Congratulations!

John

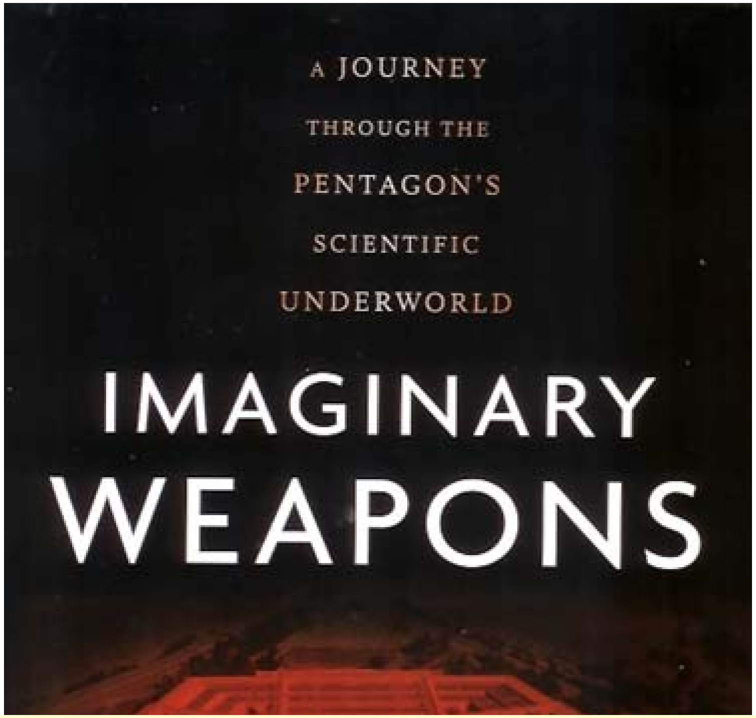
On Fifty Remarkable Years of Research at Argonne

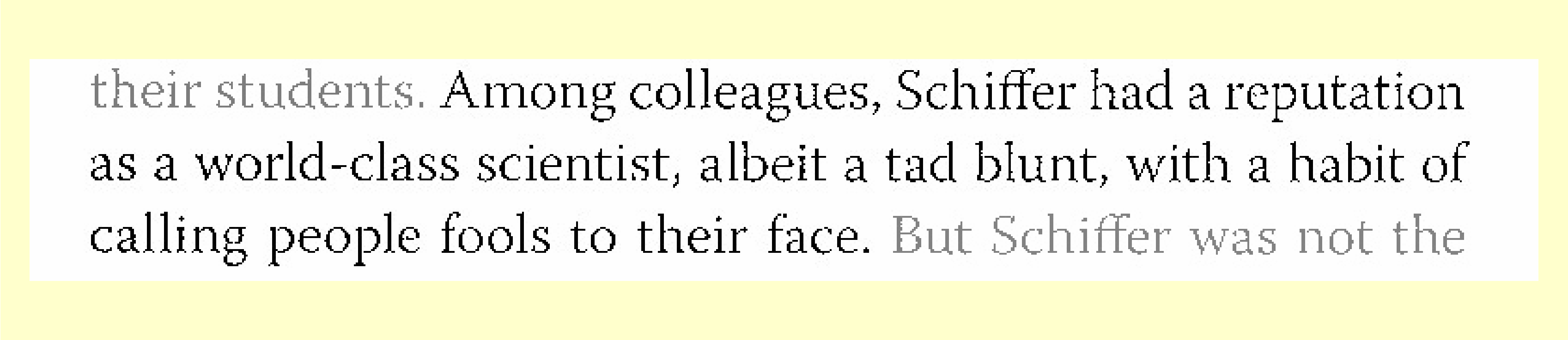
me

ert

Me again

ohn P. Schiffer

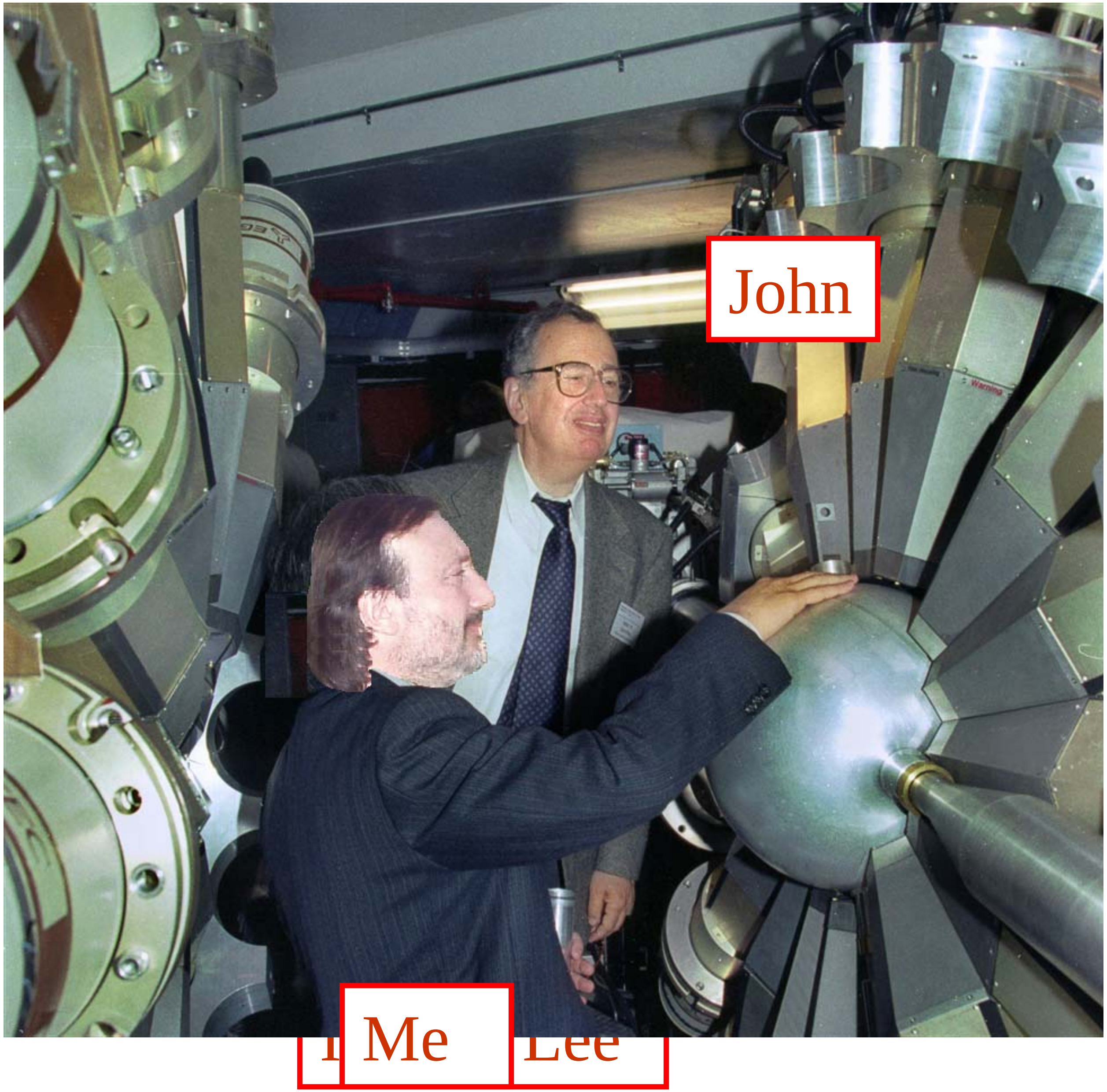


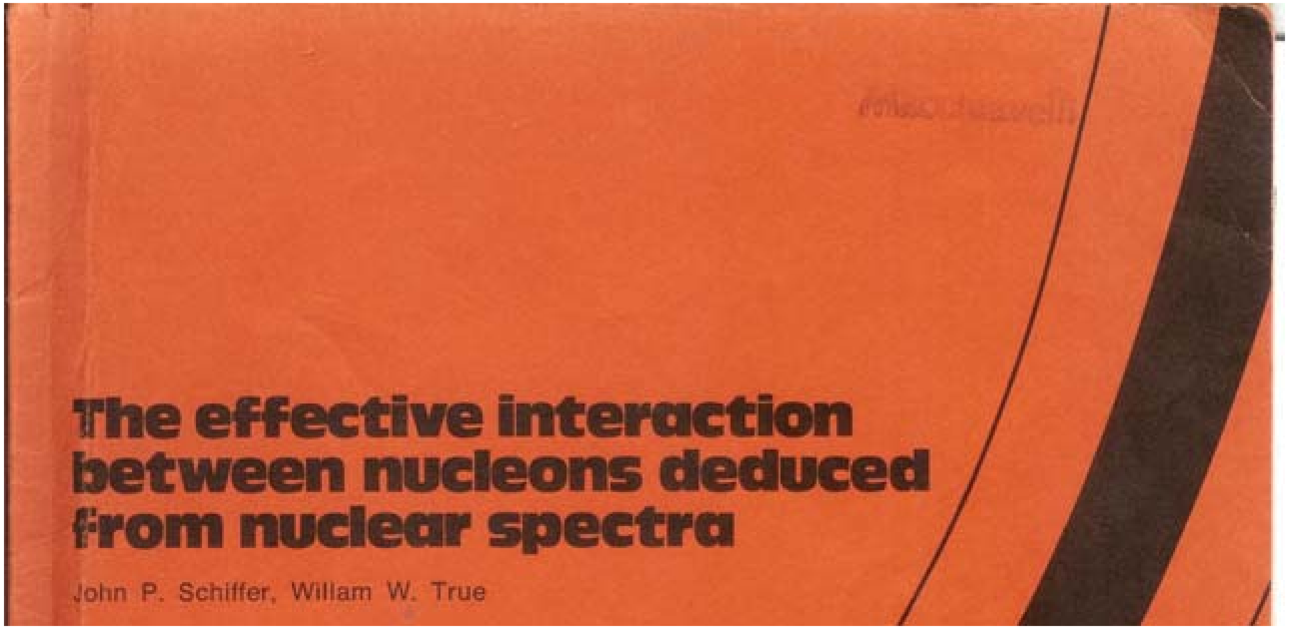

their students. Among colleagues, Schiffer had a reputation as a world-class scientist, albeit a tad blunt, with a habit of calling people fools to their face. But Schiffer was not the

Me **Me** **John**


GORDON RESEARCH CONFERENCE
Colby Sawyer College (1)
NUCLEAR CHEMISTRY

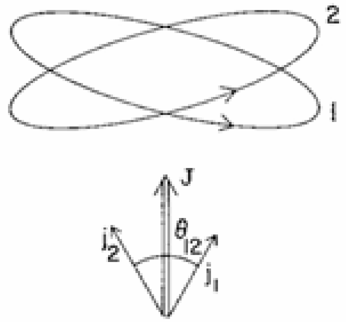
Checking a setup in GAMMASPHERE !



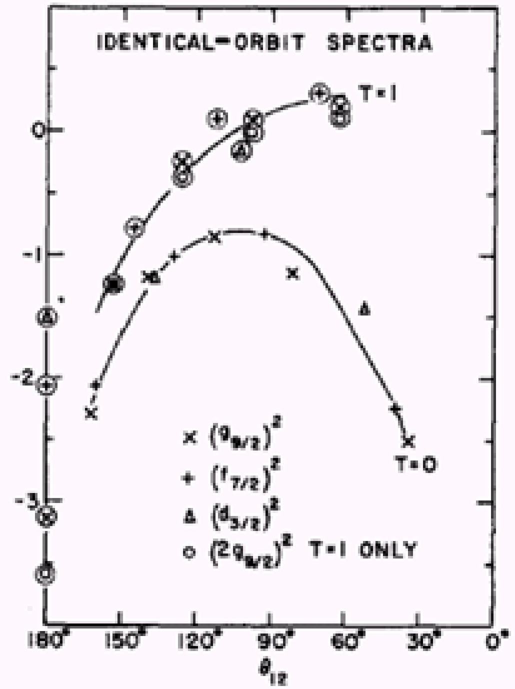


The effective interaction between nucleons deduced from nuclear spectra

John P. Schiffer, Willam W. True



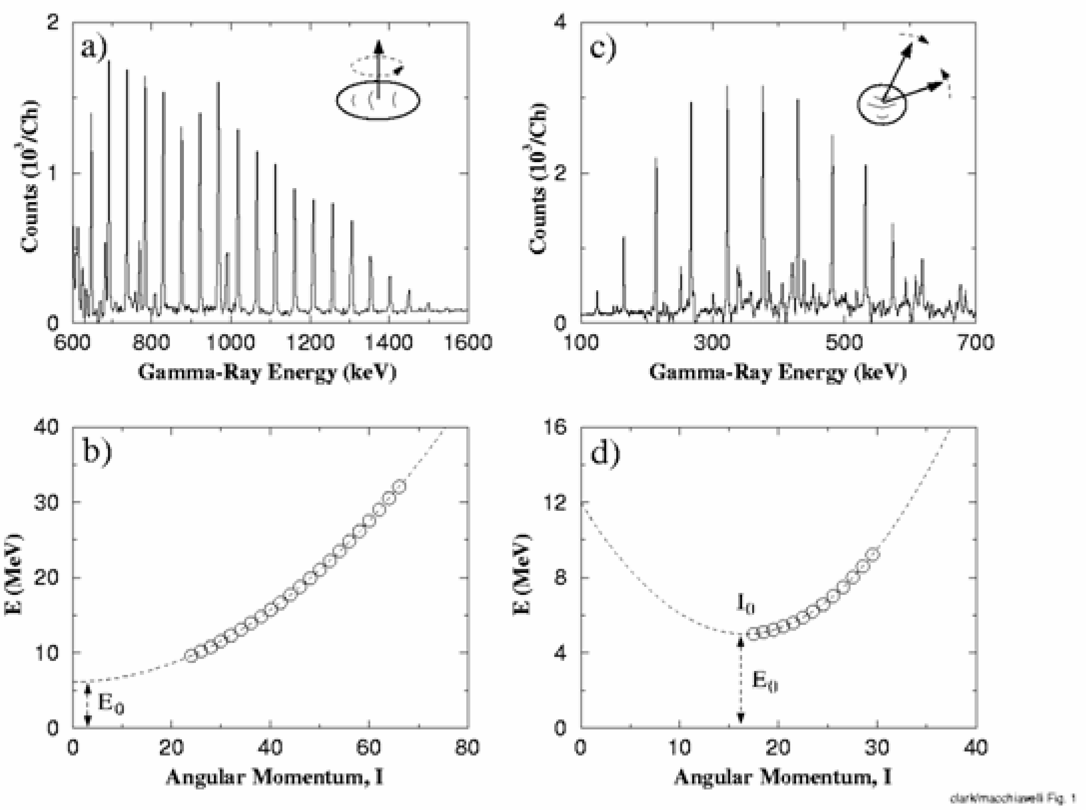
$$\theta_{12} = \cos^{-1} \frac{j_1(j_1+1) + j_2(j_2+1) - J(J+1)}{\left[2 j_1 j_2 (j_1+1)(j_2+1)\right]^{1/2}}$$

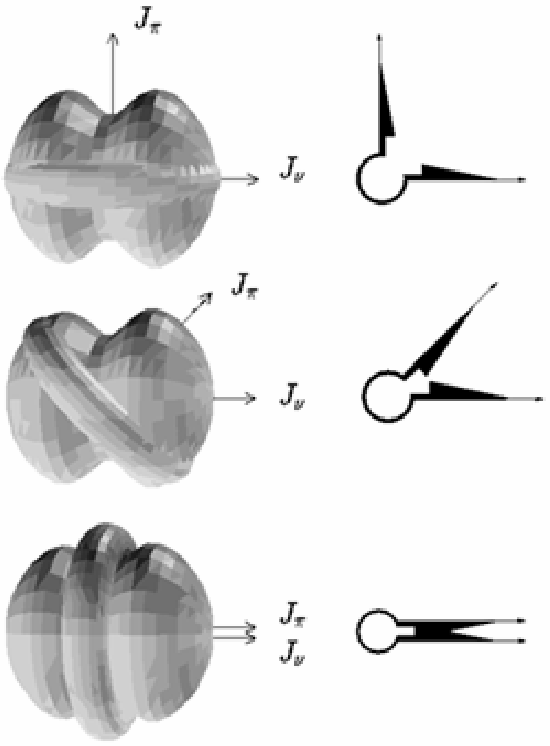


Rotational-like (Shears) bands in near-spherical nuclei

SD Band in ^{152}Dy

M1 Band in ^{199}Pb

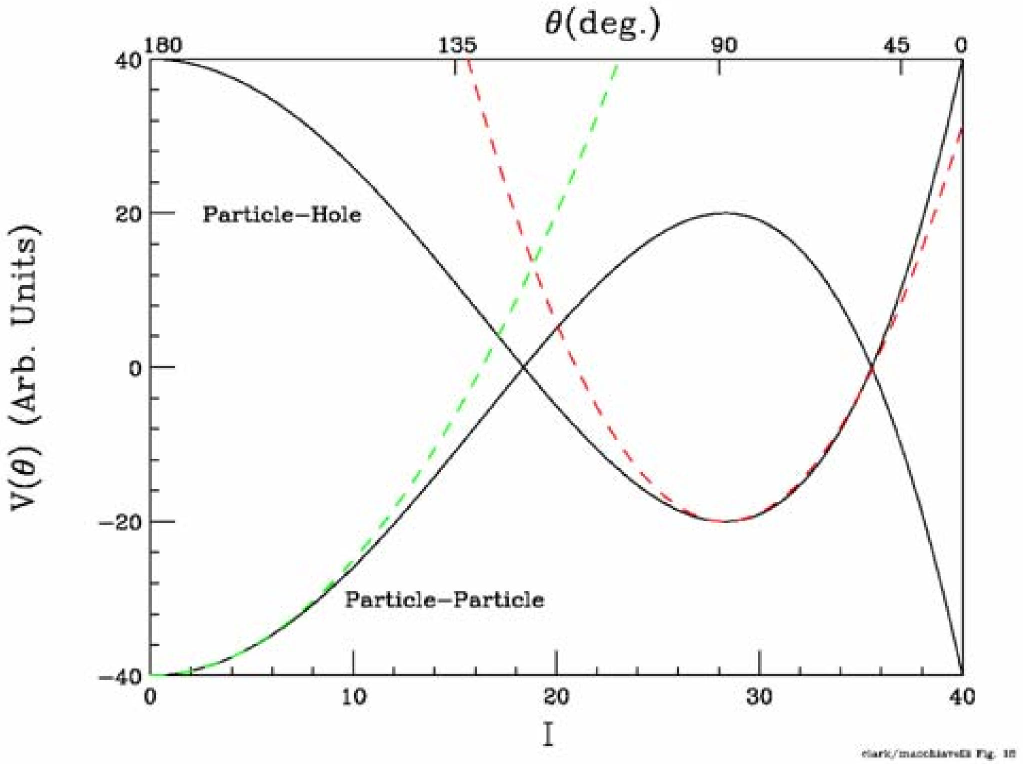




Angular momentum generated by the recoupling of the protons and neutrons components (shears)

B(M1), proportional to $\mu_\perp^2$ ⇨ should decrease with I

Effective P_2 Interaction ?

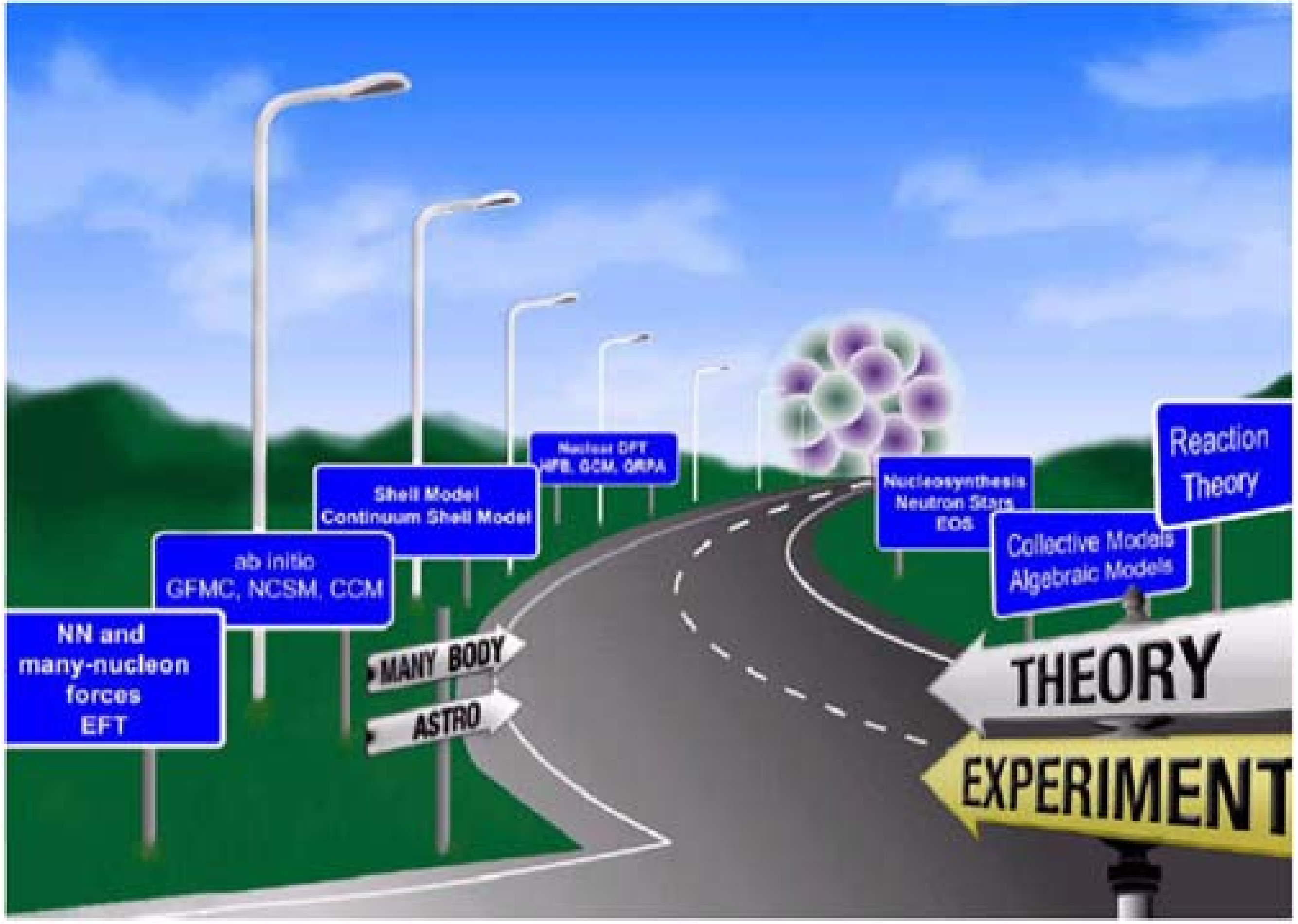


clark/macchiavelli Fig. 18

Effective P_2 interaction can give rise to the rotational-like spectrum
Particle-particle case will correspond to Anti-magnetic rotation

⇨Although the main ingredients and the general properties of the shears bands are understood, the regularity of these bands is still an important theoretical question from a microscopic point of view.

Inspired by the RIA Theory Blue Book and the recent RIA brochure ..



Transfer Reactions and Nuclear Structure:

The Road Ahead

A.O. Macchiavelli

Lawrence Berkeley National Laboratory

Many Thanks to Rod Clark, Paul Falllon, I.Yang Lee,
David Radford and Alan Wuosmaa

Nuclear Physics, The Core of Matter, the Fuel of Stars
Argonne National Laboratory, IL, September 21-22, 2006

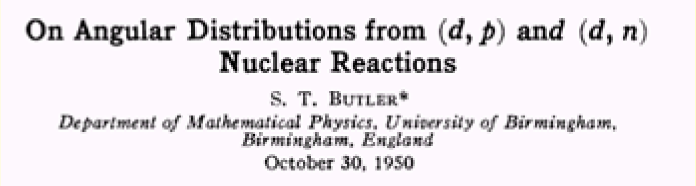
Outline

- Short introduction
- One-nucleon transfer reactions
    - Single-particle degrees of freedom
        - Spin-orbit splitting
        - Ab initio calculations
- Two-nucleon transfer reactions
    - Correlations
        - NP pairing
        - Pairing phase transition
- Heavy-ion transfer reactions
- Summary and conclusions

A central theme of study in nuclear structure has been the understanding of the elementary modes of excitation of the atomic nucleus, and their evolution with A (size), I (rotational frequency) , (N-Z) (Isospin) and E* (Temperature)

Transfer reactions have played a major role in this endeavor, particularly in the characterization of the single particle degrees of freedom and their correlations.

With the development of exotic beams and new instruments to handle the “reverse kinematics” nature of these reactions, there has been a *renaissance* of transfer reaction studies.



On Angular Distributions from (d, p) and (d, n) Nuclear Reactions

S. T. Butler*

Department of Mathematical Physics, University of Birmingham, Birmingham, England

October 30, 1950

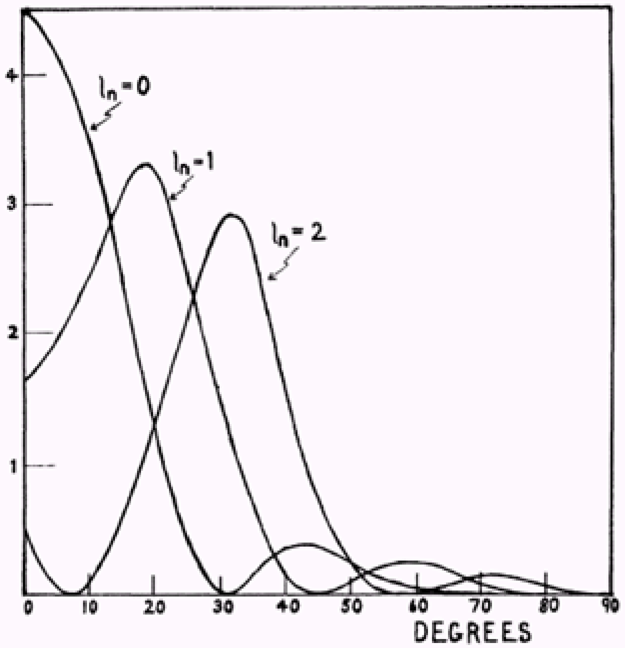


Fig. 1. Theoretical angular distributions for (d, p) and (d, n) reactions for different angular momentum transfers to the initial nucleus.

Angular distribution of the outgoing particles reflect the transferred angular momentum ⇨ l-value

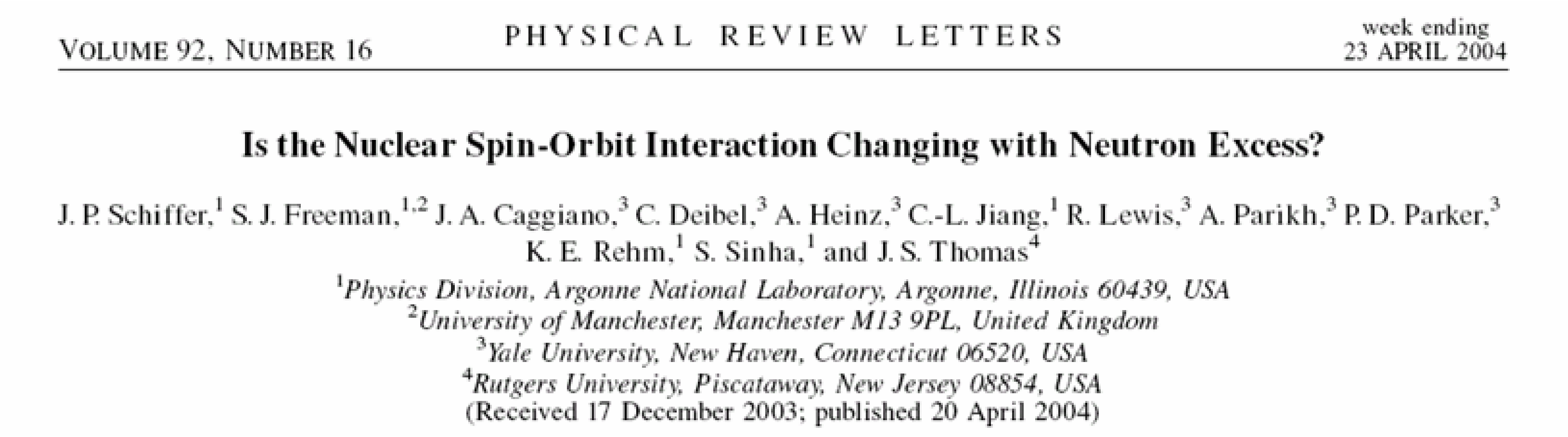
Spectroscopic factors. Overlap between initial and final state ⇨Test wave functions

Ideal tool to study the single-particle degree of freedom. Complementary to other processes that probe collective aspects.

One of the important goals in the development of exotic beams is to study the evolution of the nuclear shell structure with neutron excess.

In fact, it is already known that in light nuclei the magic numbers are not as “robust” as originally conceived.

Of particular interest here is the spin-orbit force.



VOLUME 92, NUMBER 16 PHYSICAL REVIEW LETTERS week ending 23 APRIL 2004

Is the Nuclear Spin-Orbit Interaction Changing with Neutron Excess?

J. P. Schiffer,[1] S. J. Freeman,[1,2] J. A. Caggiano,[3] C. Deibel,[3] A. Heinz,[3] C.-L. Jiang,[1] R. Lewis,[3] A. Parikh,[3] P. D. Parker,[3] K. E. Rehm,[1] S. Sinha,[1] and J. S. Thomas[4]
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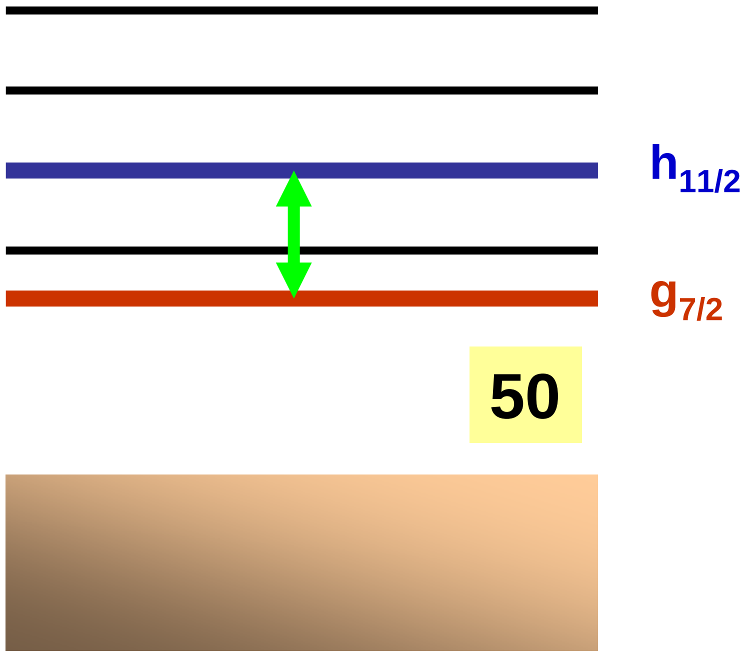
(Received 17 December 2003; published 20 April 2004)



$$\delta E \approx \hbar\omega_0 - 4.5 V_{ls} / A^{2/3}$$

Use (α,t) reaction to populate high-l orbitals

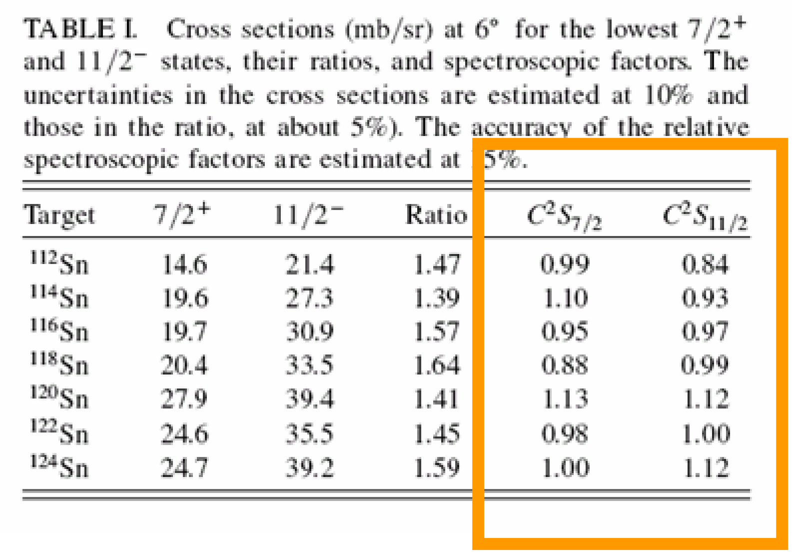
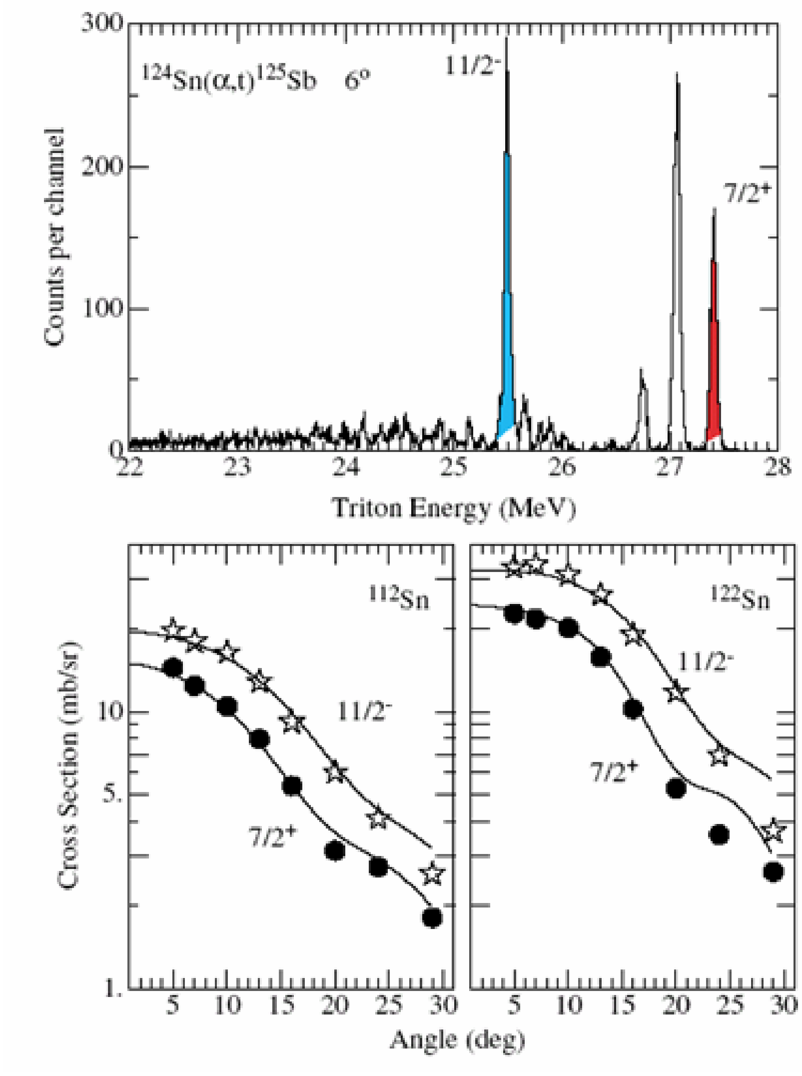
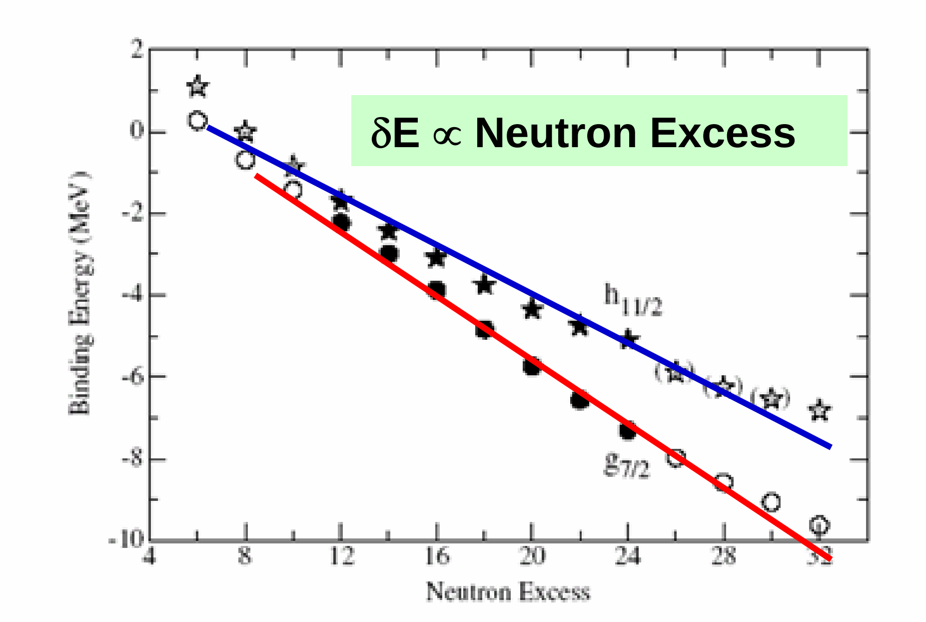


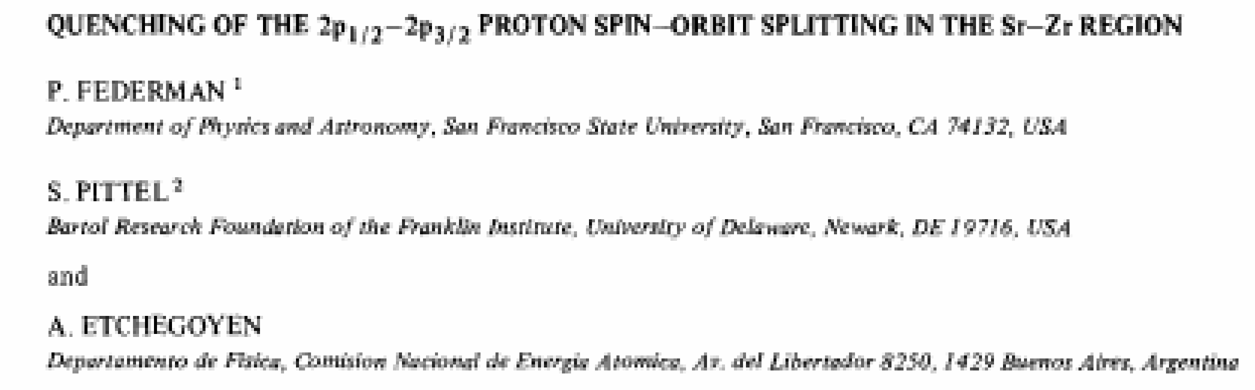
TABLE I. Cross sections (mb/sr) at 6° for the lowest 7/2$^+$ and 11/2$^-$ states, their ratios, and spectroscopic factors. The uncertainties in the cross sections are estimated at 10% and those in the ratio, at about 5%). The accuracy of the relative spectroscopic factors are estimated at 15%.

Target	7/2$^+$	11/2$^-$	Ratio	$C^2S_{7/2}$	$C^2S_{11/2}$
^{112}Sn	14.6	21.4	1.47	0.99	0.84
^{114}Sn	19.6	27.3	1.39	1.10	0.93
^{116}Sn	19.7	30.9	1.57	0.95	0.97
^{118}Sn	20.4	33.5	1.64	0.88	0.99
^{120}Sn	27.9	39.4	1.41	1.13	1.12
^{122}Sn	24.6	35.5	1.45	0.98	1.00
^{124}Sn	24.7	39.2	1.59	1.00	1.12





δE ∝ Neutron Excess



QUENCHING OF THE $2p_{1/2}$–$2p_{3/2}$ PROTON SPIN–ORBIT SPLITTING IN THE Sr–Zr REGION

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Department of Physics and Astronomy, San Francisco State University, San Francisco, CA 74132, USA

S. PITTEL [2]
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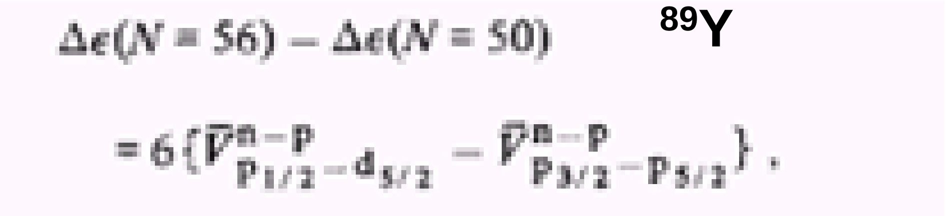
and

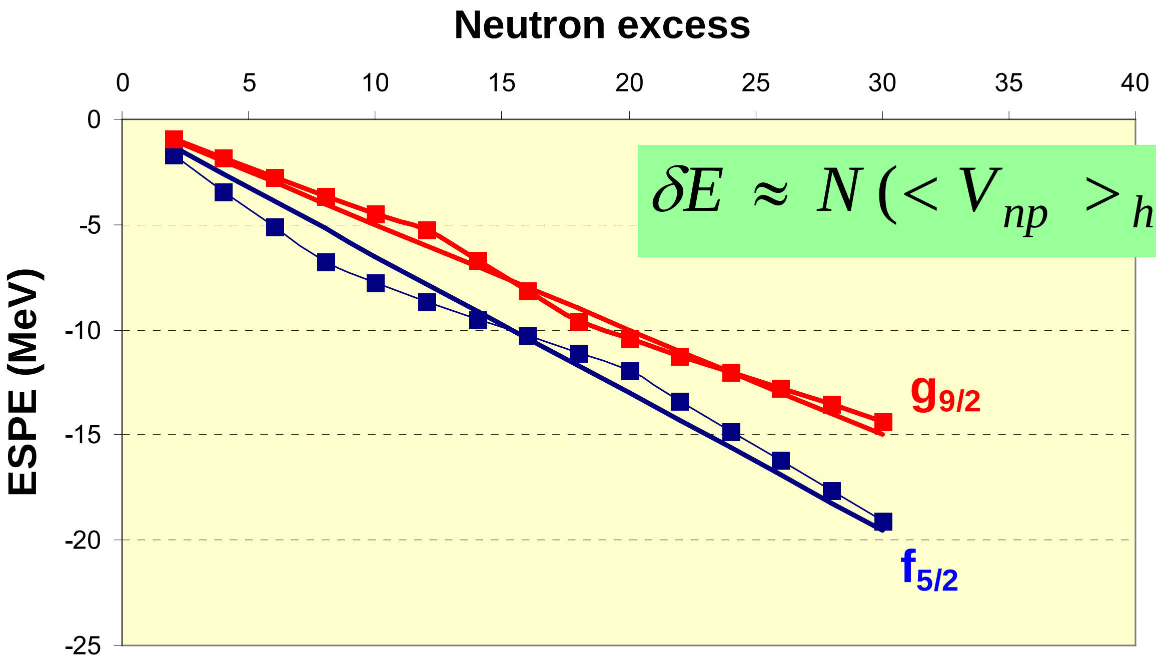
A. ETCHEGOYEN
Departamento de Física, Comisión Nacional de Energía Atómica, Av. del Libertador 8250, 1429 Buenos Aires, Argentina

^{95}Y

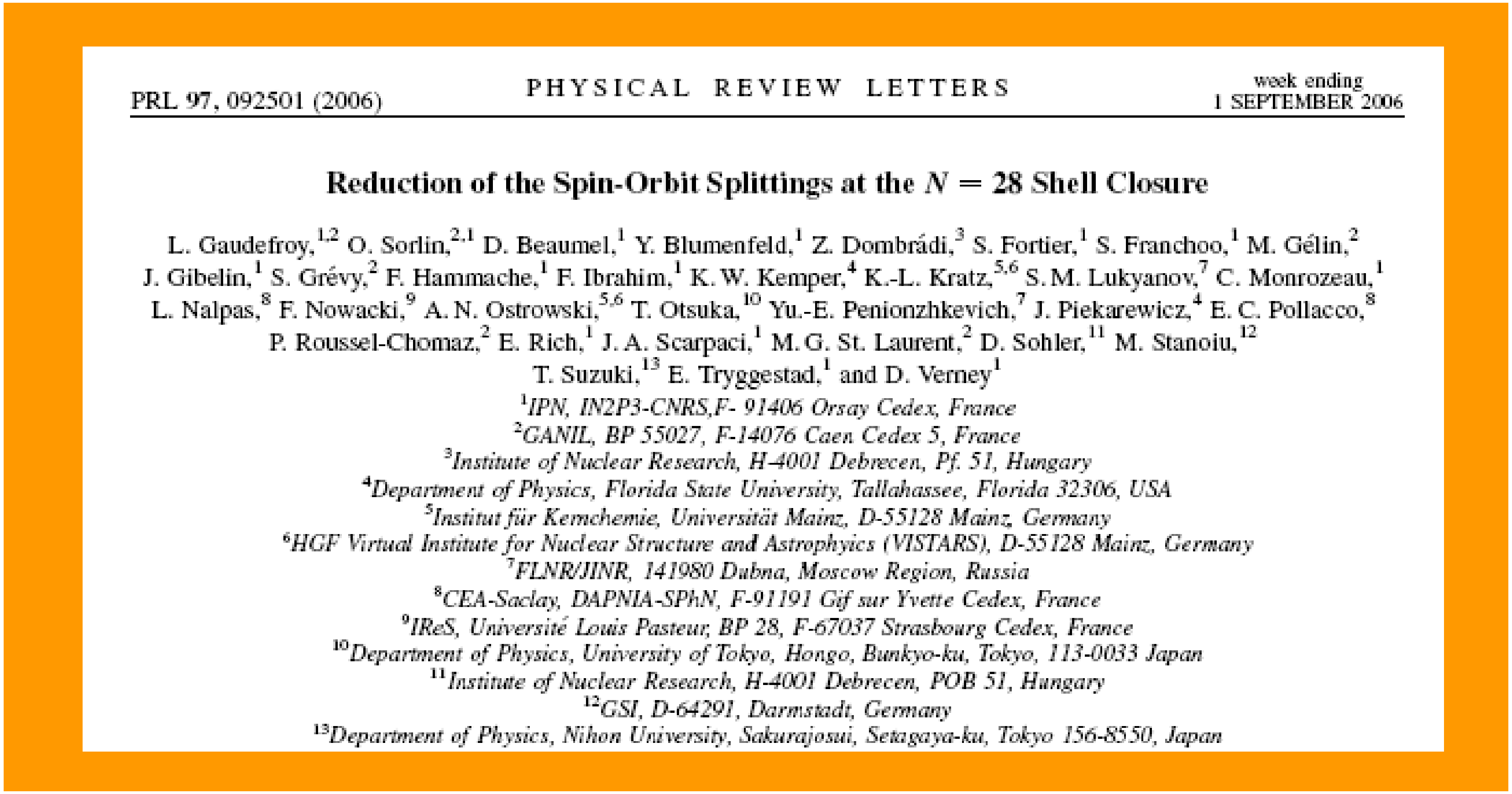
^{89}Y



$$\Delta\epsilon(N=56) - \Delta\epsilon(N=50) = 6\{\bar{V}^{n-p}_{p_{1/2}-d_{5/2}} - \bar{V}^{n-p}_{p_{3/2}-p_{5/2}}\}\,,$$



$$\delta E \approx N(< V_{np} >_{h_{11/2}} - \leq V_{np} >_{g_{7/2}})$$



PRL 97, 092501 (2006) PHYSICAL REVIEW LETTERS week ending 1 SEPTEMBER 2006

Reduction of the Spin-Orbit Splittings at the $N = 28$ Shell Closure

L. Gaudefroy,[1,2] O. Sorlin,[2,1] D. Beaumel,[1] Y. Blumenfeld,[1] Z. Dombrádi,[3] S. Fortier,[1] S. Franchoo,[1] M. Gélin,[2] J. Gibelin,[1] S. Grévy,[2] F. Hammache,[1] F. Ibrahim,[1] K. W. Kemper,[4] K.-L. Kratz,[5,6] S. M. Lukyanov,[7] C. Monrozeau,[1] L. Nalpas,[8] F. Nowacki,[9] A. N. Ostrowski,[5,6] T. Otsuka,[10] Yu.-E. Penionzhkevich,[7] J. Piekarewicz,[4] E. C. Pollacco,[8] P. Roussel-Chomaz,[2] E. Rich,[1] J. A. Scarpaci,[1] M. G. St. Laurent,[2] D. Sohler,[11] M. Stanoiu,[12] T. Suzuki,[13] E. Tryggestad,[1] and D. Verney[1]

[1]*IPN, IN2P3-CNRS,F- 91406 Orsay Cedex, France*
[2]*GANIL, BP 55027, F-14076 Caen Cedex 5, France*
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[4]*Department of Physics, Florida State University, Tallahassee, Florida 32306, USA*
[5]*Institut für Kernchemie, Universität Mainz, D-55128 Mainz, Germany*
[6]*HGF Virtual Institute for Nuclear Structure and Astrophyics (VISTARS), D-55128 Mainz, Germany*
[7]*FLNR/JINR, 141980 Dubna, Moscow Region, Russia*
[8]*CEA-Saclay, DAPNIA-SPhN, F-91191 Gif sur Yvette Cedex, France*
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^{46}Ar(d,p)^{47}Ar reaction at SPIRAL and MUST detector array

In recent years substantial progress has been made in the development of *Ab Initio* theories of light nuclei.

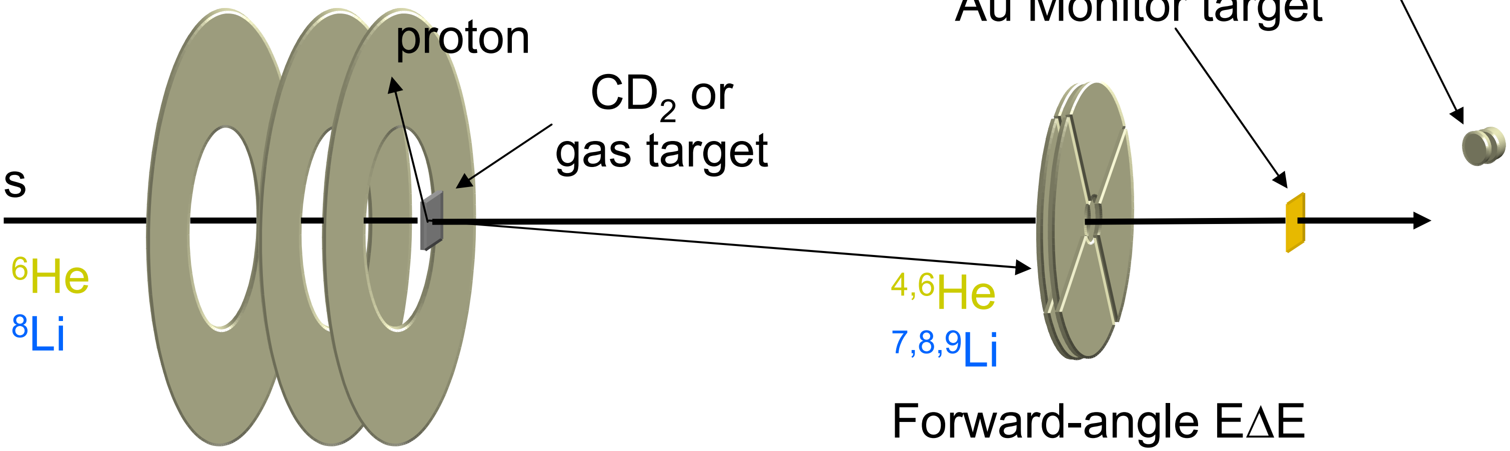
The Quantum Monte Carlo method has been very successful in reproducing BE and excitation spectra of light nuclei starting with the basic NN force and 3-body force.

PRL 94, 082502 (2005) PHYSICAL REVIEW LETTERS week ending 4 MARCH 2005

Neutron Spectroscopic Factors in ^{9}Li from ^{2}H(^{8}Li, p)^{9}Li

A. H. Wuosmaa,[1] K. E. Rehm,[2] J. P. Greene,[2] D. J. Henderson,[2] R. V. F. Janssens,[2] C. L. Jiang,[2] L. Jisonna,[3] E. F. Moore,[2]
R. C. Pardo,[2] M. Paul,[4] D. Peterson,[2] Steven C. Pieper,[2] G. Savard,[2] J. P. Schiffer,[2] R. E. Segel,[3]
S. Sinha,[2] X. Tang,[2] and R. B. Wiringa[2]
[1]*Physics Department, Western Michigan University, Kalamazoo, Michigan 49008-5252, USA*
[2]*Physics Division, Argonne National Laboratory, 9700 S. Cass Ave, Argonne Illinois 60439, USA*
[3]*Physics Department, Northwestern University, Evanston, Illinois 60208, USA*
[4]*Hebrew University, Jerusalem, Israel 91904*

"Backward" kinematics: (d,p) (^{3}He,d)



Monitor EΔE telescope

Au Monitor target

proton

CD_2 or gas target

Beam axis

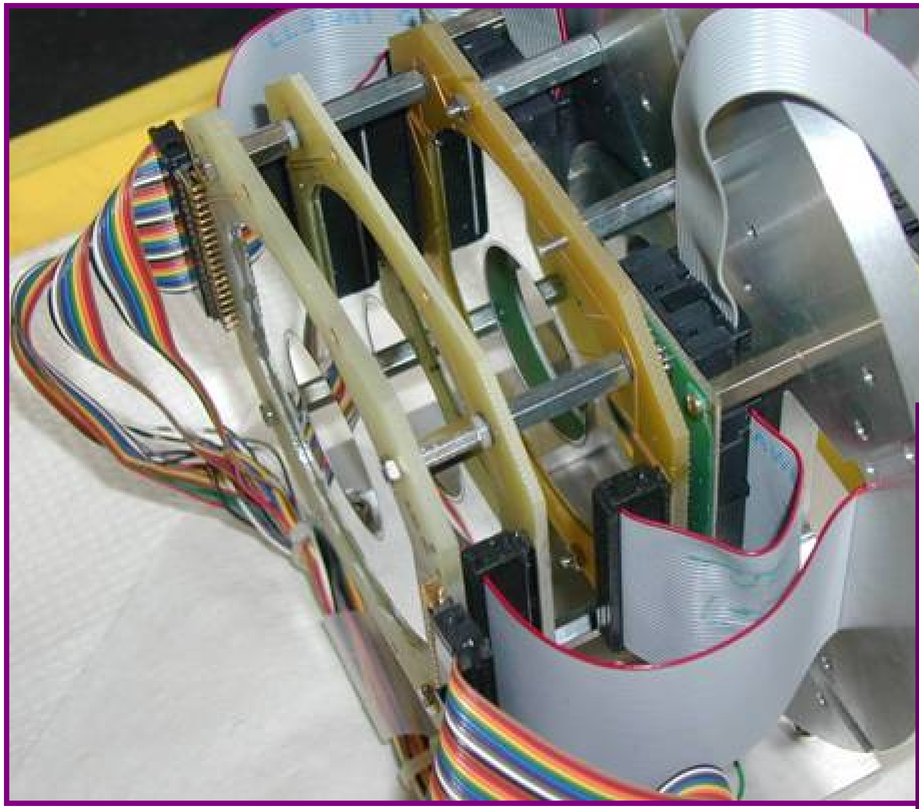
^{6}He
^{8}Li

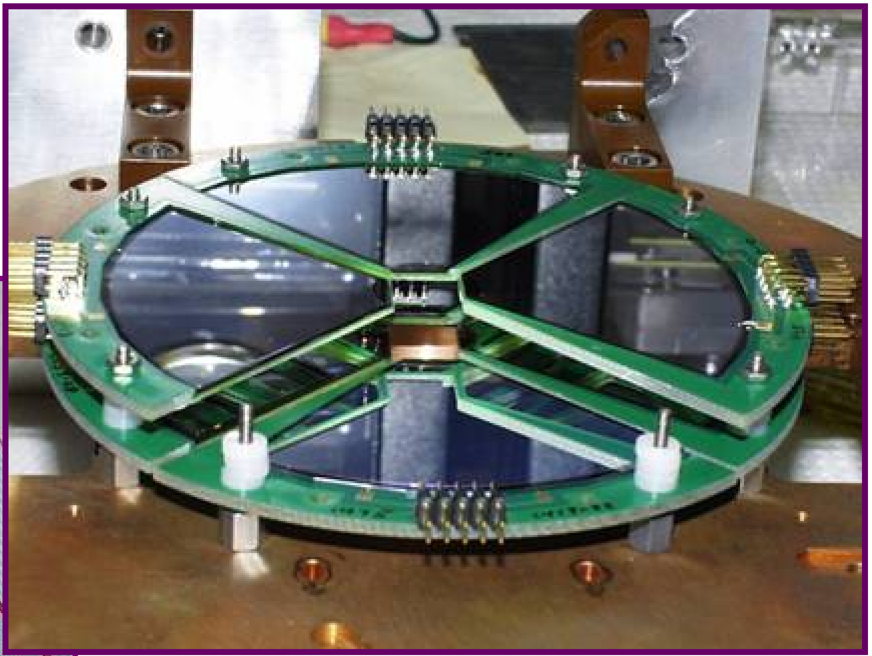
^{4,6}He
^{7,8,9}Li

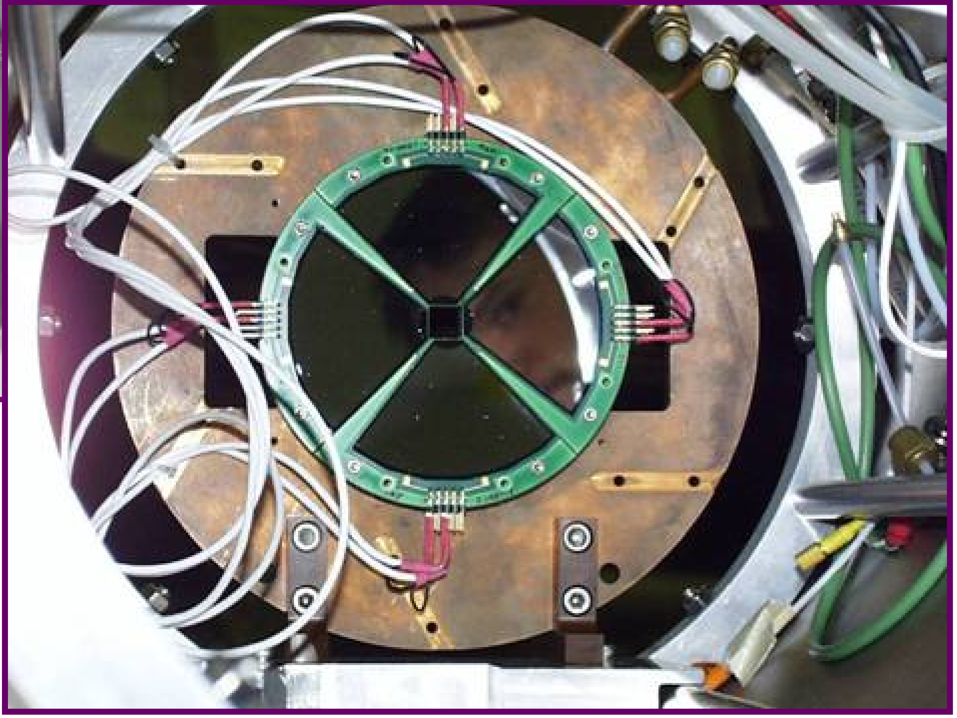
Annular silicon detectors
Ω_{lab} ~ 3.5 sr
θ_{lab}=109°-159°

Forward-angle EΔE detectors
θ_{lab}=1°-7°

Detectors

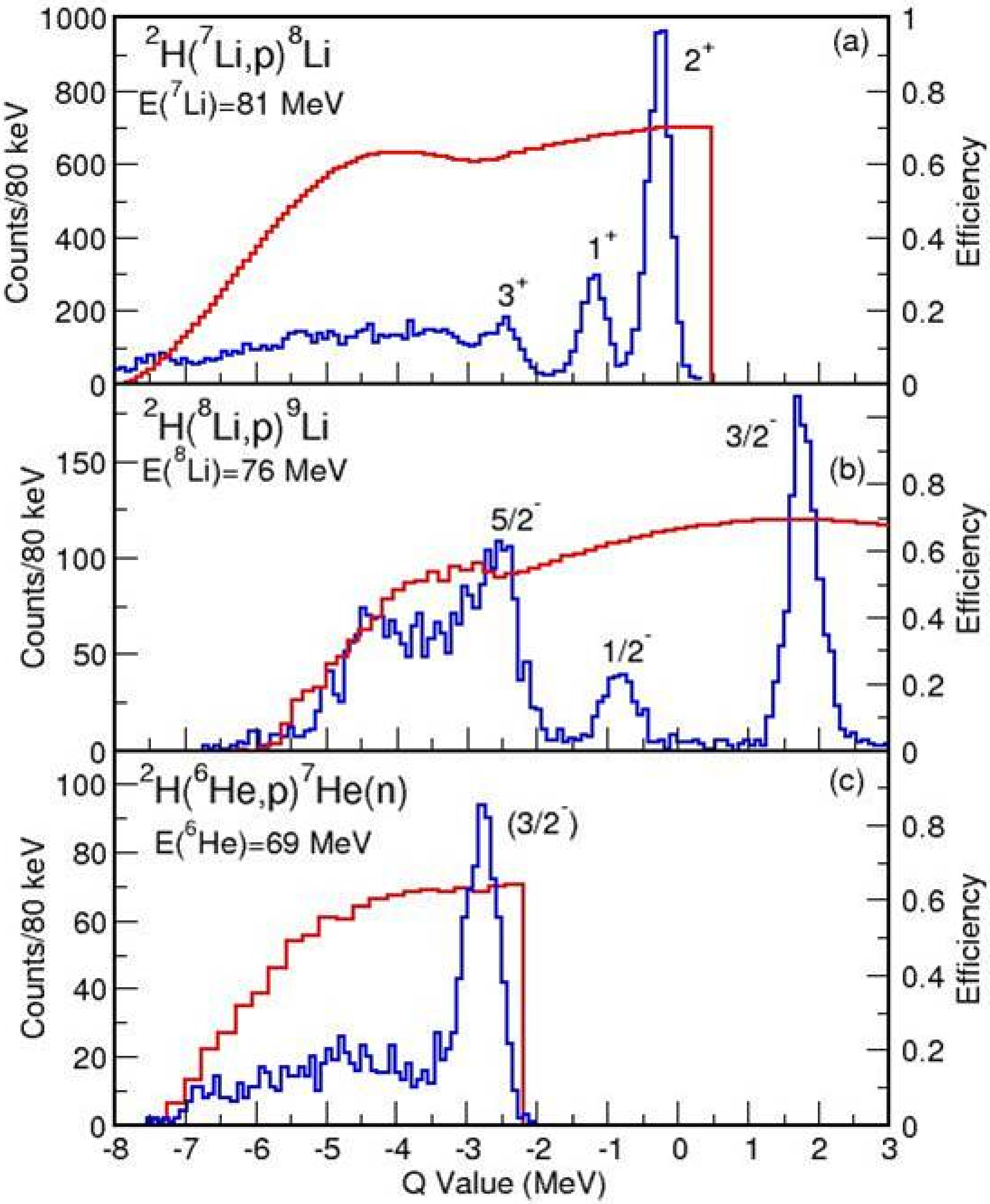






Segmented proton detectors

500μm/1000μm silicon EΔE telescope

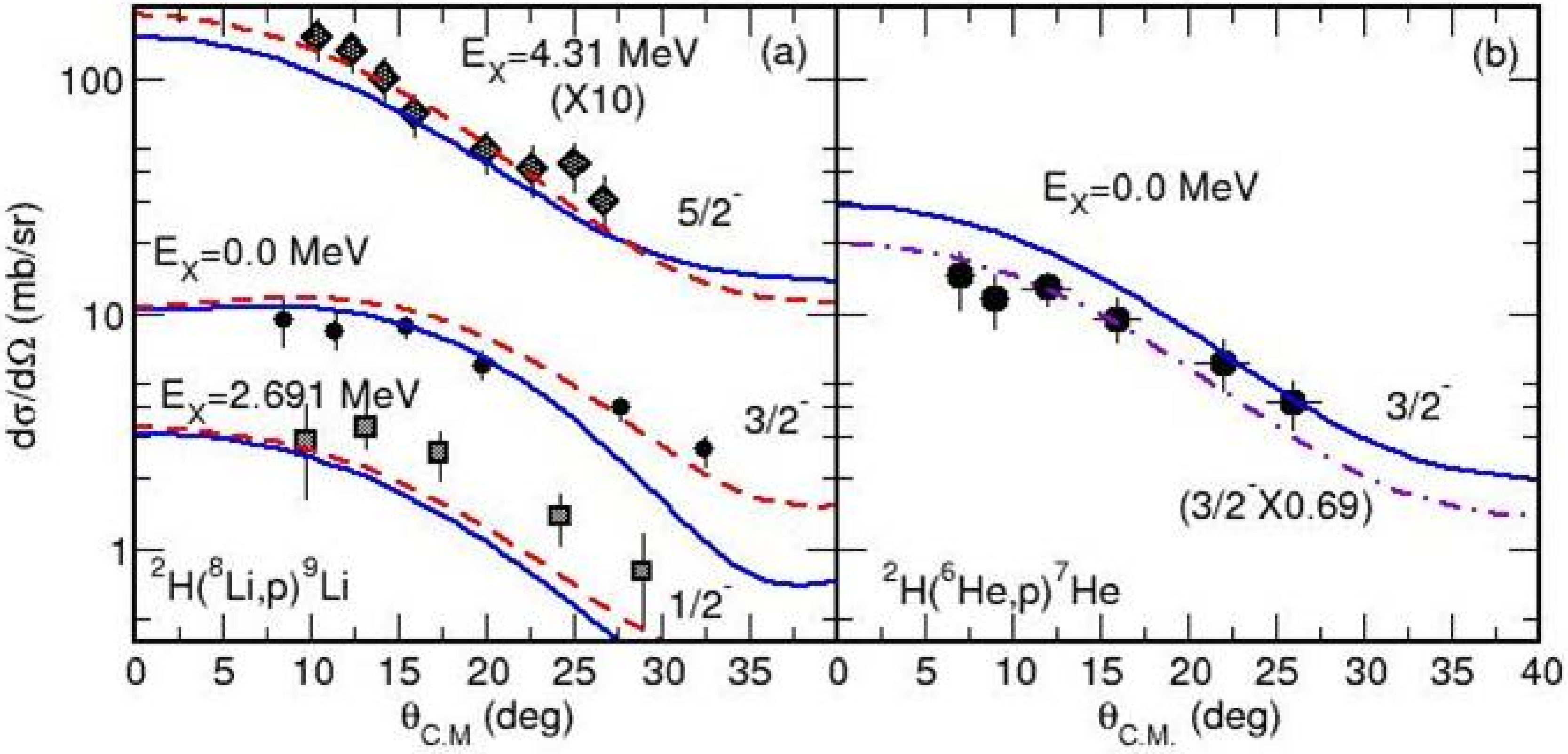


Q-value spectra from (*d*,*p*)

p-Li or *p*-^{6}He coincidences
Efficiency from Monte Carlo simulations

PRL **94**, 082502 (2005),
PRC **72**, 061301(R) (2005)

(*d*,*p*) Angular Distributions - narrow states



$^2H(^8Li,p)^9Li$ DWBA calculations: **Red**, **blue** curves: QMC predictions with different OMP, no extra normalization

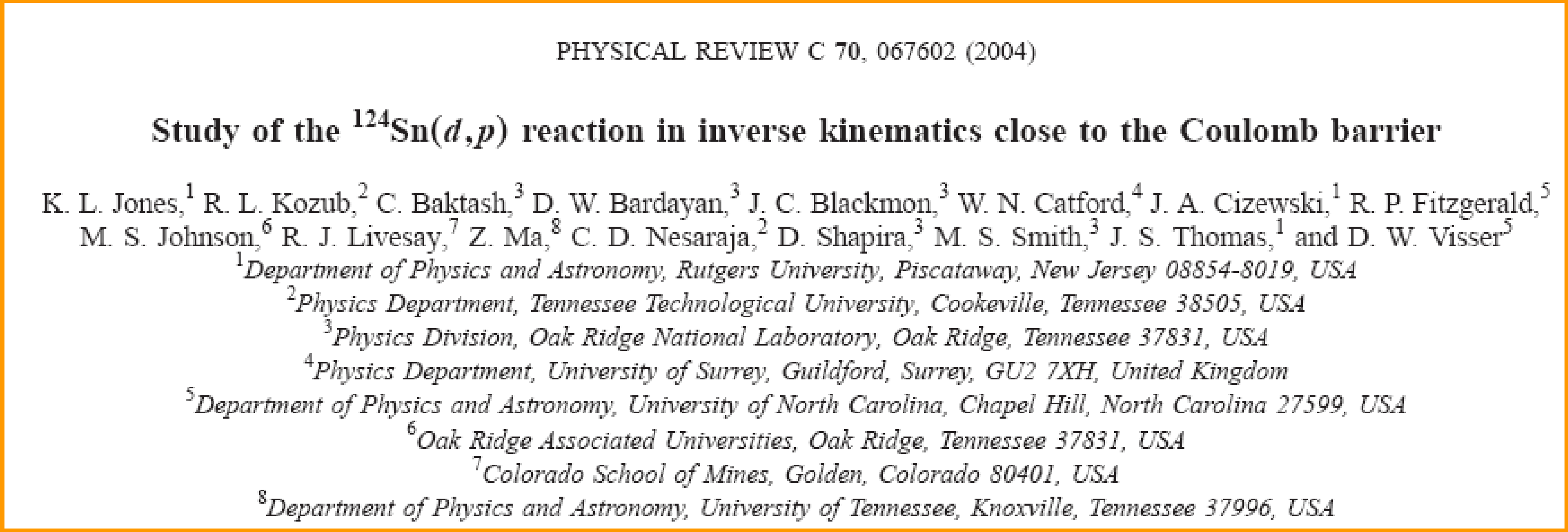
$^2H(^6He,p)^7He_{g.s.}$ DWBA calculations QMC calculations. **Blue**: no normalization **violet**- QMC X 0.69.

Optical-model parameters from Schiffer et al, PRC **164**

Shell structure near ^{132}Sn:

Neutron levels in ^{133}Sn via the ^{132}Sn(d,p)

Successful “proof of principle” experiment with ^{124}Sn



PHYSICAL REVIEW C **70**, 067602 (2004)

Study of the ^{124}Sn(d,p) reaction in inverse kinematics close to the Coulomb barrier

K. L. Jones,[1] R. L. Kozub,[2] C. Baktash,[3] D. W. Bardayan,[3] J. C. Blackmon,[3] W. N. Catford,[4] J. A. Cizewski,[1] R. P. Fitzgerald,[5]
M. S. Johnson,[6] R. J. Livesay,[7] Z. Ma,[8] C. D. Nesaraja,[2] D. Shapira,[3] M. S. Smith,[3] J. S. Thomas,[1] and D. W. Visser[5]
[1]*Department of Physics and Astronomy, Rutgers University, Piscataway, New Jersey 08854-8019, USA*
[2]*Physics Department, Tennessee Technological University, Cookeville, Tennessee 38505, USA*
[3]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
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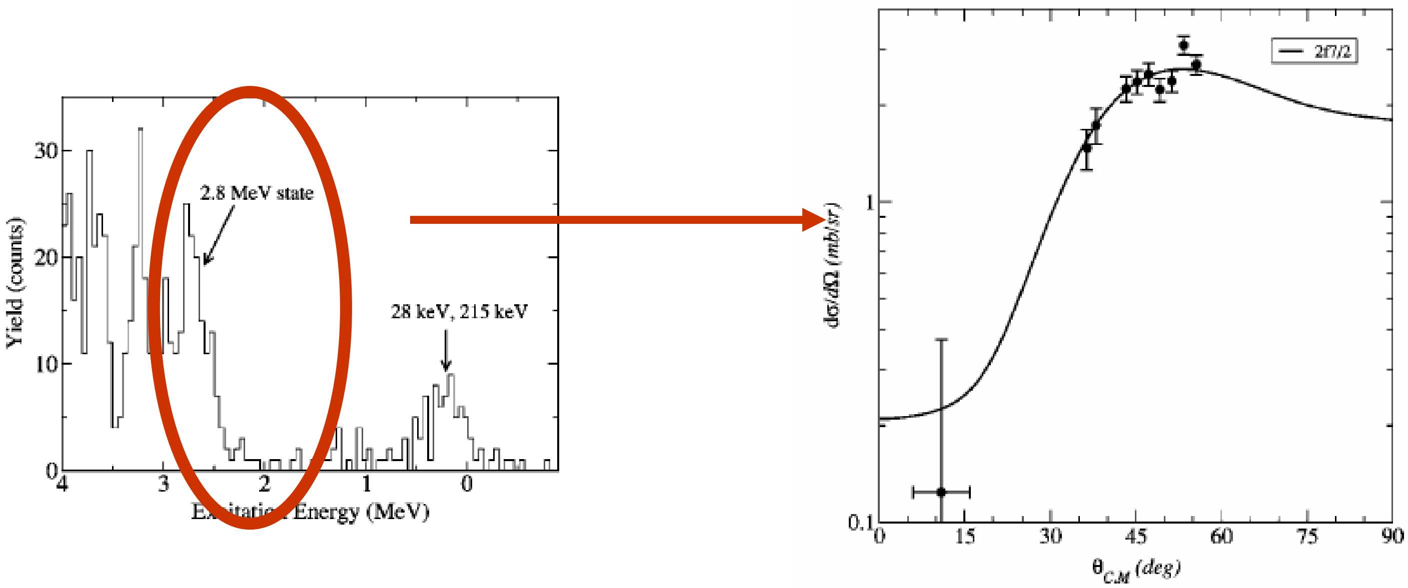
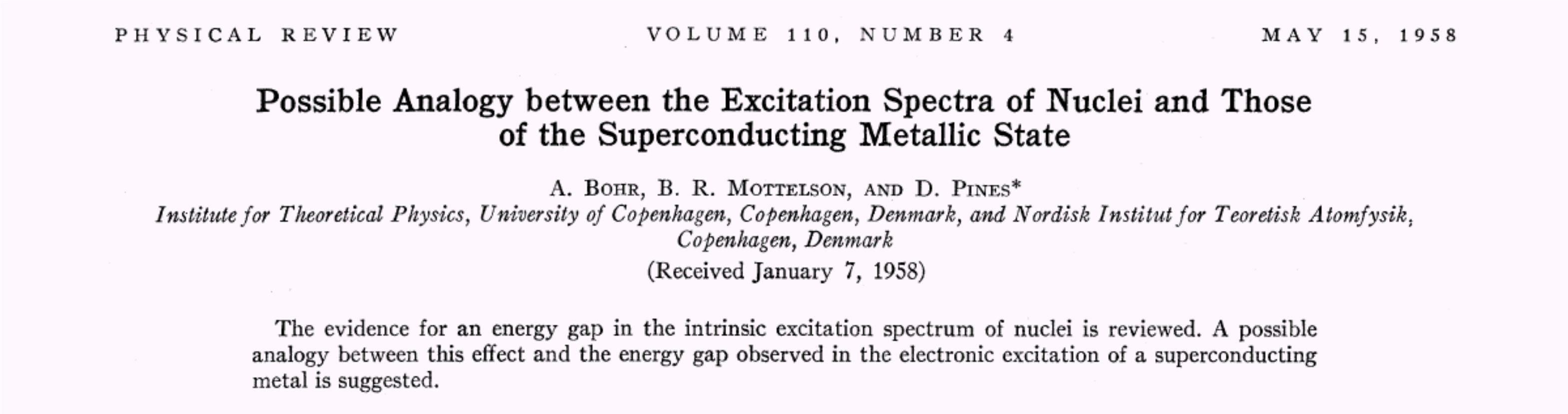
[6]*Oak Ridge Associated Universities, Oak Ridge, Tennessee 37831, USA*
[7]*Colorado School of Mines, Golden, Colorado 80401, USA*
[8]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*



THE experiment with an improved detector array should be running, as we speak, at HRIBF

PAIRING IN NUCLEI



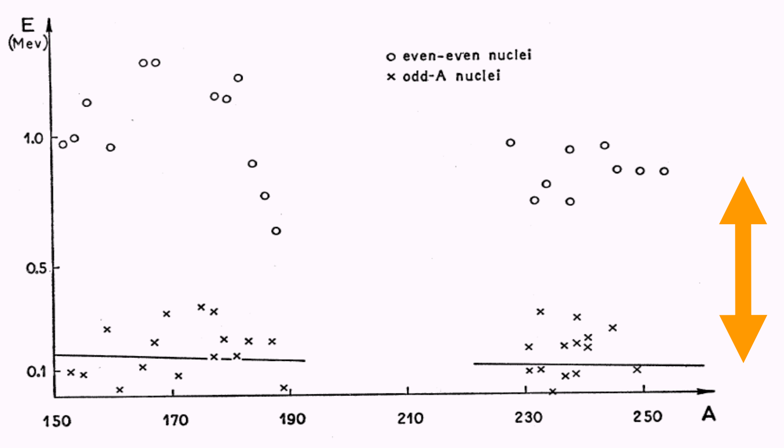
PHYSICAL REVIEW VOLUME 110, NUMBER 4 MAY 15, 1958

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.

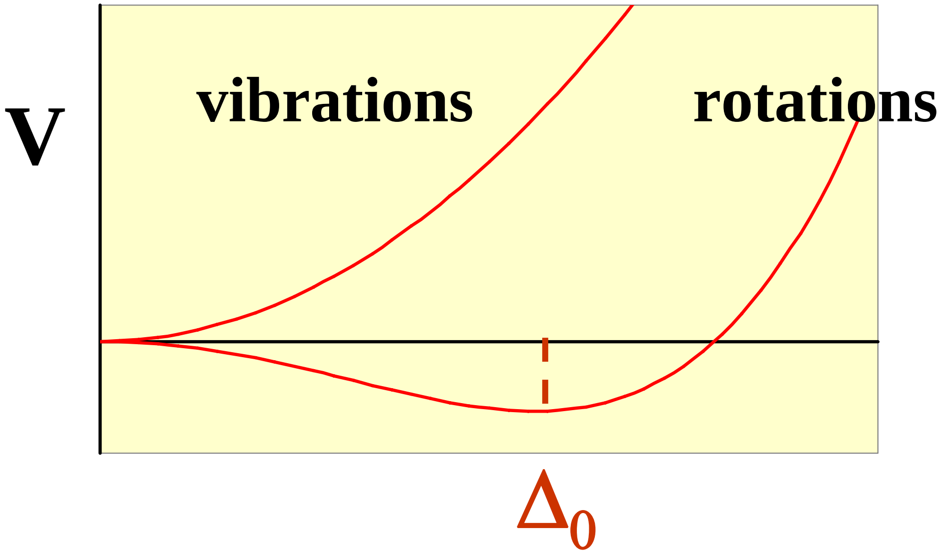


- Gap in the excitation spectra of even-A nuclei
- Odd-even mass differences
- Rotational moments of inertia

Relevance to other finite Fermion systems such as ^{3}He clusters, Fermi-gas condensates, quantum dots, metal clusters, ….

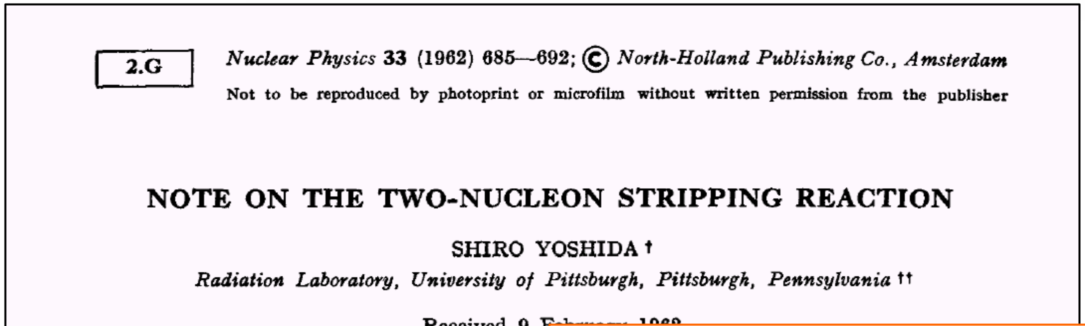
Two-nucleon Transfer Reactions

Generalized densities a+a+, aa represent the pair field and in close analogy to the collective excitations corresponding to the ordinary density, they can give rise to collective modes.



$$\Delta = G < \Sigma a_{\nu}^{+} a_{\bar{\nu}}^{+} >$$

Two particle transfer reactions like (t,p) or (p,t), where 2 neutrons are deposited or picked up at the same point in space provide an specific tool to probe the amplitude of this collective motion. The transition operator <f|a+a+|i> will be proportional to the pair density of the nucleus.



2.G *Nuclear Physics* **33** (1962) 685—692; © *North-Holland Publishing Co., Amsterdam*

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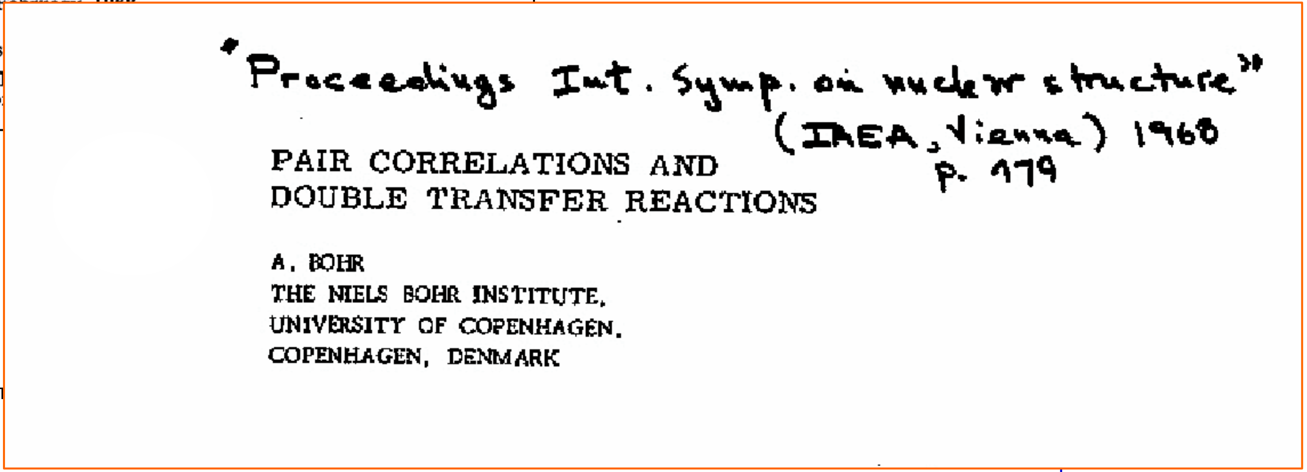
NOTE ON THE TWO-NUCLEON STRIPPING REACTION

SHIRO YOSHIDA †

Radiation Laboratory, University of Pittsburgh, Pittsburgh, Pennsylvania ††

Received 9 F

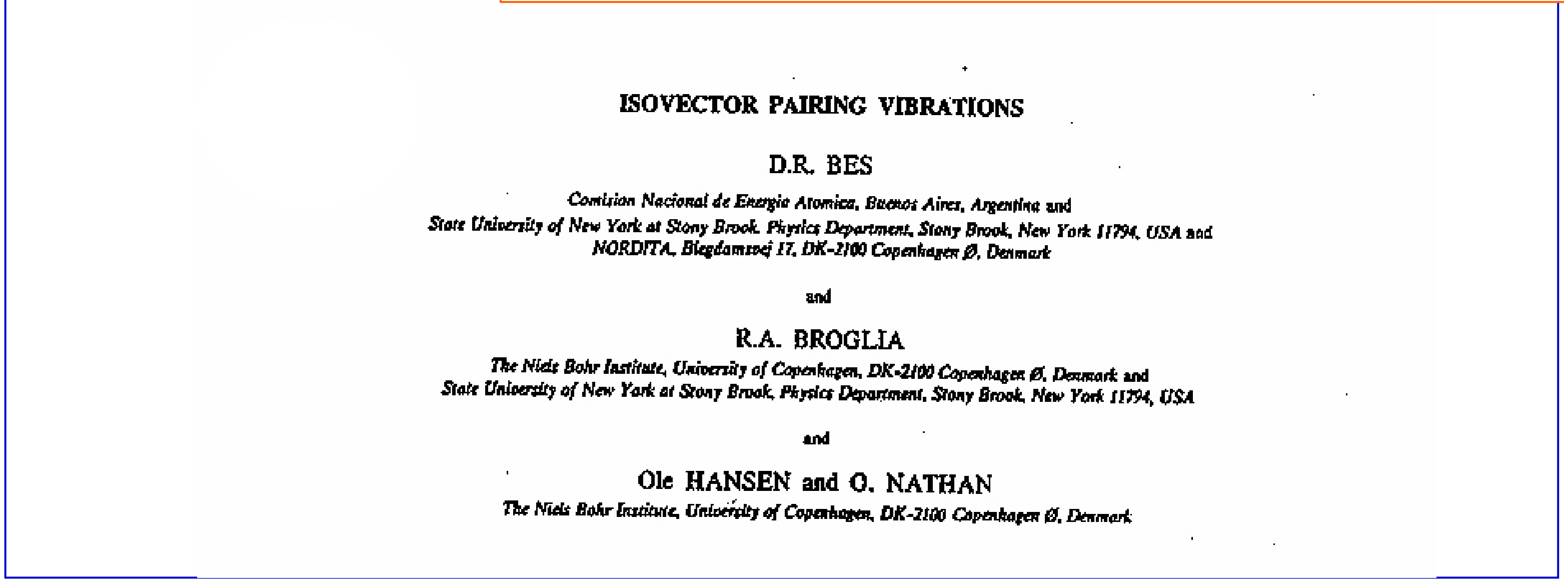
Abstract: The magnitude of the two-nucleon s
interaction model. The calculation also is a
types of reaction a collective enhancement o



"Proceedings Int. Symp. on nuclear structure"
(IAEA, Vienna) 1968
p. 179

PAIR CORRELATIONS AND DOUBLE TRANSFER REACTIONS

A. BOHR
THE NIELS BOHR INSTITUTE,
UNIVERSITY OF COPENHAGEN,
COPENHAGEN, DENMARK



PHYSICS REPORT

ISOVECTOR PAIRING VIBRATIONS

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State University of New York at Stony Brook, Physics Department, Stony Brook, New York 11794, USA

and

Ole HANSEN and O. NATHAN

The Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen Ø, Denmark

Neutron Proton Pairing

NP Pairing

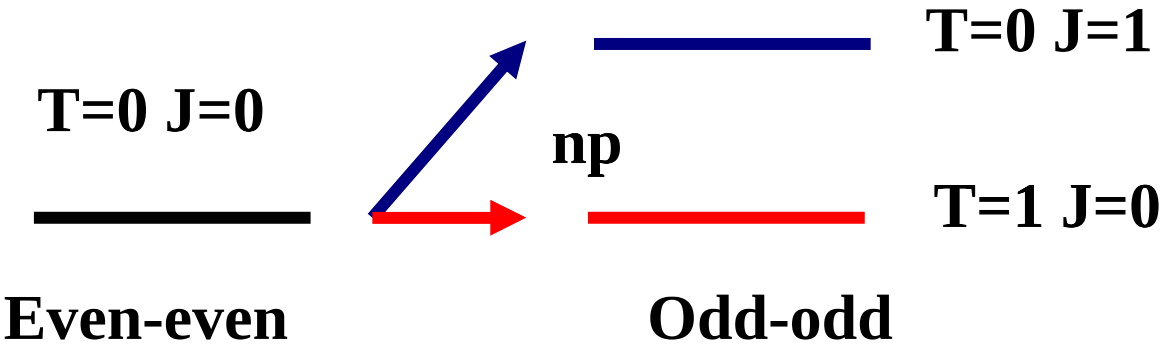
- N=Z nuclei, unique systems to study *np* correlations
  - As you move out of N=Z *nn* and *pp* pairs are favored
- Role of isoscalar (T=0) and isovector (T=1) pairing
  - Large spatial overlap of *n* and *p*
  - Pairing vibrations (normal system)
  - Pairing rotations (superfluid system)
- Does isoscalar pairing give rise to collective modes?

- What is (are) the "smoking-gun(s)"?
  - Binding energy differences
  - Ground states of odd-odd self-conjugate nuclei
  - Rotational properties: moments of inertia, alignments
  - Two-particle transfer cross-sections

(3He,p) Transfer Reactions

$\sigma \propto < 1 \,|\, T \,|\, 0 >^{2} \sim \Omega$ or Ω^{2}

σ ?



T=0 J=0

T=0 J=1

np

T=1 J=0

Even-even

Odd-odd

(^{3}He,p)

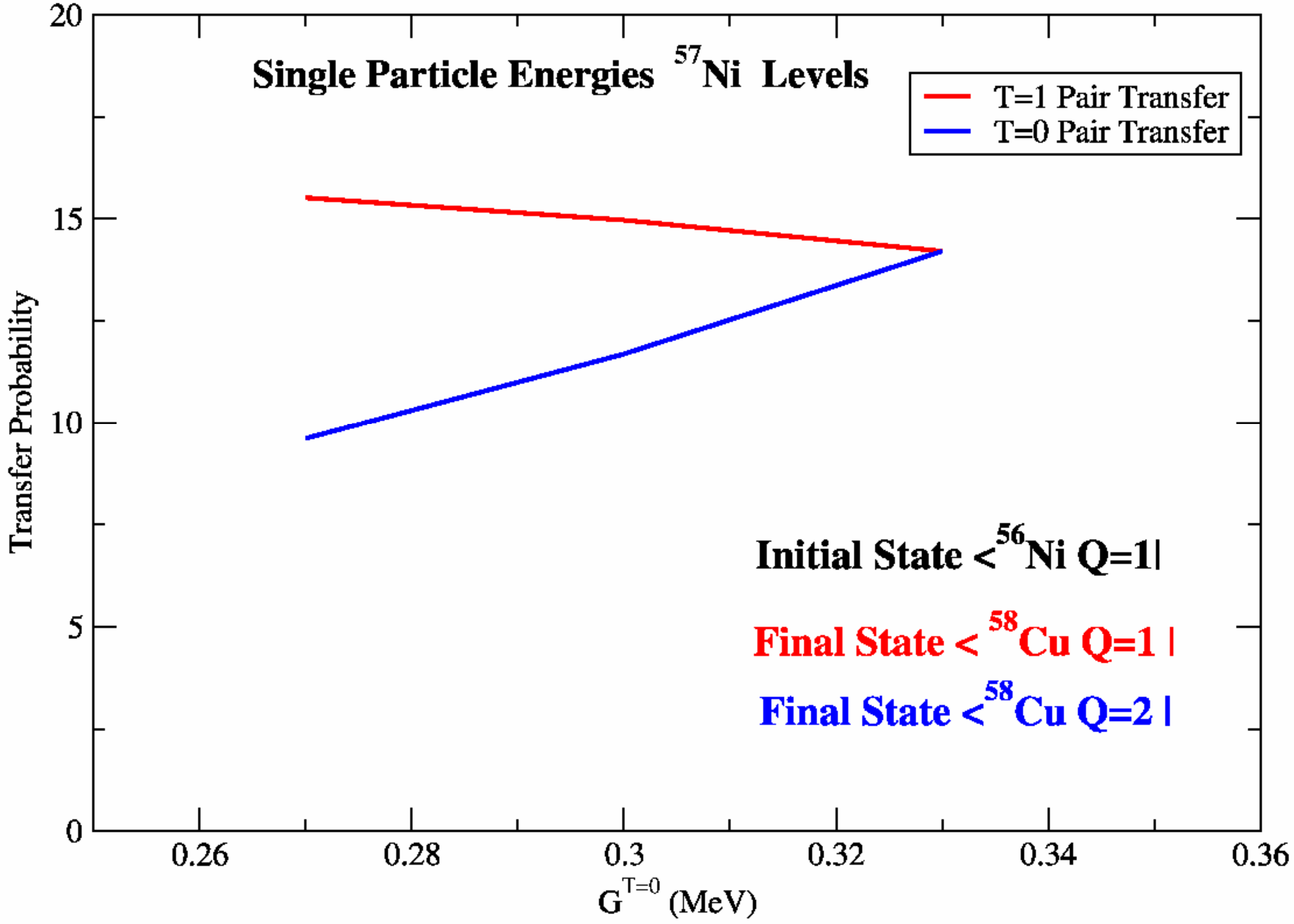
L=0 transfer – forward peaked

Measure the *np* transfer cross section to T=1 and T=0 states

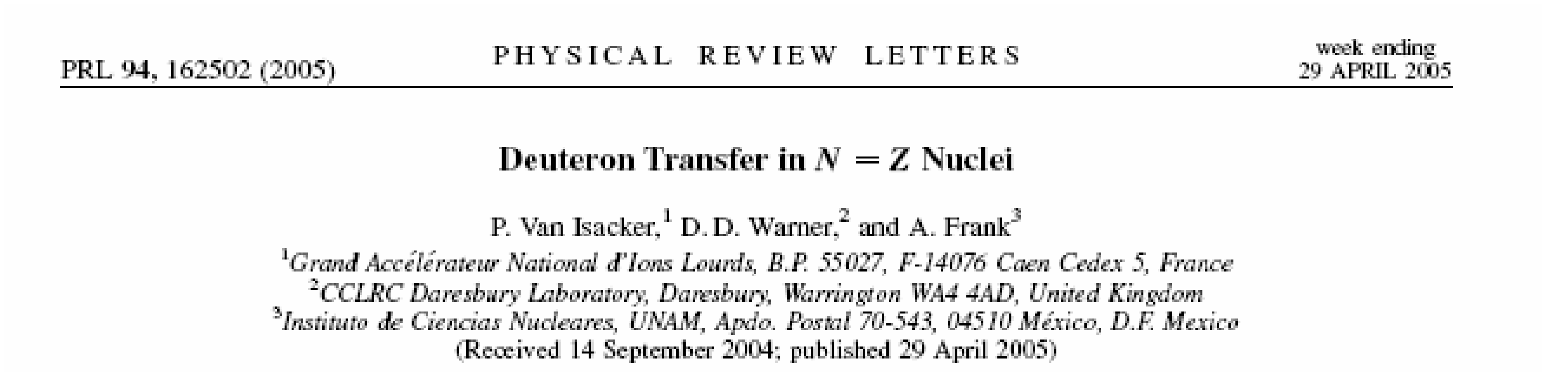
Both absolute σ(T=0) and σ(T=1) and relative σ(T=0) / σ(T=1) tell us about the character and strength of the correlations

n-p Pair Transfer Probability

$G^{T=1} = 0.33$ MeV



R.Chasman - ANL



PRL 94, 162502 (2005) PHYSICAL REVIEW LETTERS week ending 29 APRIL 2005

Deuteron Transfer in $N = Z$ Nuclei

P. Van Isacker,[1] D. D. Warner,[2] and A. Frank[3]
[1]*Grand Accélérateur National d'Ions Lourds, B.P. 55027, F-14076 Caen Cedex 5, France*
[2]*CCLRC Daresbury Laboratory, Daresbury, Warrington WA4 4AD, United Kingdom*
[3]*Instituto de Ciencias Nucleares, UNAM, Apdo. Postal 70-543, 04510 México, D.F. Mexico*

(Received 14 September 2004; published 29 April 2005)

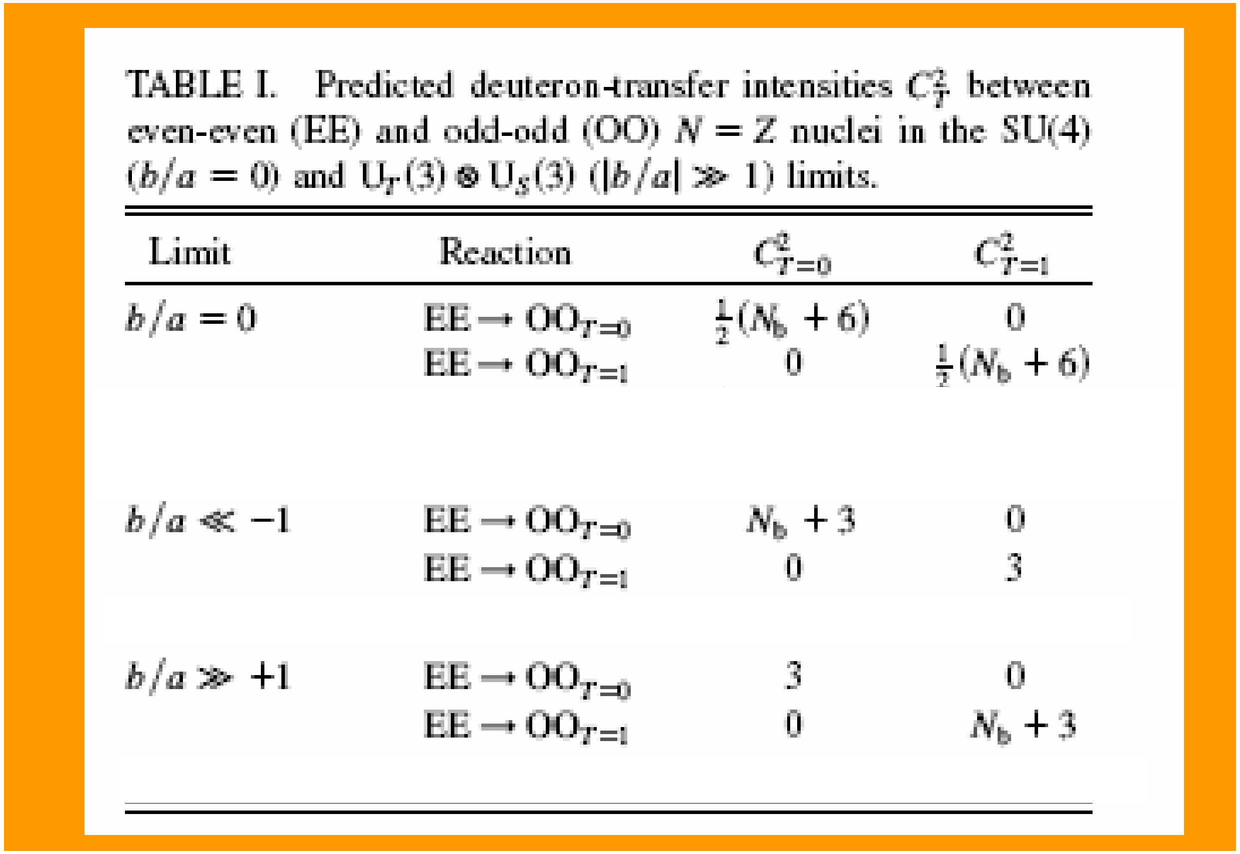
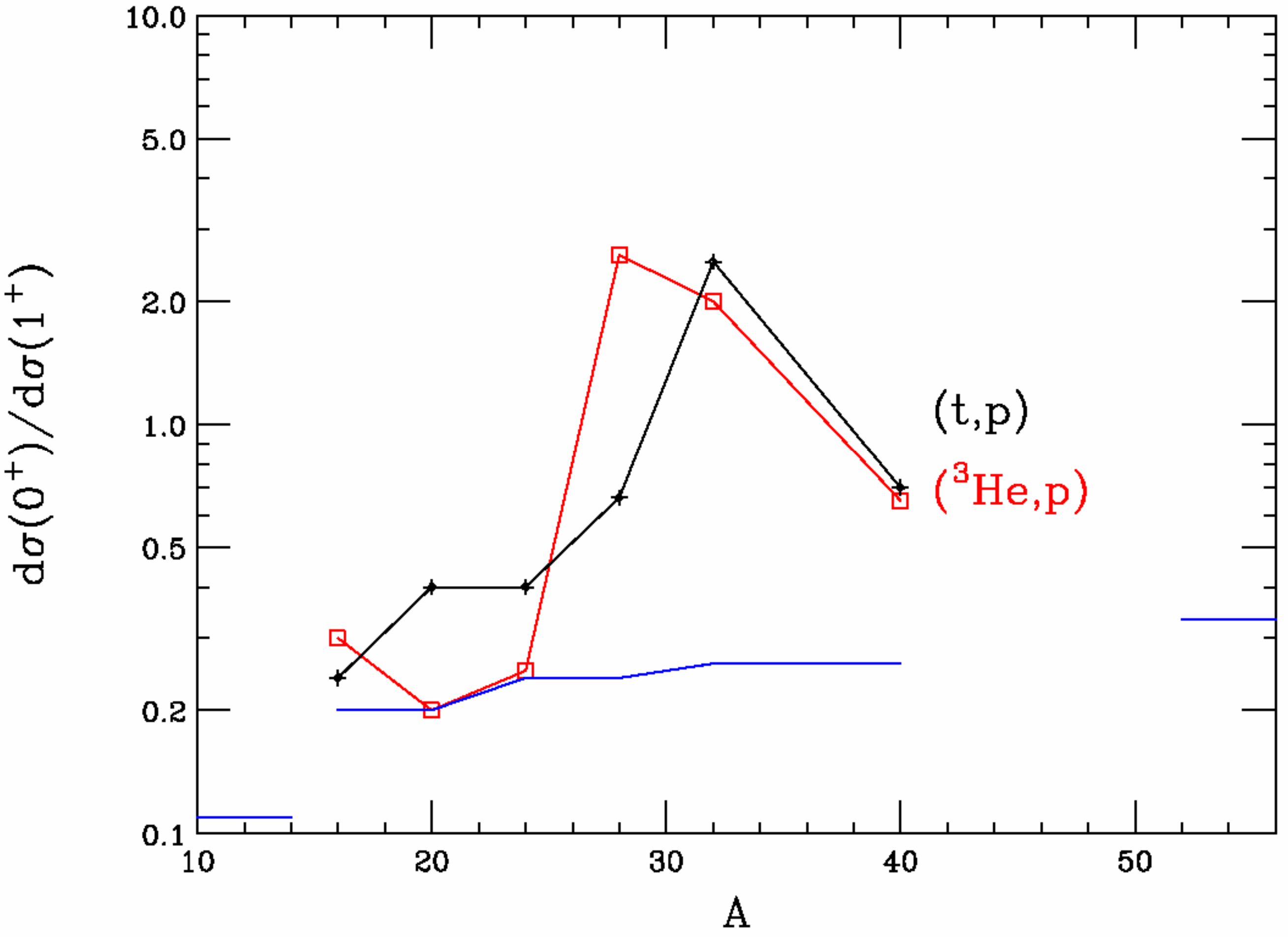


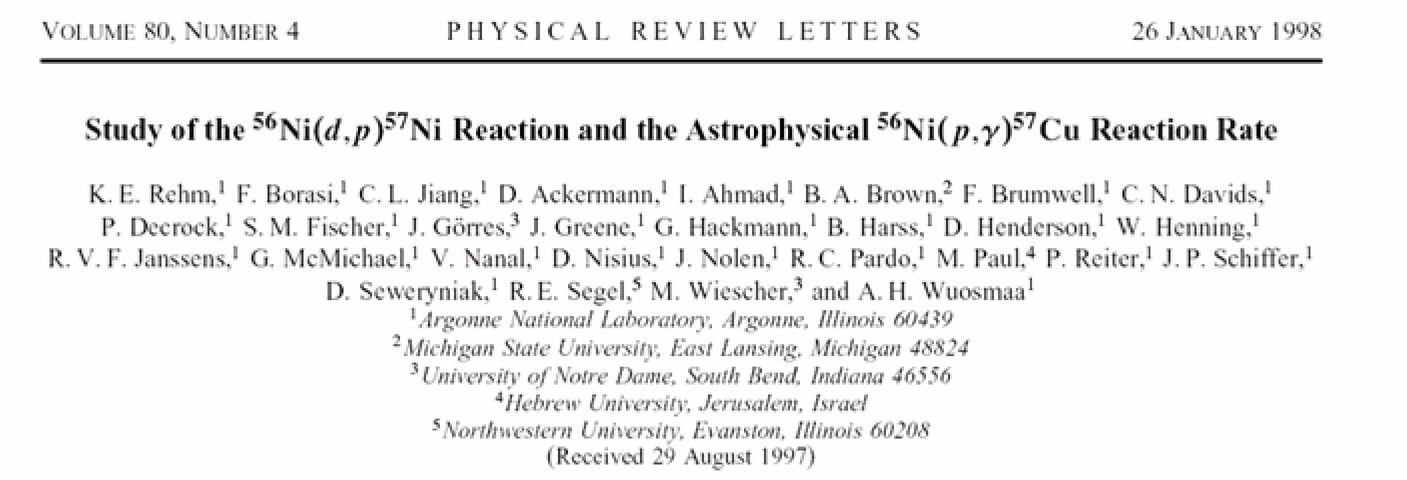
TABLE I. Predicted deuteron-transfer intensities C_T^2 between even-even (EE) and odd-odd (OO) $N = Z$ nuclei in the SU(4) ($b/a = 0$) and $\mathrm{U}_T(3) \otimes \mathrm{U}_S(3)$ ($|b/a| \gg 1$) limits.

Limit	Reaction	$C^2_{T=0}$	$C^2_{T=1}$
$b/a = 0$	$\mathrm{EE} \to \mathrm{OO}_{T=0}$	$\frac{1}{2}(N_b + 6)$	0
	$\mathrm{EE} \to \mathrm{OO}_{T=1}$	0	$\frac{1}{2}(N_b + 6)$
$b/a \ll -1$	$\mathrm{EE} \to \mathrm{OO}_{T=0}$	$N_b + 3$	0
	$\mathrm{EE} \to \mathrm{OO}_{T=1}$	0	3
$b/a \gg +1$	$\mathrm{EE} \to \mathrm{OO}_{T=0}$	3	0
	$\mathrm{EE} \to \mathrm{OO}_{T=1}$	0	$N_b + 3$

Systematic of (^{3}He,p) and (t,p) reactions in stable N=Z nuclei



Single-particle estimate ~ (spin)x(^{3}He)x(LS -> jj)



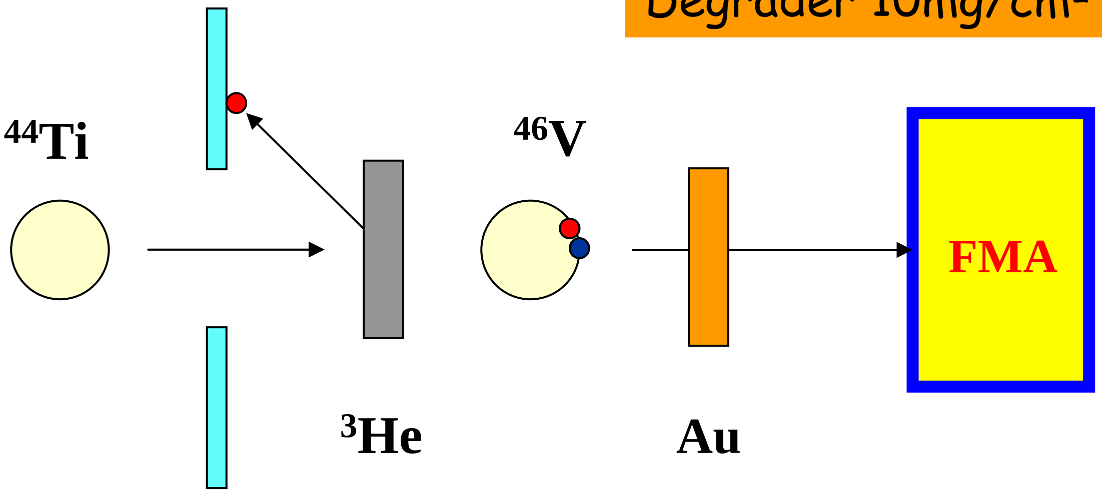
VOLUME 80, NUMBER 4 PHYSICAL REVIEW LETTERS 26 JANUARY 1998

Study of the ^{56}Ni(d,p)^{57}Ni Reaction and the Astrophysical ^{56}Ni(p,γ)^{57}Cu Reaction Rate

K. E. Rehm,[1] F. Borasi,[1] C. L. Jiang,[1] D. Ackermann,[1] I. Ahmad,[1] B. A. Brown,[2] F. Brumwell,[1] C. N. Davids,[1]
P. Decrock,[1] S. M. Fischer,[1] J. Görres,[3] J. Greene,[1] G. Hackmann,[1] B. Harss,[1] D. Henderson,[1] W. Henning,[1]
R. V. F. Janssens,[1] G. McMichael,[1] V. Nanal,[1] D. Nisius,[1] J. Nolen,[1] R. C. Pardo,[1] M. Paul,[4] P. Reiter,[1] J. P. Schiffer,[1]
D. Seweryniak,[1] R. E. Segel,[5] M. Wiescher,[3] and A. H. Wuosmaa[1]
[1] *Argonne National Laboratory, Argonne, Illinois 60439*
[2] *Michigan State University, East Lansing, Michigan 48824*
[3] *University of Notre Dame, South Bend, Indiana 46556*
[4] *Hebrew University, Jerusalem, Israel*
[5] *Northwestern University, Evanston, Illinois 60208*

(Received 29 August 1997)

Degrader 10mg/cm^2



~10^6 /sec

From ATLAS

Si detector 500μ
16x16 ~1sr

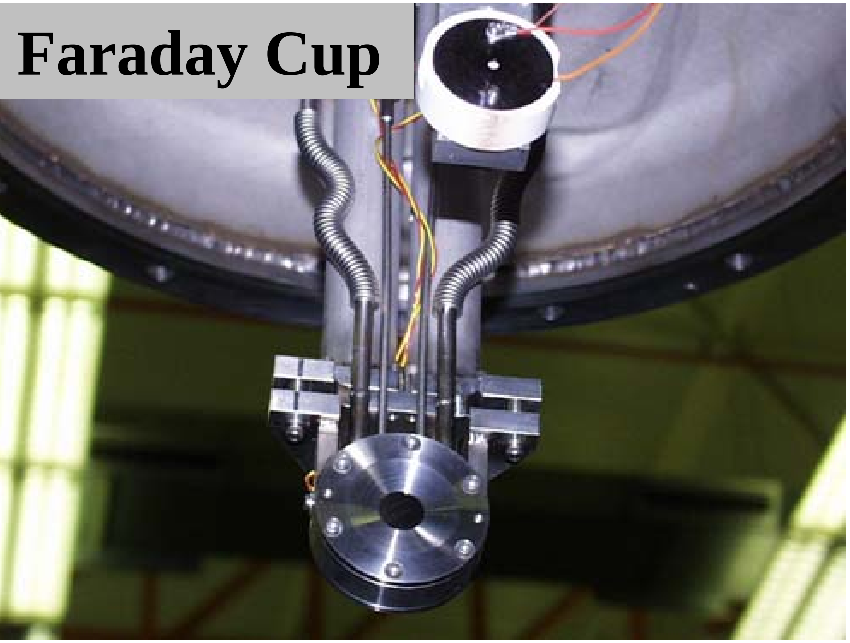
Gas cell
~100μg/cm^2

⇨ 20 counts/day

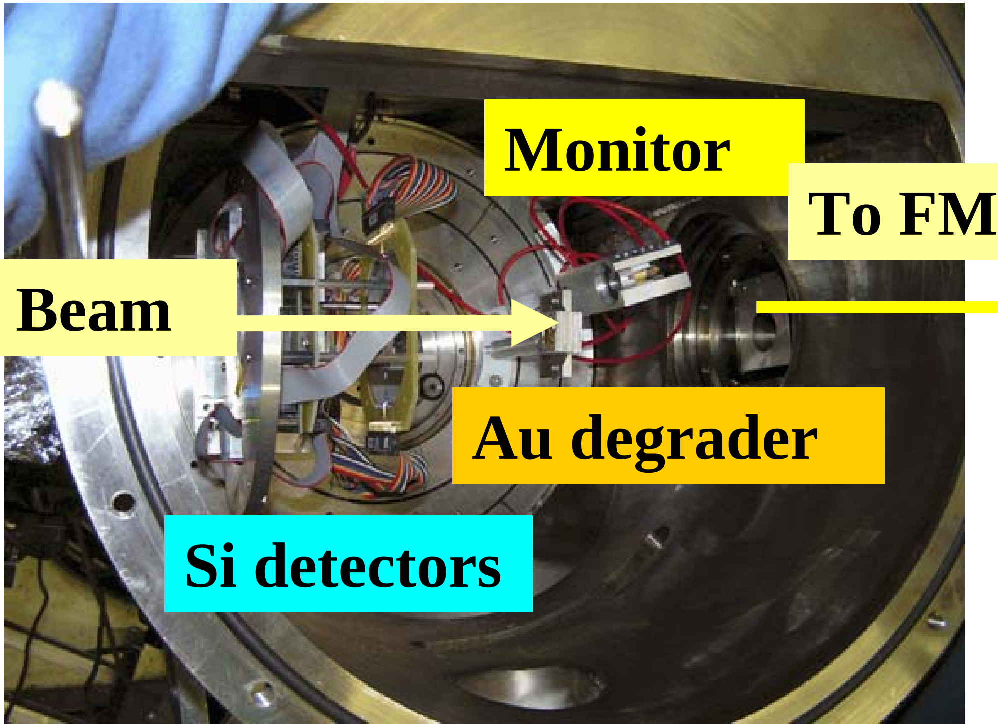
Proof of principle

A.O.Macchiavelli[1], E.Rehm[2], P.Fallon[1], M.Cromaz[1], I.Ahmad[1], C.N.Davis[2], J.Greene[2], R.V.F.Janssens[2],C.L.Jiang[2], E.F.Moore[2], R.Pardo[2], D.Seweryniak[2], J.P.Schiffer[2], A.Wuosmaa[3], J.Cizewski[3],

[1] *Lawrence Berkeley National Laboratory*
[2]*Argonne National Laboratory*
[3]*Western Michigan University*
[3] *Rutgers University*

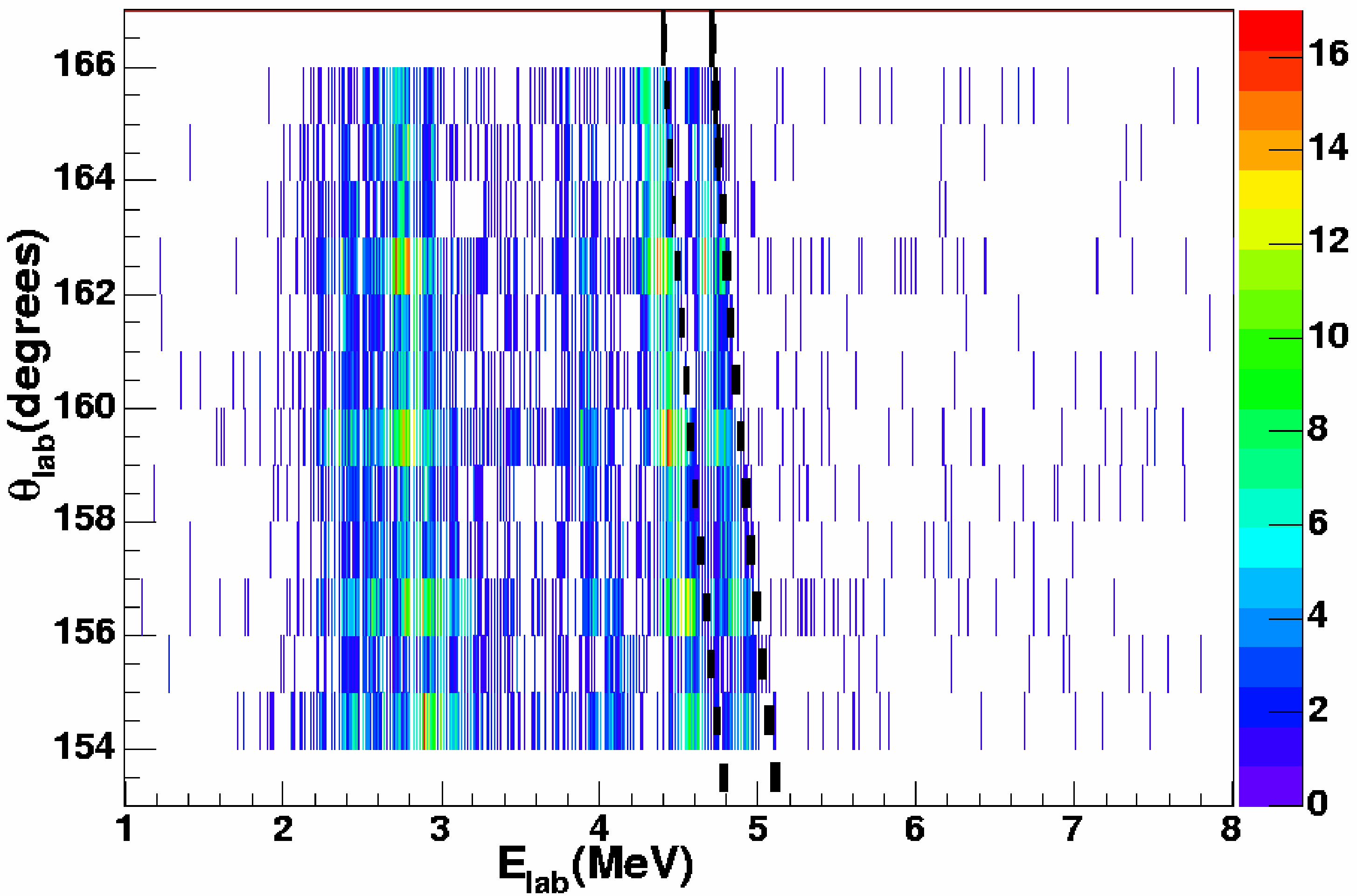


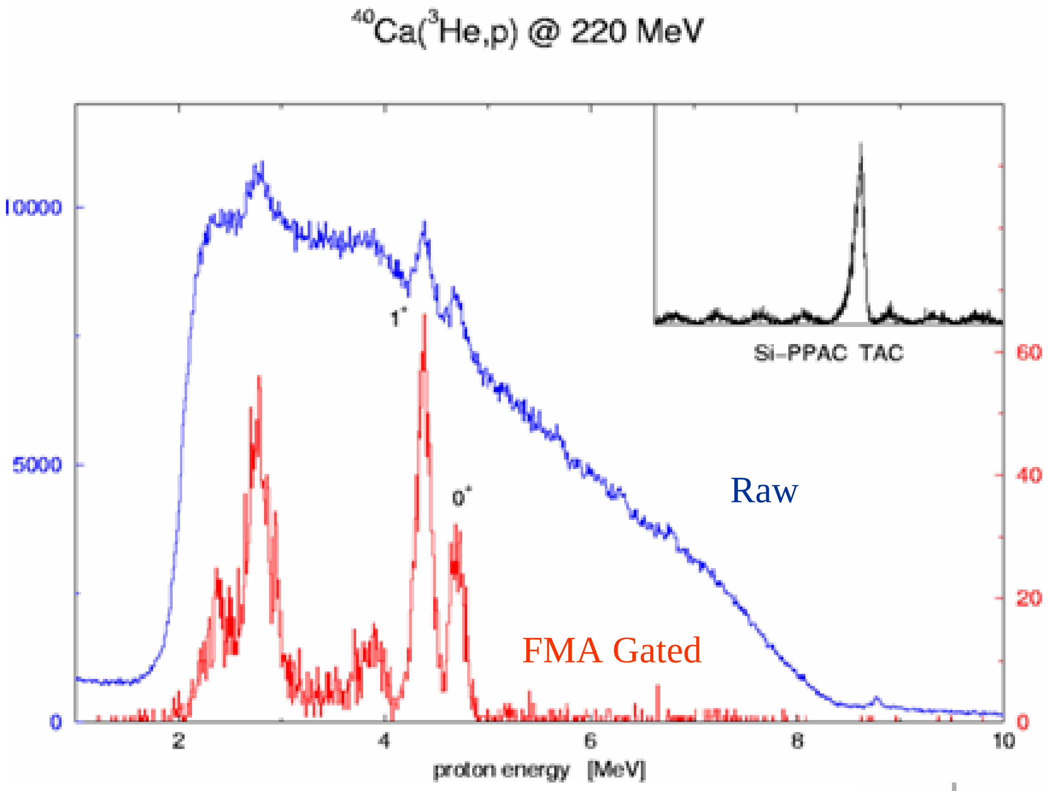
Gas Cell

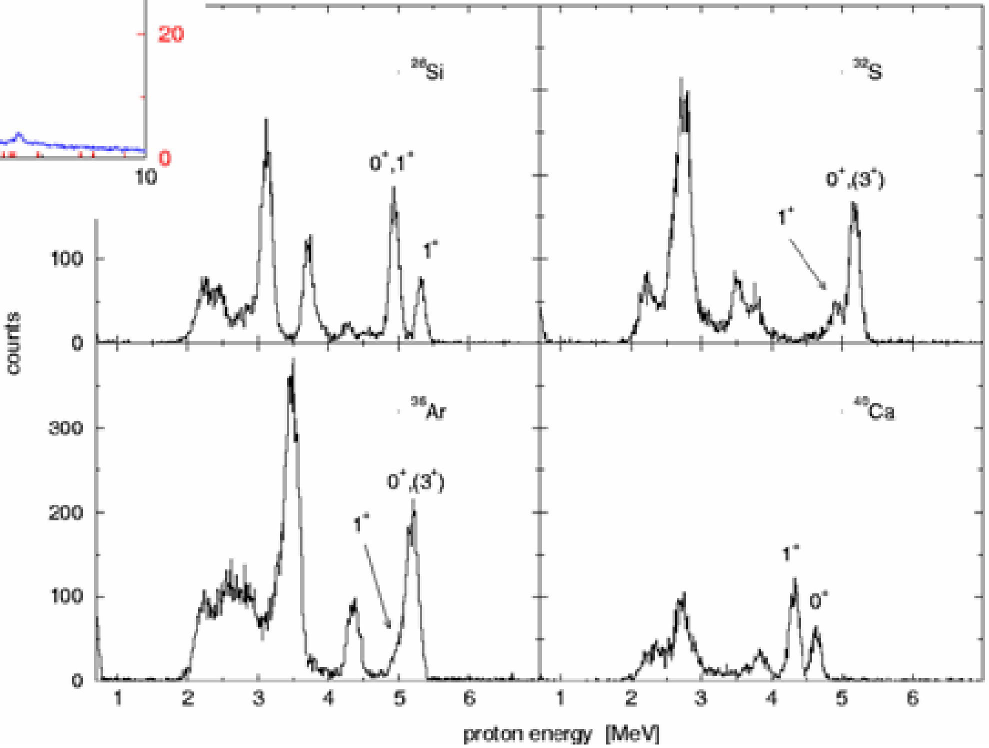


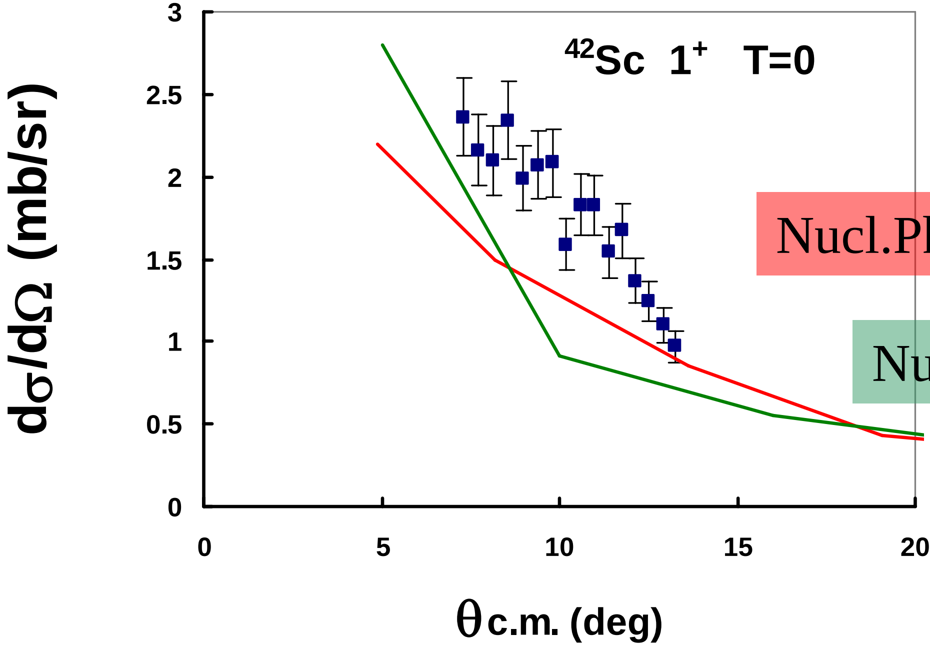
Proof of principle

Inverse kinematics -
Successful test experiment with stable beams



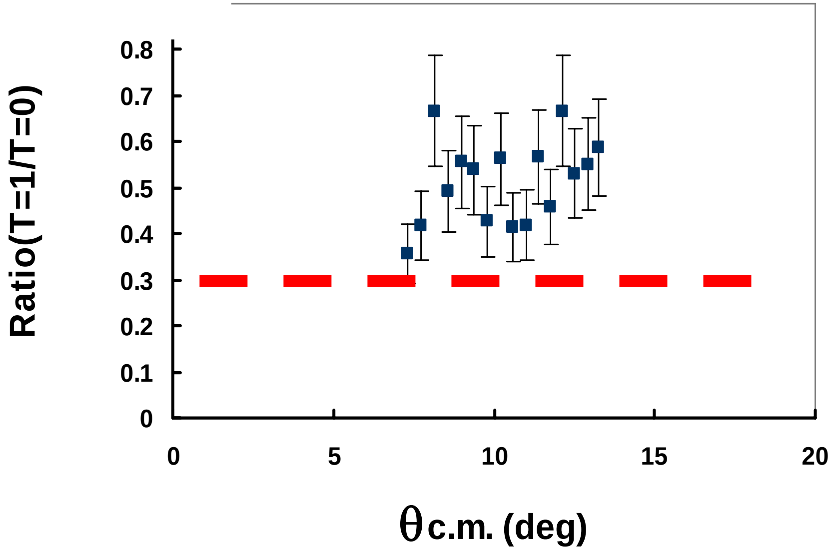

$^{40}Ca(^3He,p)$ @ 220 MeV
10000
5000
0
60
40
20
0
2
4
6
8
10
proton energy [MeV]
Si-PPAC TAC
1^+
0^+
Raw
FMA Gated


^{28}Si
$0^+,1^+$
1^+
^{32}S
$0^+,(3^+)$
1^+
^{36}Ar
$0^+,(3^+)$
1^+
^{40}Ca
1^+
0^+
counts
100
0
300
200
100
0
1
2
3
4
5
6
proton energy [MeV]



Nucl.Phys. **A80** (1966)

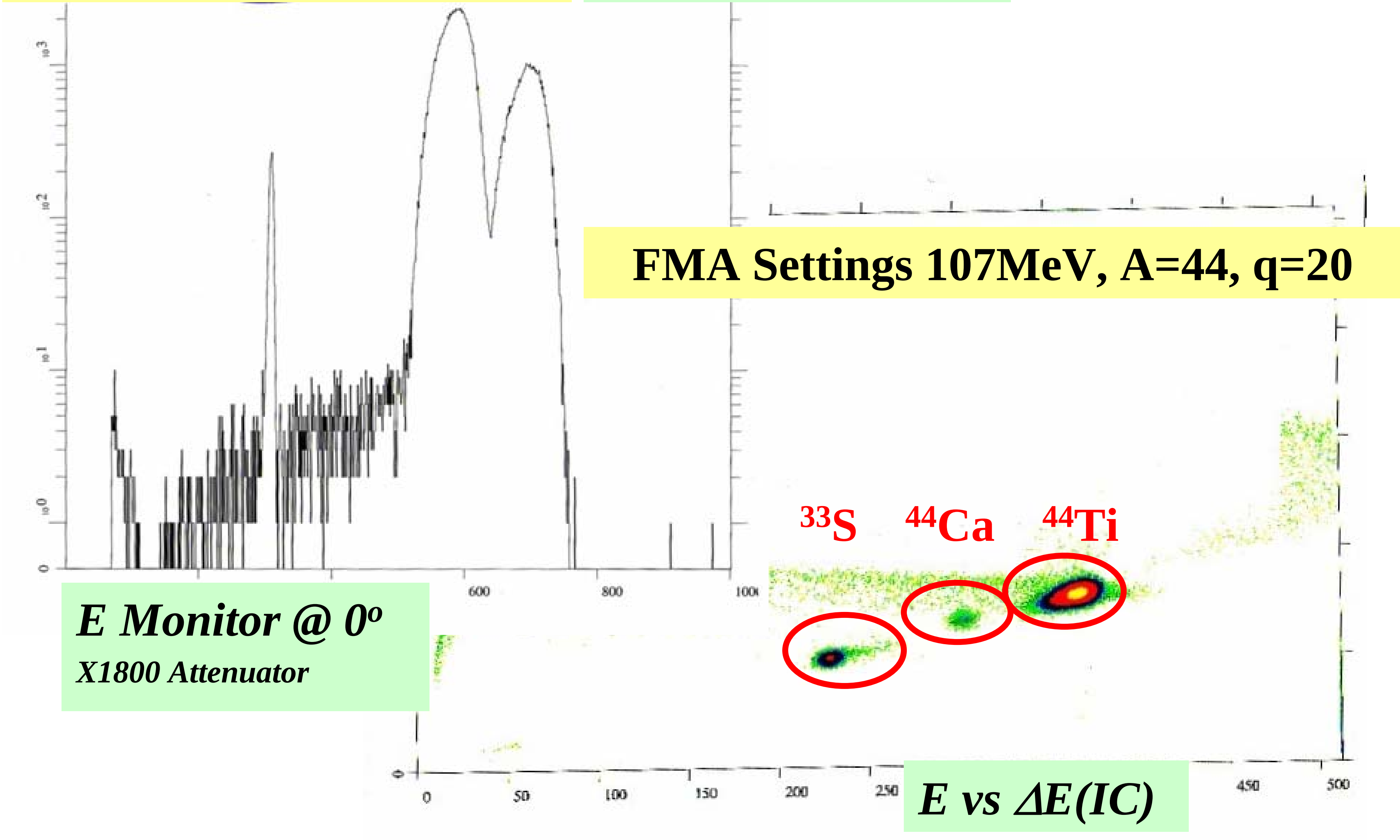
Nucl.Phys. **A116** (1968)



242 MeV ^{44}Ti Beam

^{44}Ti / ^{44}Ca = 2.5 ~890/sec

~ 1.1 x 10^{6} ^{44}Ti/sec



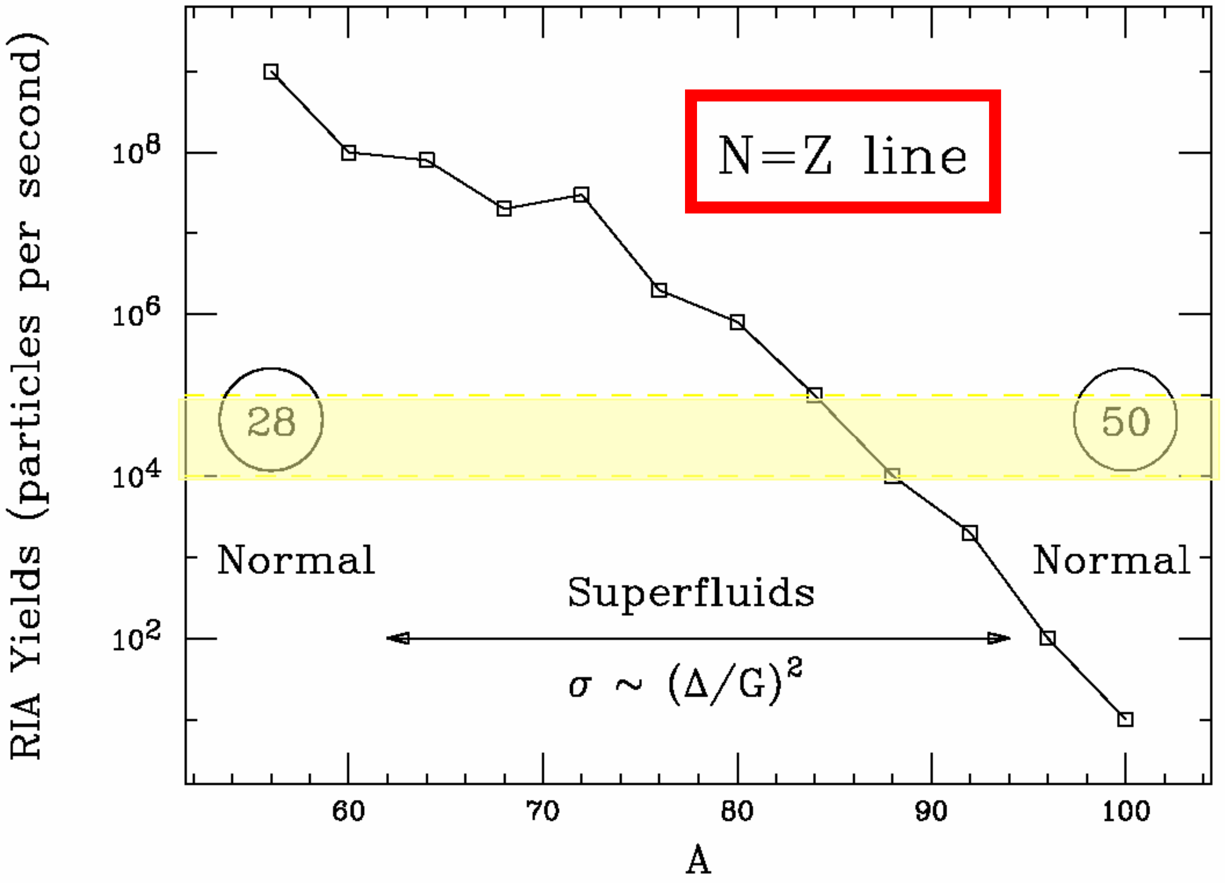
FMA Settings 107MeV, A=44, q=20

E Monitor @ 0^{o}

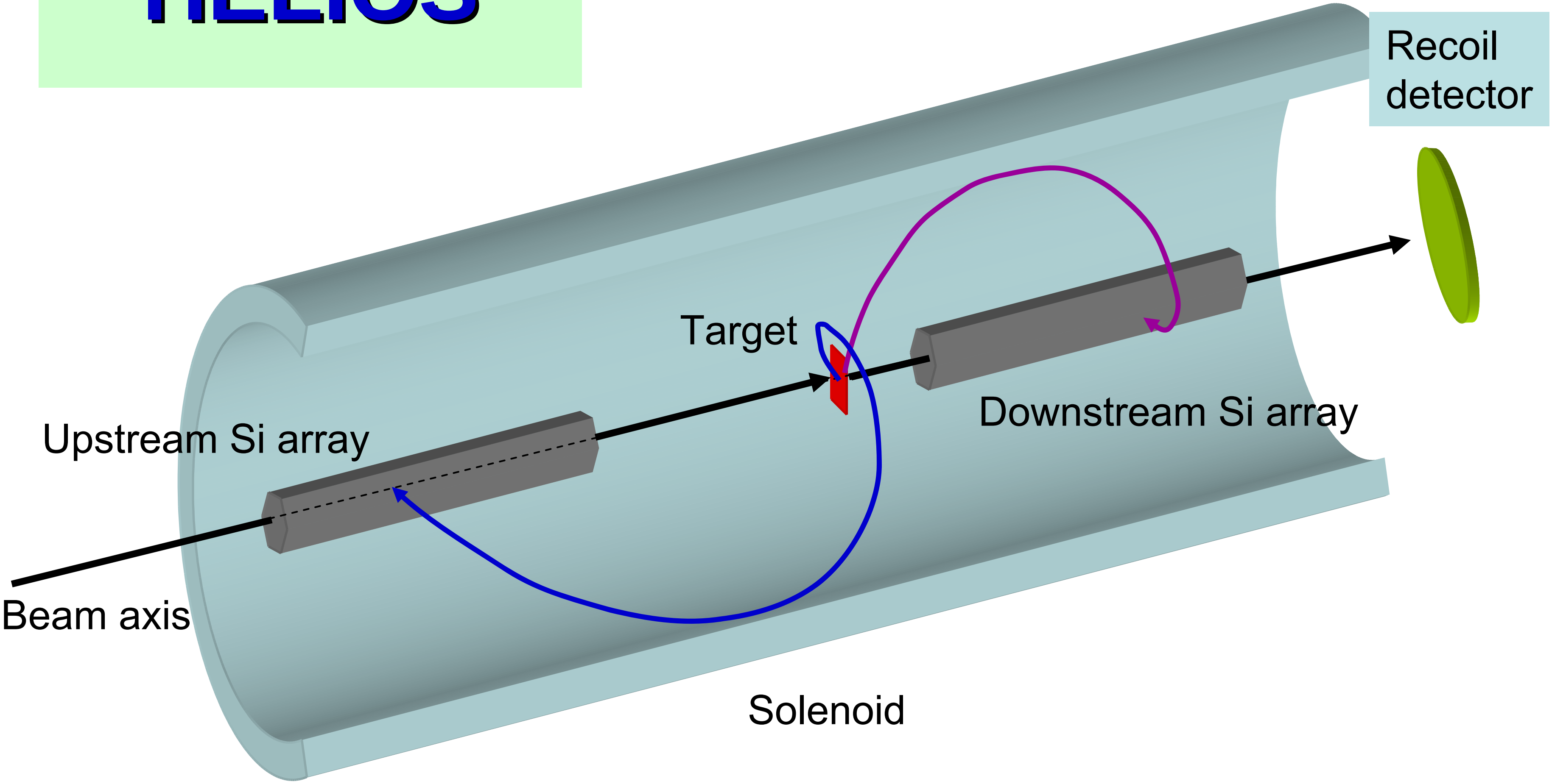
X1800 Attenuator

E vs ΔE(IC)

Looking ahead …



HELIOS



Recoil detector

Target

Downstream Si array

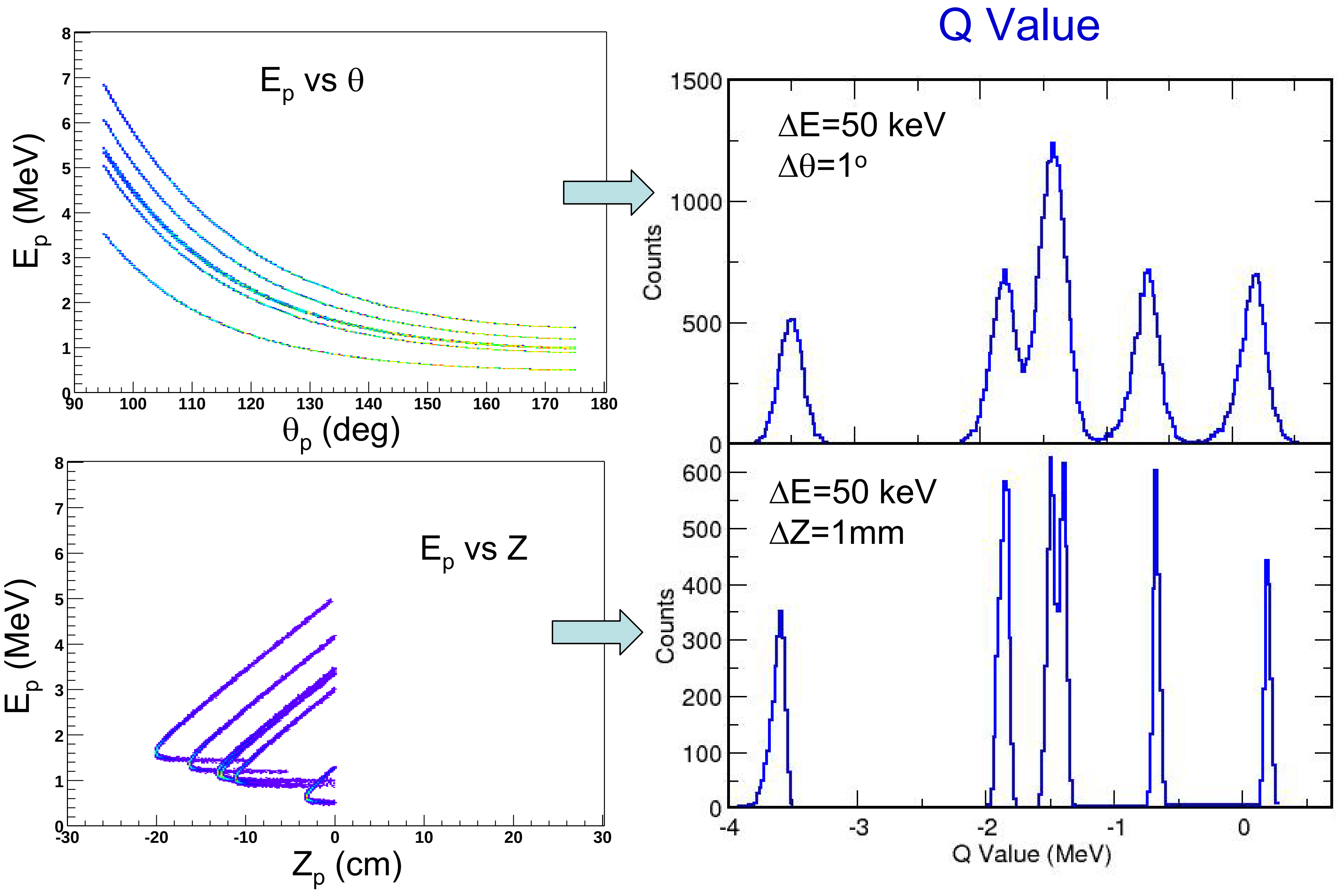
Upstream Si array

Beam axis

Solenoid

Schematic design

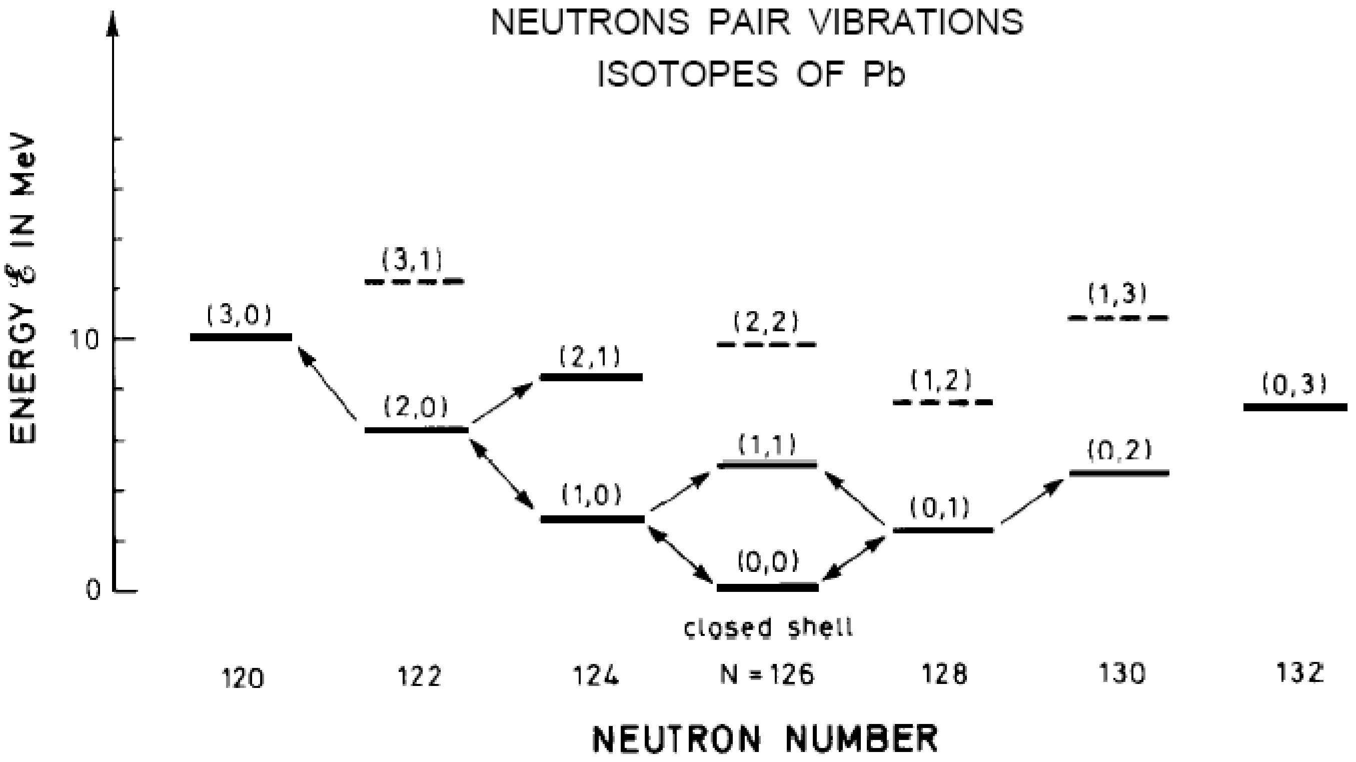
Improved resolution for (d,p)



Pairing Phase Transition

Pair-Vibrational Structures

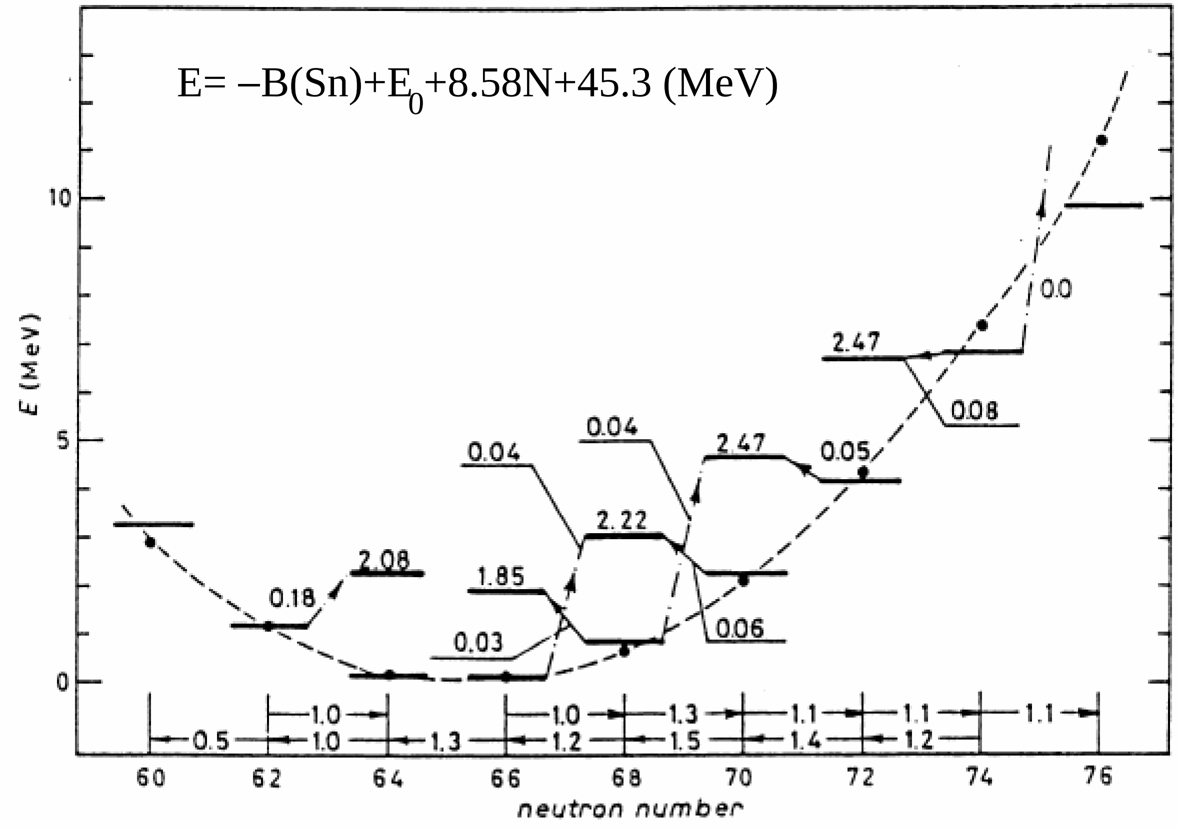
(Nobel Lecture, Ben R. Mottelson, 1975 “Elementary Modes of Excitation in the Nucleus”)



- Near closed shell nuclei (like ^{208}Pb) no static deformation of pair field.
- Corresponds to the “normal” nuclear limit.
- Fluctuations give rise to a vibrational-like excitation spectrum.
- Enhanced pair-addition and pair-removal cross-sections seen in (t,p) and (p,t) reactions (indicated by arrows).
- Large anharmonicities in spectrum must be accounted for.

Pair-Rotational Structures

(R. A. Broglia, J. Terasaki, and N. Giovanardi, Phys. Rep. 335 (2000) 1)

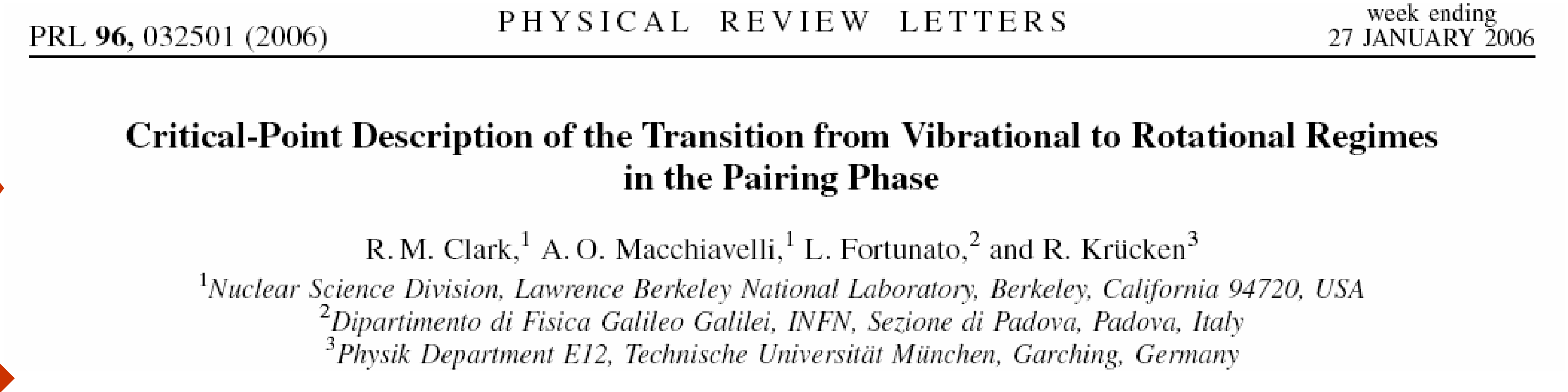


$$E= -B(Sn)+E_0+8.58N+45.3\ (\mathrm{MeV})$$

- Many like-nucleon pairs outside a closed-shell configuration (e.g. ^{116}Sn) gives rise to a static deformation of the pair field.
- Corresponds to the “superconducting” limit.
- Rotational-like (parabolic – dashed line) spectrum formed by sequence of ground states of even-N neighbors.
- Angular variable in rotational motion is gauge angle, ϕ.

Critical-Point Descriptions of Shape Transitions

F. Iachello, Phys. Rev. Lett. 85 (2000) 3580, Phys. Rev. Lett. 87 (2001) 052502.



PRL **96,** 032501 (2006) PHYSICAL REVIEW LETTERS week ending 27 JANUARY 2006

Critical-Point Description of the Transition from Vibrational to Rotational Regimes in the Pairing Phase

R. M. Clark,[1] A. O. Macchiavelli,[1] L. Fortunato,[2] and R. Krücken[3]

[1]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[2]*Dipartimento di Fisica Galileo Galilei, INFN, Sezione di Padova, Padova, Italy*
[3]*Physik Department E12, Technische Universität München, Garching, Germany*

The Collective Pairing Hamiltonian

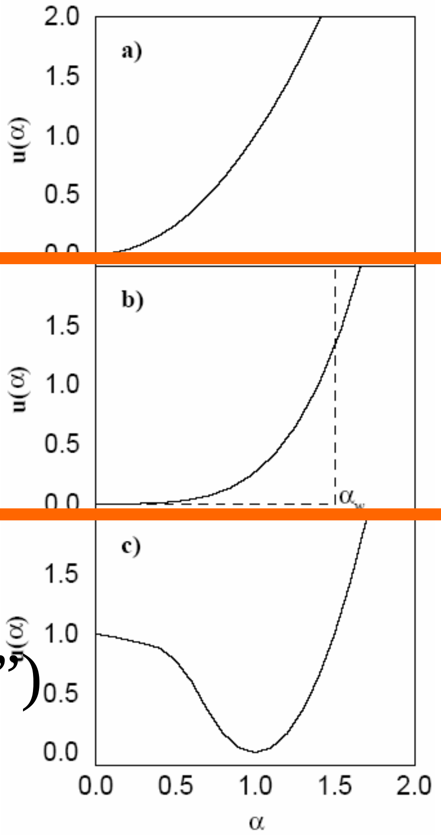
D.R. Bès, R.A. Broglia, R.P.J. Perazzo, K. Kumar, Nucl. Phys. A 143 (1970) 1.

$$-\frac{\hbar^2}{2B}\frac{\partial^2\psi}{\partial\alpha^2}-\frac{\hbar^2}{2B\alpha}\frac{\partial\psi}{\partial\alpha}+\left(\frac{\hbar^2M^2}{8B\alpha}+V(\alpha)-E\right)\psi=0$$

α is the deformation of the pair field (can be related to the gap parameter, Δ).
B is a mass parameter. M=(A-A$_0$) (number of particles, A, relative to reference, A$_0$).
$V(\alpha)$ is the potential.

Analogy between Shapes and Pairing

$$\frac{\partial^2\psi}{\partial\alpha^2}+\frac{1}{\alpha}\frac{\partial\psi}{\partial\alpha}+\left(\varepsilon-u(\alpha)-\frac{M^2}{4\alpha^2}\right)\psi=0$$



Vibrational Limit
("Normal")

$$u(\alpha)=\alpha^2$$

E(2)

Transitional
("Critical-Point")

$$u(\alpha)=0,\ \ \alpha\le\alpha_w$$
$$u(\alpha)=\infty,\ \alpha>\alpha_w$$

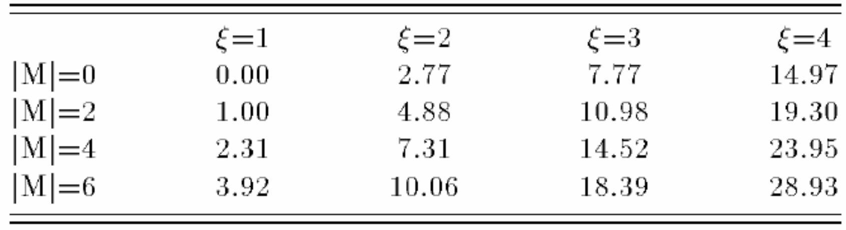
Rotational Limit
("Superconducting")

$$u(\alpha)=\delta_{\alpha_0}$$

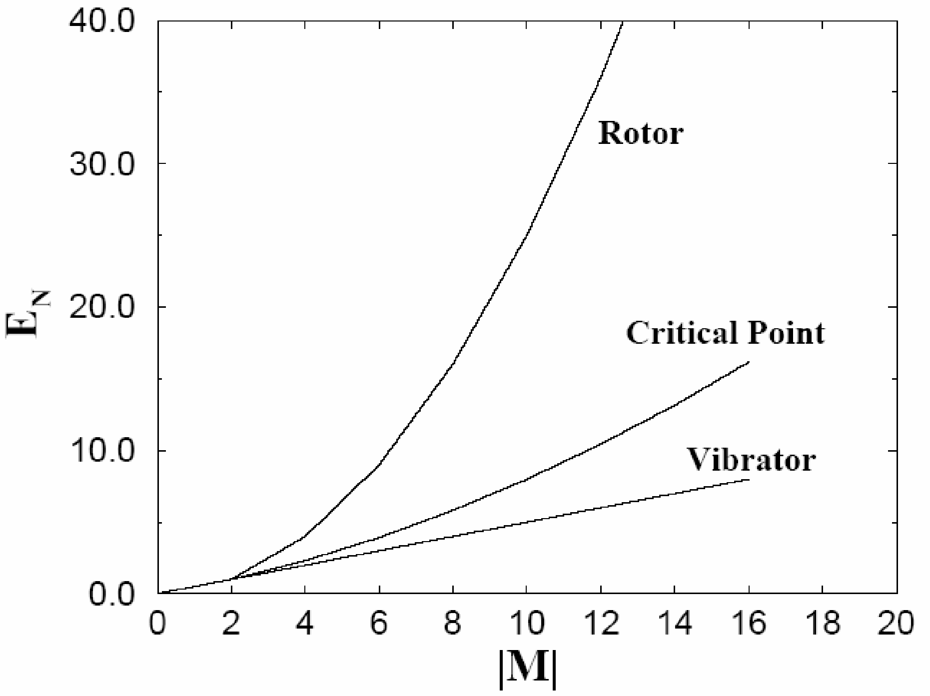
The Reduced Energy Spectrum

Normalizing energies of excited states to that of the first excited state:

$$E_N = \frac{x_{\xi,M}^2 - x_{1,0}^2}{x_{1,2}^2 - x_{1,0}^2}$$



	$\xi=1$	$\xi=2$	$\xi=3$	$\xi=4$
$\lvert M\rvert=0$	0.00	2.77	7.77	14.97
$\lvert M\rvert=2$	1.00	4.88	10.98	19.30
$\lvert M\rvert=4$	2.31	7.31	14.52	23.95
$\lvert M\rvert=6$	3.92	10.06	18.39	28.93

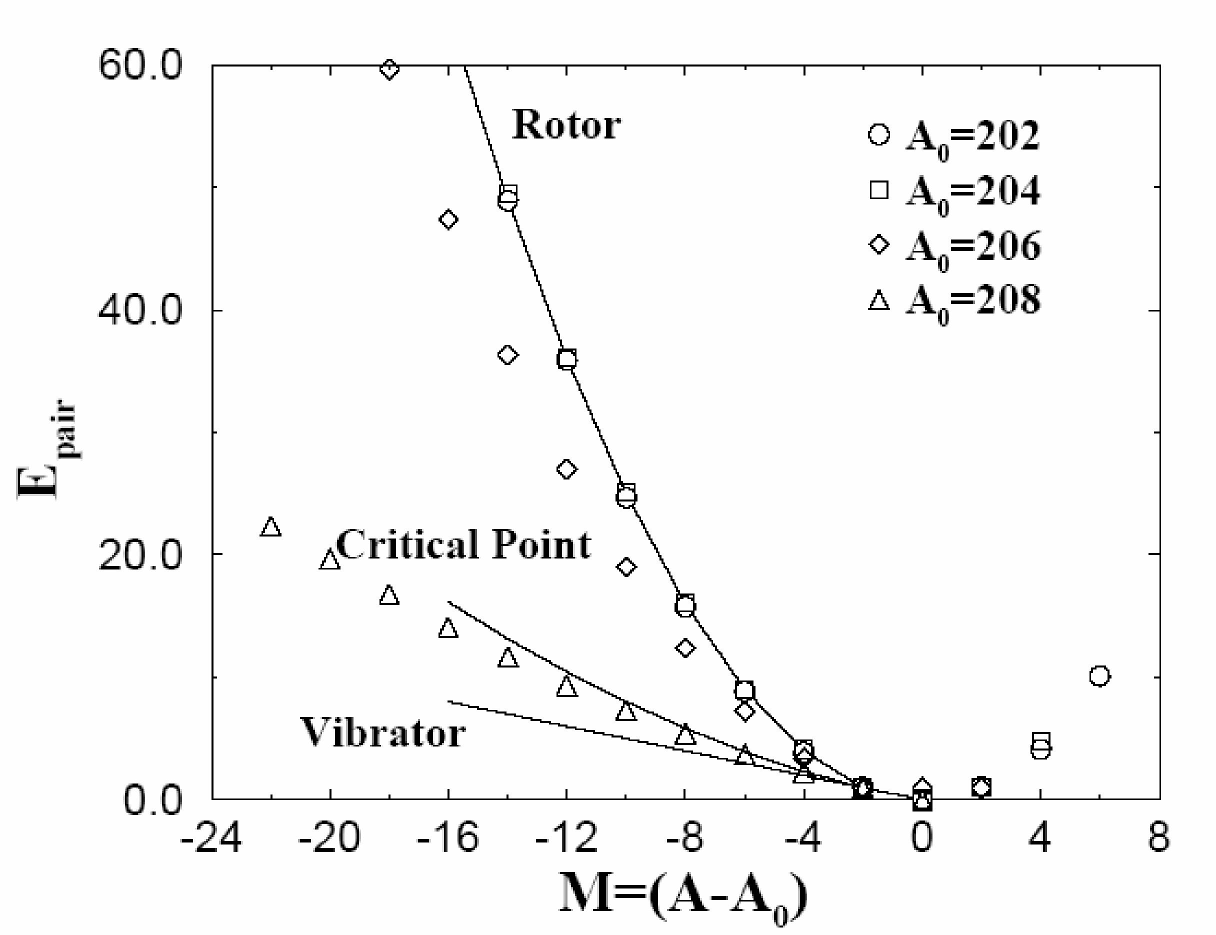


- ξ=1 sequence of states correspond empirically to the sequence formed by the 0^+ ground-states of neighboring even-even nuclei along isotopic or isotonic chain.
- ξ=1 sequence of states follows behavior between the linear dependence of a harmonic vibrator and the parabolic dependence of a deformed rotor, as expected.
- ξ>1 correspond to excited 0^+ states formed from pair excitations.

Comparison with Data

Empirical neutron pairing energy defined as: $E_{pair} = \left[\varepsilon(A) - \varepsilon(A_0)\right] - C \cdot (A - A_0)$

$\varepsilon(A) - \varepsilon(A_0)$ is difference in mass excess between isotope of mass A and reference nucleus of mass A_0 (G. Audi et al., Nucl. Phys. A 729 (2003) 337)



Only a few nucleons outside of the closed shell are required for a static pair deformation (“superconductivity”) and pair rotational sequences develop.

A comment on anharmonicities

From Bohr & Mottelson Vol. II pag. 646

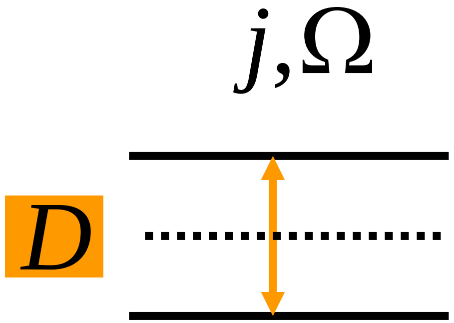
$$E \sim n\hbar\omega_0 + \frac{1}{2} V_{--} n(n-1)$$

$$V_{--} \sim 700 keV$$

Our simple estimate is

$$V_{--} \sim (2.31-2)\hbar\omega_0 \sim 800 keV$$

A simple microscopic model: Two j-shells



$$H = \frac{1}{2} D(N_2 - N_1) - G\Omega(A_1^+ + A_2^+)(A_1 + A_2)$$

$$x = 2\Omega G / D$$

“Control parameter”

$$\Omega \sim A^{2/3}$$

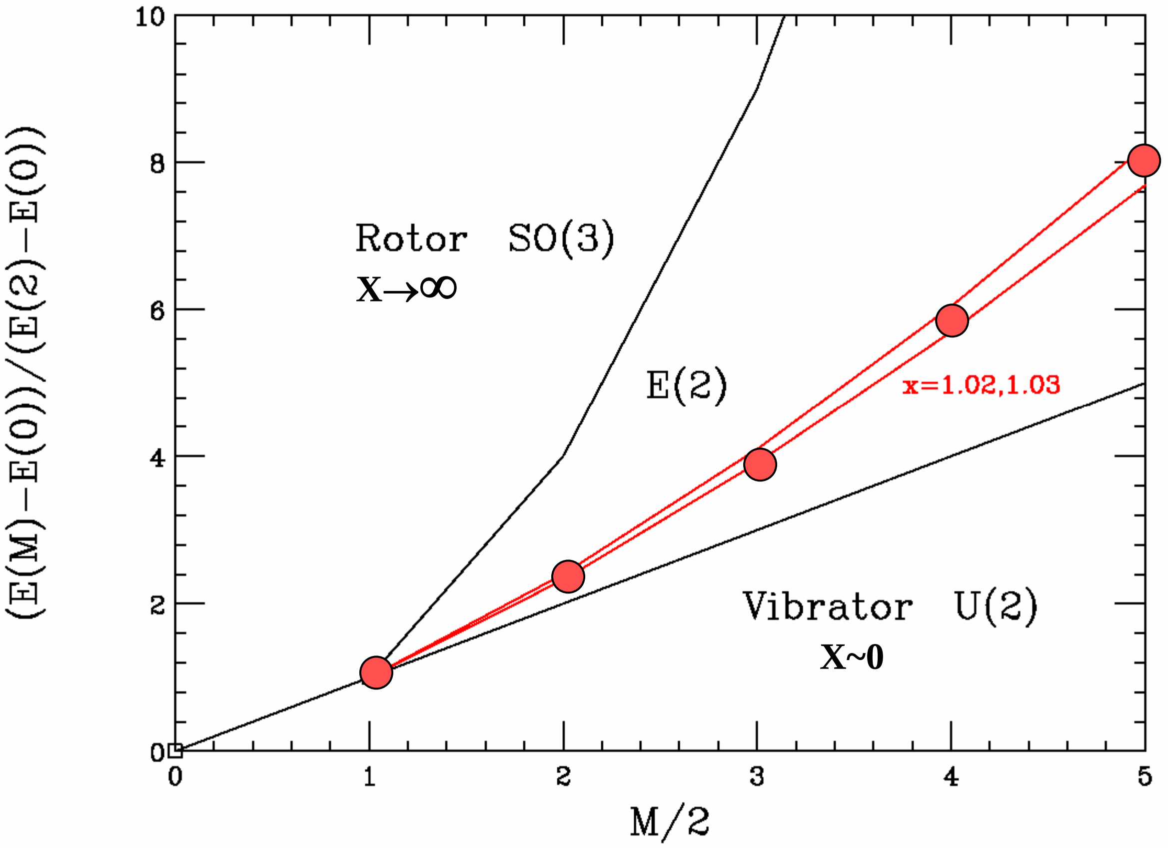
$$G \sim 20 / A$$

$$D \sim 41 / A^{1/3}$$

⇒ $x \sim 1$

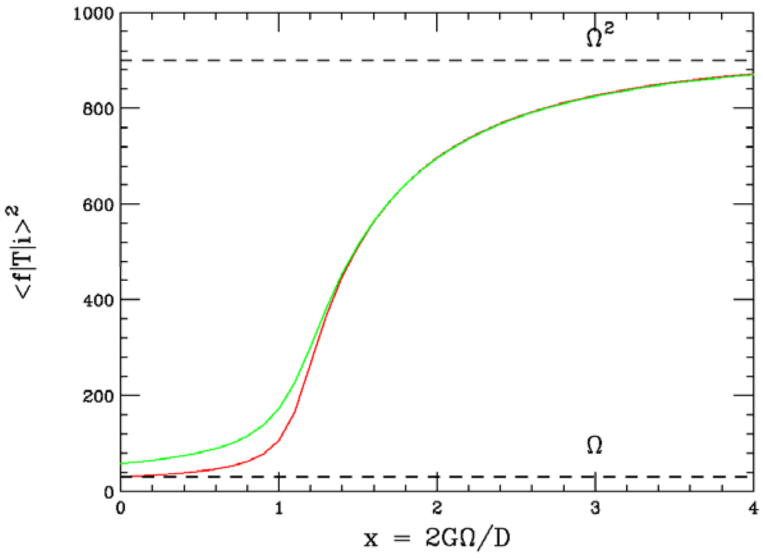
A simple microscopic model: Two j-shells

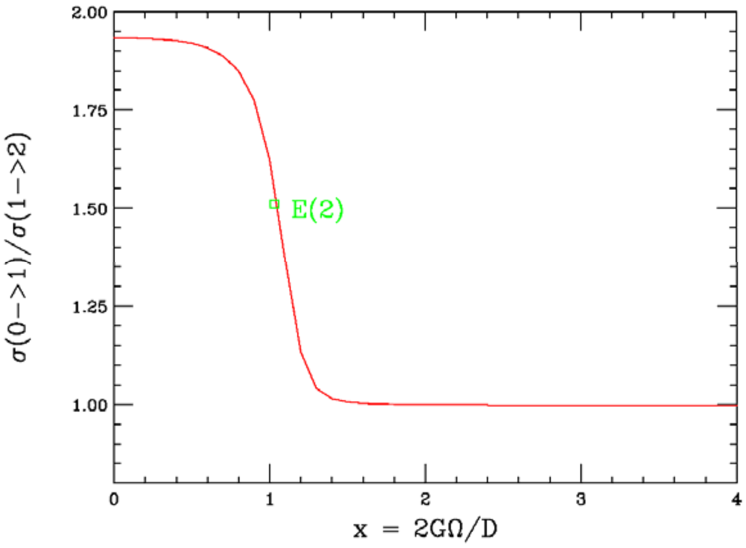
Energies



A simple microscopic model: Two j-shells

Transition probabilities





Transition Probabilities

The transition matrix elements are related to two-nucleon transfer probabilities:

$$\left\langle \psi_{\xi',M'} \middle| \hat{O} \middle| \psi_{\xi,M} \right\rangle = \int \psi^*_{\xi',M'} \hat{O} \psi_{\xi,M} \, d\tau$$

where, the volume element is: $d\tau = 2B\alpha \cdot d\alpha \cdot d\phi$

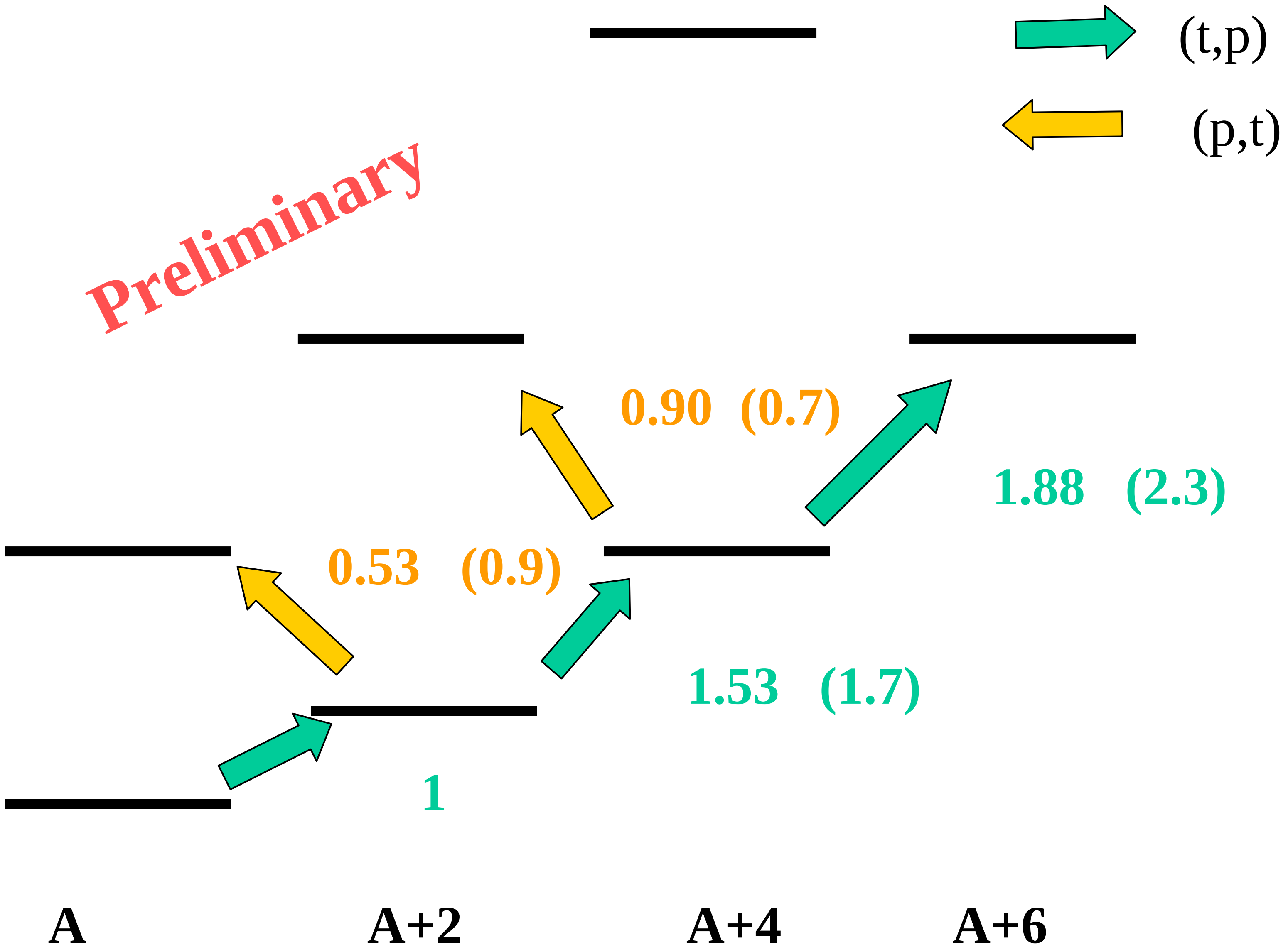
and the pair-transfer operator is: $\hat{O} = \alpha_{\pm 2} = \alpha e^{\pm 2i\phi}$

One then finds:

$$\left\langle \psi_{\xi',M'} \middle| \hat{O} \middle| \psi_{\xi,M} \right\rangle \propto \int_0^{\alpha_w} \psi^*_{\xi',M'} \alpha^2 \psi_{\xi,M} \, d\alpha$$

The integrals can be solved numerically.

Transition Probabilities



(t,p)

(p,t)

Preliminary

0.90 (0.7)

1.88 (2.3)

0.53 (0.9)

1.53 (1.7)

1

A

A+2

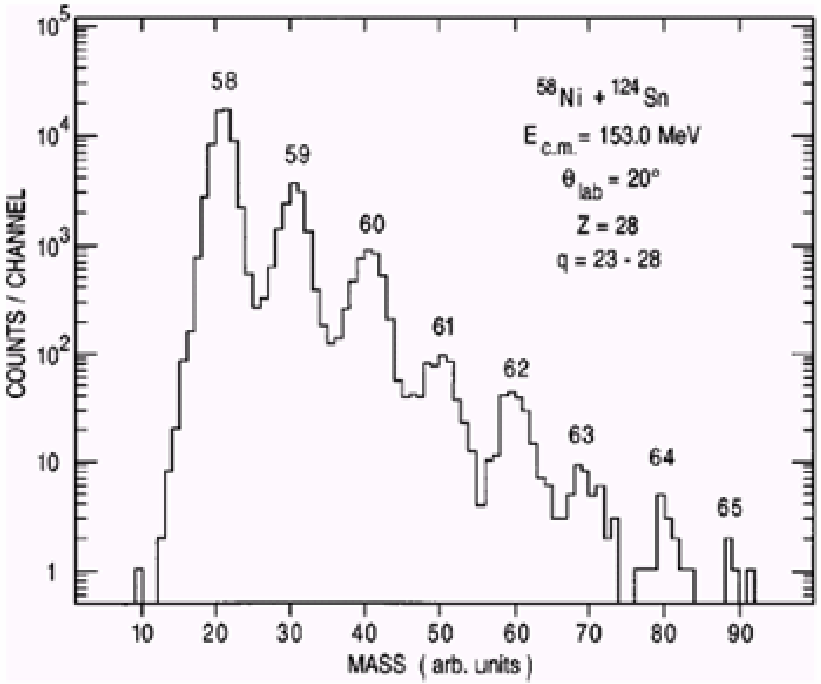
A+4

A+6

Heavy Ion Transfer

A Few Words on Heavy Ion Transfer Reactions

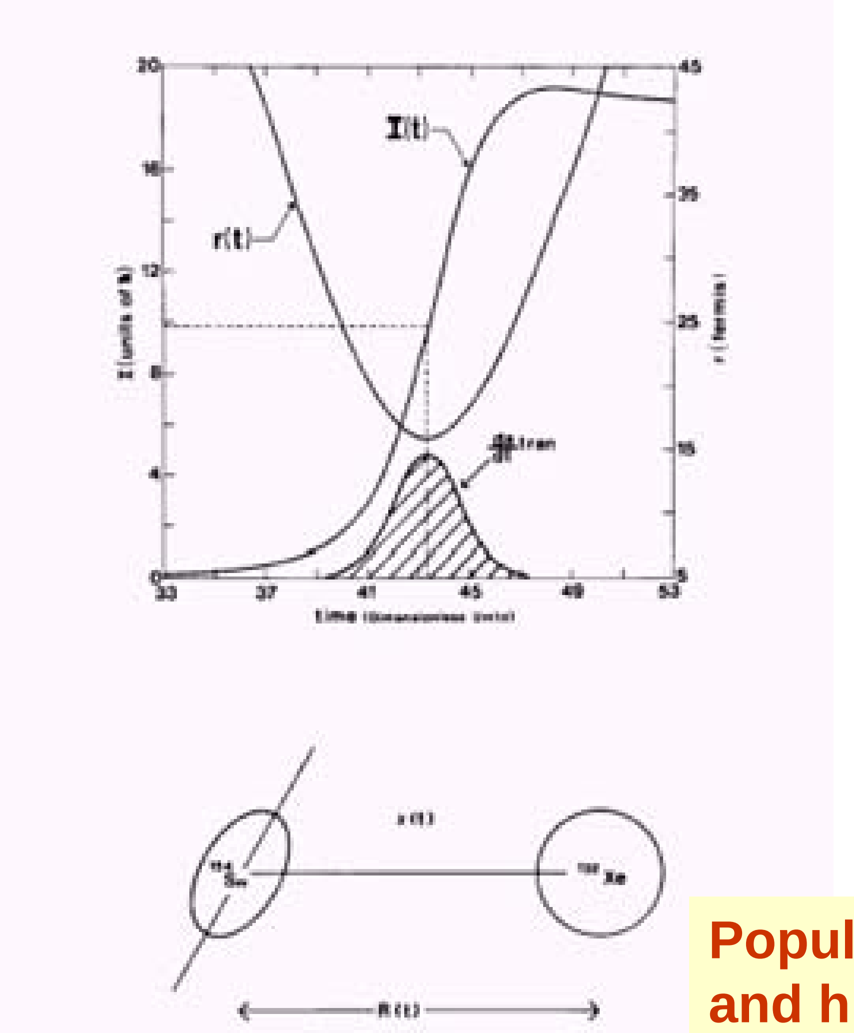
Multiple nucleon transfer

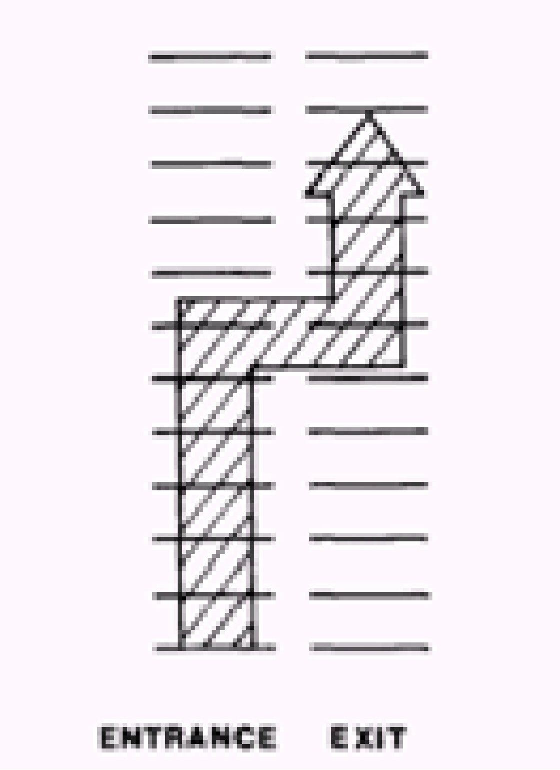


C.L.Jiang et al. PRC57(1998)

$\Delta M/M$, $\Delta L/L$ and $\Delta E/E \ll 1$

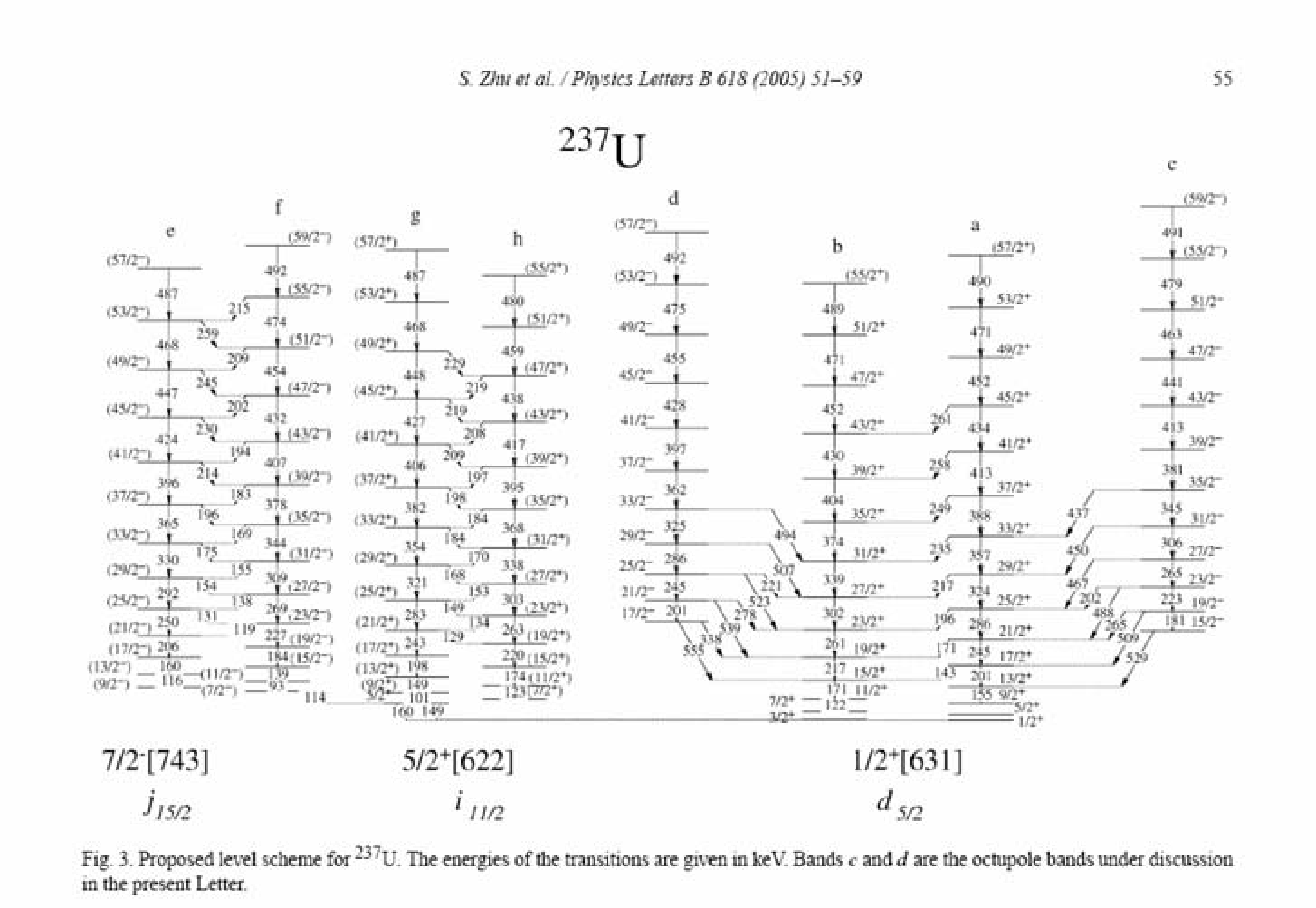
Large Sommerfeld parameter $\eta \gg 1$ allows for a semi-classical description. ⇨ Classical trajectory and tunneling





Population of high angular momentum and high excitation energy states

⇨ population mechanism, followed by γ-ray spectroscopy



S. Zhu et al. / Physics Letters B 618 (2005) 51–59 55

Fig. 3. Proposed level scheme for ^{237}U. The energies of the transitions are given in keV. Bands *c* and *d* are the octupole bands under discussion in the present Letter.

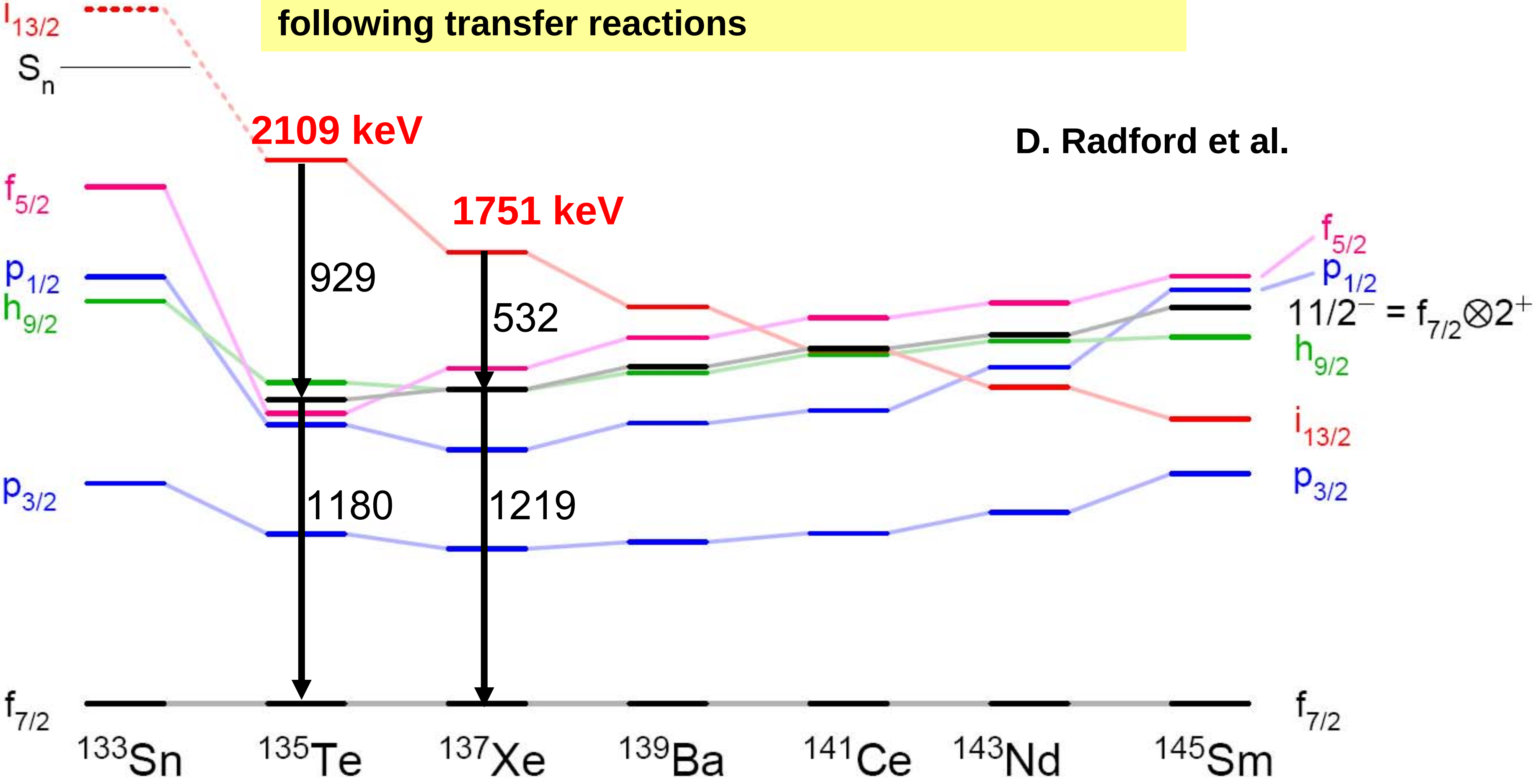
One neutron pickup reaction, ^{207}Pb+^{238}U in GAMMASPHERE

to study octupole correlations in actinides

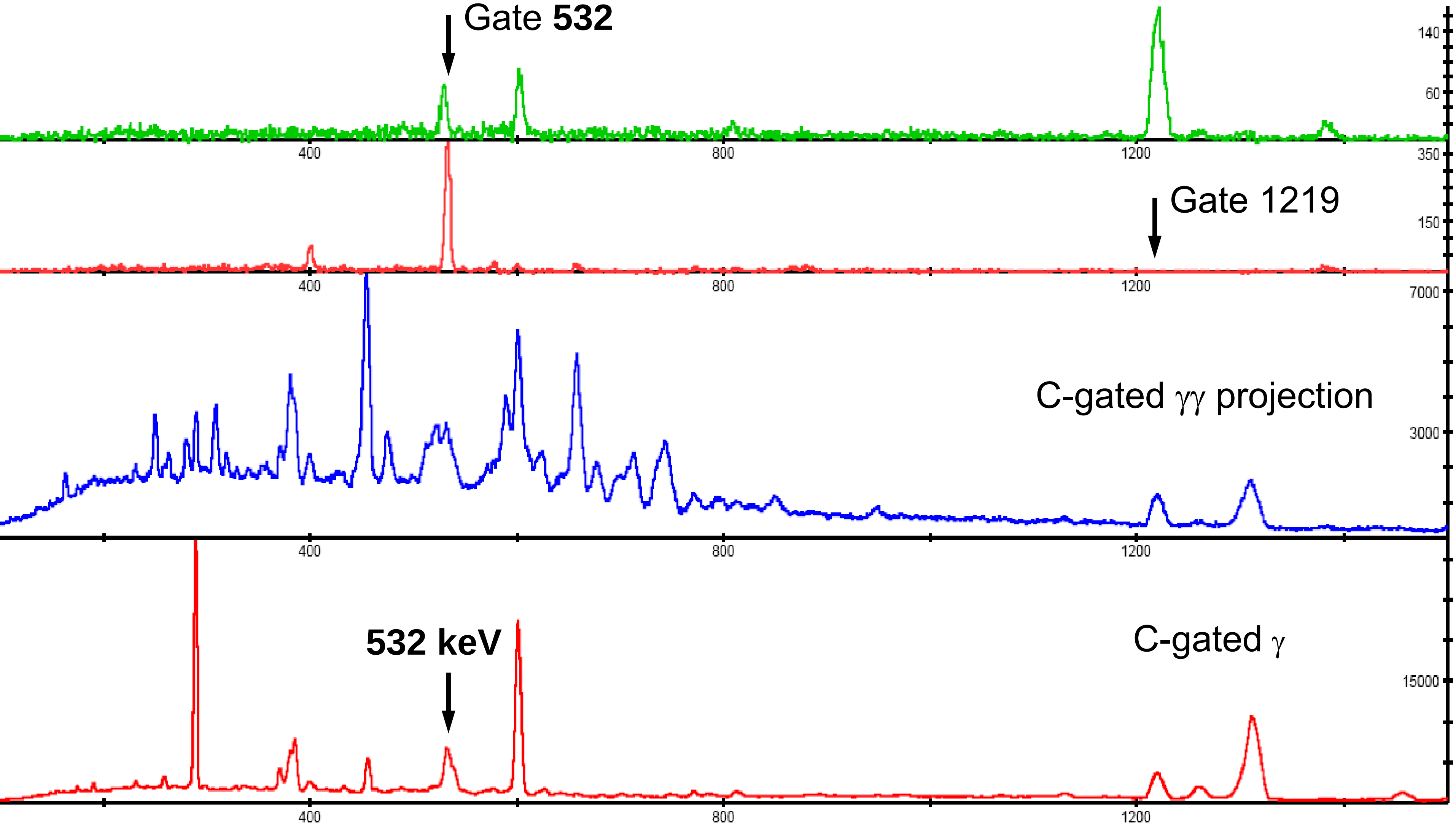
Spin-orbit splitting again

N = 83 level energy systematics

Spectroscopy with CLARION and GAMMASPHERE following transfer reactions



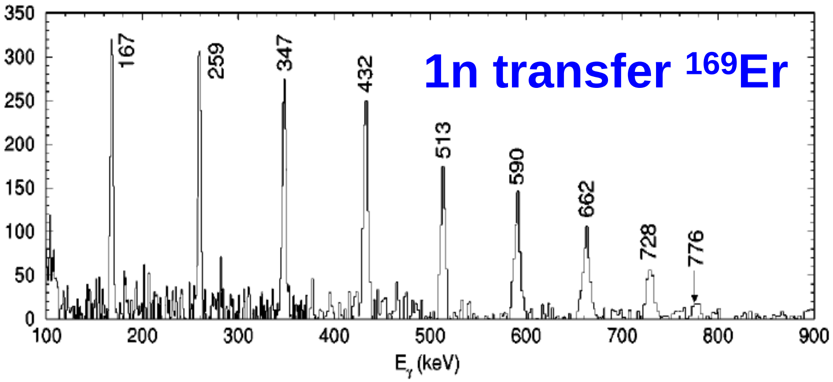
^{13}C(^{136}Xe,^{12}C)^{137}Xe 560 MeV



GRETINA: 1π array

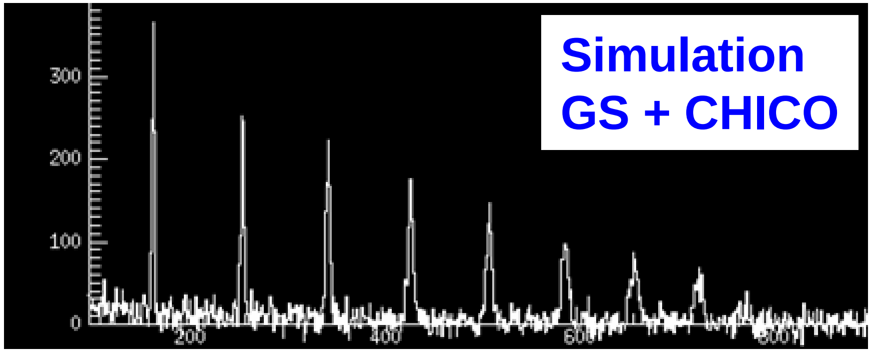
Transfer reactions with re-accelerated RIBS and stable beams

^{238}U + ^{170}Er   5.7 MeV/u
GS + CHICO
3 ·10^{9} p/s (0.5 pna),   0.5 mg/cm^{2}
3 days, γ–γ–γ



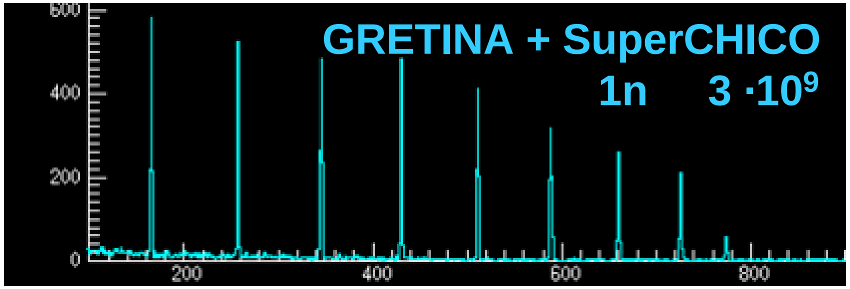
1n transfer ^{169}Er

C.Y. Wu et al., PRC 70, 014313 (2004)



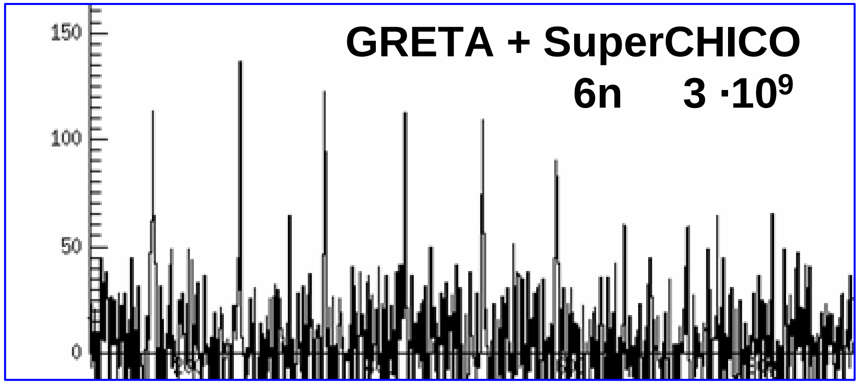
Simulation
GS + CHICO

Simulation ^{170}Er + ^{238}U   5.7 MeV/u



GRETINA + SuperCHICO
1n   3 ·10^{9}

GRETINA + SuperCHICO
3n   3 ·10^{9}



GRETA + SuperCHICO
6n   3 ·10^{9}

Conclusions

Transfer Reactions have provided a wealth of information that has shaped our current understanding of the structure of atomic nuclei. They will continue to provide a unique tool as we embark in our experimental study of very-neutron (proton) rich nuclei.

Existing and planned exotic beam facilities worldwide and new detector systems with increased sensitivity and resolving power not only will allow us to answer some burning questions we have today, but most likely will open up a window to new and unexpected phenomena.

As so eloquently expressed in the title of the conference, the nucleus and its structure are of paramount importance to many aspects of physics.

I believe the road ahead looks inviting!

Thank You!