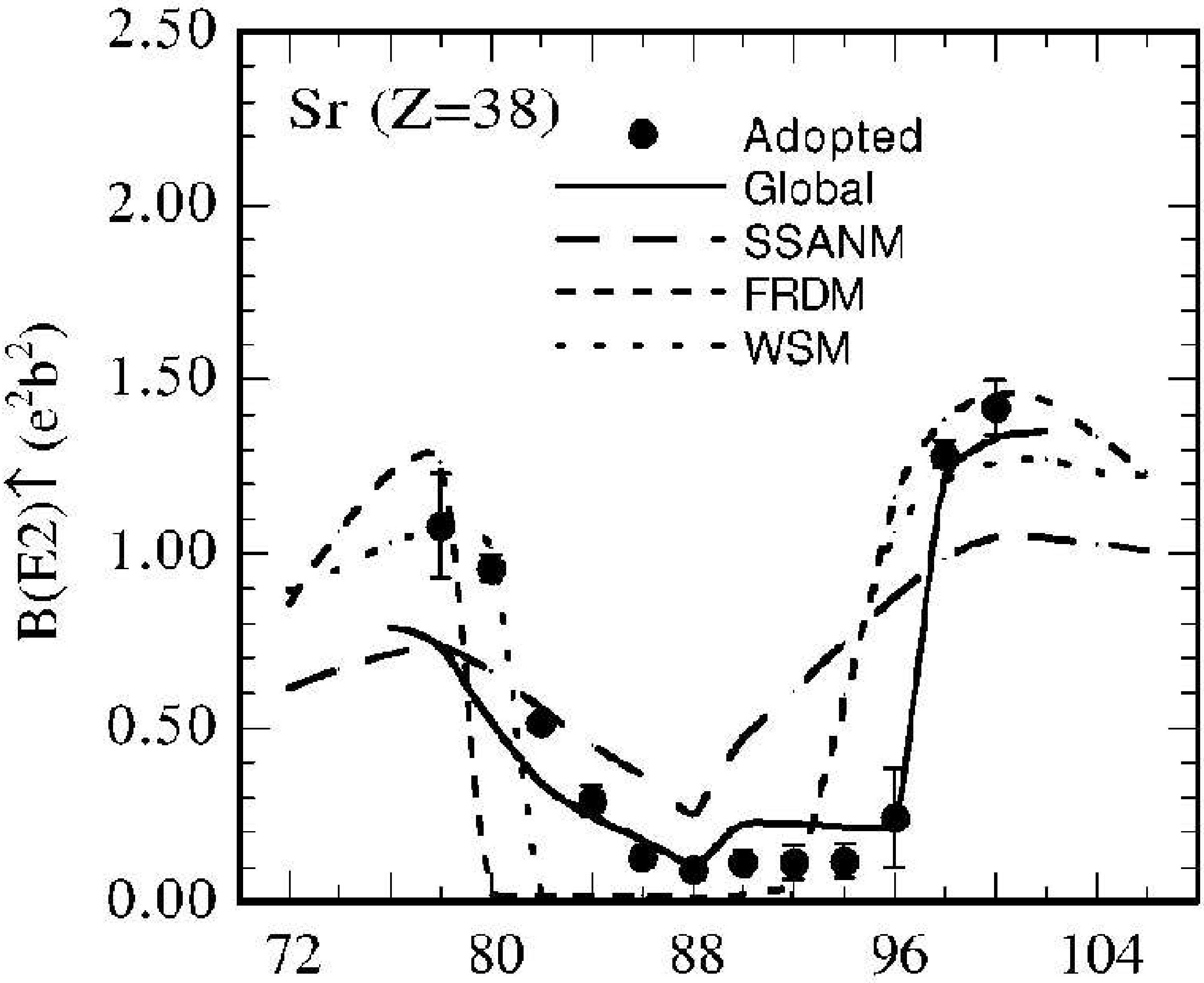
A Generalized Grodzins Relation for the quasi rotational ground band for nuclei with : $\mathbf{E(2_1) < 0,1 * E(2_2)}$

$$\mathbf{(E(I+2) - E(I)) * B(E2; I+2 \Rightarrow I) *}$$

$$\mathbf{*(2I+5)/(I+1) * (I+2) = const}$$



“Horizontal” Grodzins relation (vs A). S. Raman, ADNDT 78 (2001)



S. Raman, ADNDT 78 (2001)

Test of the “vertical” Spin Dependent Generalized Grodzins Relation

154Sm	ΔE_g	B(E2)↓	G(J)	Gen.Grodzins
J.....	MeV....	Wu	....	Wu*MeV
2	0.082	174(5)	2.5	**35.7(6)**
4	0.185	244(6)	0.75	**33.8(6)**
6	0.277	290(8)	0.433	**34.8(10)**
8	0.359	318(17)	0.304	**34.7(15)**
10	0.430	314(16)	0.233	**31.5(15)**
2_2	1.178			

$$\mathbf{(E(I+2)-E(I))*B(E2;I+2\Rightarrow I)*(2I+5)/(I+1)*(I+2)}$$

$$\mathbf{=(E(2)*B(E2;2\Rightarrow 0)*5/2=Const}$$

For nuclei with : $E(2_1) < 0,1 * E(2_2)$

150Nd	ΔE_g	B(E2)↓	G(J)	Gen.Grodzins
J.....	MeV....	Wu	....	Wu*MeV
2	.130	103(1)	2.5	33.5(3)
4	.251	179(1)	0.75	33.7(2)
6	.339	210(8)	0.433	30.8(16)
8	.410	275(26)	0.304	34.3(30)
10	.469	203(11)	0.233	22.2(11)

Phys.Rev.Lett. 88, 232501 (2002) R.Krucken, B.Albanna, C.Bialik, R.F.Casten, J.R.Cooper, A.Dewald, N.V.Zamfir, C.J.Barton, C.W.Beausang, M.A.Caprio, A.A.Hecht, T.Klug, J.R.Novak, N.Pietralla, P.von Brentano B(E2) Values in 150Nd and the Critical Point Symmetry X(5)

The Spin Dependent Generalized Grodzins Relation gives the spin dependence of the B(E2) in the quasi rotational ground state band from the energies:

The relation is derived from the Bohr Hamiltonian. $\mathbf{\hat{H} = \hat{T}(B) + V(Q_{2\mu})}$ where V is the potential energy depending only on the quadrupole moment operator $Q_{2\mu}$.

It holds when a constant mass parameter B is used and the rotational energies are small compared to the vibrational energies of the band-heads of the β and γ bands : $\mathbf{E(2_1) < 0.1 * E(2_2)}$. Thus it does not hold for vibrational nuclei.

The energies and the B(E2)'s of the rigid rotor nuclei have been tested empirically . Thus the generalization of the Grodzins relation is empirically checked for the rigid rotor case.

In general the energies deviate significantly from the rigid rotor, because the (variable) moments of inertia are spin dependent . Then the relation predicts corresponding deviations in the B(E2)t's. from the rigid rotor.It should be tested .

Experimental nuclear spectroscopy 3

Trieste IAEA April 2005

Peter von Brentano ,IKP Universität zu Köln, Germany

Lecture 3:

We continue the discussion of the progress made in the low spin nuclear spectroscopy putting an emphasis again on the measurements of lifetimes and transition matrix elements of nuclear states. In the second lecture the focus was on heavy ion fusion reactions and in particularly on the problem of unknown side feeding. Here we discuss in particular

the (n,n′γ) fusion reaction

resonant (γ, γ') reaction :

(γ, γ') coincidence spectroscopy following beta decay

Here we discuss in particular the spectroscopy of isovector excitations

Comparison of spectra from

(n,n′γ) and from

resonant (γ, γ') reactions and from

(γ, γ') coincidence spectra following beta decay .

These reactions produce beautiful spectra.

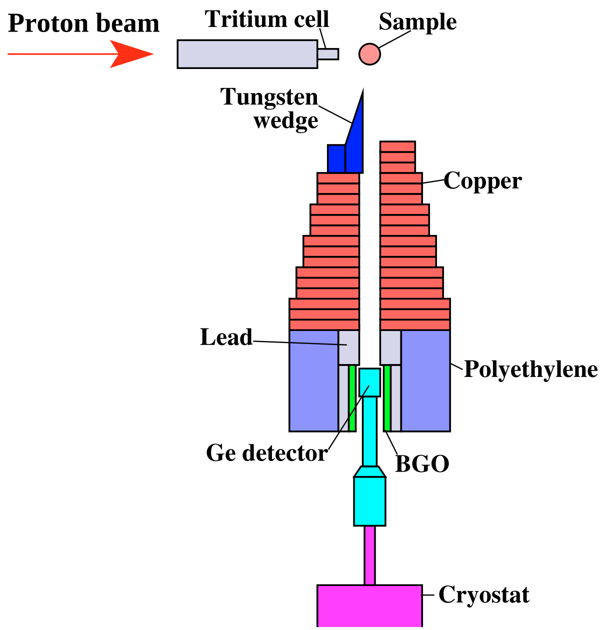
We show 3 Setups for low spin spectroscopy

in Lexington, in Stuttgart and @ FN-Tandem @ Cologne.

Lifetimes from(n,n′γ) reactions and from resonant

(γ, γ') reactions

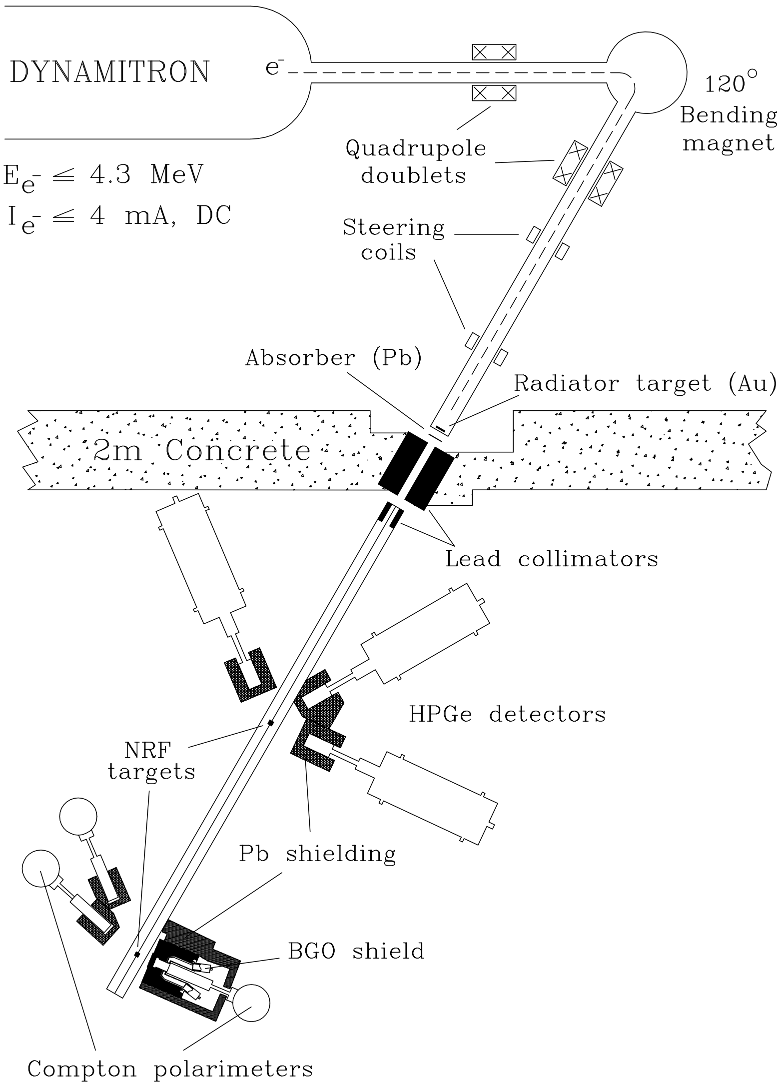
Experimental setup at the Van de Graaff accelerator of the University of Kentucky



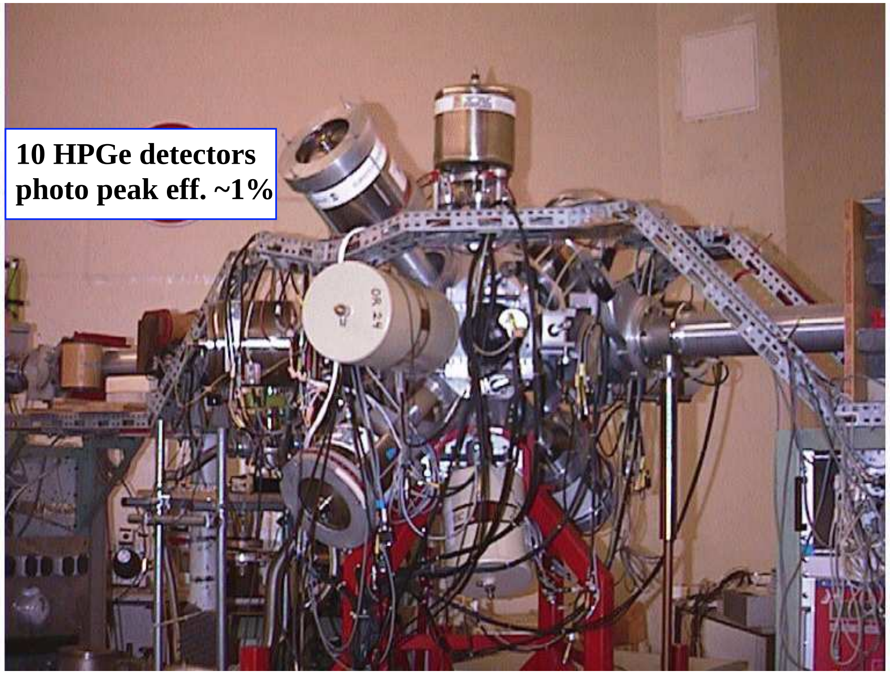
Angular distributions: J , δ, τ

Excitation function: level scheme, J

NRF – setup at the Stuttgart Dynamitron



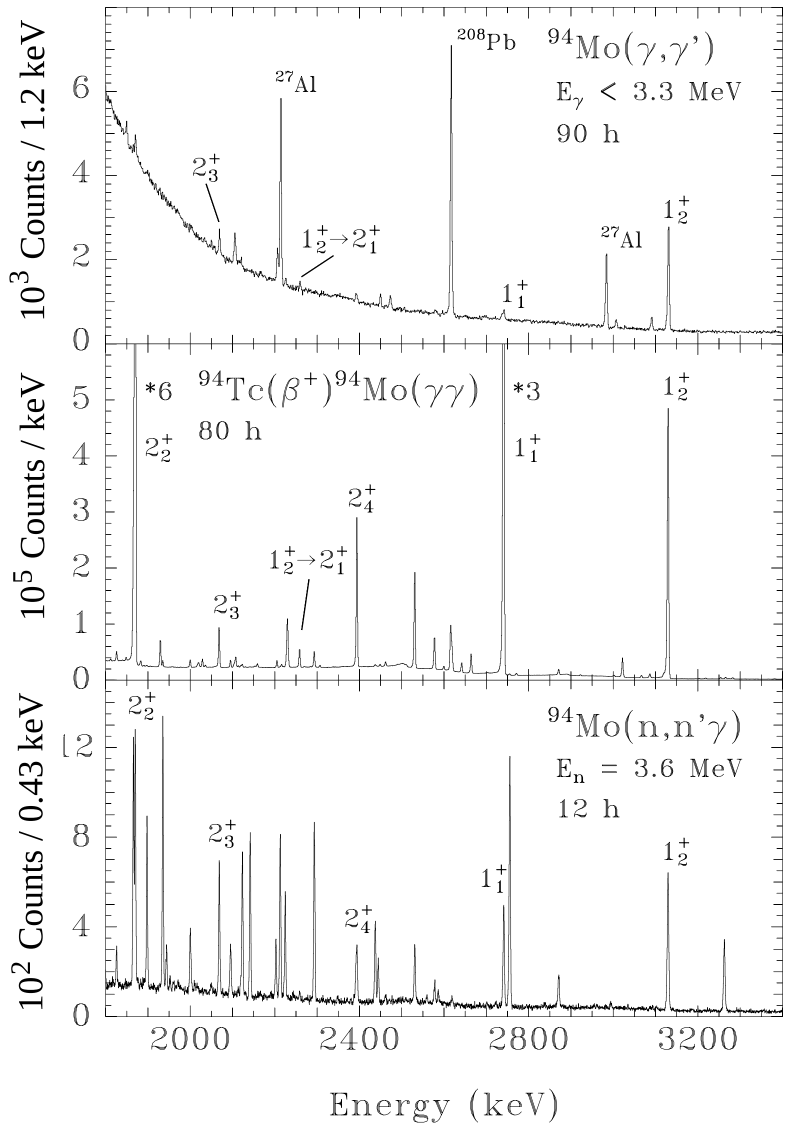
$\gamma\gamma$−coincidence experiments at the Cologne Osiris spectrometer



Observables

- γ energies
- branching ratios
- multipole mixing ratios
- effective lifetimes in in−beam experiments from Doppler−shifts

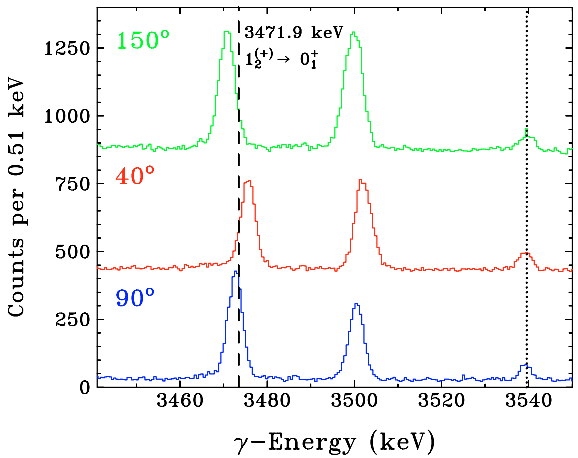
γ-ray spectra of ^{94}Mo from different experiments

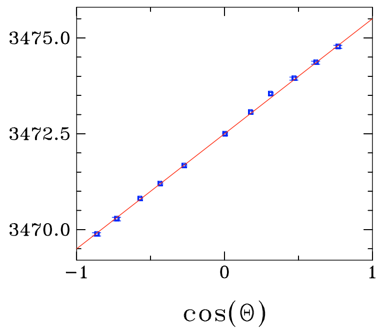


(n,n′γ) Spectroscopy: Steve Yates & Co Lexington

The (n,n′γ) reaction is a fusion reaction . But there is no coulomb barrier for the neutron. As there is no coulomb barrier for the (n,n′γ) reaction the populated spins start with spin zero. As all compound nucleus fusion reactions the reaction is "complete" in a given window of spins and excitation energies. A disadvantage is that due to statistics the data are usually singles data. A remedy is to measure excitation functions. By comparing two spectra at two different neutron energies one can find the states with the higher excitation energy . This allows to determine the excitation energies of the states from singles excitation measurements without the need to do γ,γ coincidence spectra . Thus from excitation functions and from angular distributions one can obtain energies , spins and deltas (E2/M1 mixing ratios) and one obtains fairly complete level schemes. A further big advantage of the (n,n′γ) spectroscopy is the use of the Dopper shift attenuation method to obtain life times. The big advantage here is that one can eliminate the unknown side feeding which has an unknown time delay. This is done again by considering only the states with the highest excitation energies for which there is no indirect side feeding. Thus the (n,n′γ) spectroscopy gives also quite reliable lifetimes.

Lifetime determination from Doppler shifts





F(τ)=0.884(6)
τ=7.6(9) fs

$$E_\gamma(\theta) = E_0 \left(1 + F(\tau)\frac{v_{\mathrm{cm}}}{c}\right) \cos\theta \qquad (1)$$

$F(\tau)$ **Doppler shift attenuation factor**
θ **emission angle relative to the incident beam**

Recent examples of the low spin spectroscopy of isovector excitations in the mass 90 region come from the Koeln Lexington Stuttgart Collaboration. E.g. :

C.Fransen, N.Pietralla, Z.Ammar, D.Bandyopadhyay, N.Boukharouba, P.von Brentano, A.Dewald, J.Gableske, A.Gade, J.Jolie, U.Kneissl, S.R.Lesher, A.F.Lisetskiy, M.T.McEllistrem, M.Merrick, H.H.Pitz, N.Warr, V.Werner, S.W.Yates
Phys. Rev. C 67, 024307 (2003)

Comprehensive studies of low-spin collective excitations in 94Mo

Gamma spectroscopy following beta decay:

(γ,γ') coincidence spectroscopy from nuclei populated by beta decay is a very powerful tool. These reactions produce beautiful spectra, as there is no background from the E2 giant resonance in particular and the continuum contributions in general.The reaction is not complete because the beta decay populates selective states. This disadvantage is off set to a large extent by the very low background, the high statistics and the coincidence spectra, which are obtained in large arrays. A big progress in spectroscopy was in the parallel use of several reactions to study one nucleus. In Koeln it was found that combinations of some of the reactions (p,n), $(^3He,n)$, $(^3He,p)$, $(^4He,n)$, $(^4He,nn)$, $(^6Li,3n)$ with beta decay data and with heavy ion xn reactions produced very “complete data”

Lifetimes of highly excited states from NRF

@ S-Dalinac (Darmstadt) or

@Dynamitron (Stuttgart)

@Linac Rossendorf

NRF = Nuclear resonance fluorescence

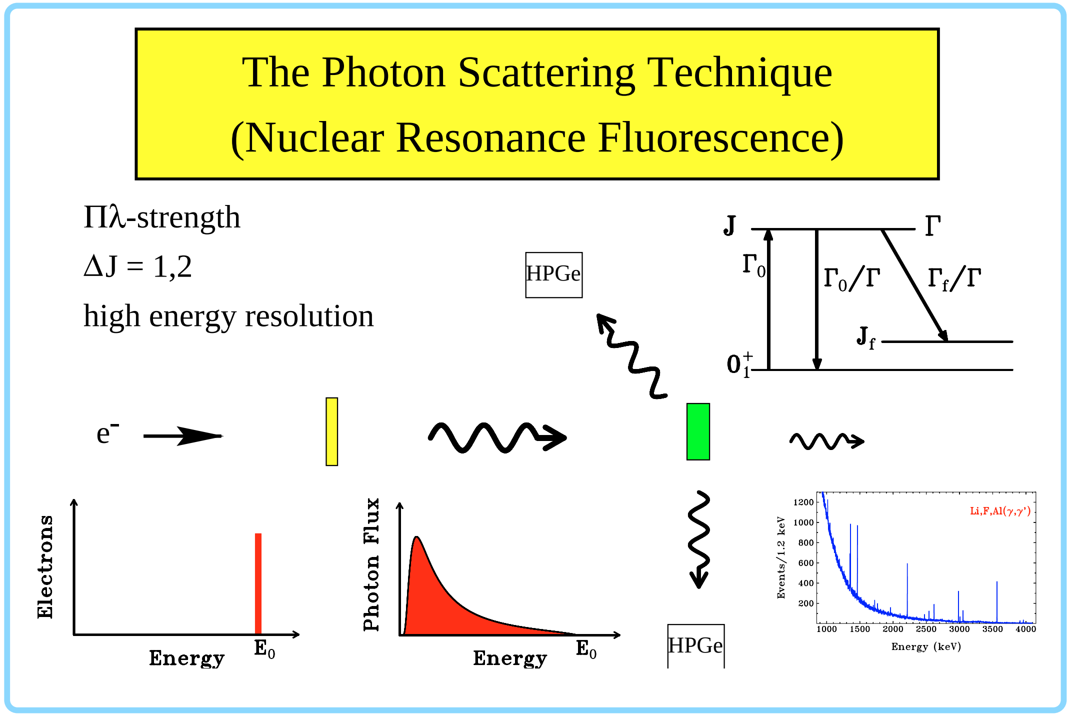
NRF = Resonant inelastic photon scattering

NRF = $A(\gamma,\gamma)A*$

Resonance reaction:

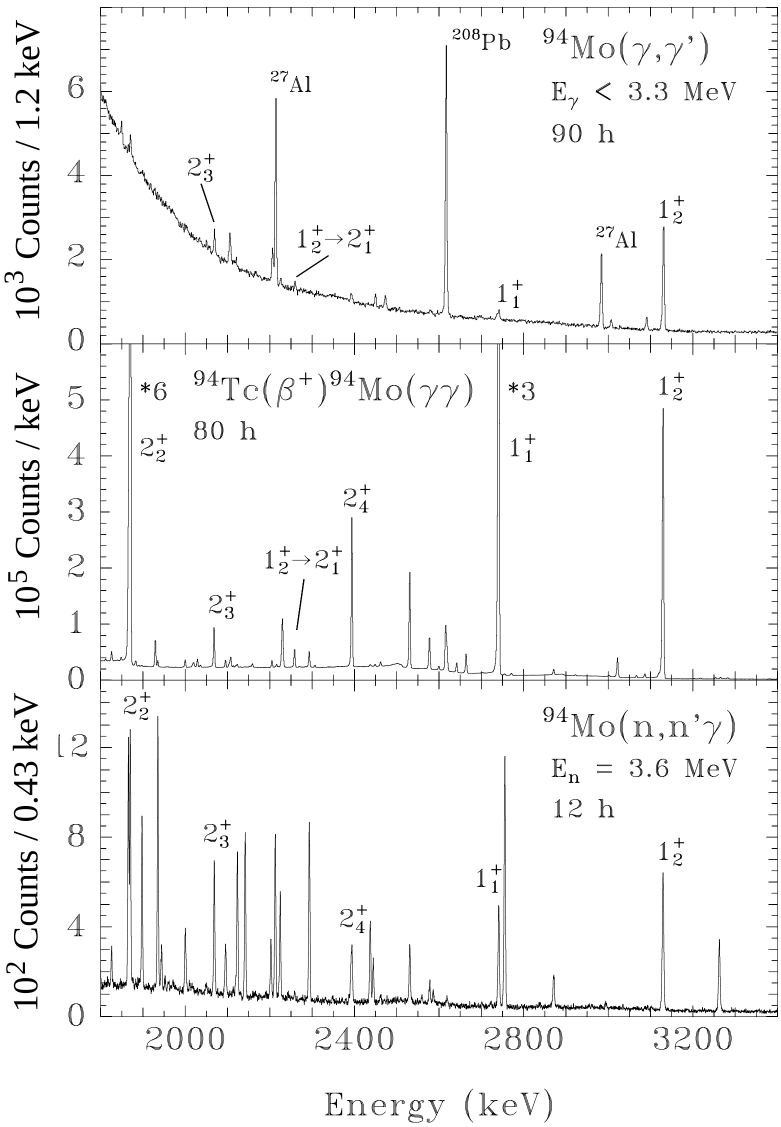
$$A + \gamma \Rightarrow$$

$$A**(E,I) \Rightarrow \gamma + A*$$



U.Kneissl, H.H.Pitz and A.Zilges. Prog. Part. Nucl. Physics Vol. 37 p 349 1996

γ −ray spectra of ^{94}Mo from different experiments



Comments on NRF = Nuclear resonance fluorescence spectroscopy

The method uses the secondary beam approach which is the basis of the rare isotopes beam spectroscopy. Here the primary electron beam(which has good energy resolution) is converted into a bremsstrahlung photon beam (which has bad energy resolution)which is used to induce the resonance reaction.

$$A + \gamma \Rightarrow A * *(E, I) \Rightarrow \gamma + A*$$

It is surprising that the background in the spectra is so low and that the peaks in the spectrum show up so clearly above the background. This works in particular at the low electron energies of a few MeV. This is Ulrich Kneissl's secret.

The NRF spectroscopy allows to measure in particular

energies E, total lifetimes respectively partial lifetimes which are obtained from the total life time by considering the branched decay. Alternatively one gives the decay constants λ_k from the lifetimes or from the partial lifetimes respectively one obtains the electromagnetic transition probabilities B(E,M, λ_k) , which are crucial observables. Furthermore one obtains spins J from the angular distributions of the gammas and parities from measurements of the linear polarization of the gammas. Finally one can obtain in rotational nuclei the K quantum number. Summing up one can measure by NRF spectroscopy a formidable array of observables :

E, B(M1), B(E1), B(E2), J,π, K

Review of NRF

U.Kneissl, H.H.Pitz and A.Zilges. Prog. Part. Nucl. Physics Vol. 37 p 349 1996

see also references contained therein

Review of Scissor mode : A Richter Prog. Part. Nucl. Physics Vol. 34 p261 1995

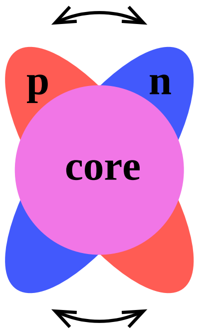
see also references contained therein. Examles are e.g

R.-D.Herzberg, I.Bauske, P.von Brentano, Th.Eckert, R.Fischer, W.Geiger, U.Kneissl, J.Margraf, H.Maser, N.Pietralla, H.H.Pitz, A.Zilges, Nucl.Phys. A592, 211 (1995) Lifetimes of Two-Phonon 1- States in Even N = 82 Nuclei

J.Bryssinck, L.Govor, D.Belic, F.Bauwens, O.Beck, P.von Brentano, D.De Frenne, T.Eckert, C.Fransen, K.Govaert, R.-D.Herzberg, E.Jacobs, U.Kneissl, H.Maser, A.Nord, N.Pietralla, H.H.Pitz, V.Yu.Ponomarev, V.Werner, Phys.Rev. C59, 1930 (1999)

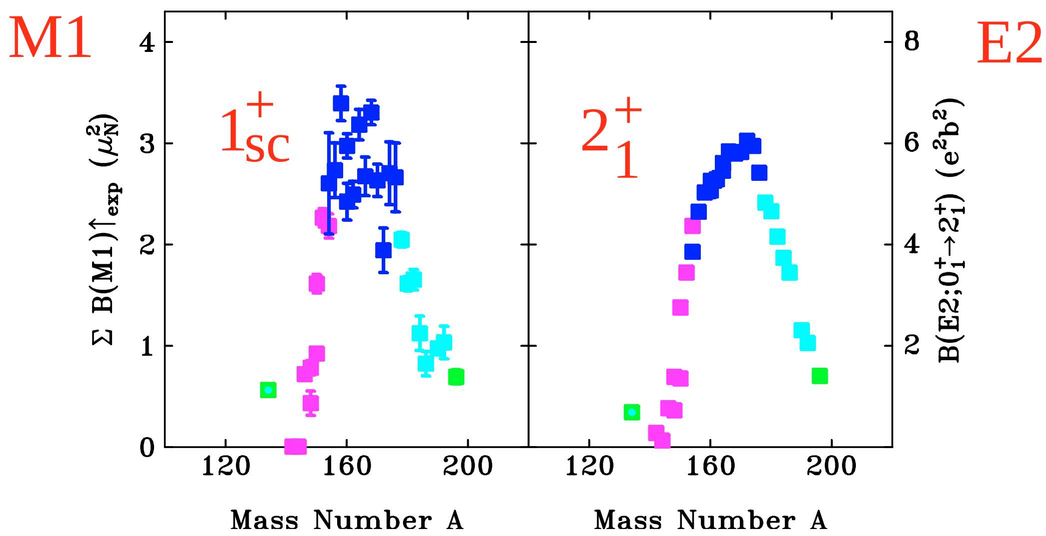
Uniform Properties of Jpi = 1- Two-Phonon States in the Semimagic Even-Even Tin Isotopes 116,118,120,122,124Sn

Collectivity of the scissors mode



1^{+}_{sc}

Rare earth region



Köln – Stuttgart – Darmstadt – Rossendorf collaboration

N. Pietralla et al., Phys. Rev. C 58, 184 (1998)

Recent examples of the low spin spectroscopy of isovector excitations in the mass 90 region e.g. ^{92}Zr and ^{94}Mo come from the

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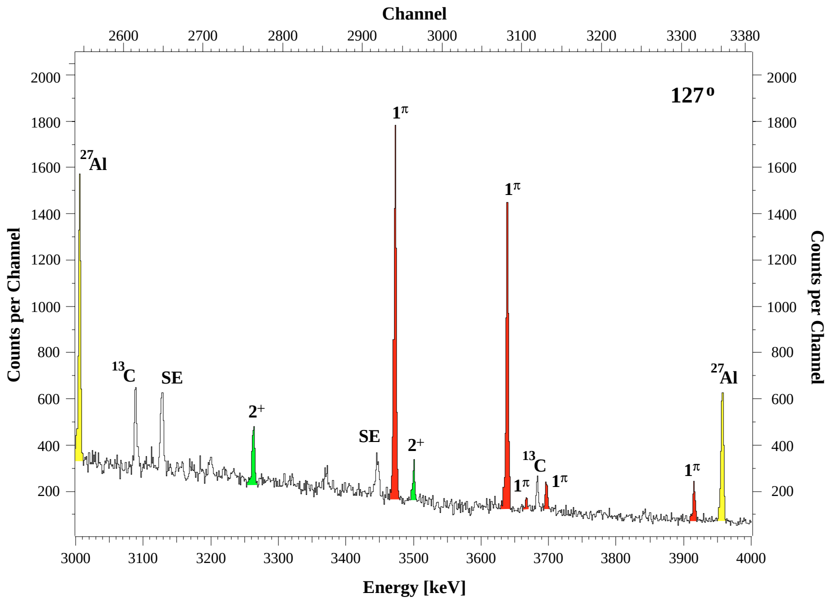
C.Fransen, N.Pietralla, Z.Ammar, D.Bandyopadhyay, N.Boukharouba, P.von Brentano, A.Dewald, J.Gableske, A.Gade, J.Jolie, U.Kneissl, S.R.Lesher, A.F.Lisetskiy, M.T.McEllistrem, M.Merrick, H.H.Pitz, N.Warr, V.Werner, S.W.Yates

Phys. Rev. C 67, 024307 (2003)

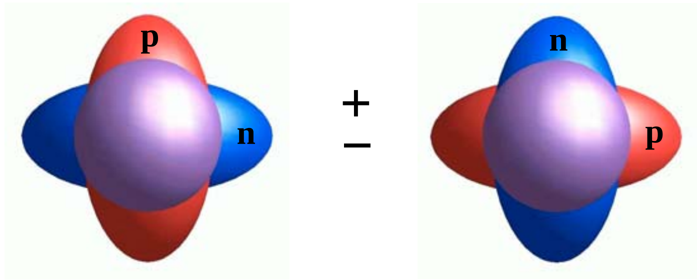
Comprehensive studies of low-spin collective excitations in 94Mo

Institut für Kernphysik
UNIVERSITÄT ZU KÖLN

$^{92}Zr(\gamma,\gamma')$



Isoscalar and isovector excitations in vibrator nuclei



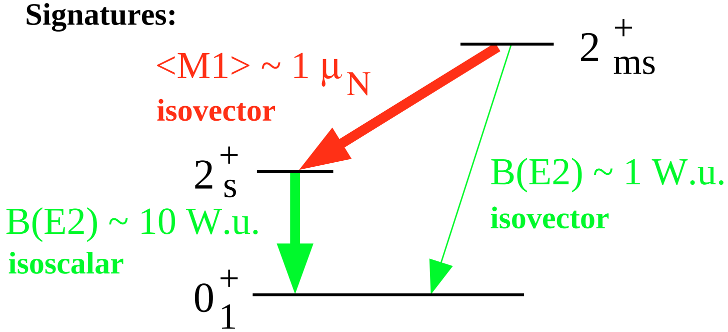
Isoscalar quadrupole vibration: symmetric

$$|2^+_\mathrm{s}\rangle \propto |2^+_\mathrm{p}\rangle + |2^+_\mathrm{n}\rangle$$

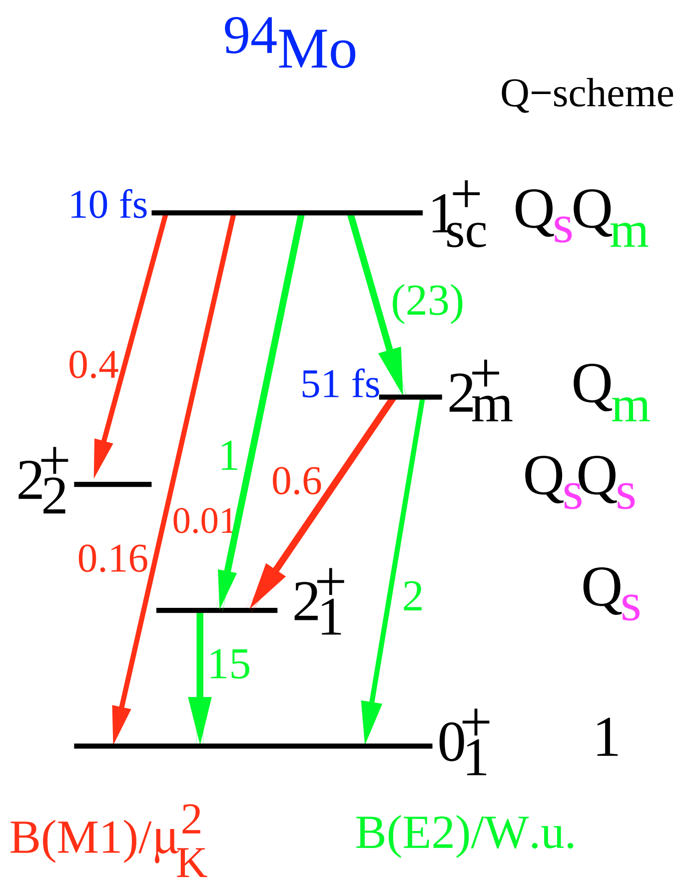
Isovector quadrupole vibration: mixed−symmetric

$$|2^+_\mathrm{ms}\rangle \propto a \cdot |2^+_\mathrm{p}\rangle - b \cdot |2^+_\mathrm{n}\rangle$$

Signatures:

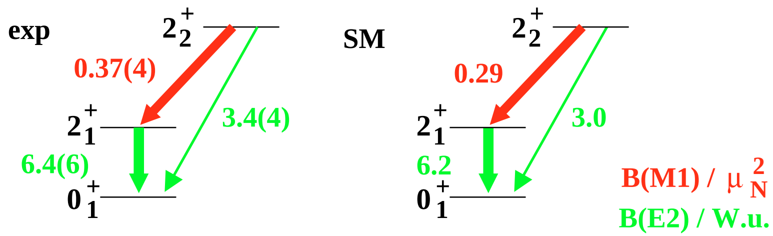


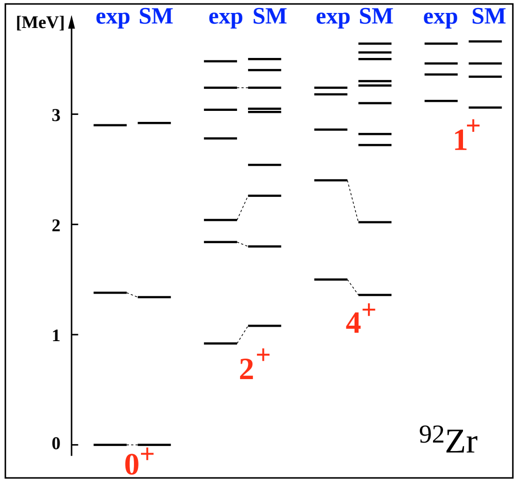
MS states in ^{94}Mo



C. Fransen, N. Pietralla et al., Phys. Rev. C 67 (2003) 024307

Shell model fit for ^{92}Zr





V. Werner, PhD thesis, University of Cologne 2004

	exp	SM
$g(2^+_1) =$	−0.18(1)	−0.18
$g(4^+_1) =$	−0.5(1)	−0.38

G. Jacobs et al., Phys. Lett. B468, 13 (1999)