Discoveries
that change the course of a field

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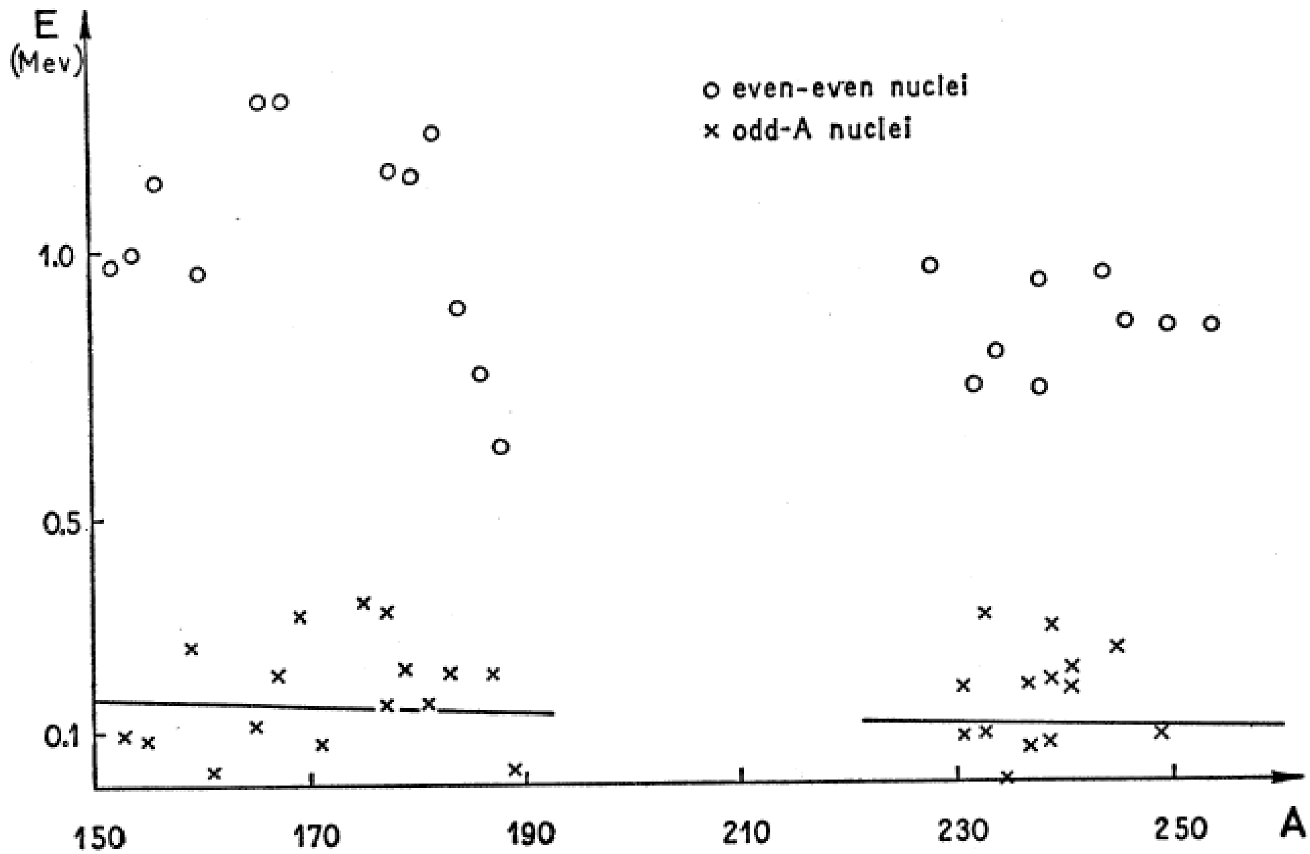
Possible Analogy between the Excitation Spectra of Nuclei and Those of the Superconducting Metallic State

A. BOHR, B. R. MOTTELSON, AND D. PINES*
Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark, and Nordisk Institut for Teoretisk Atomfysik, Copenhagen, Denmark

(Received January 7, 1958)

The evidence for an energy gap in the intrinsic excitation spectrum of nuclei is reviewed. A possible analogy between this effect and the energy gap observed in the electronic excitation of a superconducting metal is suggested.

average level spaceing
$\delta = 50/A$



Possible Analogy between the Excitation Spectra of Nuclei and Those of the Superconducting Metallic State

The evidence for an energy gap in the intrinsic excitation spectrum of nuclei is reviewed. A possible analogy between this effect and the energy gap observed in the electronic excitation of a superconducting metal is suggested.

Start of BCS and Hartree Fock Bogolyubov theory of nuclei

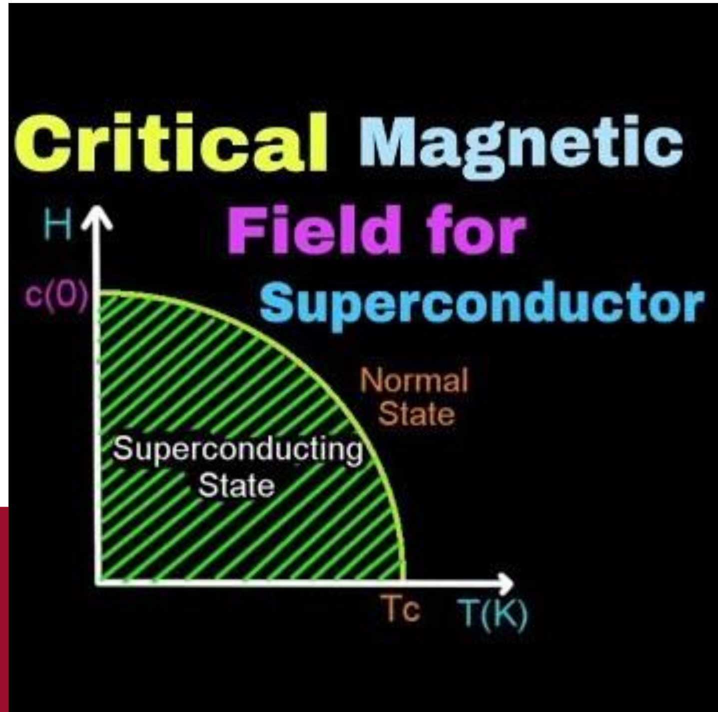
VOLUME 5, NUMBER 11 PHYSICAL REVIEW LETTERS DECEMBER 1, 1960

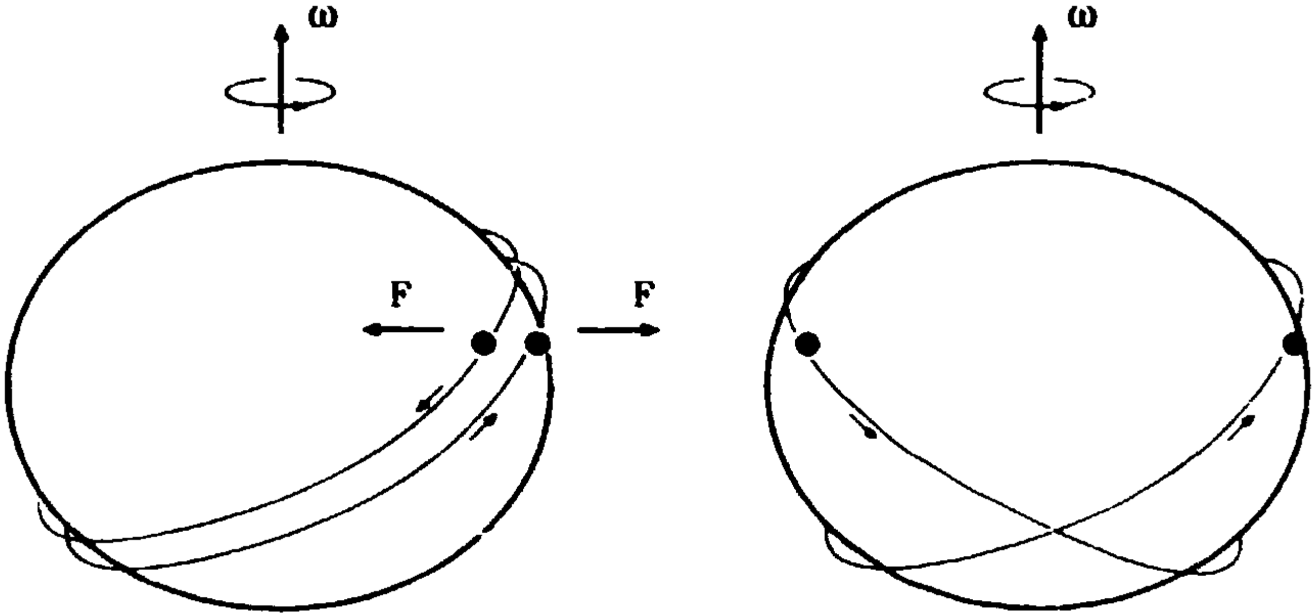
EFFECT OF NUCLEAR ROTATION ON THE PAIRING CORRELATION

Ben R. Mottelson and J. G. Valatin*
NORDITA and The Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark
(Received November 8, 1960)

An analogy with the correlations in superconductors has proved to be rather fruitful in interpreting the nuclear features mentioned above. '

Pursuing this analogy, the close formal correspondence of the equations of motion in a constant magnetic field and in a rotating reference system suggests that the critical magnetic field phenomena of superconductors should also have their counterpart in the rotational spectra of nuclei.





Indeed, the pairing force couples two particles in time- reversed single-particle states, and a rotation has an opposite effect on the particles forming the pair. The Coriolis forces act in opposite directions and tend to decouple the pairing correlations. This is in analogy with the effect of the magnetic forces in a metal, which act with a different sign on electrons moving in opposite directions and destroy the pairing when the field reaches a critical value. The observation or nonobservation of this effect in the rotational spectra of nuclei could serve as a test of the description of the pairing correlations in nuclei.

Mottelson-Valatin effect (nuclear Meissner effect)

Estimation of the critical spin (’frequency’)

- ’For Ic> 12 in A=180 and Ic>18 for A=238’

And

- The moment of inertia **J** will approach **J**_rigid

Inspiration from studies at Berkley…

- **1963-65 Hans Ryde was on sabbatical at Cal Tech**
- **He visited Dick Diamond and Frank Stephens, world leaders in studying ‘high-spin’ states using heavy ions from the HILAC and various detectors: conversion electron, NaI, early small Ge(Li)**
- **Ground-state bands in deformed nuclei had regular spacings, evidence for *centrifugal stretching* - physics in I = 12 - 18 range**

Ground-state rotational band transitions

Transition	Yb^{164}	Yb^{166}	Hf^{166}	Hf^{168}	Hf^{170}	Hf^{172}	W^{172}	W^{174}	W^{17}
2 → 0	122.5 A	101.8 A	158.7 A	123.9 A	100.0 A	94.5 A	122.9 A	111.9 A	108.7
4 → 2	261.5 A	227.9 A	311.0 A	261.1 A	220.6 A	213.4 A	254.0 A	243.1 A	239.8
6 → 4	374.0 A	337.4 A	426.9 A	371.1 A	320.5 A	319.1 A	350.3 A	349.2 A	350.9
8 → 6	461.3 A	430.0 A	509.5 A	456.1 A	400.2 A	408.8 A	419.3 A	432.5 A	440.6
10 → 8	528.4 A	506.8 A	564.0 A	522.0 A	462.0 A	483.6 A	469.6 A	498.0 A	508.2
12 → 10	574.5 B	567.8 A	593.8 A	569.4 A	510.0 A	543.1 A	512.5 A	551.2 A	557.3
14 → 12	606 C	602.7 C	613.4 C	606.5 C	550.3 A	588.6 A	548.5 A	594.0 B	595.1
16 → 14		627.8 C			583.7 A	621.9 B	576.2 B		624.2
18 → 16					614.3 B	641.8 B	596.8 C		
20 → 18					652 C				

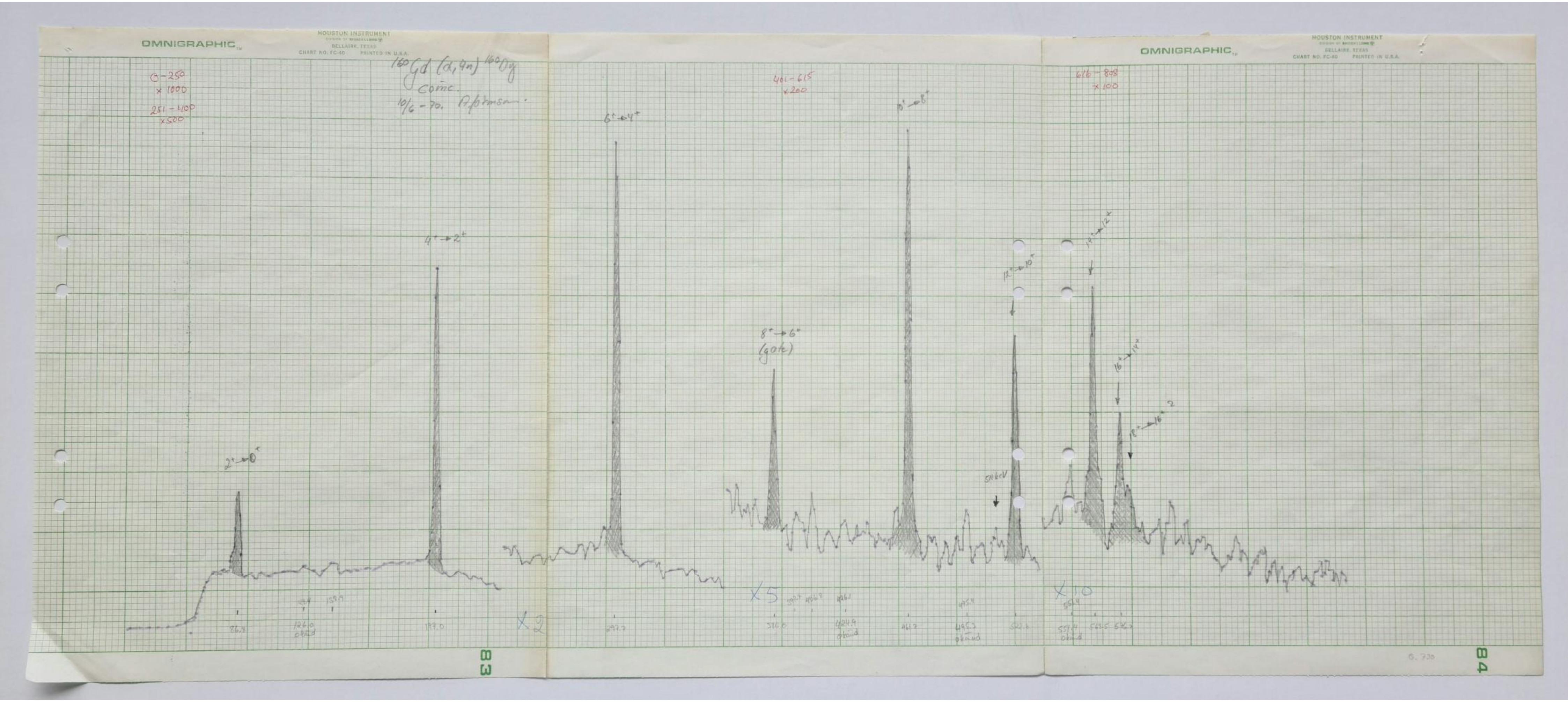
Stephens, Lark, Diamond, Nucl. Phys. **63**, 82 (1965)

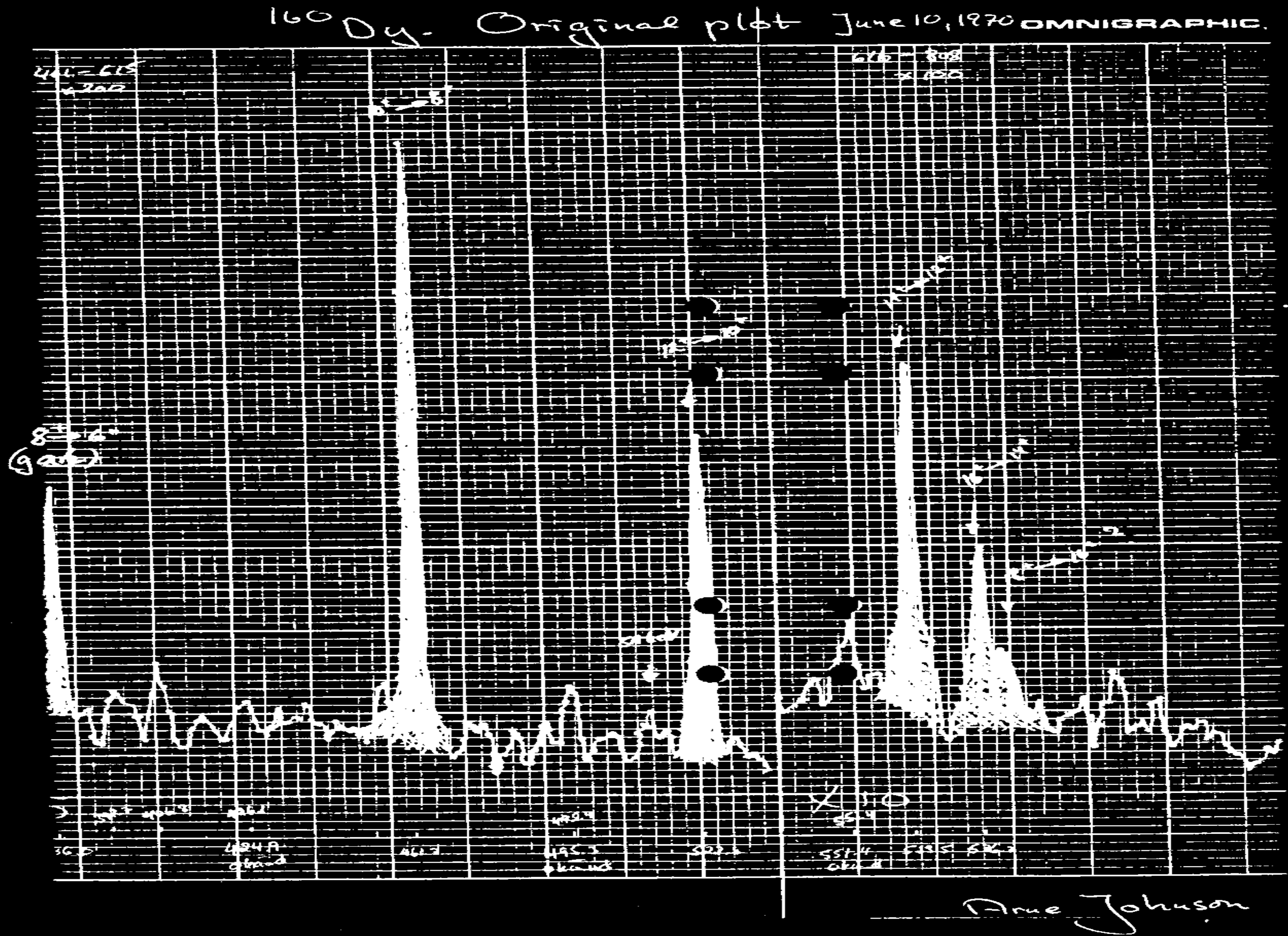
Stockholm - 1968

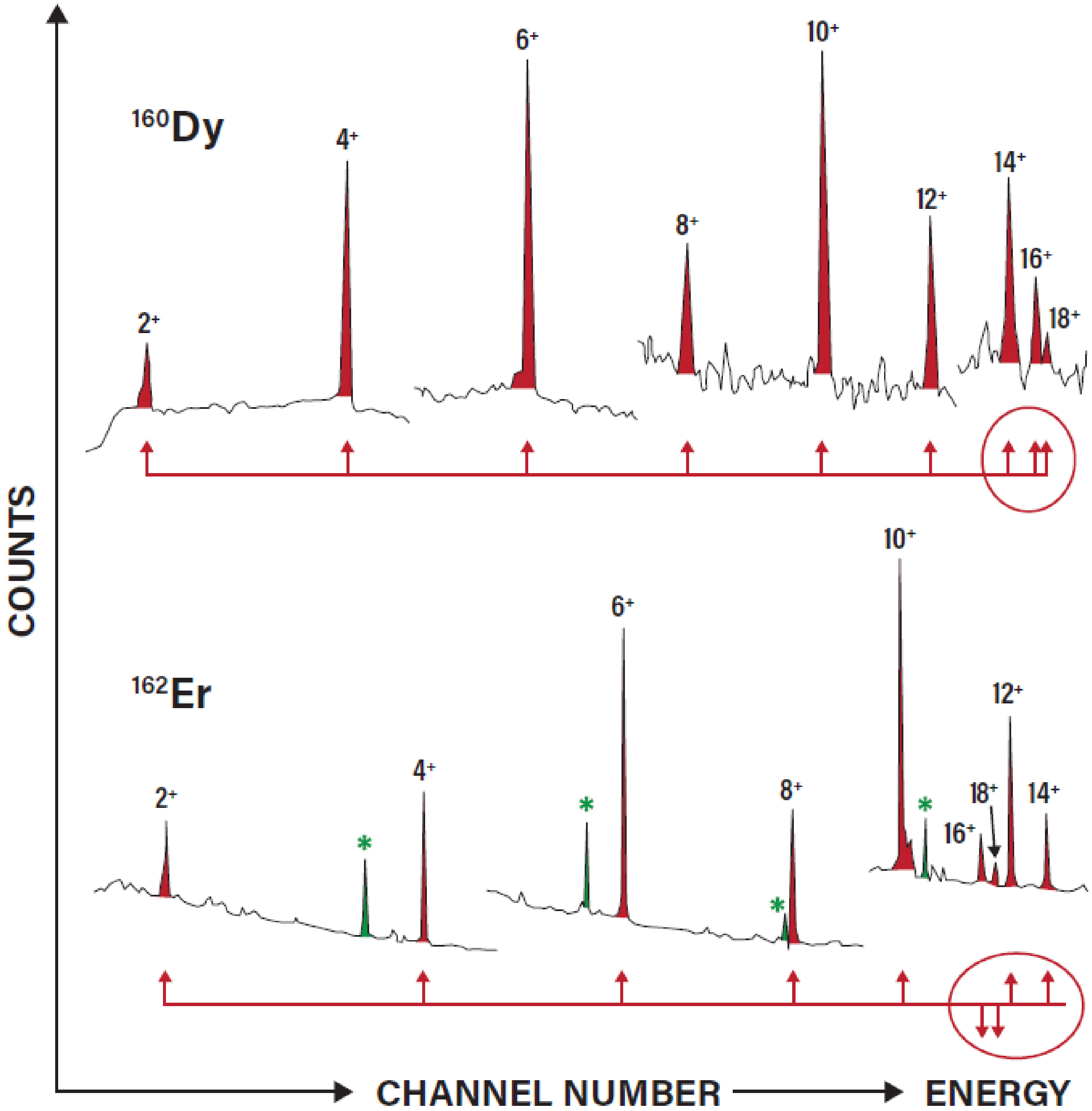
- Hans came back to Stockholm in 1965
- Led the effort to extract an α beam from the 225 cm cyclotron at the Institute of Physics
- March, 1968 - started working with a young grad student, Arne Johnson (14 years younger than Hans)
- Performed experiments with two 43 cm^3 Ge(Li) detectors and the reaction $^{160}Gd(\alpha,Xn)^{160}Dy$, ^{161}Dy

Program to study odd-A nuclei

Arne Johnson original spectrum
160Gd(alpha,4n)160Dy




160 Dy. Original plot June 10, 1970
OMNIGRAPHIC.
424A
445.3
551.4
X 10
Arne Johnson


COUNTS
160Dy
2+
4+
6+
8+
10+
12+
14+
16+
18+
162Er
2+
4+
6+
8+
10+
12+
14+
16+
18+
*
CHANNEL NUMBER
ENERGY

KØBENHAVNS UNIVERSITET
NIELS BOHR INSTITUTET

BLEGDAMSVEJ 17, 2100 KØBENHAVN Ø
TELEFON: (01) TRia 1616
TELEGRAMADR.: PHYSICUM, KØBENHAVN

16 October, 1970

Dr. A. Johnson and Dr. H. Ryde
Forskningsinstitutet för Atomfysik
Stockholm 50

Dear Arne and Hans,

Thank you for the preprint of your note which indeed makes a very exciting story. It appears that you have rather convincing evidence for the occurrence of something quite remarkable for angular momentum values in the region $I \approx 16$; this is exhibited, perhaps, even more dramatically in a plot of the moment of inertia as a function of the rotational frequency (see the enclosed figure). The frequency is defined by the canonical relation appropriate for an axial symmetric rotor

$$\omega = \frac{dE}{d\sqrt{I(I+1)}}$$

or

$$\omega^2 = 4\, I(I+1) \left(\frac{dE}{dI(I+1)}\right)^2$$

In the last expression, the energy derivative is taken from the observed transition energies

$$\left(\frac{dE}{dI(I+1)}\right)_{I(I+1) = I_1^2 - I_1 + 1\,*} = \frac{E(I_1) - E(I_1-2)}{4I_1 - 2}$$

The moment of inertia is also defined in terms of the derivative of the observed energy

$$\frac{2\mathcal{J}}{\hbar^2} = \left(\frac{dE}{dI(I+1)}\right)^{-1}$$

Another interesting feature of your data concerns the value of $\mathcal{J}$ at the singular point. If the pairing correlation were to completely disappear, one would expect $\mathcal{J} \approx \mathcal{J}_{rig}$. However, since the transition frequency for neutrons and protons may be quite

$* = \frac{1}{2}\left(I_1(I_1+1) + (I_1-2)(I_1-1)\right)$

different, the value of $\mathcal{J}$ is likely to be somewhat below $\mathcal{J}_{rig}$ after the first transition.

As a very minor point, it would seem that in referring to the pair correlated state, it would be more appropriate to use the more general expression superfluid rather than superconducting. Also, as you mentioned, the suggested title may be somewhat too general. Another possibility might be "Evidence for a "Singularity" in the Nuclear Rotational Band Structure".

We note that you quote the old article with Pines as a reference for the suggestion of a phase transition; however, this point was first discussed in a paper with Valatin (B.R. Mottelson and J.G. Valatin, Phys.Rev. Lett. 5, 511 (1960)). There is a large subsequent literature on the subject, but it may be difficult to select any particular paper.

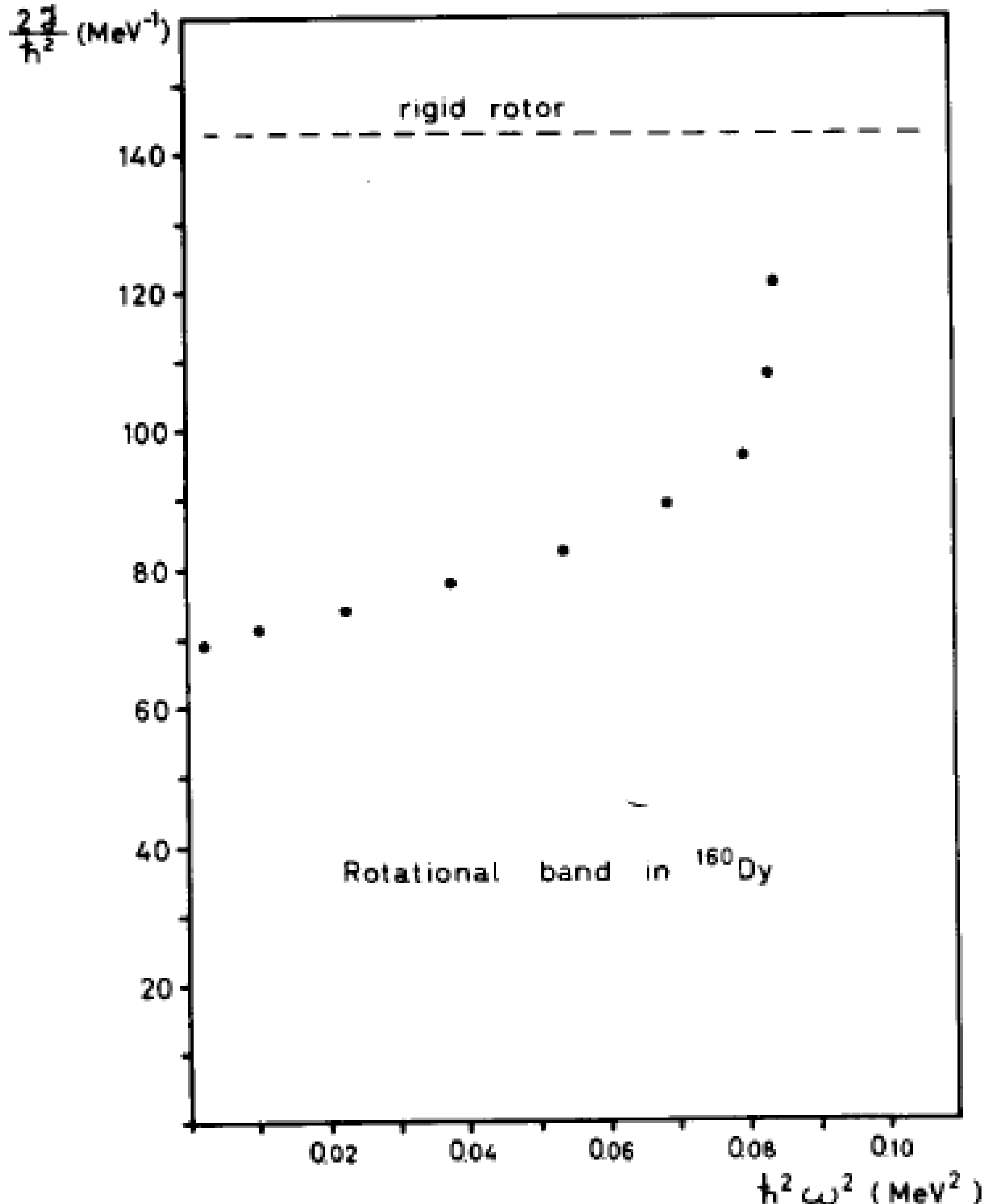
We send our compliments and best wishes for continued successful hunting in this exciting field.

A. Bohr B. Mottelson

EVIDENCE FOR A "SINGULARITY" IN THE NUCLEAR ROTATIONAL BAND STRUCTURE

PLB34 (1971)605

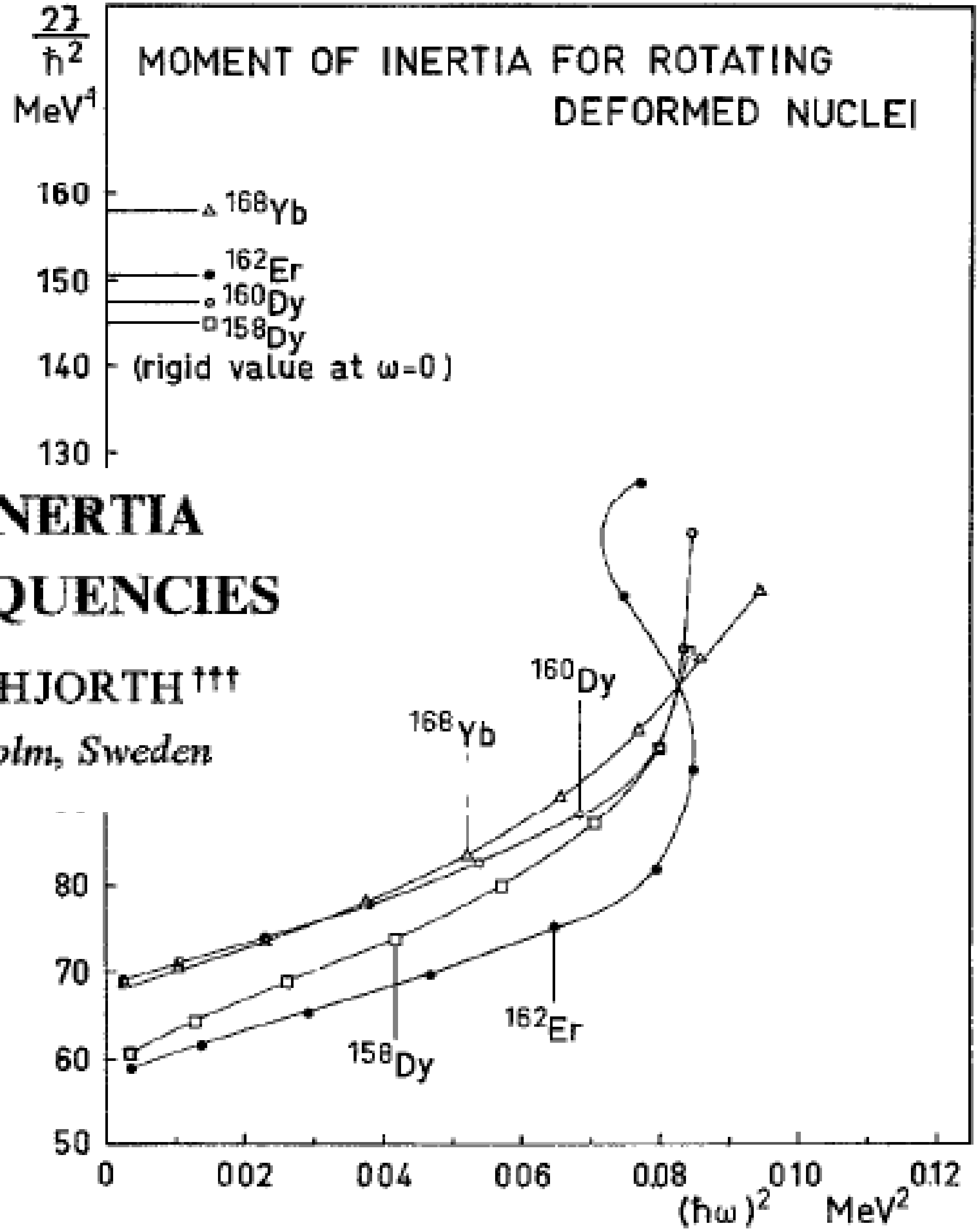
A. JOHNSON, H. RYDE* and J. SZTARKIER
Research Institute for Physics, Stockholm, Sweden



NPA179(1972)753

NUCLEAR MOMENT OF INERTIA AT HIGH ROTATIONAL FREQUENCIES

A. JOHNSON[†], H. RYDE[††] and S. A. HJORTH[†††]
Research Institute for Physics, Stockholm, Sweden



Was this the observation of the Mottelson Valatin effect?

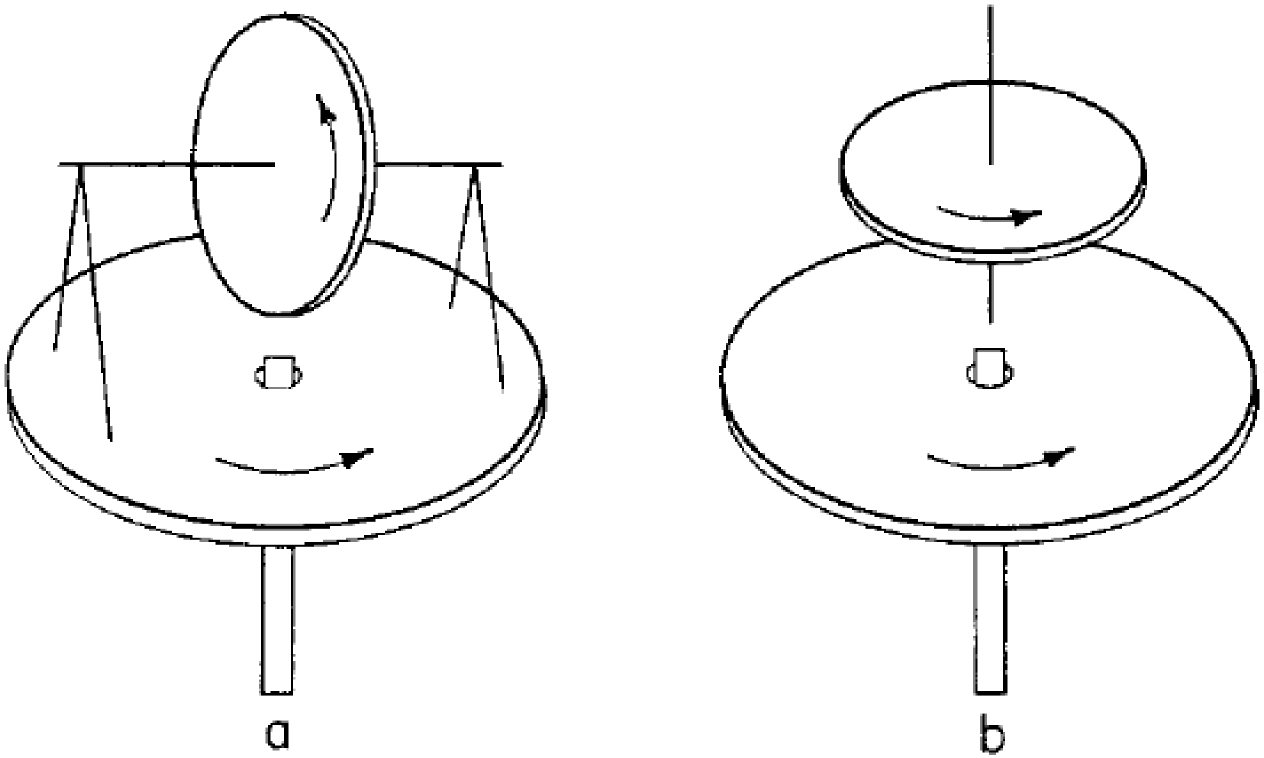
CORIOLIS EFFECTS IN THE YRAST STATES

F. S. STEPHENS † and R. S. SIMON
Sektion Physik, Universität München, München, Germany ††

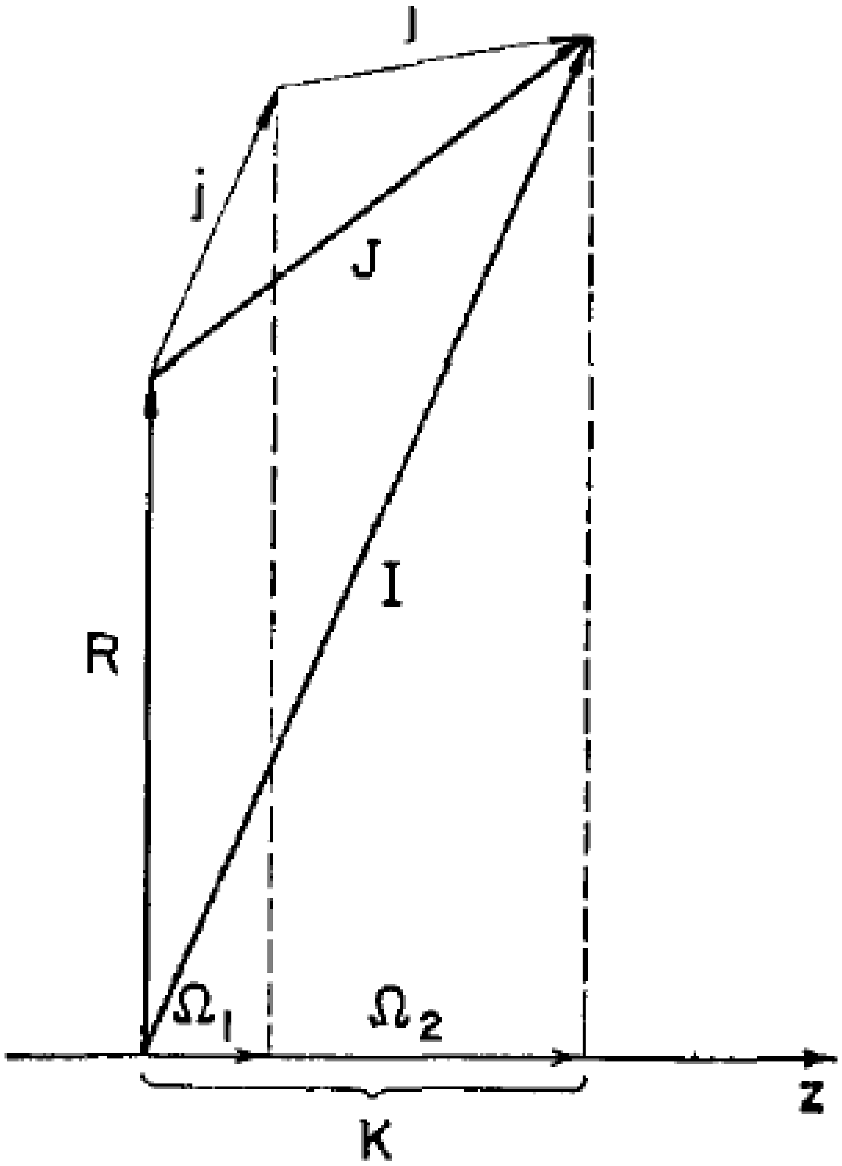
NPA183(1972)157

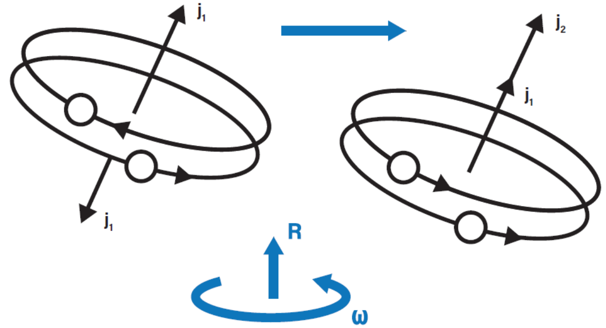
Very recently Johnson et al. have found some irregularities in the rotational energy spacings of rare-earth nuclei just in the region of spin where they are populated heavily in these (HI, Xn) reactions. It is too early to say how general this behaviour is, but it lends very strong support to the previous proposal that a major change is occurring in the **yrast** levels near this point. Johnson *et al*. suggest that this change is due to the phase transition associated with the loss of pairing correlations predicted by Mottelson and Valatin “) to occur at around this spin value.

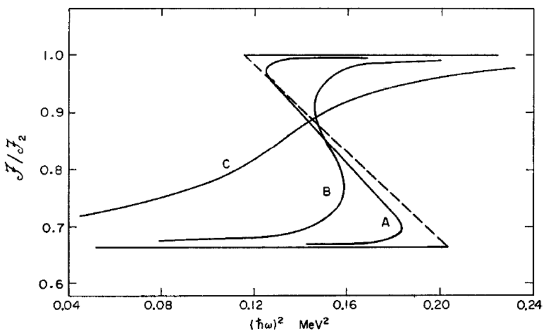
$$H_C = -\frac{\hbar^2}{2\mathscr{I}} \langle \Omega \pm 1 | j_\pm | \Omega \rangle \sqrt{(I \mp K)(I \pm K + 1)} f(U, V),$$



Coriolis effect on a spinning wheel

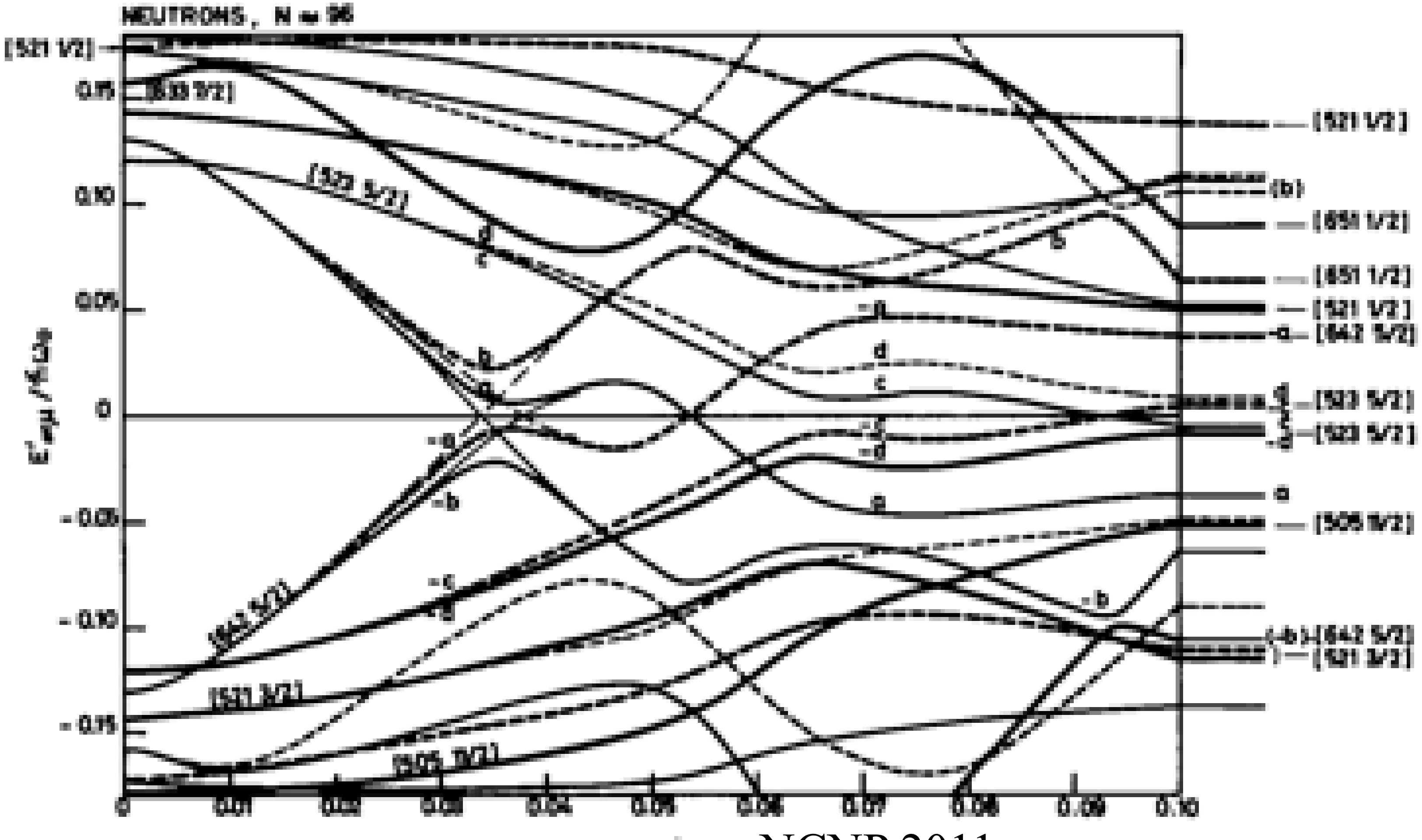

j
j
J
I
R
Ω_1
Ω_2
z
K

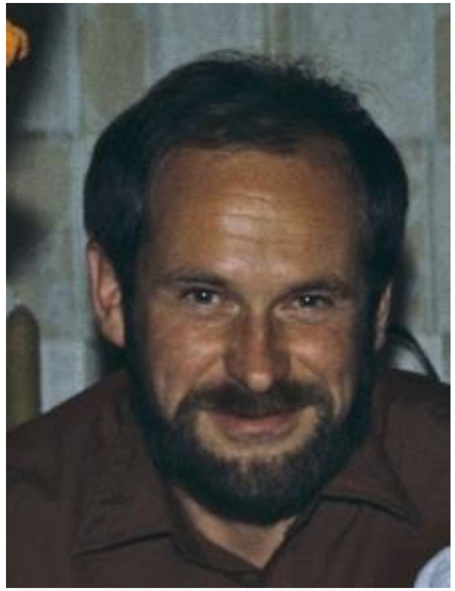

j_1
j_2
j_1
j_1
R
ω


1.0
0.9
0.8
0.7
0.6
0.04
0.08
0.12
0.16
0.20
0.24
A
B
C
$(\hbar\omega)^2$ MeV^2

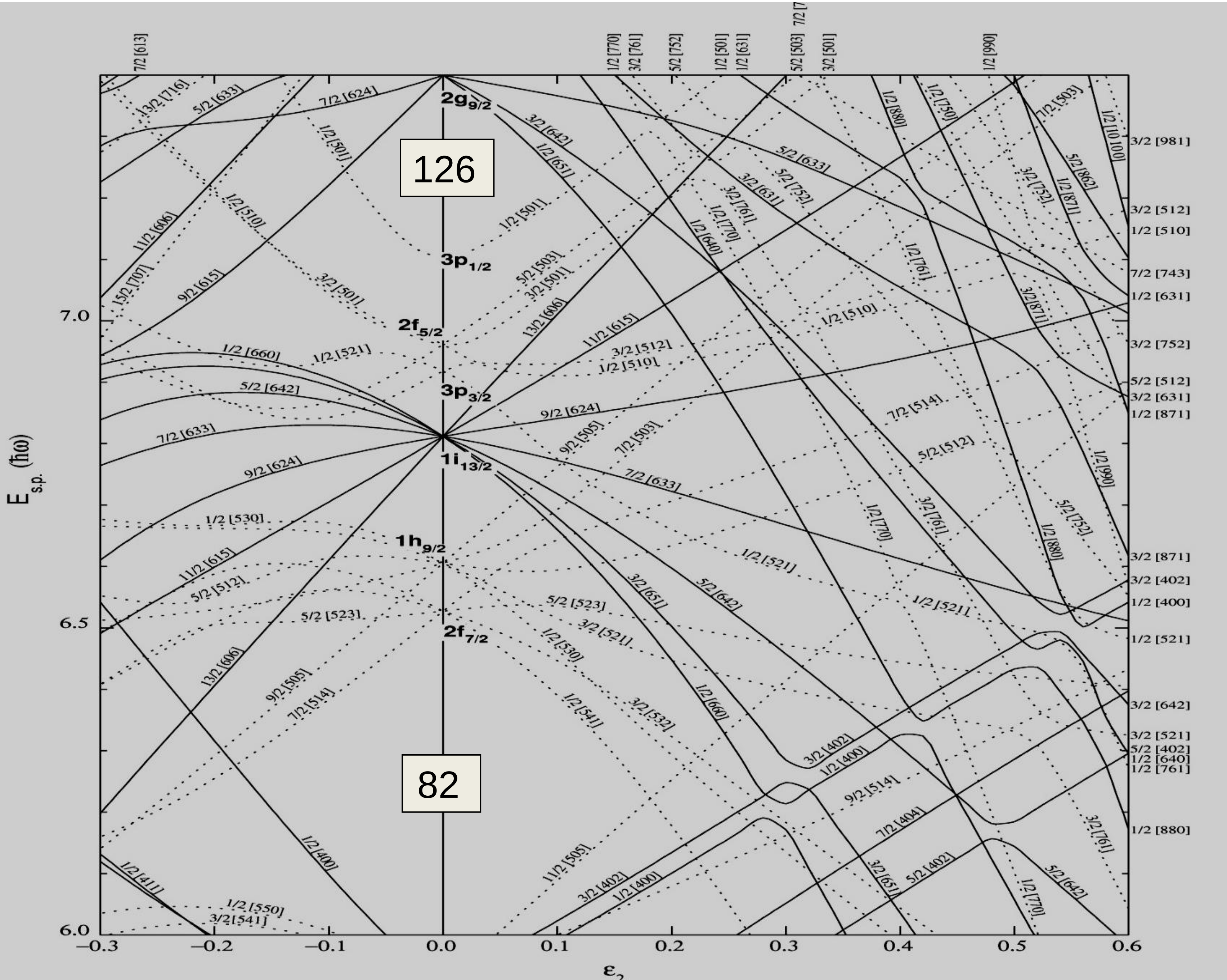
Cranked Shell Model - huge success

- Ragnar Bengtsson and Stefan Frauendorf, Nucl. Phys. A314, 27; A327, 139 (1979)
- This formalism explained many bands and crossings at high spins in many nuclei



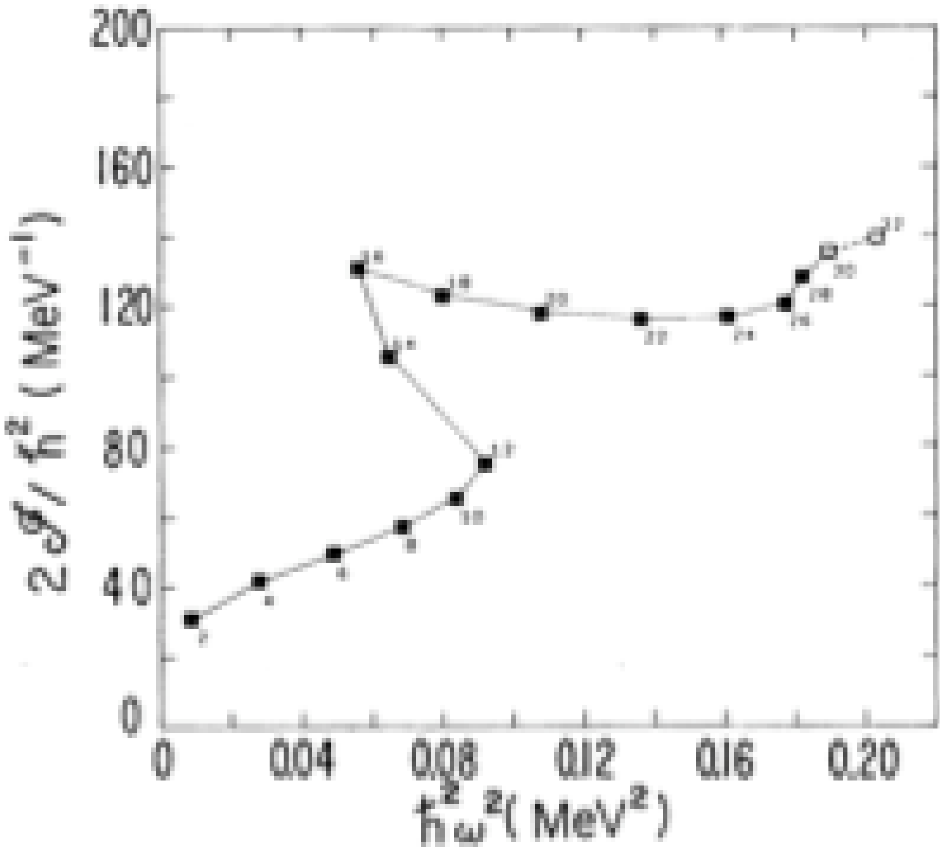


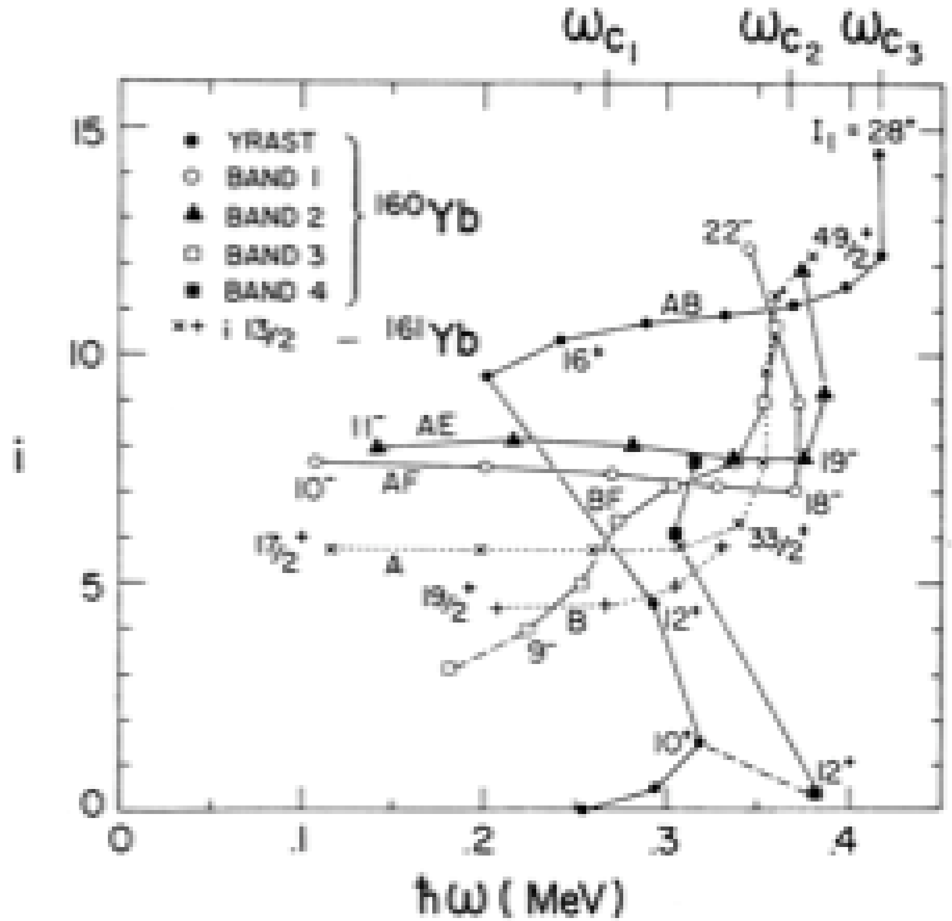
CSM built on deformed single-particle model of Sven Gösta Nilsson from 1950s



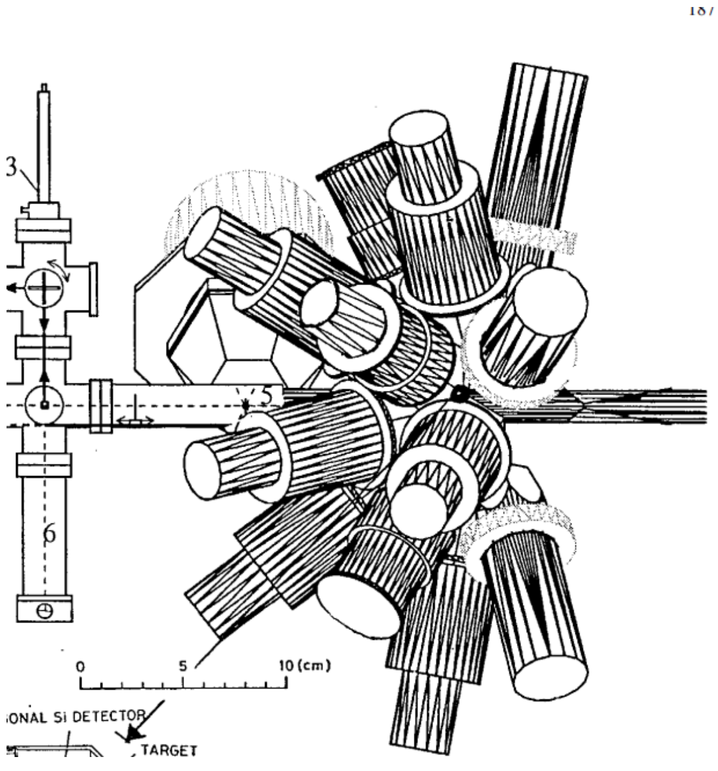
1970s - push to I = 20 to 30 regime

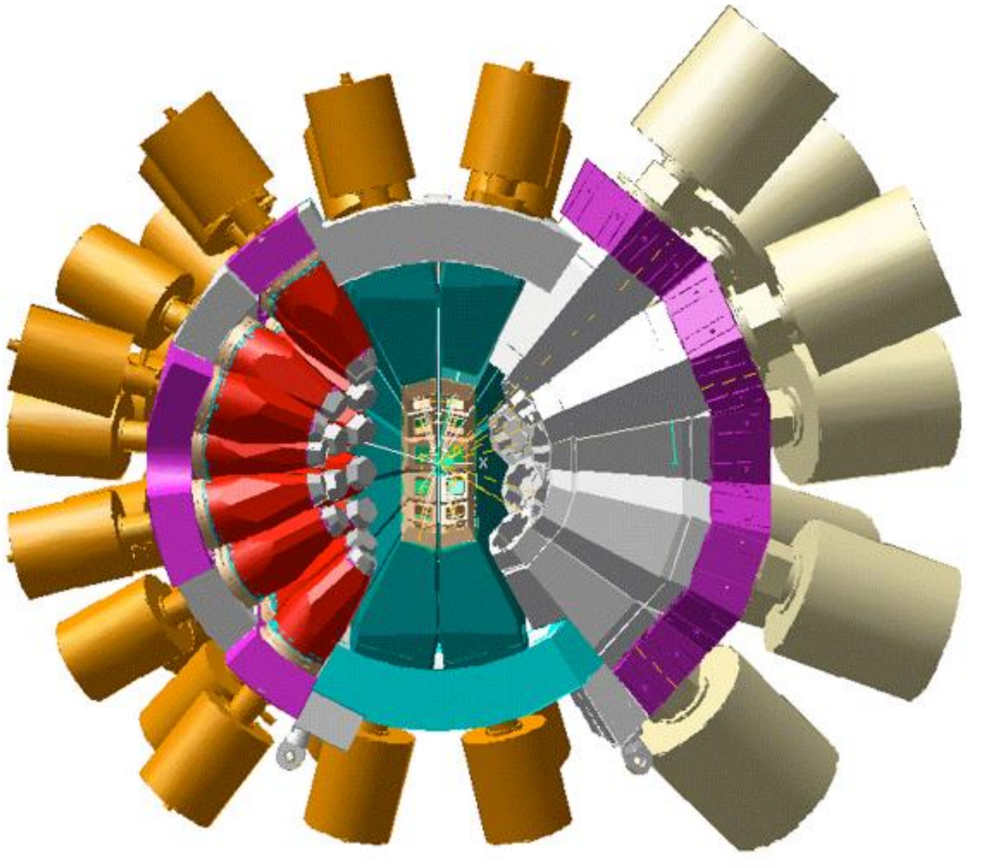
- First case of a *second backbend:* "Second Discontinuity in the Yrast Levels of ^{158}Er - I. Y. Lee et al, PRL 38, 1454 (1977) - Berkeley experiment
- Also present in isotone ^{160}Yb - Beck et al., PRL 42, 493 (1979) - Strasbourg experiment - not an isolated occurrence
- *Blocking* experiment - Riedinger et al., PRL 44, 568 (1980) - Copenhagen experiment





Unprecedented detector development



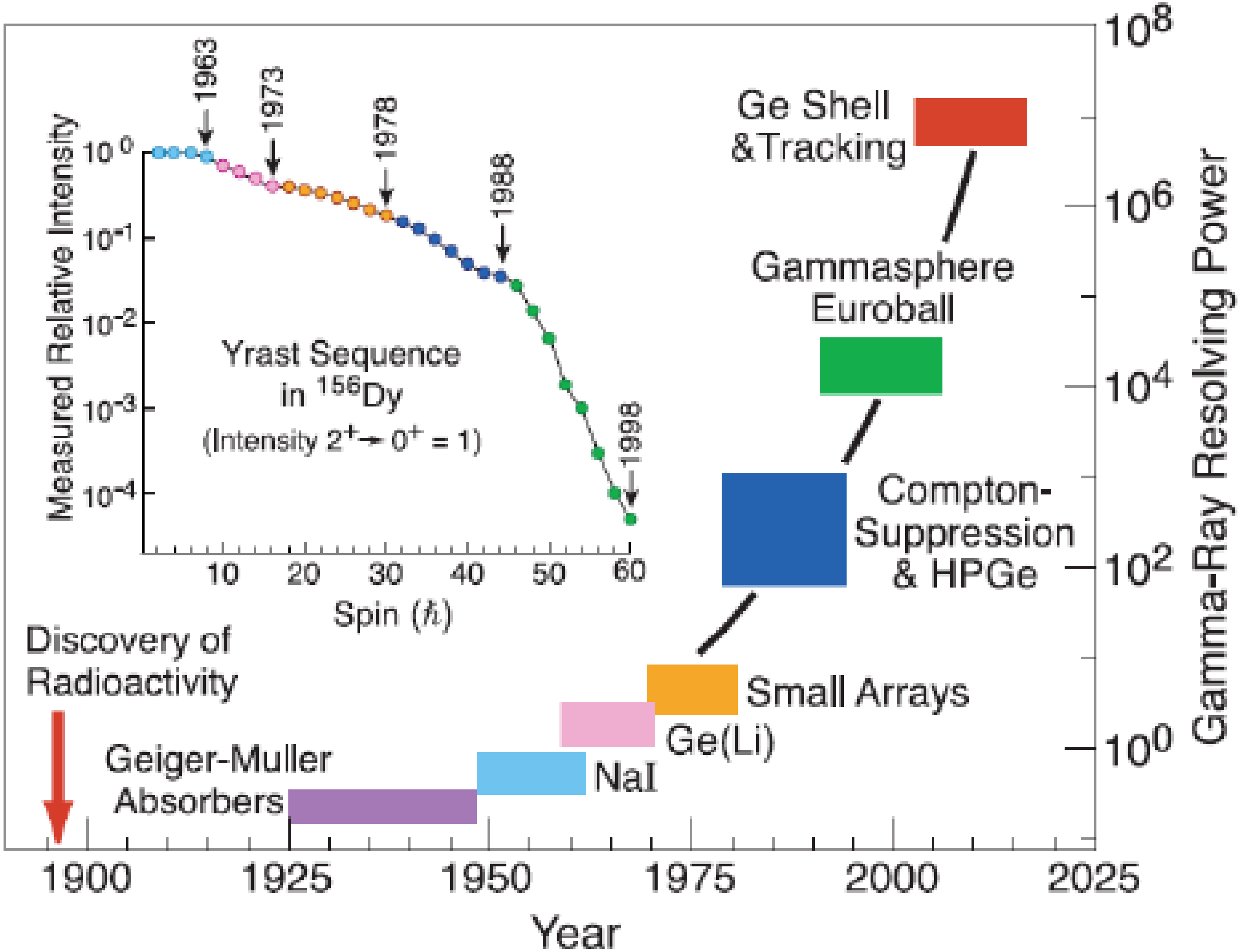


Nordball Pex Array

Euroball

>700 backbends now observed.
Lots of important theory work

Huge progress in 40 years in resolving power of γ-ray detector systems and the high-spin states that can be accessed



Nuc Phys. A503 (1989)244

SPECTROSCOPY OF ^{123}La AND CONFIGURATION DEPENDENT PROTON PAIRING

R. WYSS, F. LIDÉN, J. NYBERG[1] and A. JOHNSON

Manne Siegbahn Institute of Physics, Frescativägen 24, S-104 05 Stockholm, Sweden
and
The Royal Institute of Technology, Physics Department I, S-100 44 Stockholm, Sweden

D.J.G. LOVE, A.H. NELSON[2], D.W. BANES[3] and J. SIMPSON

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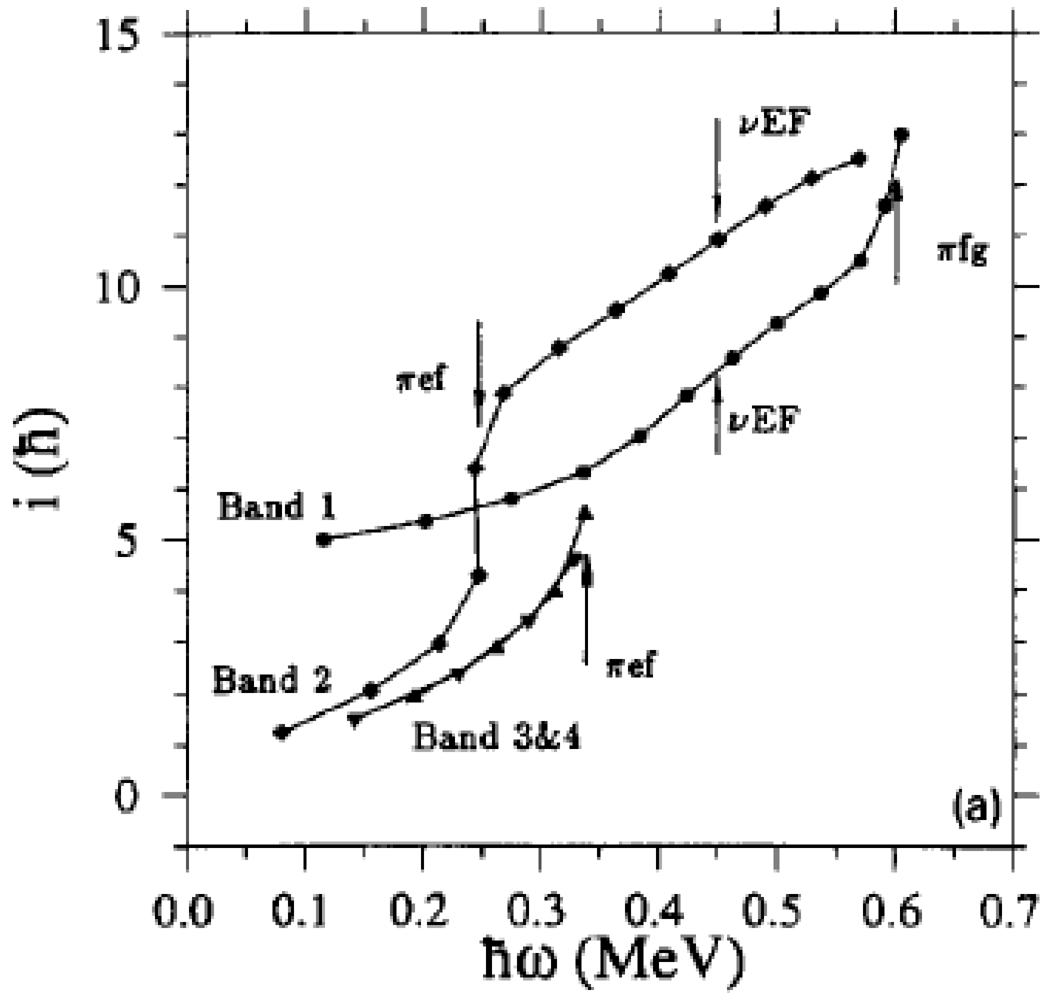
A. KIRWAN[4]

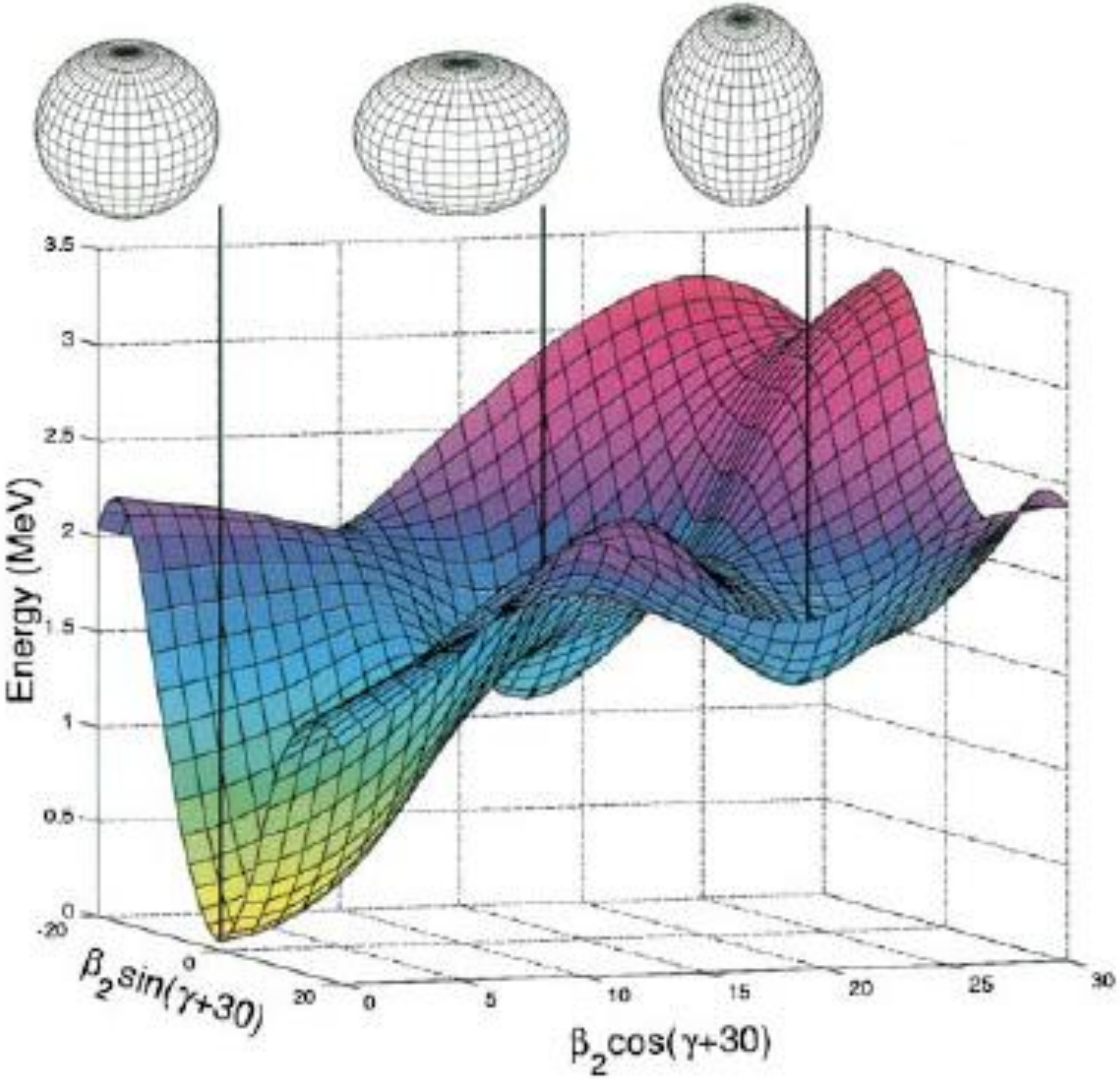
Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 3BX, UK

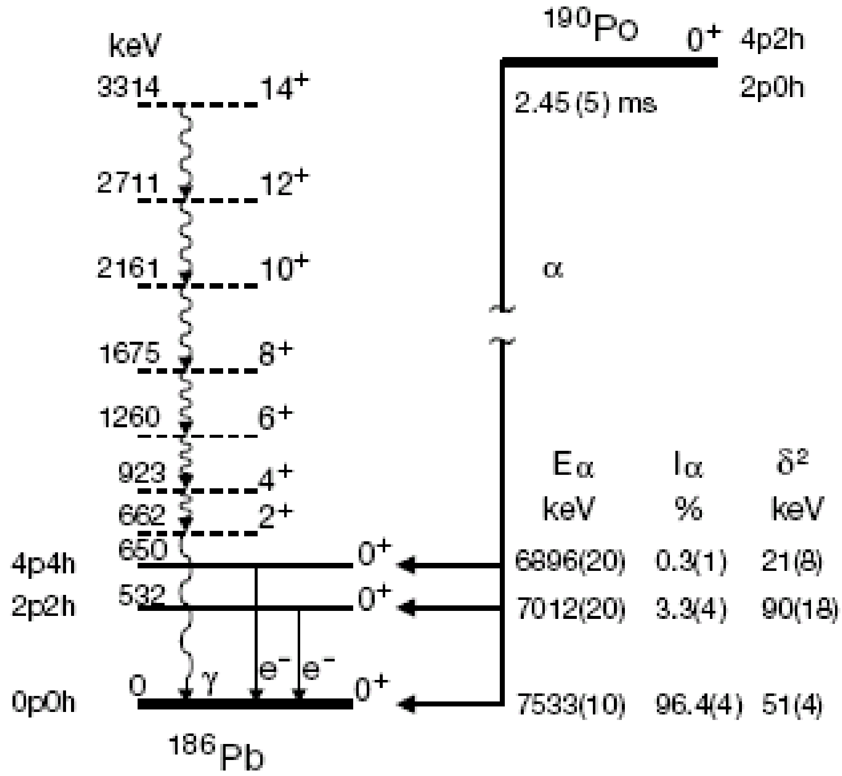
R. BENGTSSON



15
10
5
0
i (ħ)
νEF
πfg
πef
νEF
Band 1
Band 2
πef
Band 3&4
(a)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
ħω (MeV)

'The discovery of a prolate-oblate-spherical shape triplet of spin 0^+ states in the atomic nucleus ^{186}Pb', A.N. Andreyev, et.al Nature, Vol. 405 (2000) 430





PES calculations with WS potential -> TRS calculations

Extended TRS - Model

- Deformed single particle WS potential
- Liquid drop and Strutinsky shell correction (Wigner Kirkwood)
- Developped symmetry restauration –
  particle number fluctuation via Lipking Nogami correction and gauge symmetry restauration of pairing field via double stretched QQ pairing interaction
- Minimized in deformation space
- Application to high-spin, superdeformed, shape coexistence, high-K isomers, odd-even mass differences, radii, masses, N=Z nuclei, competition of T=1 and T=0 pairing
- Collaborators: **W Satula, F Xu,** P Magierski, A Bhagwatt

HFB-LNC equations

$$\begin{pmatrix} h & \Delta - 4\lambda_2 \kappa \\ -\Delta^* + 4\lambda_2 \kappa^* & -h^* \end{pmatrix}\begin{pmatrix} U \\ V \end{pmatrix} = (\mathscr{E} + \lambda_2)\begin{pmatrix} U \\ V \end{pmatrix},$$

$$h_{\alpha\beta} = (e_\alpha - \lambda)\delta_{\alpha\beta} - \omega j^{(x)}_{\alpha\beta} + \Gamma_{\alpha\beta}, \quad \Gamma_{\alpha\beta} = \sum_{\gamma\delta} \bar{v}_{\alpha\gamma\beta\delta}\,\rho_{\delta\gamma},$$

$$\Delta_{\alpha\beta} = \frac{1}{2}\sum_{\gamma\delta} \bar{v}_{\alpha\beta\gamma\delta}\,\kappa_{\gamma\delta}.$$

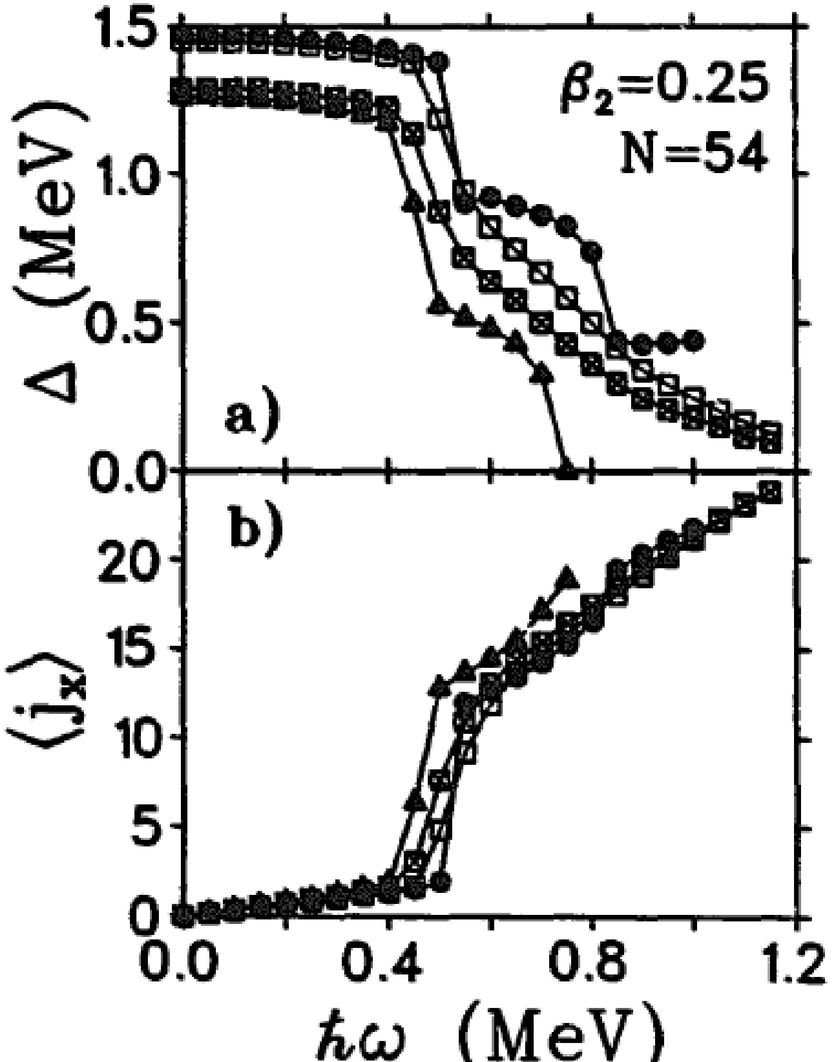
$$\bar{v}^{(\lambda\mu)}_{\alpha\beta\gamma\delta} = -G_{\lambda\mu}\, g^{(\lambda\mu)}_{\alpha\beta}\, g^{*(\lambda\mu)}_{\gamma\delta},$$

$$g^{(\lambda\mu)}_{\alpha\beta} = \begin{cases} \delta_{\alpha\bar{\beta}} & \lambda = 0, \quad \mu = 0, \\ \langle \alpha | \tilde{Q}_\mu | \bar{\beta} \rangle, & \lambda = 2, \quad \mu = 0, 1, 2. \end{cases}$$

Physica Scripta. Vol. T56, 159–166, 1995

The Lipkin–Nogami formalism for the cranked mean field

W. Satuła[a,1], R. Wyss[a], P. Magierski[b]



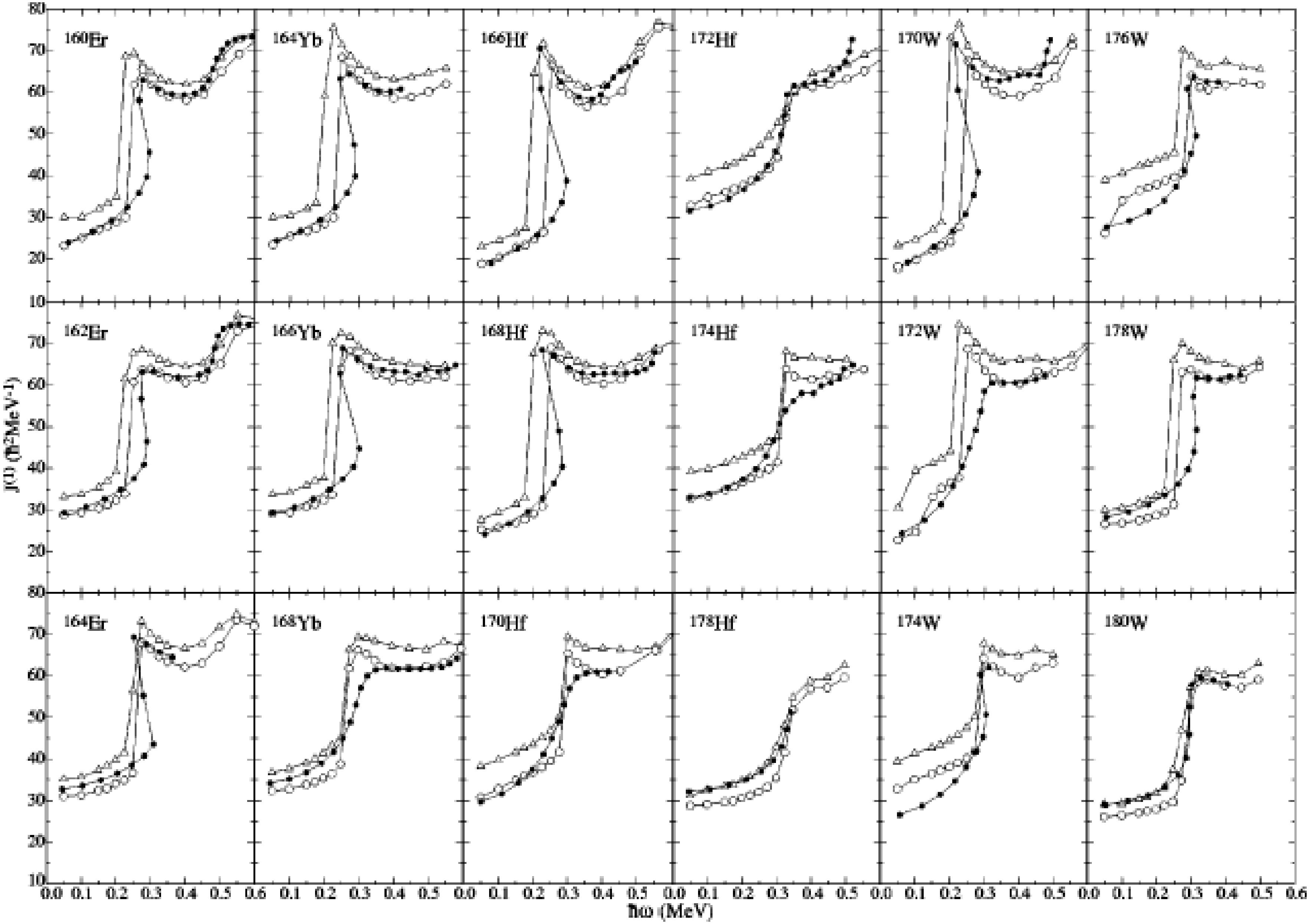
NPA578(1994)45

Comparision between HFBC, LN and PNP

Mean-field and blocking effects on odd-even mass differences and rotational motion of nuclei

F. R. Xu,[1,*] R. Wyss,[2] and P. M. Walker[1]

PRC51 (1999)051301



Is there a Meissner effect in Nuclei?

Iso cranking hamiltonian

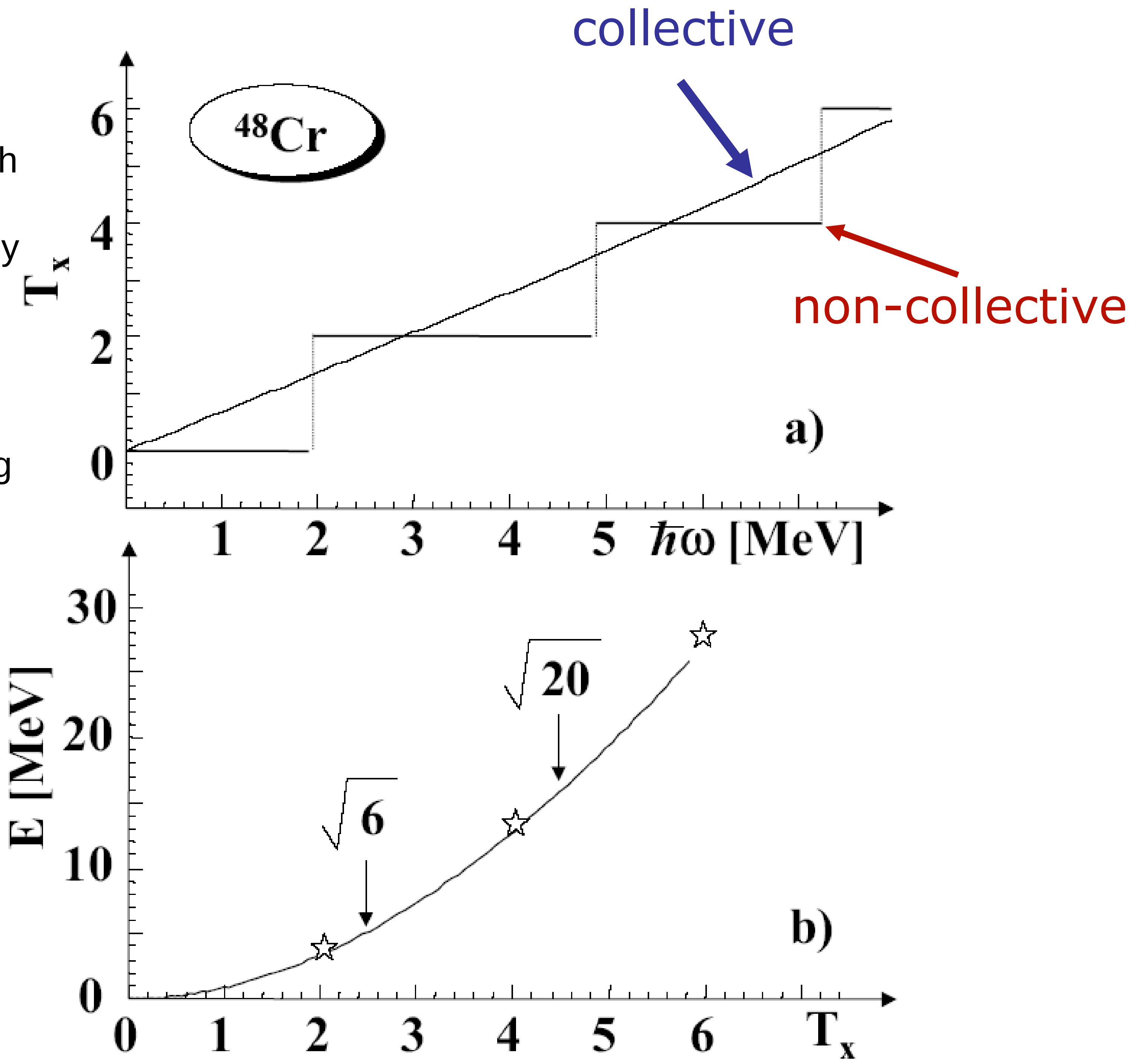
$$\hat{H}^{\omega_\tau} = \hat{h}_{\rm sp} - G_{t=1}\hat{\boldsymbol{P}}_1^\dagger \hat{\boldsymbol{P}}_1 - G_{t=0}\hat{\boldsymbol{P}}_0^\dagger \hat{\boldsymbol{P}}_0 - \vec{\omega}_\tau \vec{\hat{t}},$$

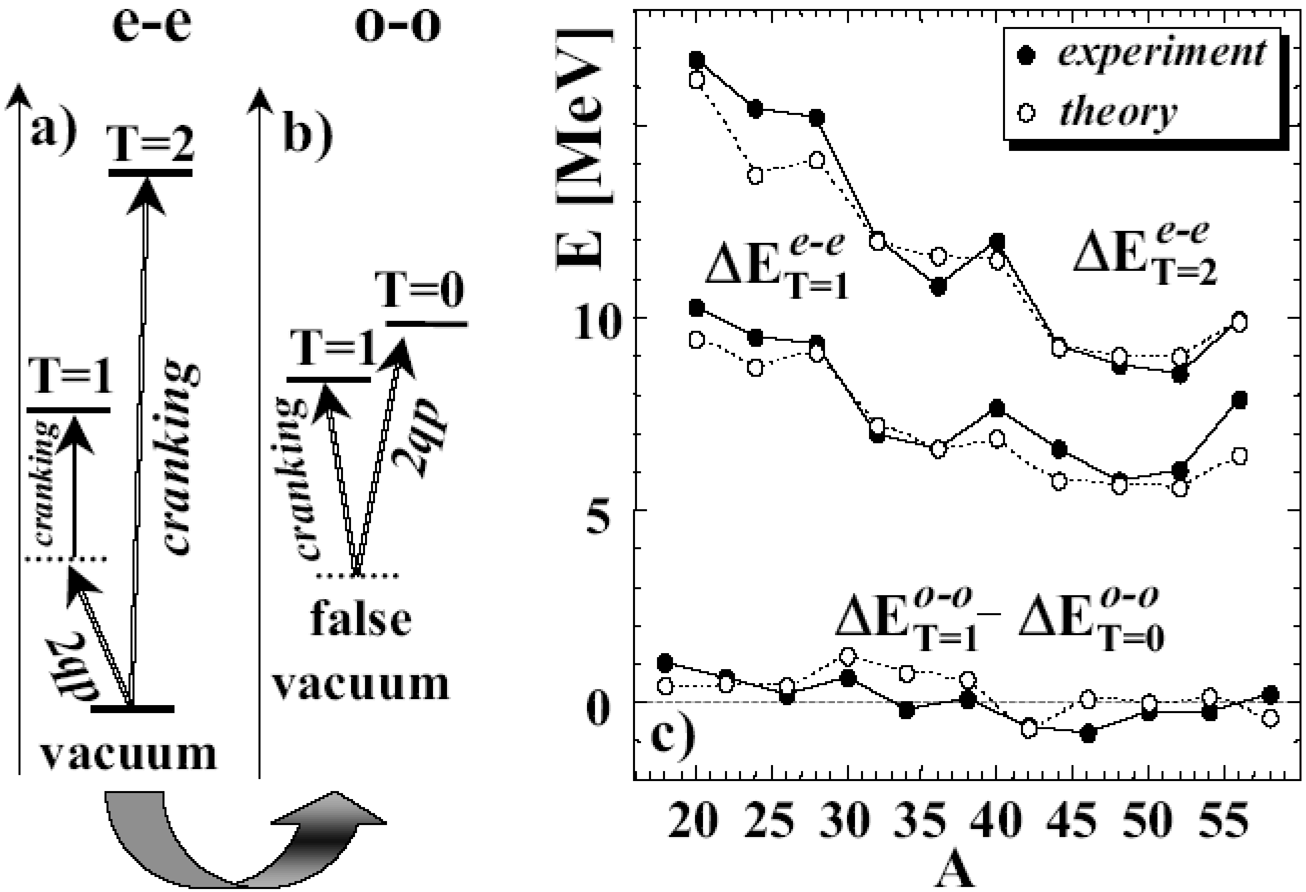
$$\hat{P}^\dagger_{1\pm1} = \sum_{i>0} \hat{a}^\dagger_{in(p)} \hat{a}^\dagger_{\bar{i}n(p)} \quad \hat{P}^\dagger_{10} = \frac{1}{\sqrt{2}}\sum_{i>0}(\hat{a}^\dagger_{in}\hat{a}^\dagger_{\bar{i}p} + \hat{a}^\dagger_{ip}\hat{a}^\dagger_{\bar{i}n}) \quad P_0^\dagger = \frac{1}{\sqrt{2}}\sum_{i>0}(a^\dagger_{in}a^\dagger_{\bar{i}p} - a^\dagger_{ip}a^\dagger_{\bar{i}n}).$$

$$\sqrt{\langle \hat{t}_x \rangle^2 + \langle \hat{t}_y \rangle^2} = \sqrt{T(T+1)}.$$

In the s.p. Model, one deals with 'non' collective rotations – the values of Tx jump discontinously at the crossing frequencies.

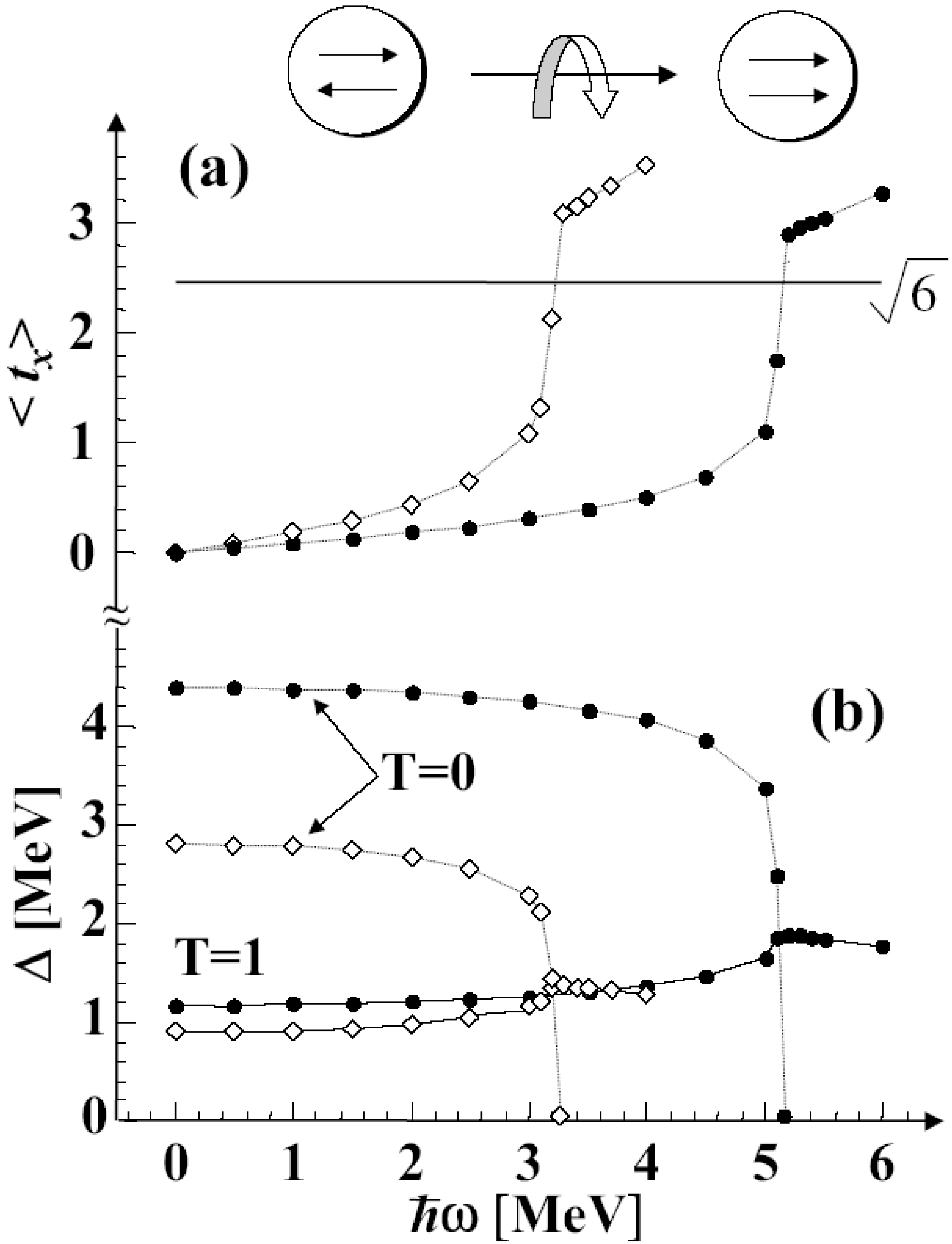
When T=1 pairing is switched on, the rotation is collective (smooth) and the corresponding values for iso spin excitations are given by the cranking condition, <Tx>=sqrt(T(T+1)) (taking into account quantum fluctuations)





e-e
o-o
a)
T=2
T=1
cranking
cranking
2qp
vacuum
b)
T=0
T=1
cranking
2qp
false
vacuum
experiment
theory
E [MeV]
$\Delta E^{e-e}_{T=1}$
$\Delta E^{e-e}_{T=2}$
$\Delta E^{o-o}_{T=1} - \Delta E^{o-o}_{T=0}$
10
5
0
c)
20 25 30 35 40 45 50 55
A

The alignment in iso space *tx* and the respons of T=1 and T=0 pair field. Calculations for 24Mg and 48Cr.



Meissner effect in isospace!

Nuclear Physics News 32, 2022 - Issue 2

https://www.tandfonline.com/doi/full/10.1080/10619127.2022.2063000

feature article

Fifty Years of Backbending

R. Wyss[1] and M. A. Riley[2]
[1]*KTH Royal Institute of Technology, Alba Nova, 10691 Stockholm, Sweden*
[2]*Department of Physics, Florida State University, Tallahassee, Florida 32306, USA*

Thanks for slides from Mark Riley and Lee Riedinger

Arne is elegant and he is fun!

From Lee Riedinger, thank you very much!