Aspects of Pairing in Atomic Nuclei

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BERKELEY LAB

U.S. DEPARTMENT OF ENERGY | Office of Science

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Lecture II

Outline

The pairing phase transition

A simple (2 j-shell) model

Transfer Reactions

Some examples

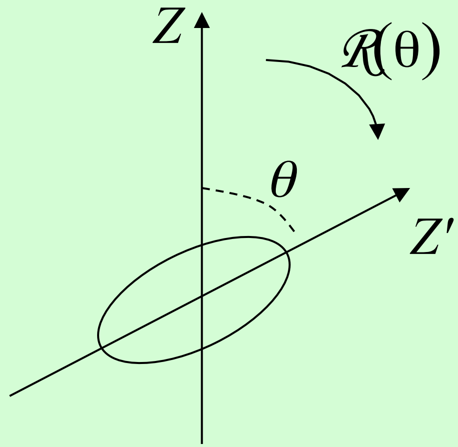
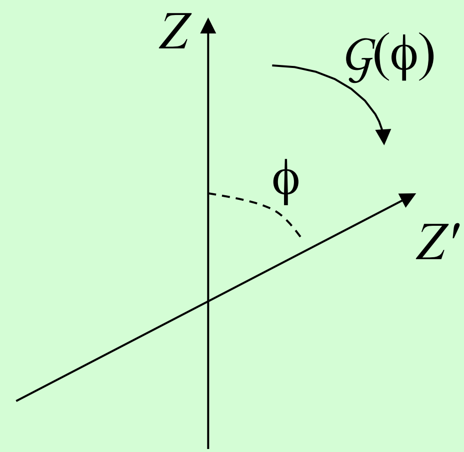
Neutron-proton pairing

Pairing in weakly bound systems

Summary and conclusions

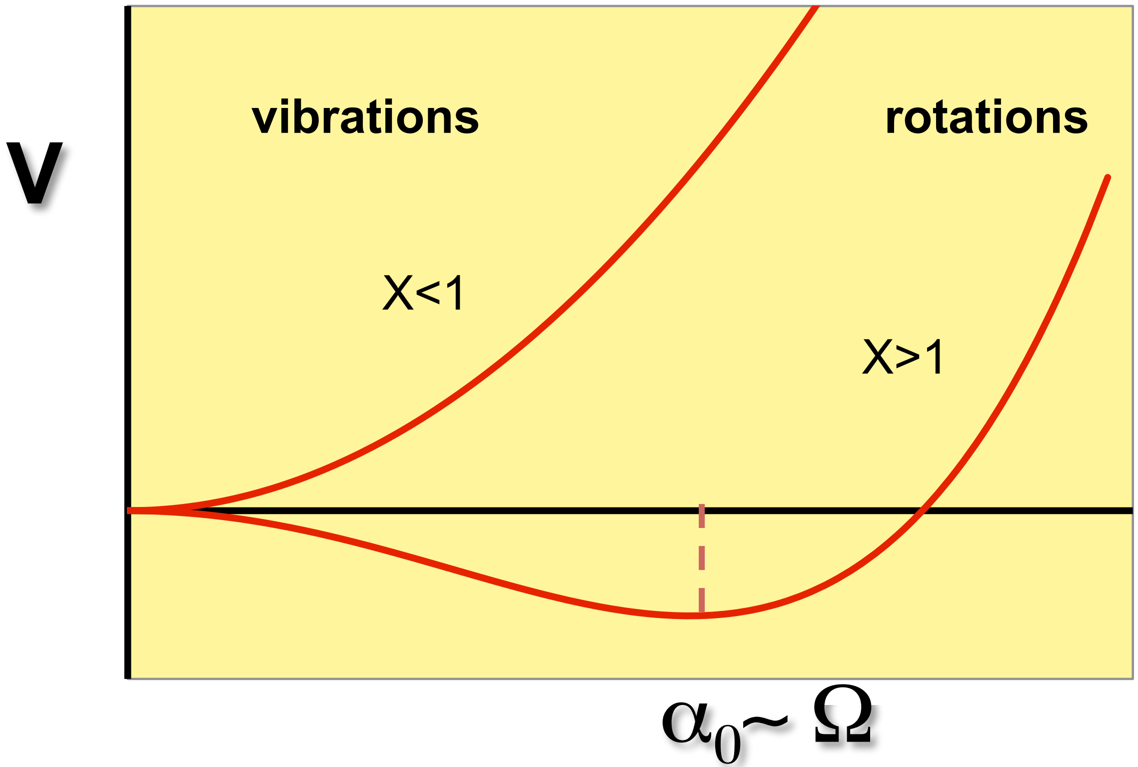
The Analogy of the Collective Model for Shapes and Pairing

(R.A. Broglia, O. Hansen, C. Riedel, Adv. Nucl. Phys. 6 (1973) 287)

Shape Transitions	Pairing Transitions
$\mathcal{R}(\theta)=\exp(-iI\theta)$	$\mathcal{G}(\phi)=\exp(-i\mathcal{N}\phi)$
Angular Momentum, I	Particle Number, $\mathcal{N}$
	
β, γ, Euler angles θ	Pair deformation, α Gauge angle, ϕ
Violation of spherical symmetry	Violation of particle number
Physical space	Abstract "gauge" space

“Control parameter”

$$x = \Omega G / D$$



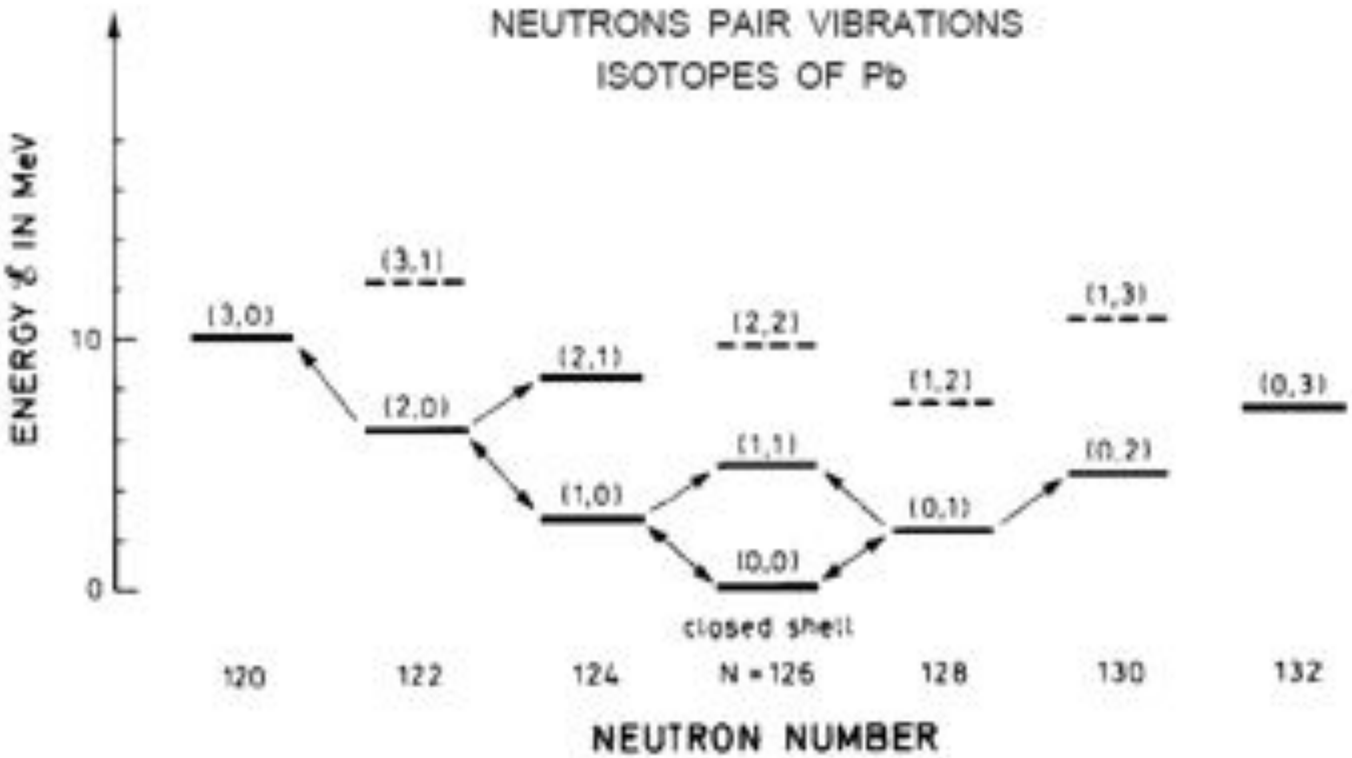
Deformation of the pair-field

$$\alpha = \frac{\Delta}{G} = <\sum a^+_{\bar{v}} a^+_v>$$

Problem #2

Pair-Vibrational Structures

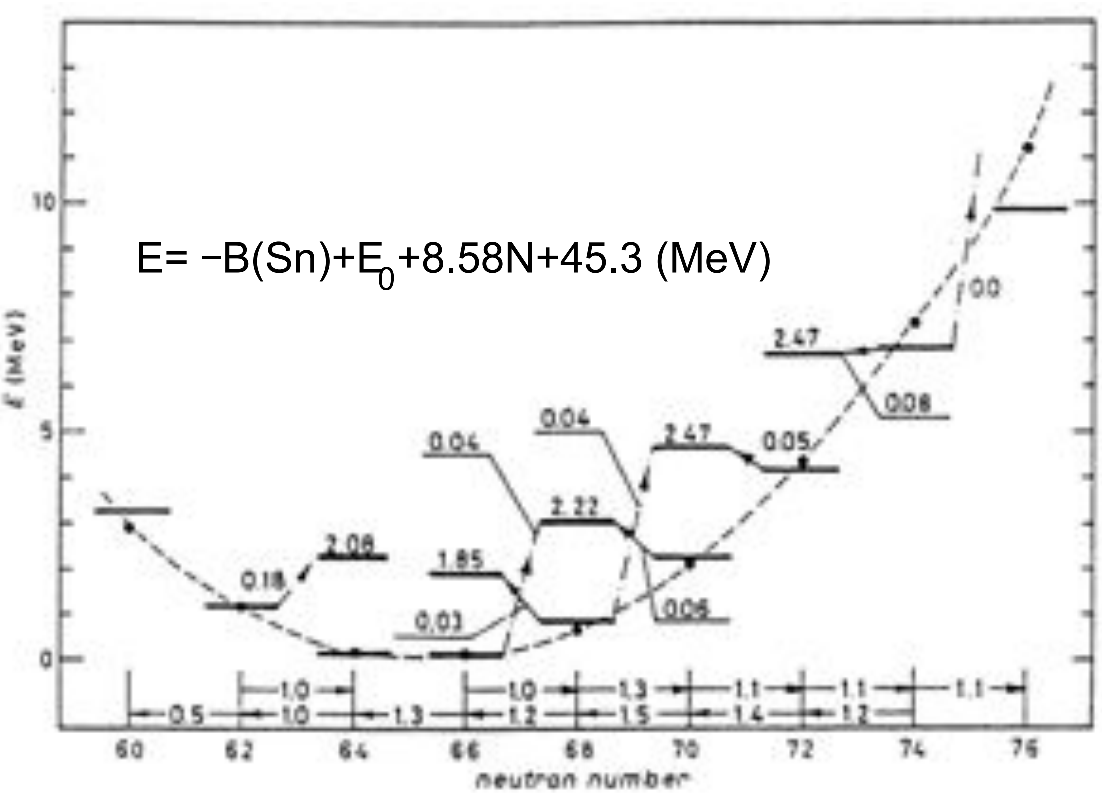
(Nobel Lecture, Ben R. Mottelson, 1975 “Elementary Modes of Excitation in the Nucleus”)



• 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).

Pair-Rotational Structures

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



- 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.

"Realistic" potentials

1.A:1.D.2

Nuclear Physics **A134** (1969) 1—59;

NEUTRON PAIRING STATES IN DOUBLY EVEN NUCLEI

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Received 12 May 1969

Fig 40 Potential energy surface for ^{208}Pb

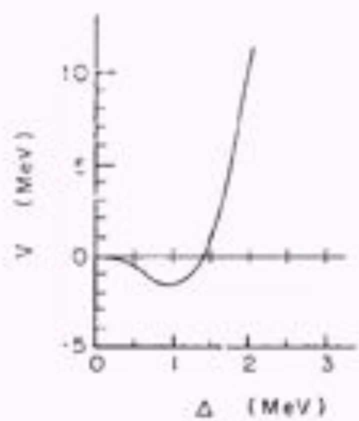
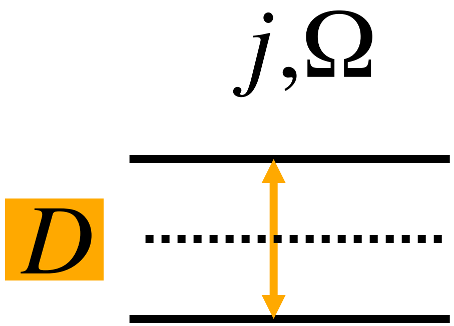


Fig. 41 Potential energy surface for ^{120}Sn

A simple microscopic model: Two j-shells

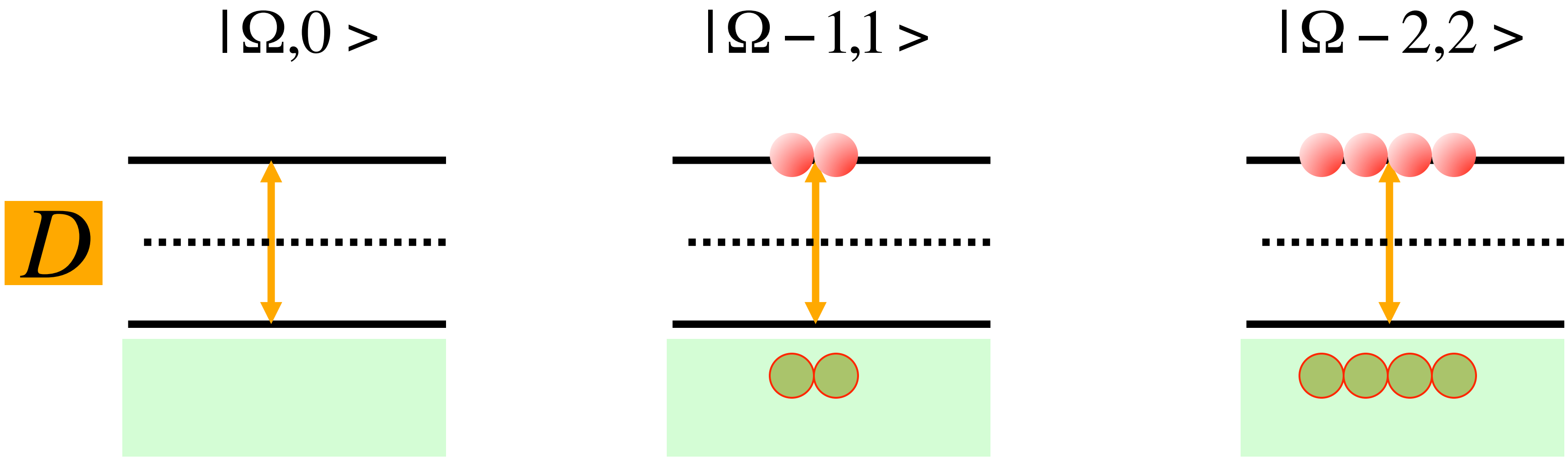


$$H = \frac{D}{2}(N_{j2} - N_{j1}) - \frac{1}{4}G(P_{j1}^{\dagger} + P_{j2}^{\dagger})(P_{j1} + P_{j2})$$

$$N_j = \sum_m a_{jm}^{\dagger} a_{jm}. \qquad P_j^{\dagger} = \sum_{m>0} (-1)^{j+m} a_{jm}^{\dagger} a_{j-m}^{\dagger}$$

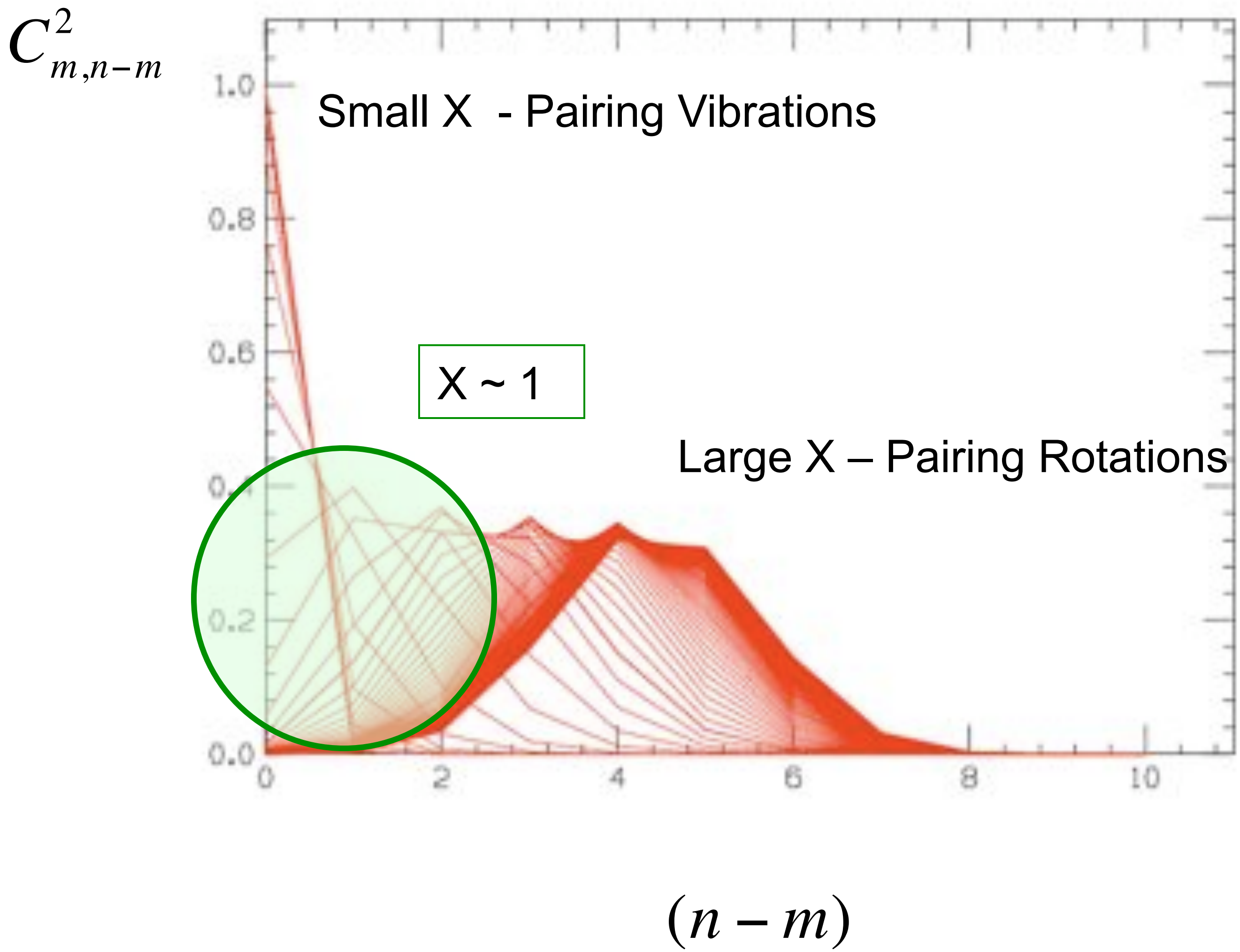
"Control parameter"

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

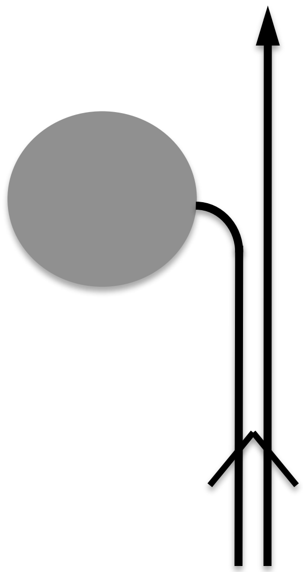


$$|m, n-m\rangle = M_m^{-1}(P_{j1}^\dagger)^m (P_{j2}^\dagger)^{n-m}|0\rangle,$$

$$\varphi = \sum C_{m,n-m} \mid m, n-m >$$



Specific Probes



$$< A+1 \mid a^{+} \mid A >$$

Spectroscopic (U, V) Factors

With

$$V_{2j}(U_{2j}) = v_j^2(u_j^2)$$

Odd target

$$\frac{d\sigma}{d\Omega}(d,p) = PV_{2j}{}^{(f)}$$

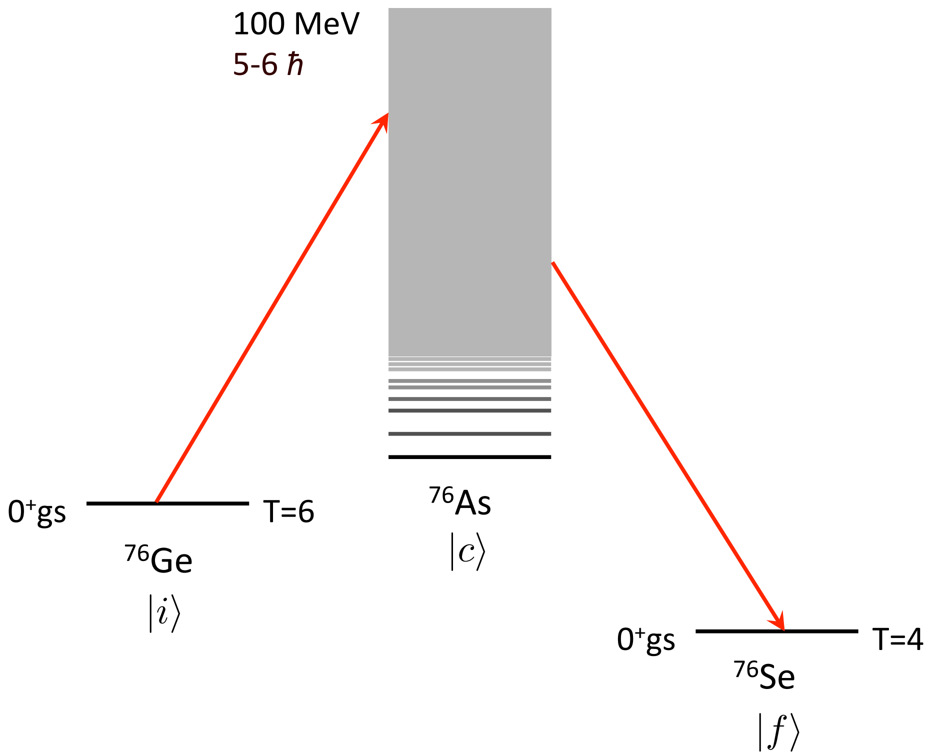
Even target

$$\frac{d\sigma}{d\Omega}(d,p) = (2j+1)PU_{2j}{}^{(i)}$$

$$U_{2j} = 1 - V_{2j},$$

$$\sum (2j+1)V_{2j} = N$$

Neutrinoless Double-Beta Decay



Neutrinos are the only neutral elementary fermions and could be their own antiparticle.
If neutrinoless DBBD indicates this MAJORANA property.

A measured decay rate could provide the first determination of the absolute neutrino mass ***if*** the nuclear matrix elements known.

Initial and final wave functions critical.

Courtesy of Sean Freeman

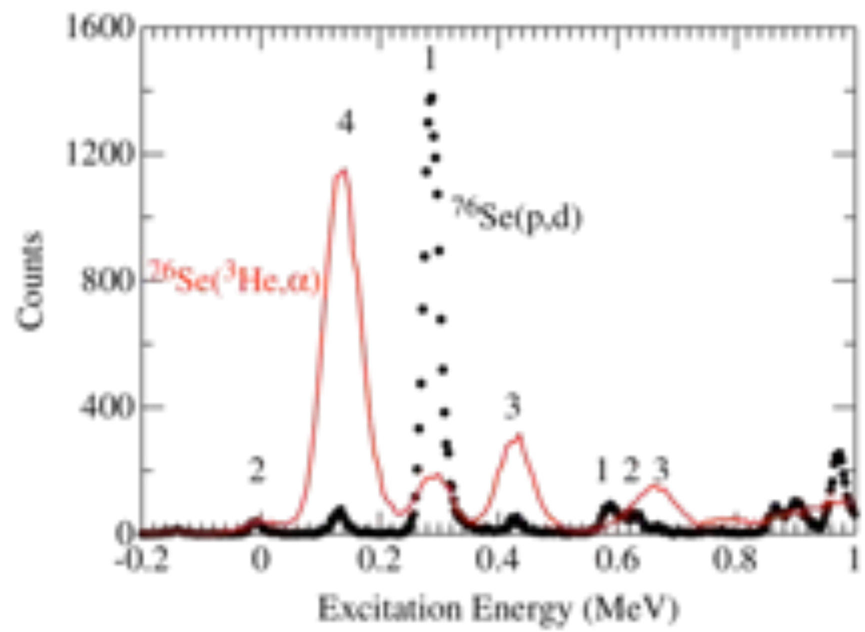
Single-particle occupancies are a measurable characteristic of a gs wave function that might help test input to DBBD matrix elements.

Neutron-transfer reactions done at Yale near 10 MeV/A:

^{74,76}Ge/^{76,78}Se (d,p) and (p,d)
^{74,76}Ge/^{76,78}Se (α,^{3}He) and (^{3}He,α)

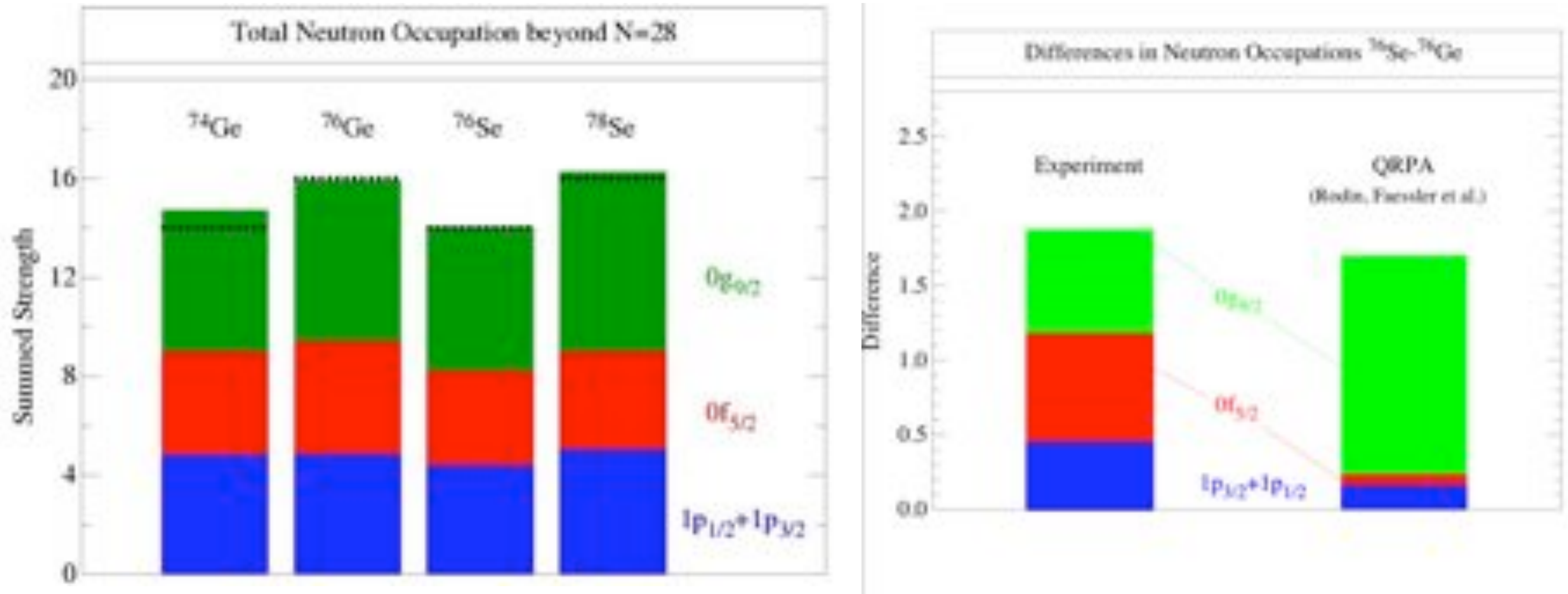
Reactions with different Q values to ensure observation across all L-transfers.

Neutron-adding AND neutron-removing reactions: mid-shell nuclei with partial occupancy of *fpg* orbitals.
Measurements of *occupancy* ***and*** *vacancy* in *removing* ***and*** *adding* reactions should add up to *(2j+1)*.



J. P. Schiffer *et al*. PRL **100** 112501 (2008)

Courtesy of Sean Freeman



Fermi surface seems considerably more diffuse than QRPA.
Neutrons from three to four orbits are changing substantially between ^{76}Ge and ^{76}Se, while in QRPA the change is almost entirely in the $0g_{9/2}$.

Consequences on the calculated matrix for 0ν2β remain to be explored: it is obvious, however, that there are deficiencies in the approach or the method.

J. P. Schiffer *et al*. PRL **100** 112501 (2008)

Courtesy of Sean Freeman

2.G Nuclear Physics 33 (1962) 685—692;

NOTE ON THE TWO-NUCLEON STRIPPING REACTION

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

Received 9 February 1962

Abstract: The magnitude of the two-nucleon stripping reactions is calculated using the pairin interaction model. The calculation also is applied to final states of collective type. For som types of reaction a collective enhancement of the reaction cross section is predicted.

Proc. Int. Symp. On Nuclear Structure, IAEA – Vienna, 1968, Pag. 179

PAIR CORRELATIONS AND DOUBLE TRANSFER REACTIONS

A. BOHR
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PHYSICS REPORTS (Section C of Physics Letters) 34, No. 1 (1977) 1-63. NORTH-HOLLAND PUBLISHING COMPANY

ISOVECTOR PAIRING VIBRATIONS

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and

Ole HANSEN and O. NATHAN
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Adv. Nucl. Phys. **6** , 287 (1973)

Chapter 3

TWO-NEUTRON TRANSFER REACTIONS AND THE PAIRING MODEL

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Los Alamos, New Mexico 87544

and

Claus Riedel
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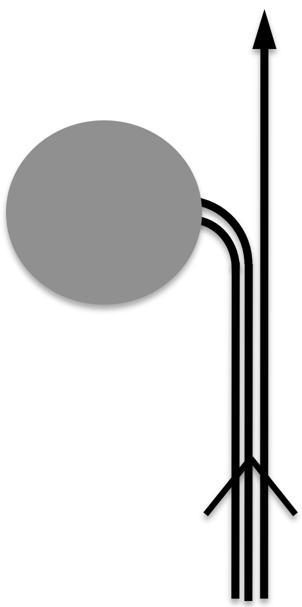
and
Physics Department, University of Karl Marx Stadt
Karl Marx Stadt, D.D.R.

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 operators $<f|a^{+}a^{+}|i>$, $<f|aa|i>$ are the analogous to the transition probabilities BE2's on the quadrupole case.

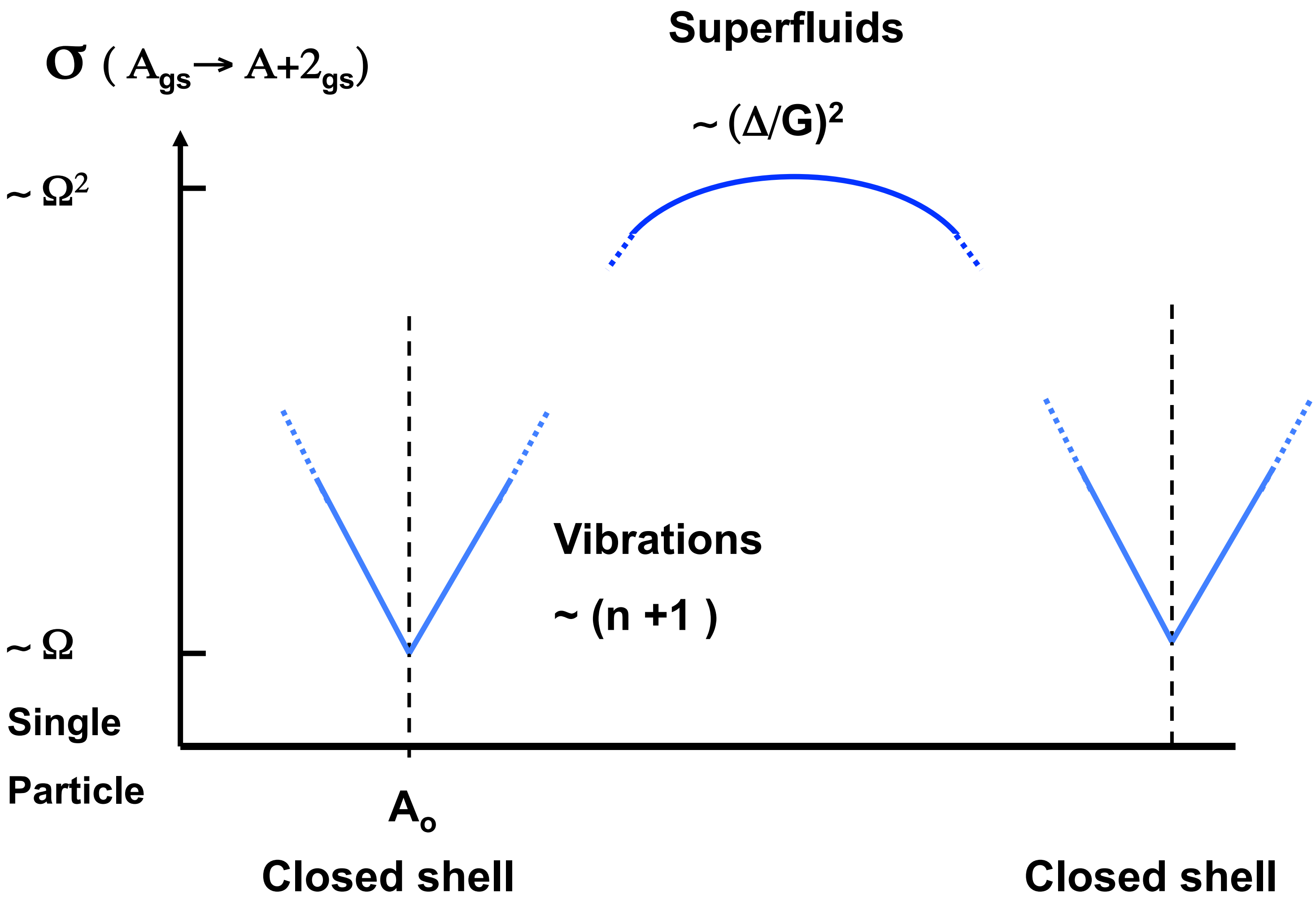


Process amplitude proportional to :

$$< A+2 \mid a^{+} a^{+} \mid A >$$

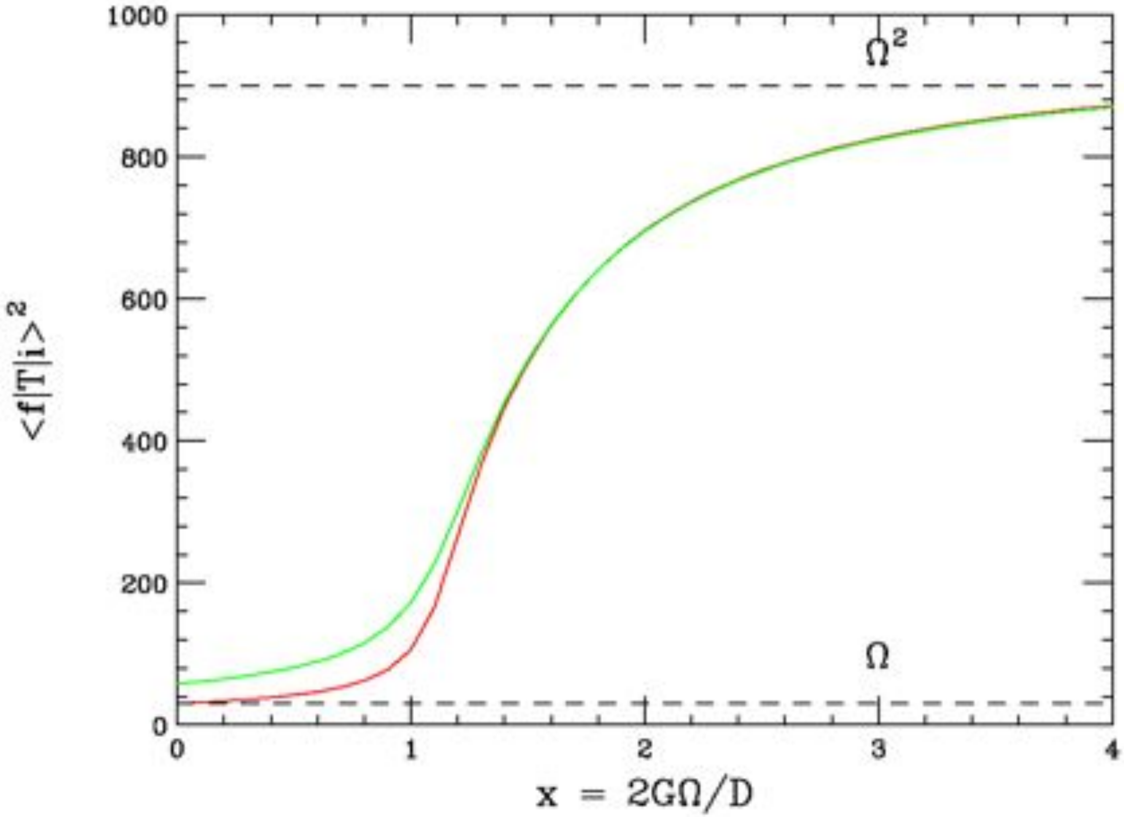
Pair correlations result in a constructive interference of reaction amplitudes giving a enhanced two-nucleon transfer.

Problem #3,4



Systematic relative measurements and within a given nucleus.

The results from the Two j-shells model



PHYSICAL REVIEW C 85, 034317 (2012)

Pair-transfer probability in open- and closed-shell Sn isotopes

M. Grasso,[1] D. Lacroix,[2] and A. Vitturi[3,4]
[1]*Institut de Physique Nucléaire, IN2P3-CNRS, Université Paris-Sud, F-91406 Orsay Cedex, France*
[2]*Grand Accélérateur National d'Ions Lourds (GANIL), CEA/DSM-CNRS/IN2P3, Boulevard Henri Becquerel, F-14076 Caen, France*
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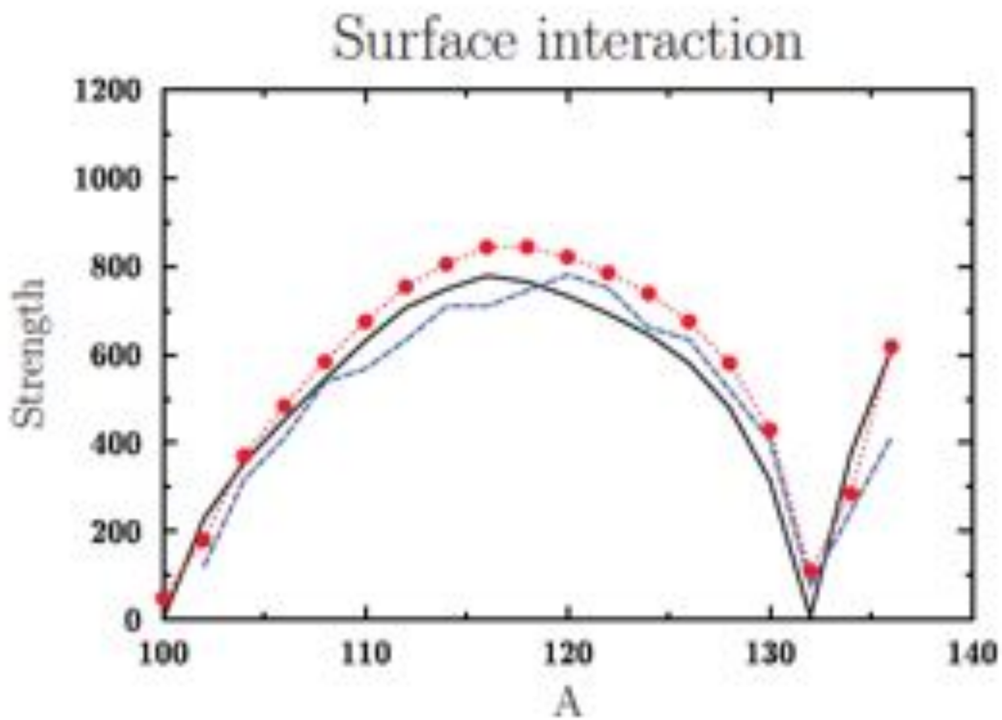
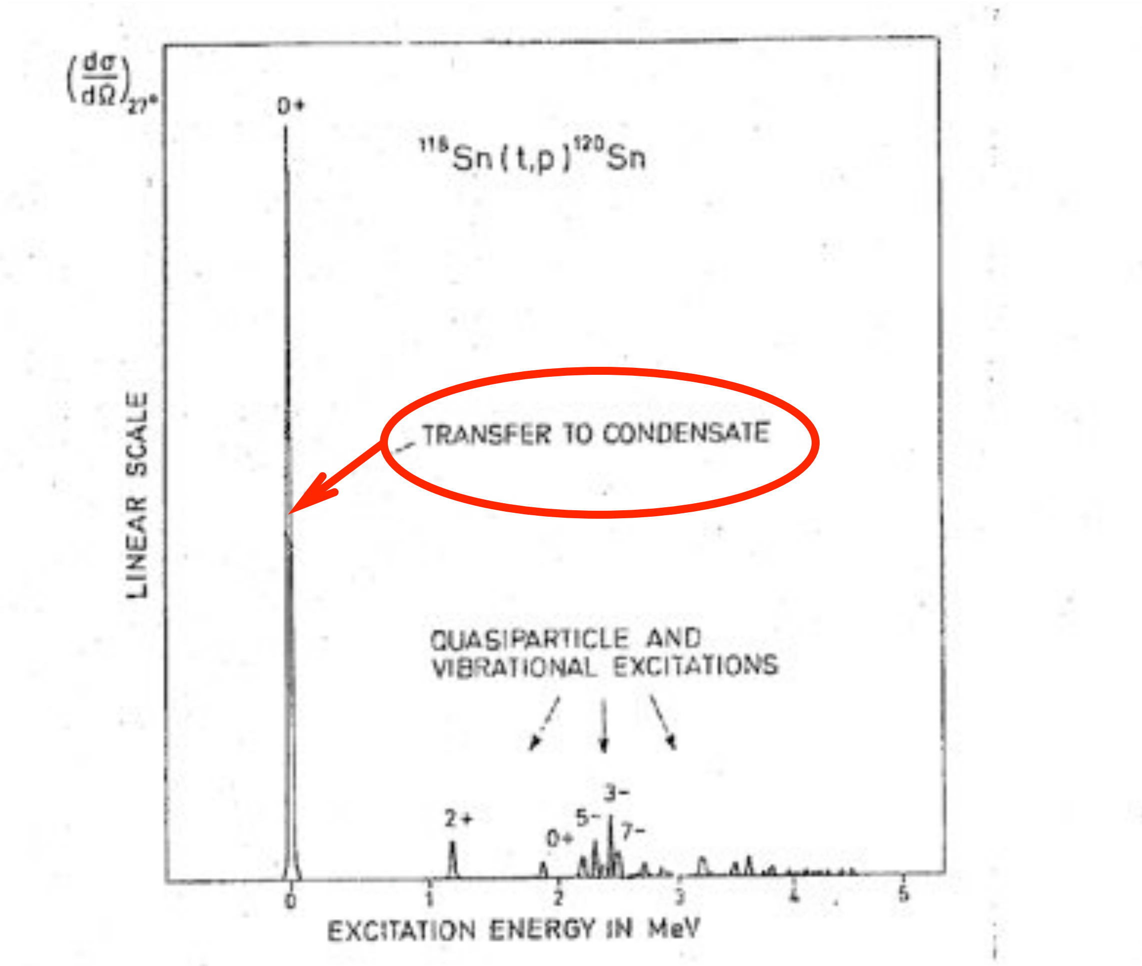
[4]*Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Padova, via Marzolo 8, I-35131 Padova, Italy*



An example of a "superfluid" nucleus (pairing rotations)



DWBA Analysis

Direct One-step

Two-neutron in relative 0S state

Zero-range approximation

Common normalization factor

Relative cross-sections

J.H.Bjerregaard *et al.* NPA 110 **1** (1968)

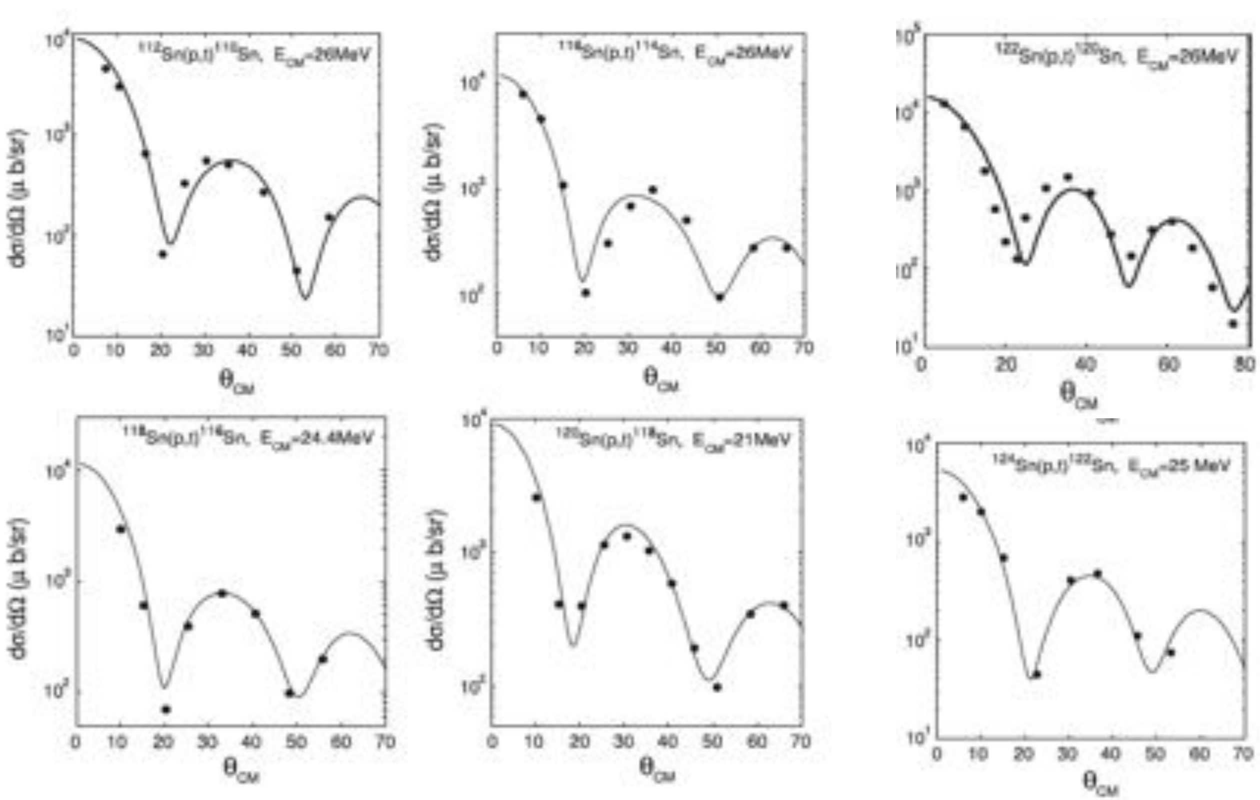
Calculation of the Transition from Pairing Vibrational to Pairing Rotational Regimes between Magic Nuclei ^{100}Sn and ^{132}Sn via Two-Nucleon Transfer Reactions

G. Potel and F. Barranco

Departamento de Fisica Atomica, Molecular y Nuclear y Departamento de Fisica Aplicada III, Universidad de Sevilla, Spain

F. Marini, A. Idini, E. Vigezzi, and R. A. Broglia

INFN, Sezione di Milano and Departimento di Fisica, Universita di Milano, Via Celoria 16, 20133 Milano, Italy

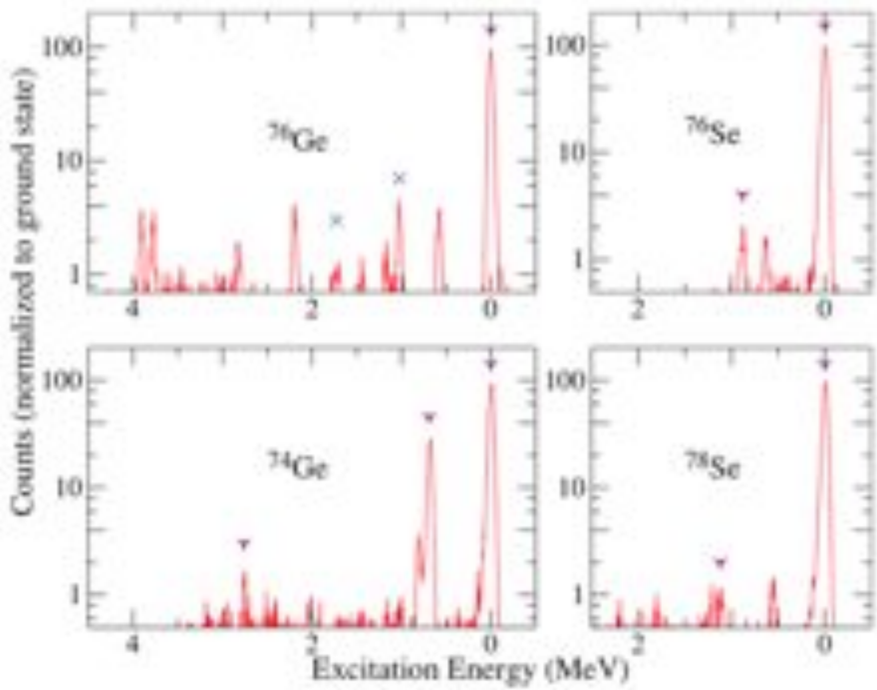


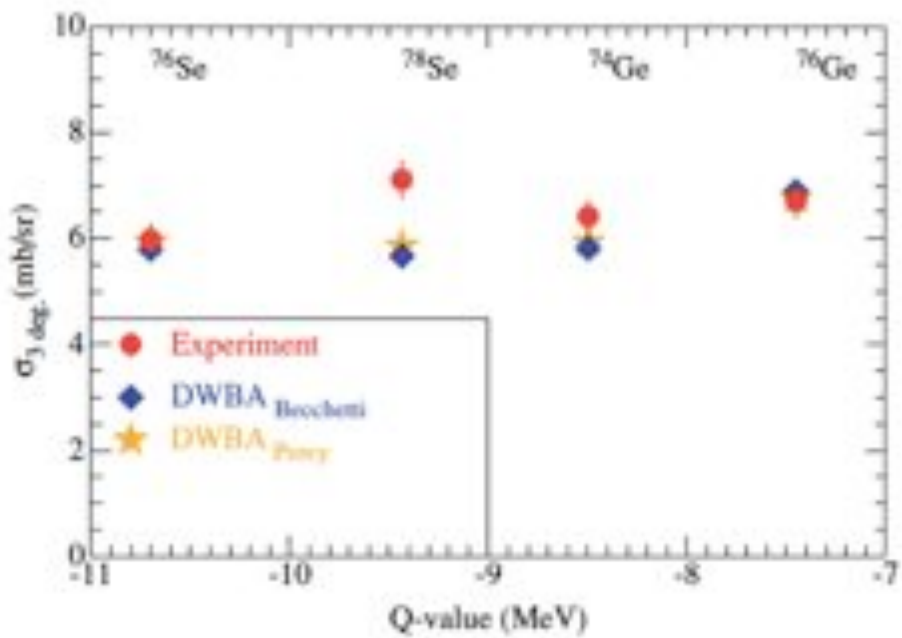
PHYSICAL REVIEW C 75, 051301(R) (2007)

Pair correlations in nuclei involved in neutrinoless double β decay: ^{76}Ge and ^{76}Se

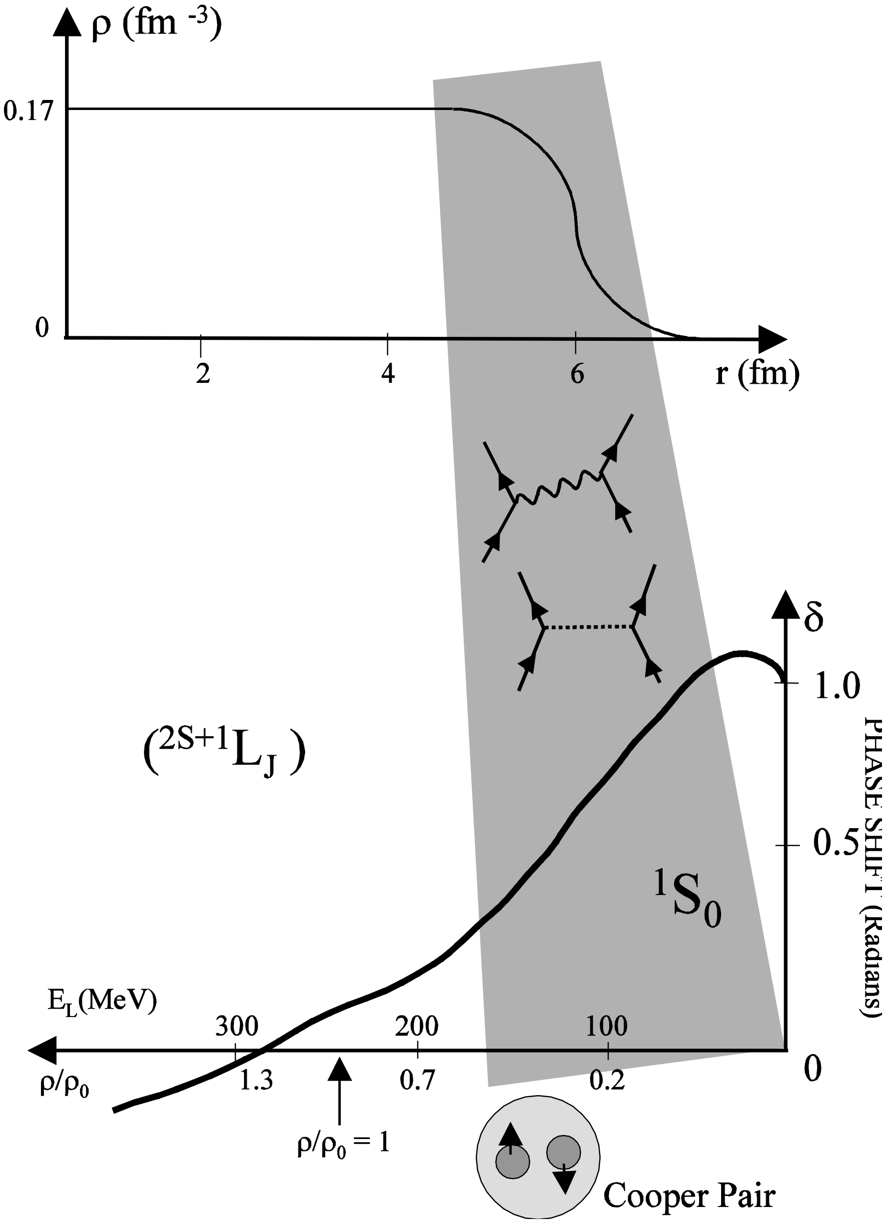
S. J. Freeman,[1] J. P. Schiffer,[2,*] A. C. C. Villari,[3] J. A. Clark,[4] C. Deibel,[4] S. Gros,[2] A. Heinz,[4] D. Hirata,[3,5] C. L. Jiang,[2] B. P. Kay,[1] A. Parikh,[4] P. D. Parker,[4] J. Qian,[4] K. E. Rehm,[2] X. D. Tang,[2] V. Werner,[4] and C. Wrede[4]
[1]Schuster Laboratory, University of Manchester, Manchester M13 9PL, United Kingdom
[2]Argonne National Laboratory, Argonne, Illinois 60439, USA
[3]GANIL (IN2P3/CNRS-DSM/CEA), B. P. 55027 F-14076 Caen Cedex 5, France
[4]A. W. Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520, USA
[5]The Open University, Dept. of Physics and Astronomy, Milton Keynes, MK7 6AA, United Kingdom

20MeV protons Yale Tandem.   Split-pole spectrograph.

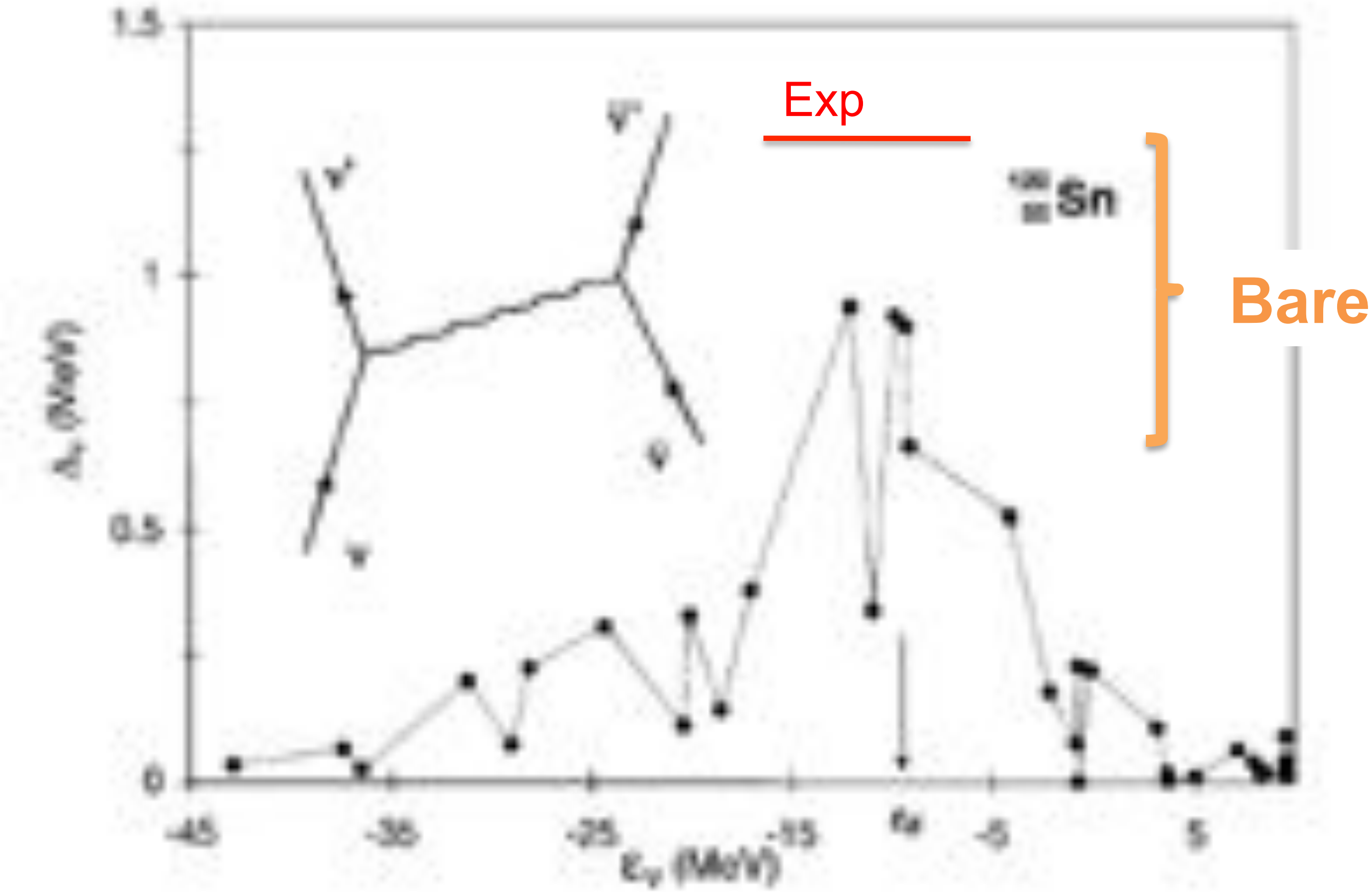




For ^{76}Ge and ^{76}Se (p,t) strength is predominately to the ground states, indicating they can be described as simple BCS paired states with quantitatively similar pair correlations.

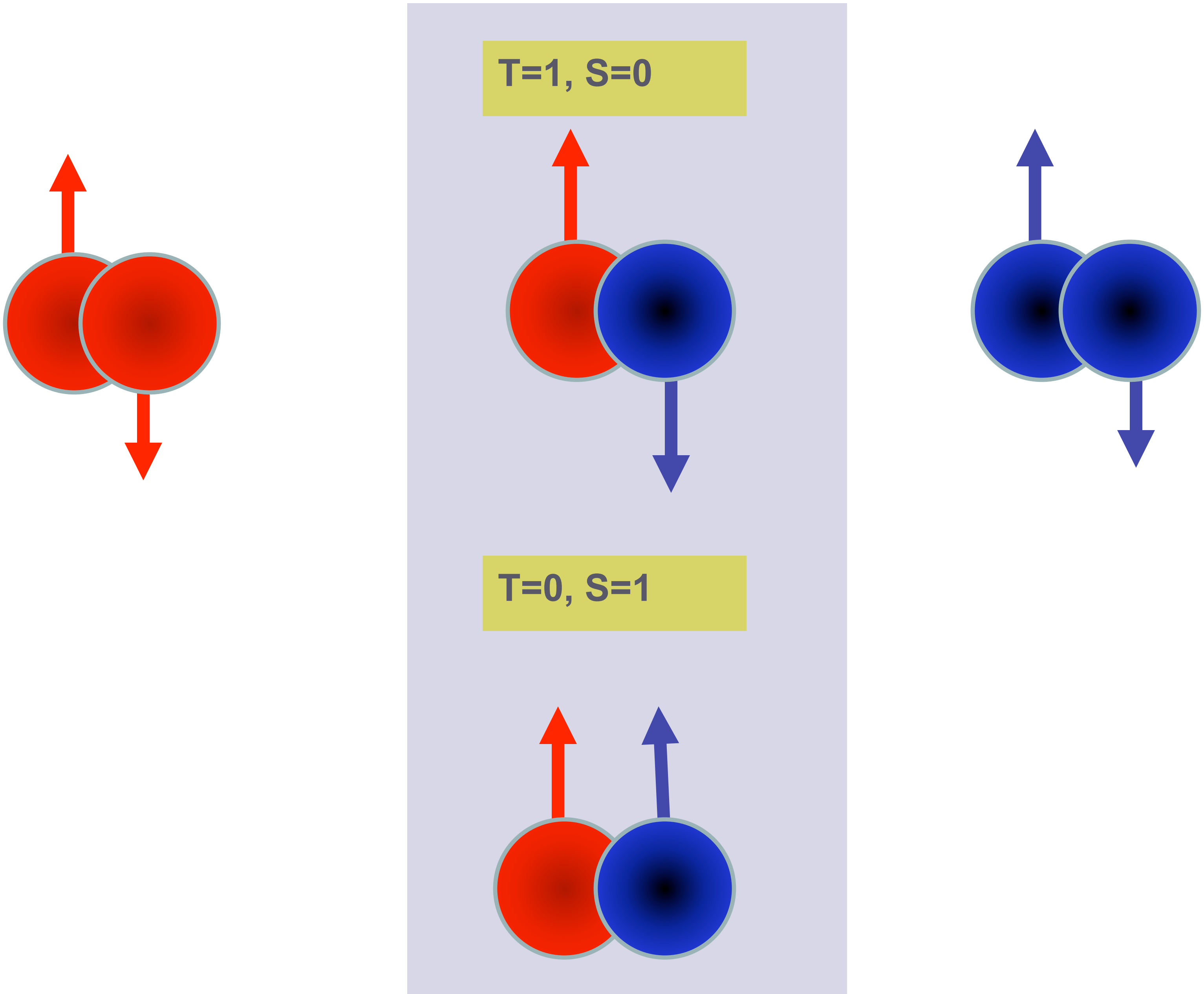


D. Brink, R.A. Broglia, Superfluidity in nuclei



F. Barranco et al., Eur. J. Phys. A21(2004) 57

Neutron-Proton Pairing



$T_z=0$

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?

Possible Signals

BE differences can be described by an appropriate combination of the symmetry energy and the isovector pairing energy. Evidence for full isovector pairing (nn,np,pp) - charge independence.

Isovector Pairing-Vibrations around ^{40}Ca and ^{56}Ni

Odd-odd low lying states: quasi-deuteron structure.
Lisetskiy, Jolos, Pietralla, von Brentano

Rotational properties ("delayed alignments") consistent with T=1 cranking model.
Fischer, Lister - Afanasjev, Frauendorf

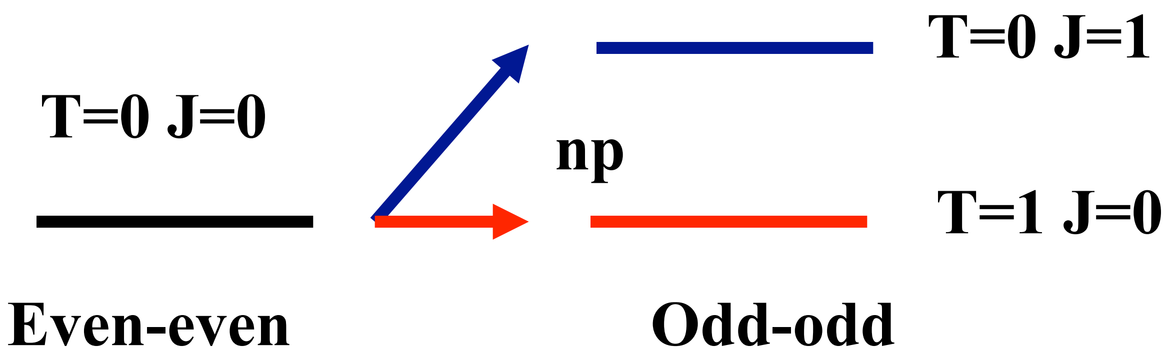
Beta Decay: Strong N=Z-2➔ N=Z - 0^+ ➔1^+ transition.
Gadea, Algora, et al.

Spin-aligned neutron-proton coupling scheme in ^{92}Pd
Bo Cederwall et al. , Nature ,   Piet Van Isacker

Could transfer reactions be the smoking gun?

(p, ^{3}He) (^{3}He,p)	$\Delta T=0,1$
(d,α), (α,d)	$\Delta T=0$
(α, ^{6}Li), (^{6}Li,α)	$\Delta T=0$

σ ?



(^{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) <u>and</u> relative σ(T=0) / σ(T=1) tell us about the character and strength of the correlations

Volume 37B, number 4 PHYSICS LETTERS 13 December 197

ENHANCEMENT OF DEUTERON TRANSFER REACTIONS BY NEUTRON-PROTON PAIRING CORRELATIONS*

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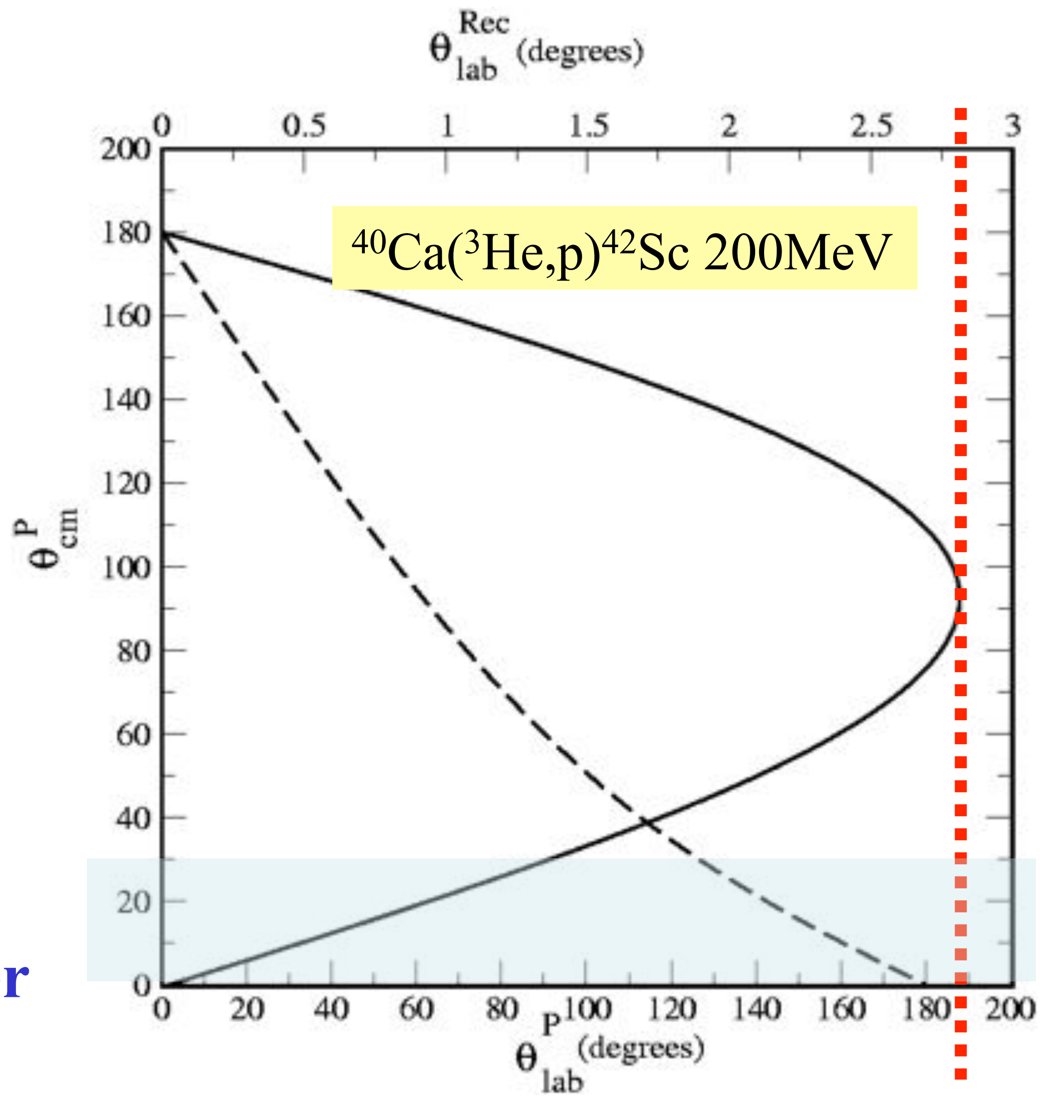
Received 7 October 1971

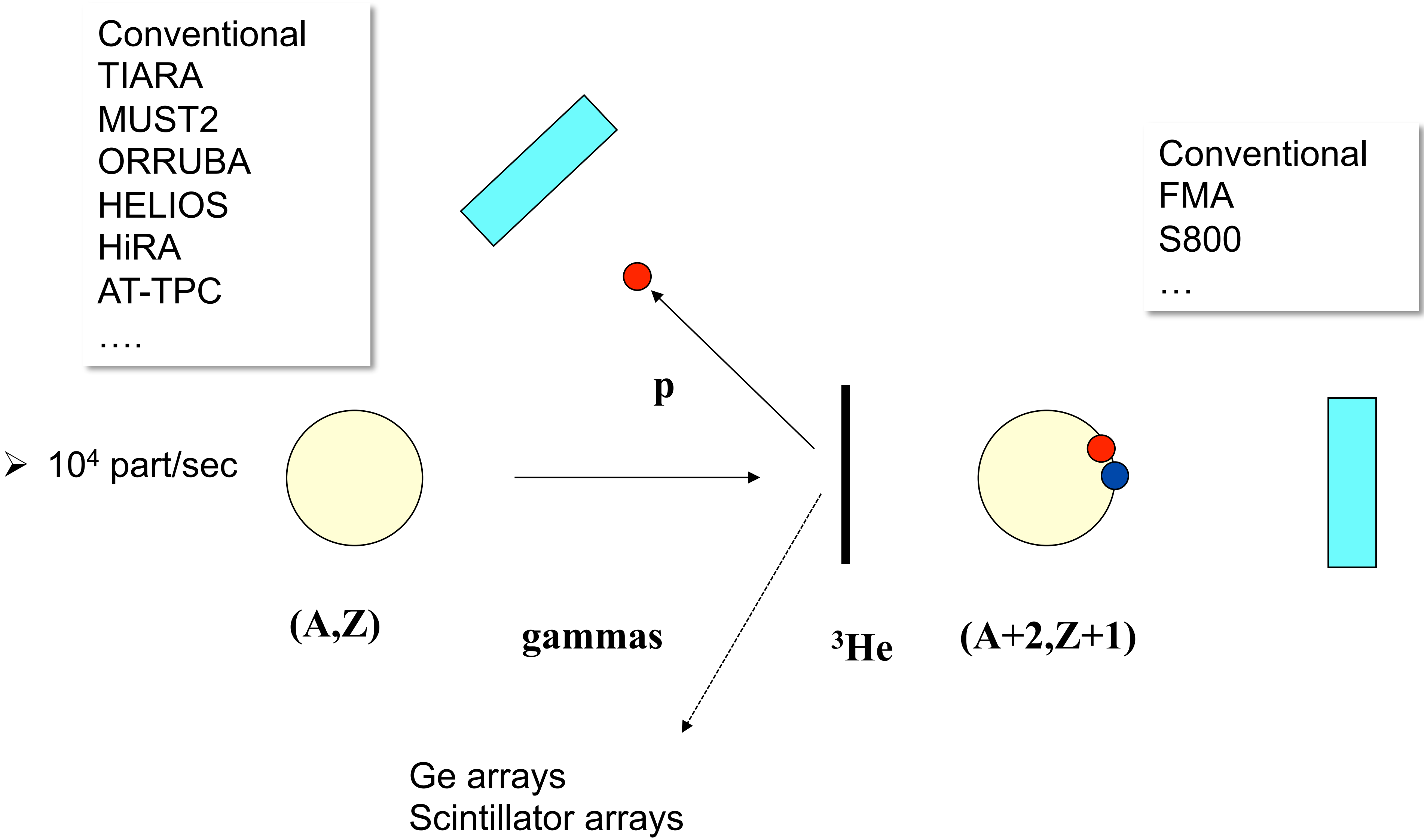
It is shown for $^{36}Ar\,(p,{}^{3}He)^{34}Cl$ that the transfer of a neutron-proton pair is enhanced as compared to the shell model if one takes into account $T = 0$ and $T = 1$ neutron-proton pairing correlations in the description of target and residual nucleus.

$$d\sigma / d\Omega \approx 2.5 d\sigma / d\Omega_{sp}$$

^{40}Ca last stable N=Z

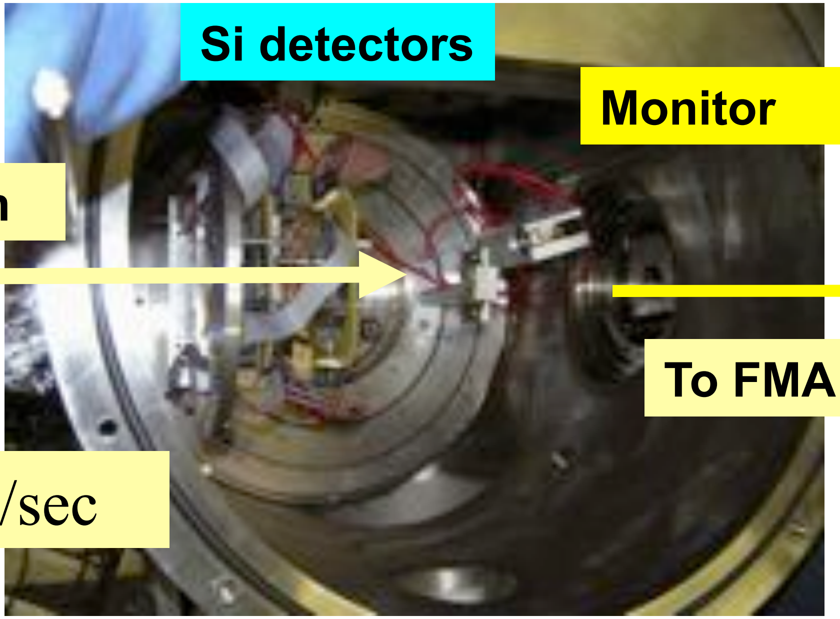


L=0 transfer



Measure E(Θ), dσ/dΩ (Θ), σ

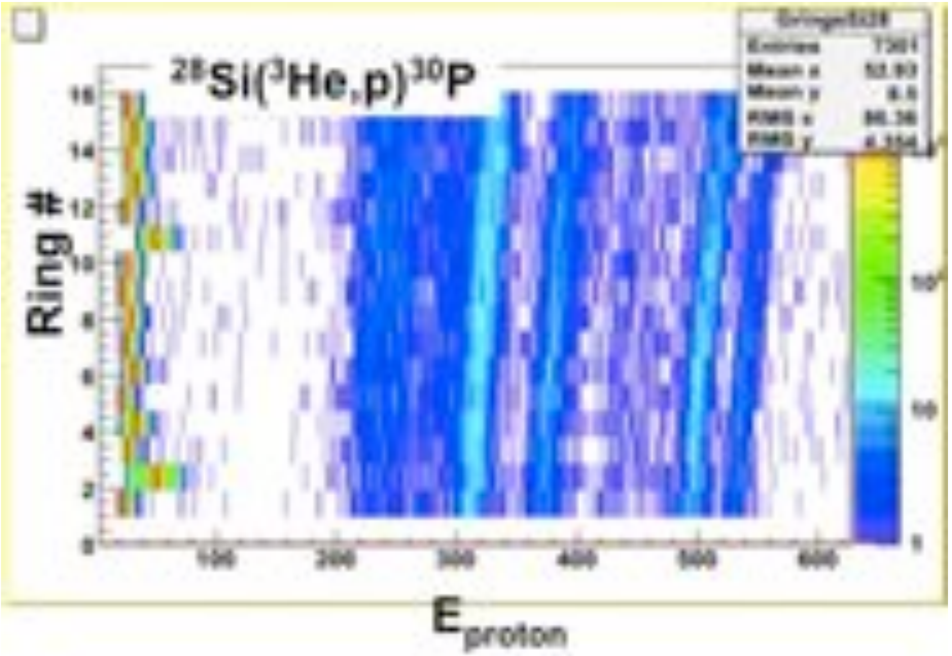
Proof of Principle



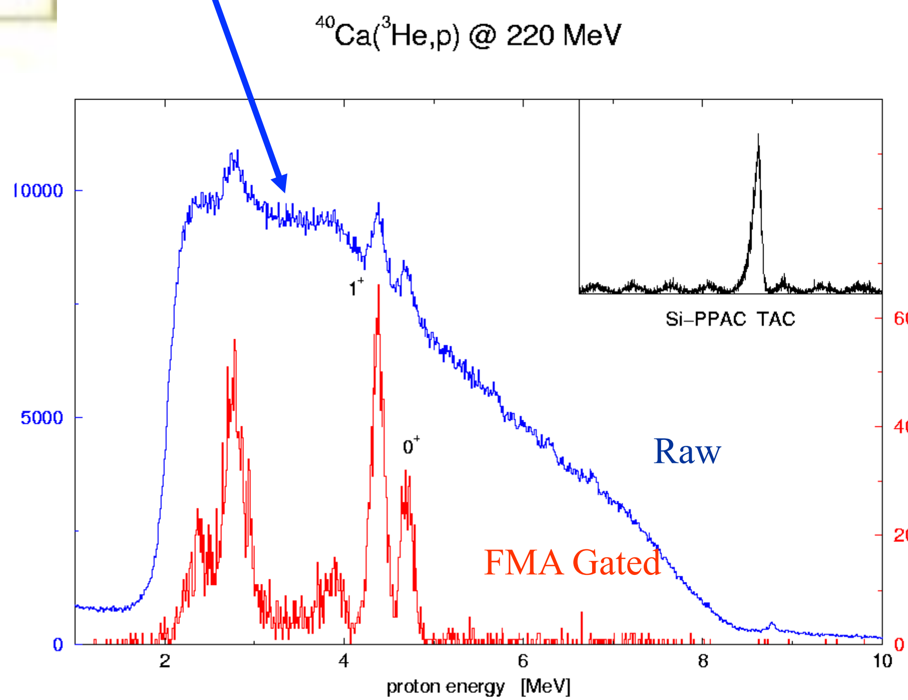
Si detector 500μ
16x16 ~1sr

Gas cell
~100μg/cm^2

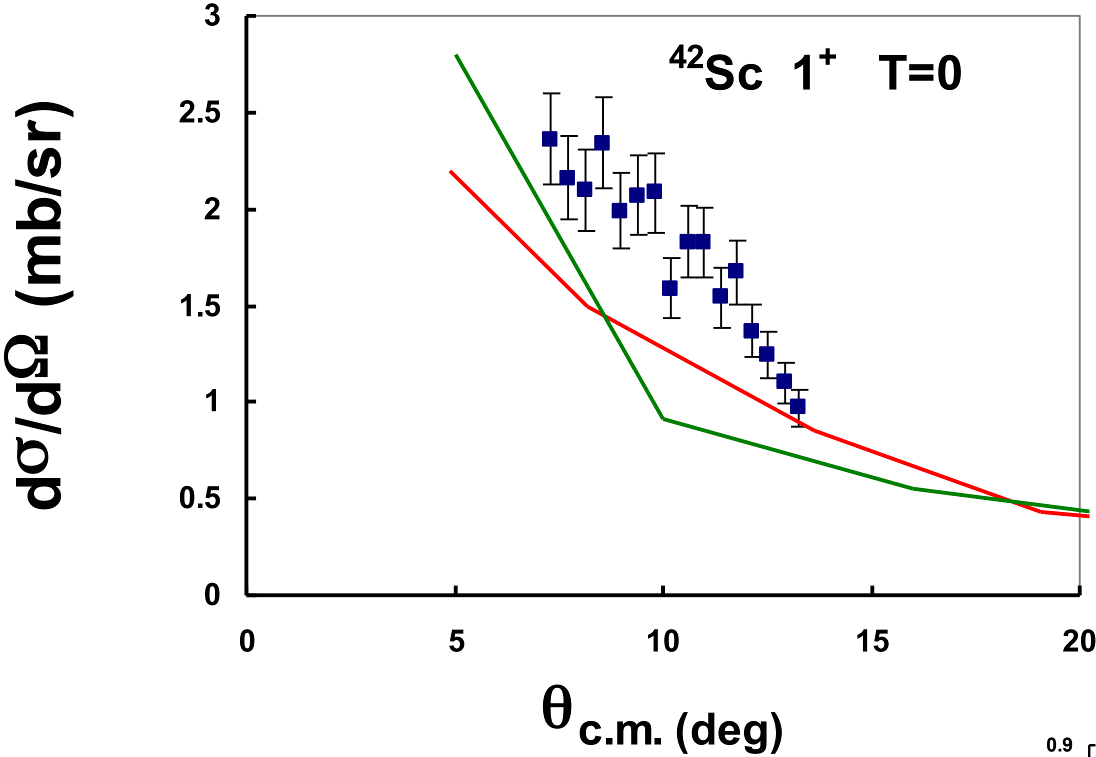
~ 20 counts/day



Evaporation protons

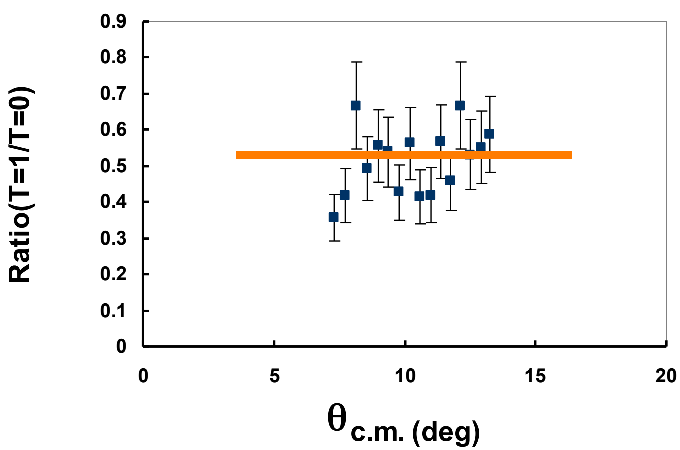


Proof of Principle



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

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



The ^{44}Ti Beam at ATLAS

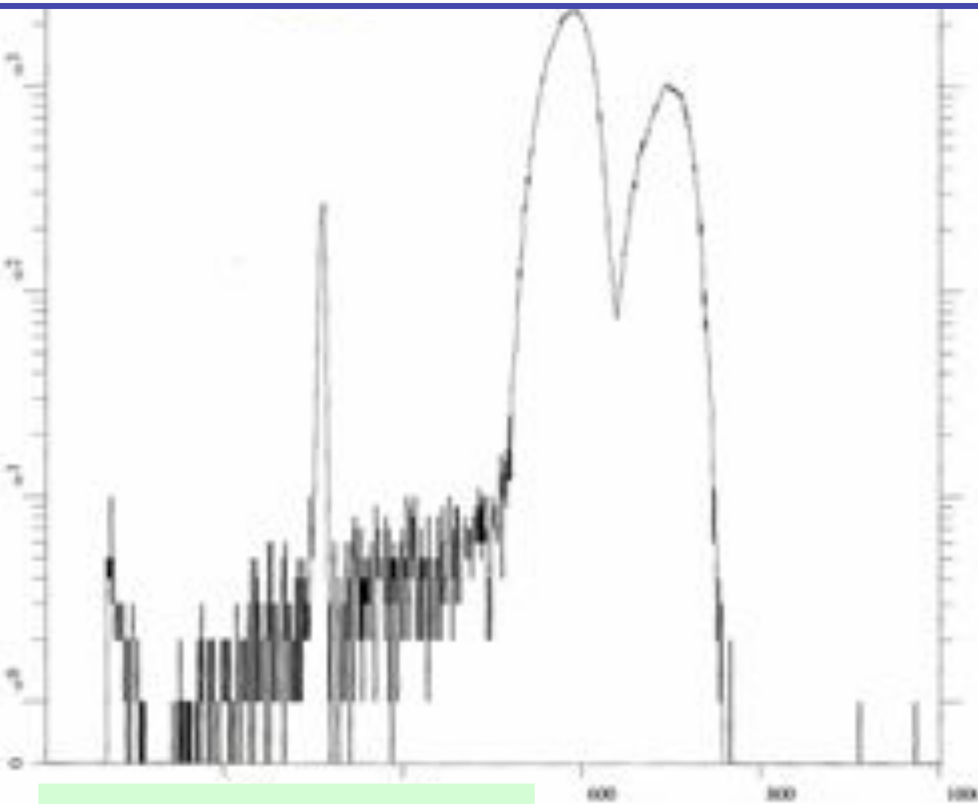
Purchased 100μCi of ^{44}Ti from LANL ~ 20k$

Some *“Nuclear“* Chemistry

Tandem Ion-Source

^{44}Ti @ 242 MeV

^{44}Ti / ^{44}Ca = 2.5 ⇨ Need FMA selection

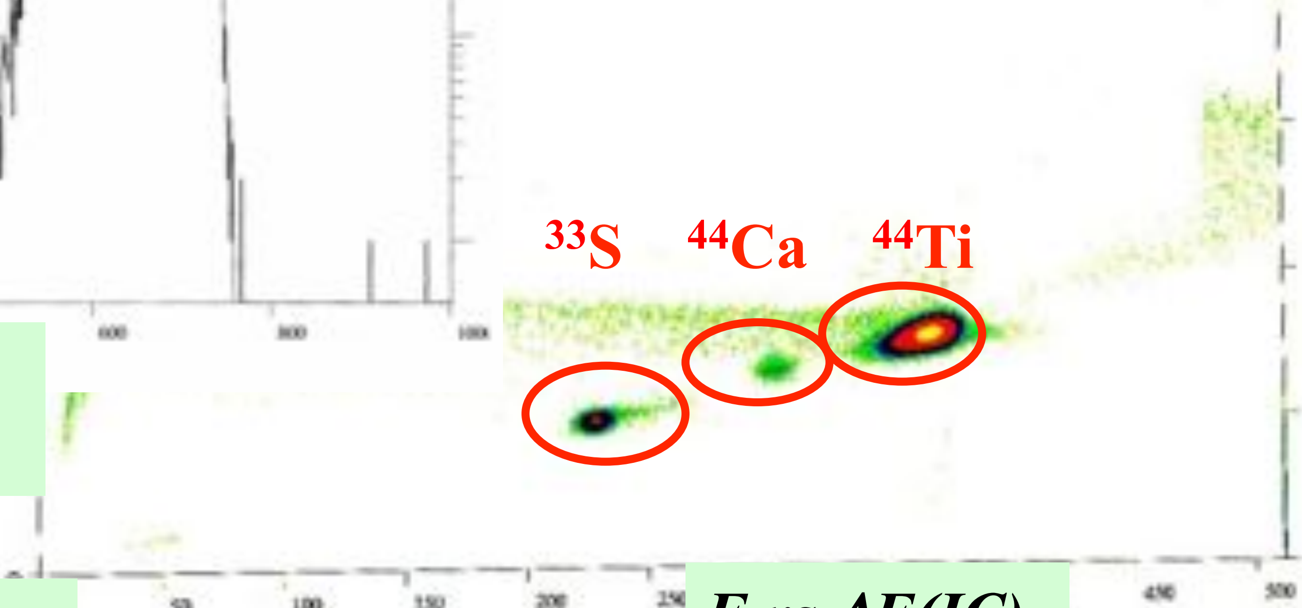


E Monitor @ 0^{o}

X1800 Attenuator

FMA Settings

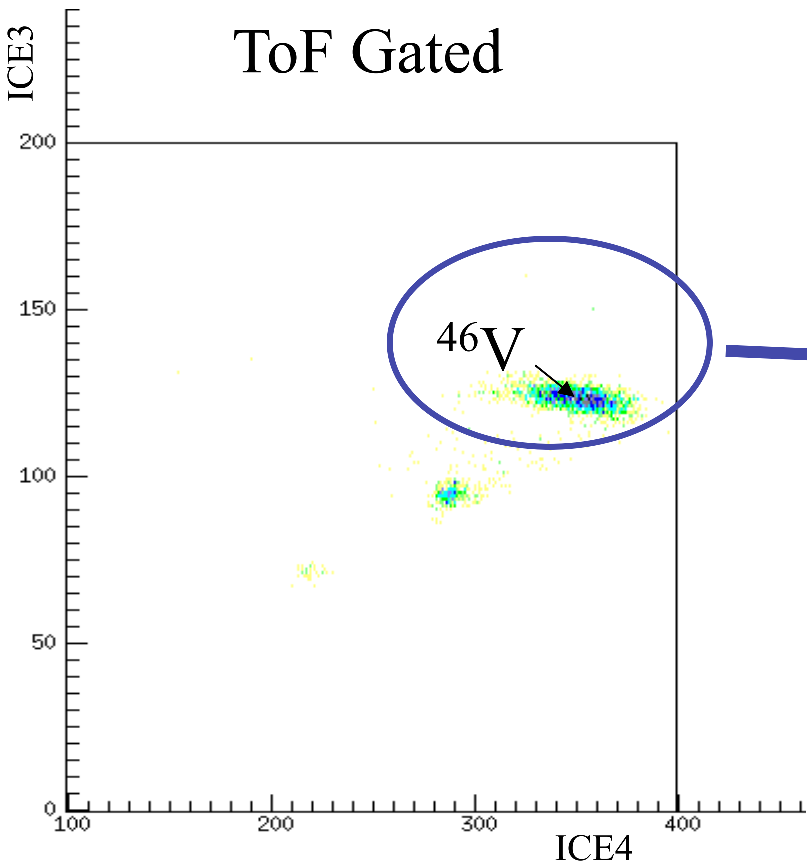
107MeV, A=44, q=20^{+}



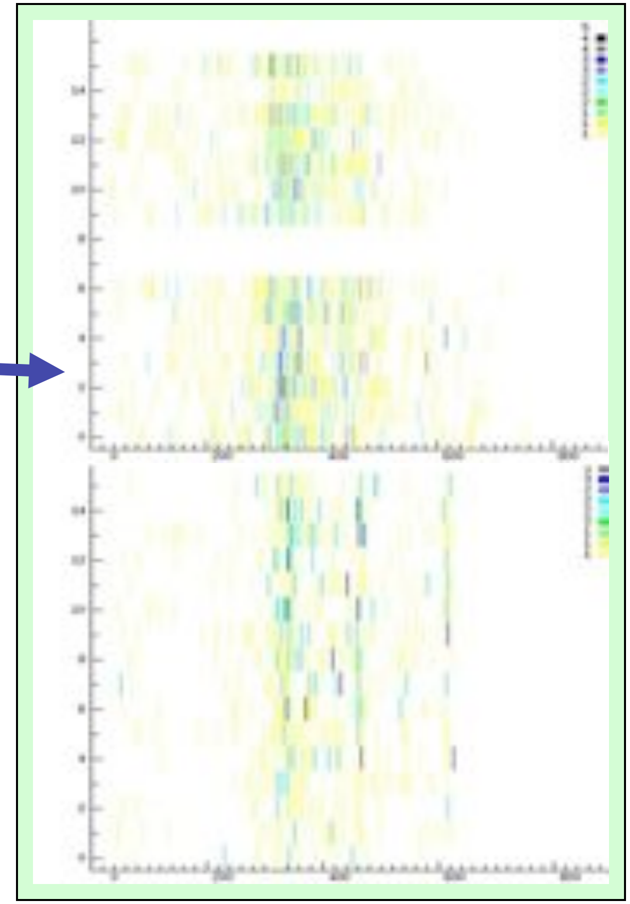
E vs ΔE(IC)

~ 5 x 10^{5} ^{44}Ti/sec

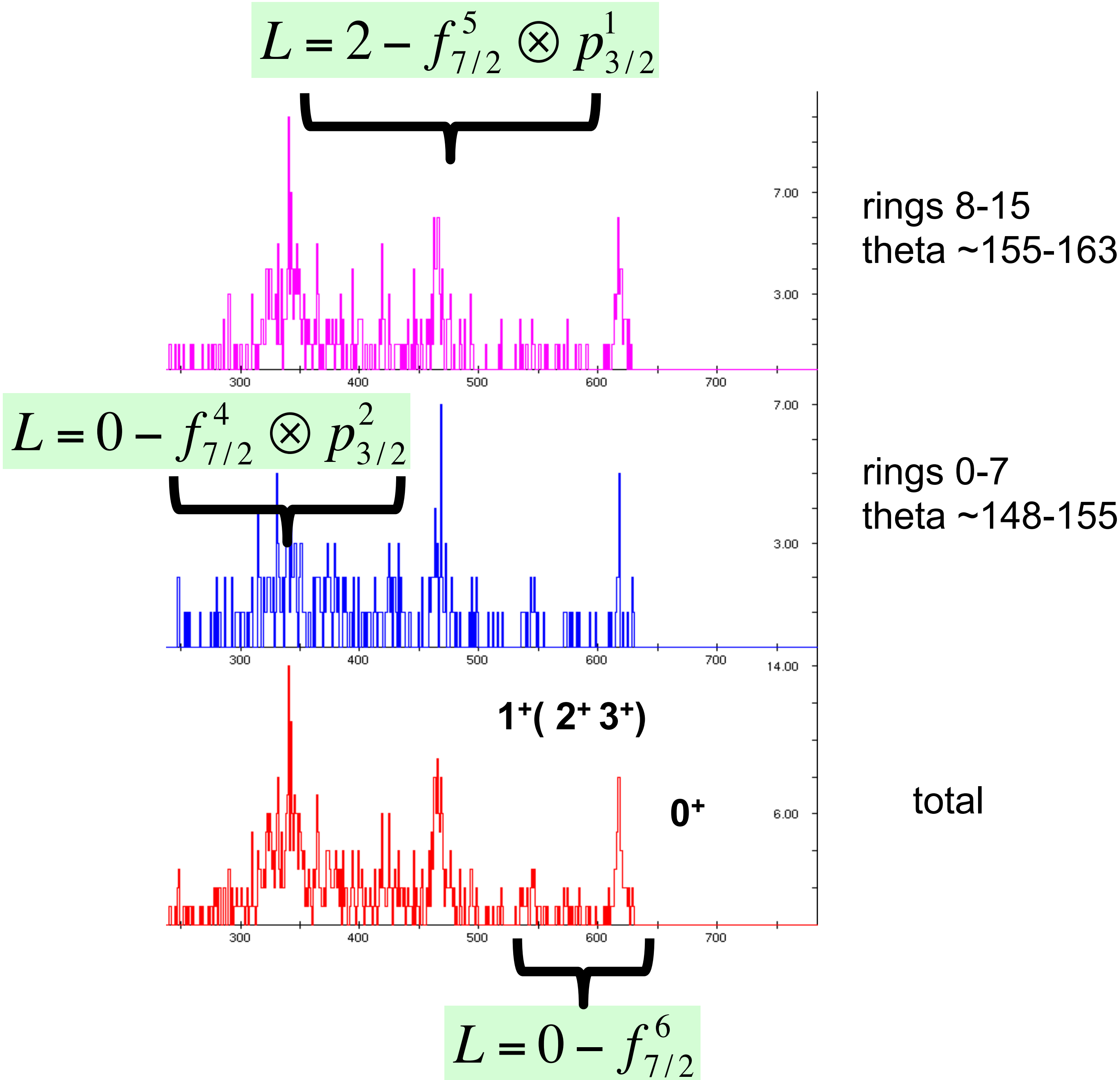
A=46 ^{44}Ti (^{3}He,p) → ^{46}V



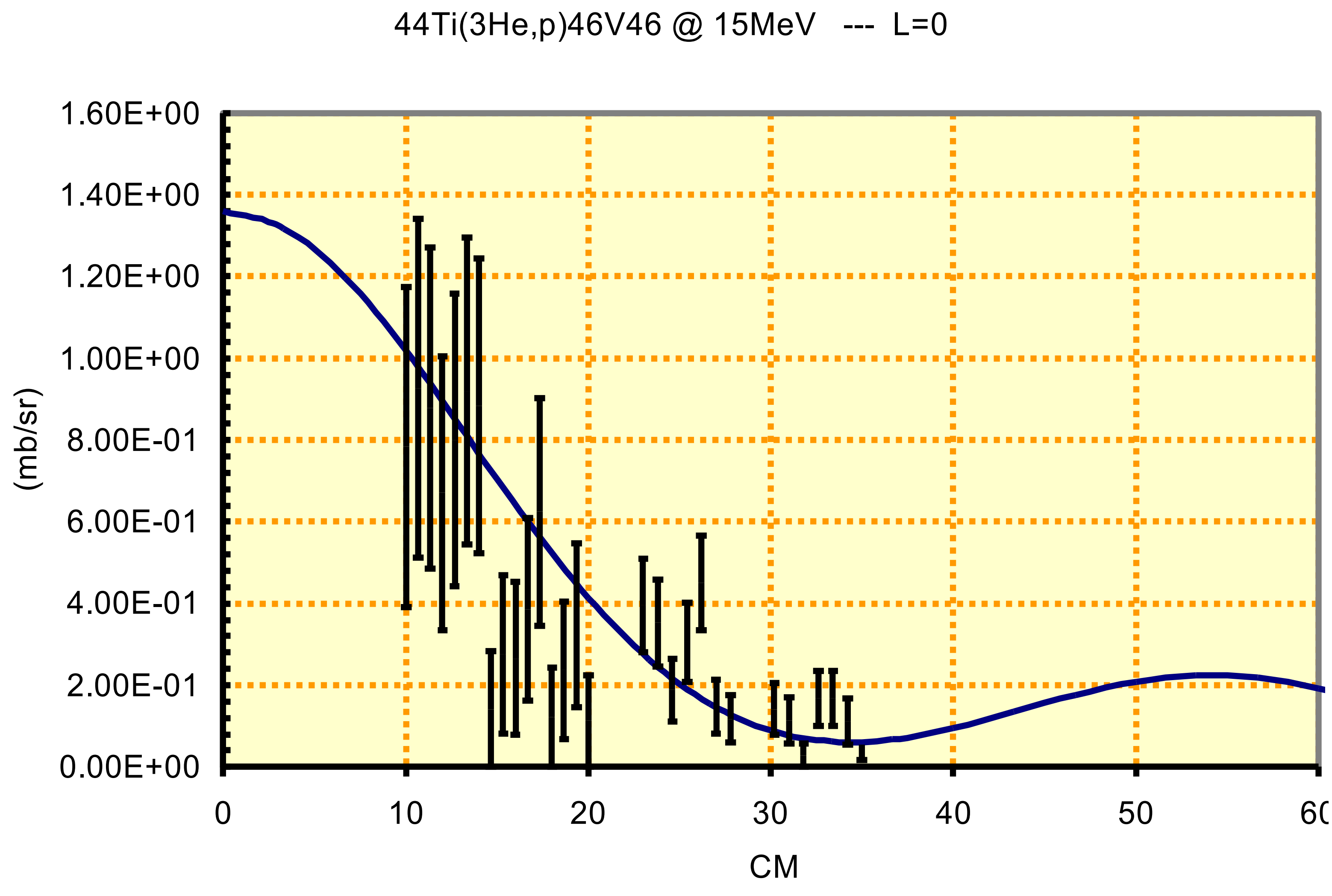
Ring #



Proton E (10keV)



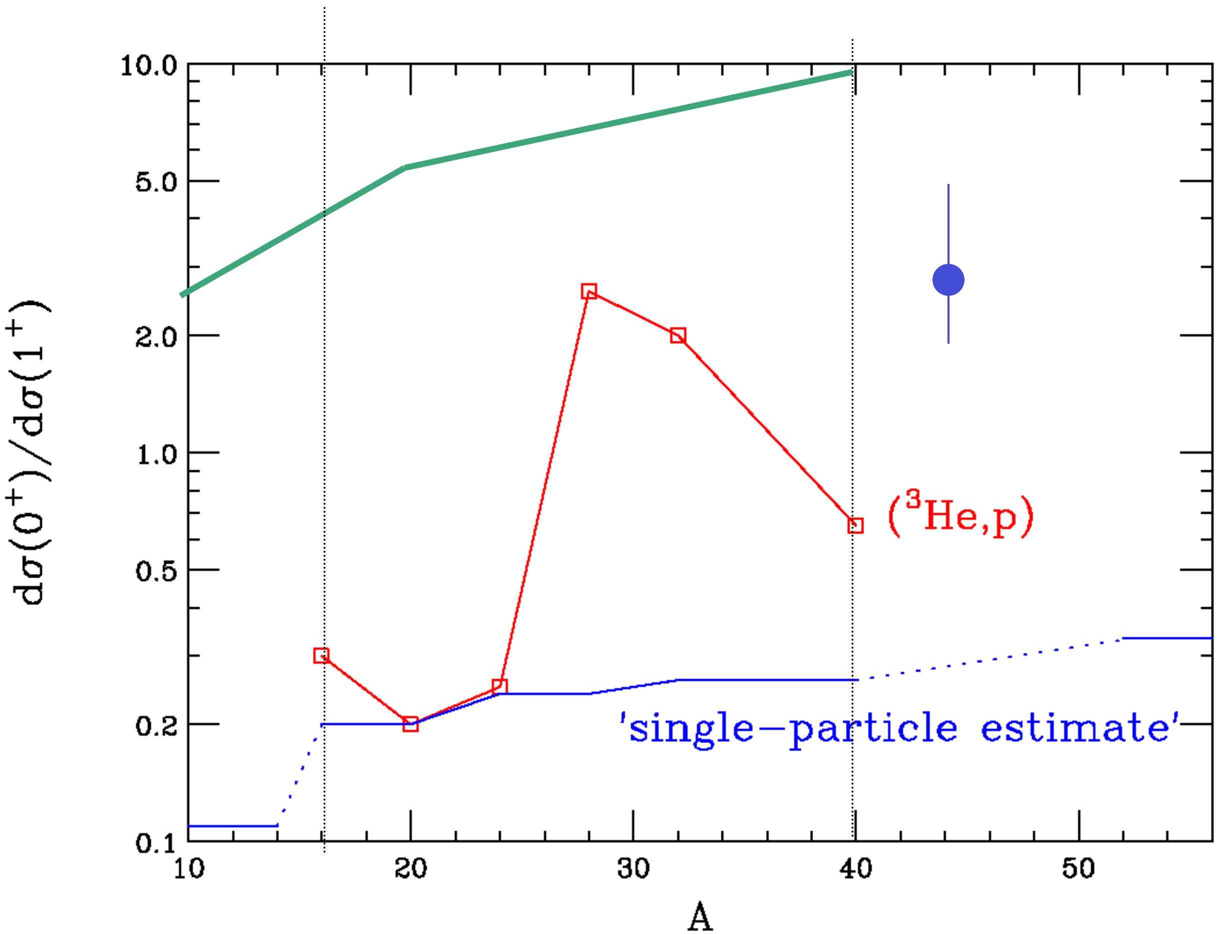
$L = 2 - f_{7/2}^{5} \otimes p_{3/2}^{1}$
7.00
3.00
300
400
500
600
700
rings 8-15
theta ~155-163
$L = 0 - f_{7/2}^{4} \otimes p_{3/2}^{2}$
7.00
3.00
300
400
500
600
700
rings 0-7
theta ~148-155
14.00
6.00
$1^{+}(2^{+}\ 3^{+})$
0^{+}
total
300
400
500
600
700
$L = 0 - f_{7/2}^{6}$



44Ti(3He,p)46V46 @ 15MeV --- L=0
(mb/sr)
1.60E+00
1.40E+00
1.20E+00
1.00E+00
8.00E-01
6.00E-01
4.00E-01
2.00E-01
0.00E+00
0
10
20
30
40
50
60
CM

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

Superfluid limit ~ $(\Delta_{T=1}/G)^2$



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

Next Steps

^{48}Cr, ^{56}Ni GANIL MUST2 + EXOGAM (d,α) reaction

^{48}Cr ,^{72}Kr Experiment approved at ISAC2 *LBNL, ANL, TRIUMF*

LOI for ReA3 at NSCL using the AT-TPC *LBNL, NSCL*

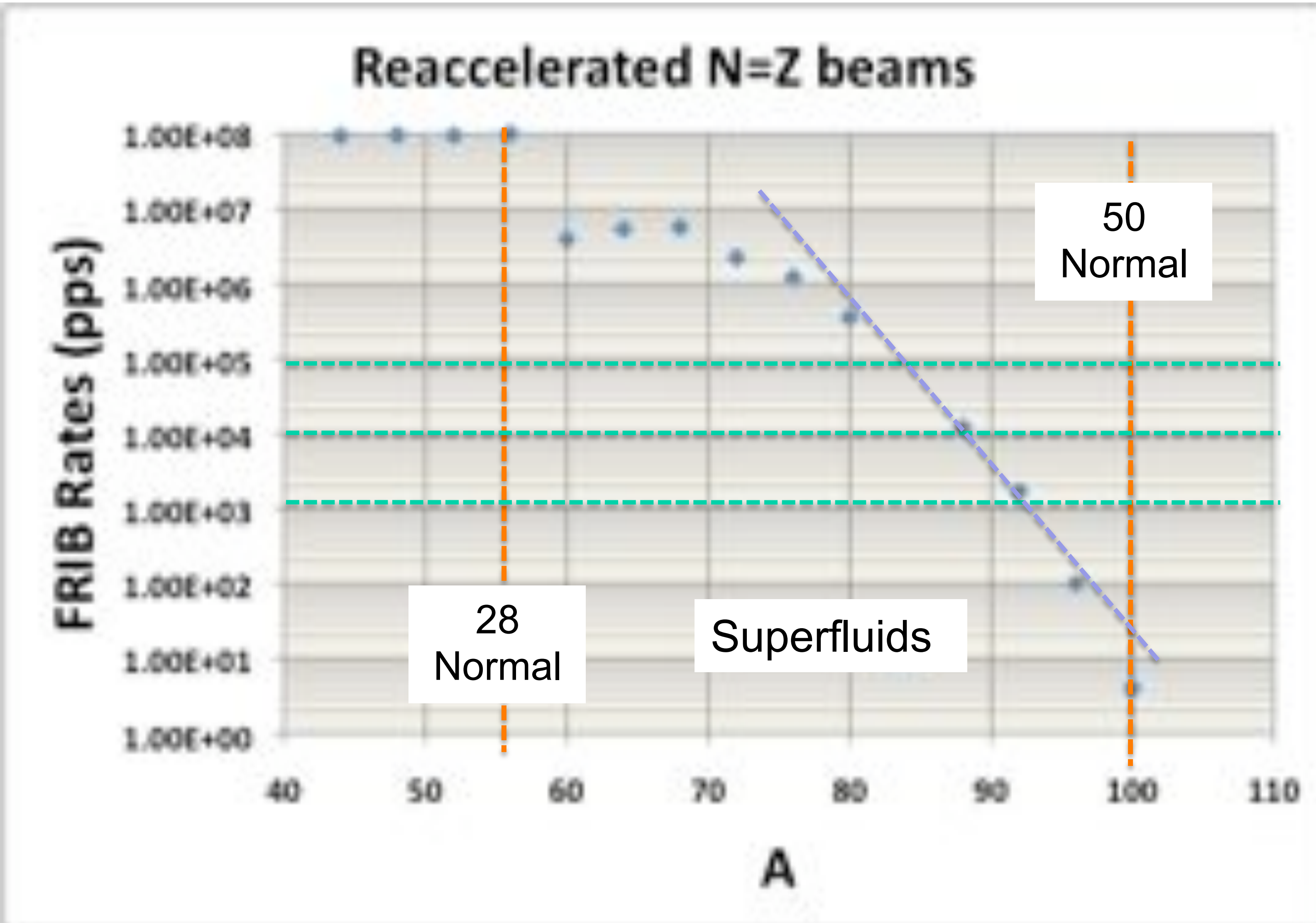
LOI for HIE ISOLDE *D.Jenkins et al.*

(p,^{3}He) Reaction using HiRA at NSCL

Revisiting (p,^{3}He) and (^{3}He,p) reactions
in stable targets *J.Lee et al.*

Also (t,p) , (p,t) , charge exchange

Single nucleon transfer: (d,p), (^{3}He,d), ….



Simple Setup

HELIOS

AT-TPC

Although simple arguments may suggest that isoscalar pairing should be important, it is still not clear if it gives rise to collective modes.

Spin-orbit **cf. New results by Bertsch *et al*.**

J=1 pairs P-wave contribution to matrix-elements

Core polarization

Direct reactions are unique tools in our experimental study of exotic nuclei.

Two particle transfer reactions provide specific tools to probe the amplitude of pairing collective modes.

(p,^{3}He) and (^{3}He,p) are the *"classical"* probes we can use to firmly elucidate this question, particularly in the region from ^{56}Ni to ^{100}Sn

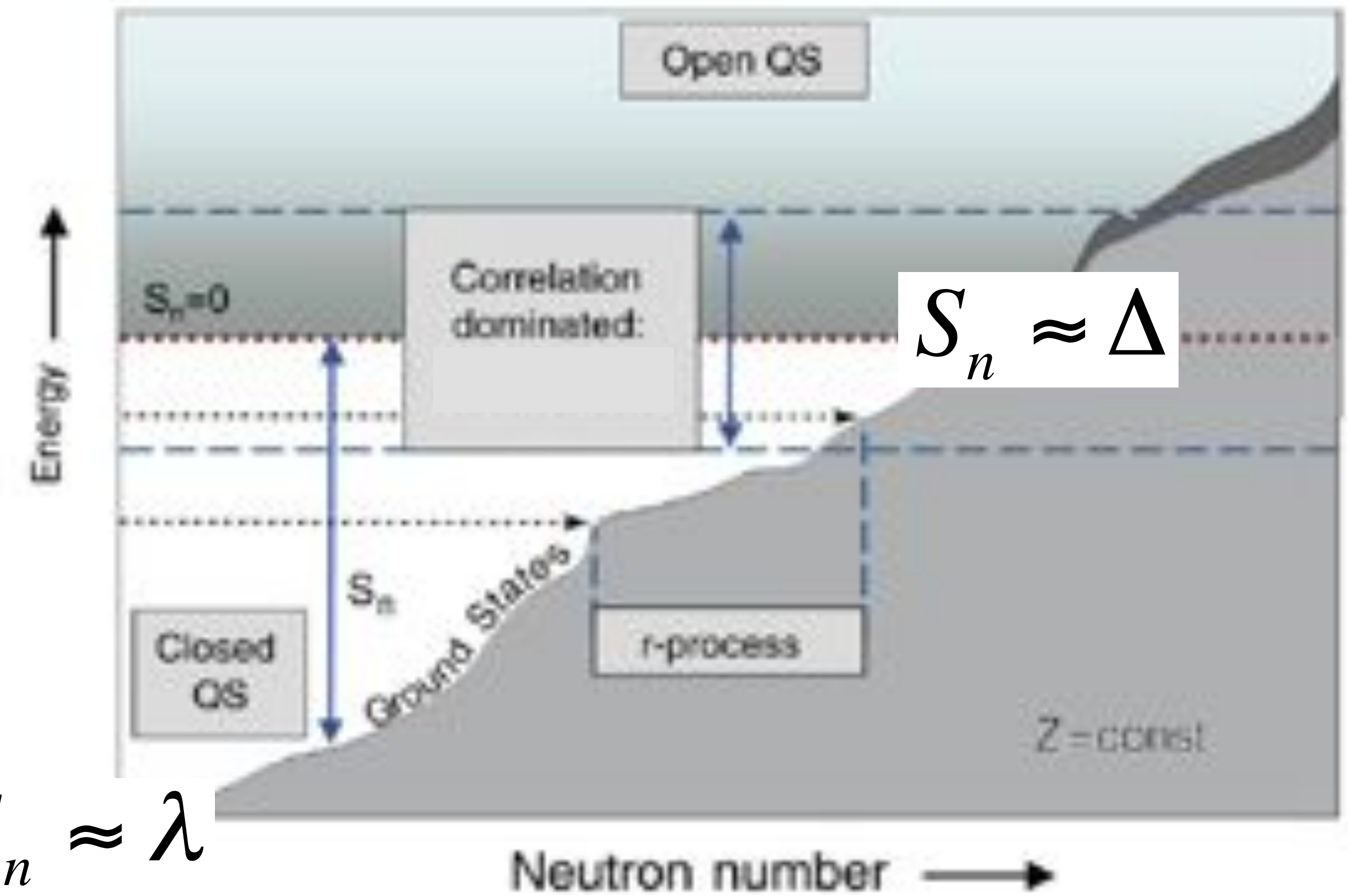
Radioactive beams require inverse kinematics:

Proof of principle with stable beams

Successful first experiment with a ^{44}Ti beam

Pairing in weakly bound systems

J. Dobaczewski et al. / Progress in Particle and Nuclear Physics 59 (2007) 432–445



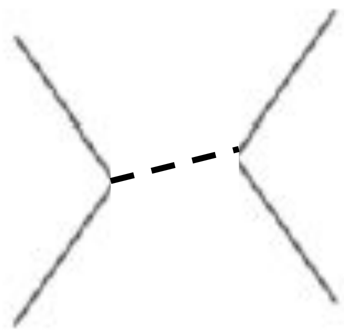
$S_n \approx \Delta$

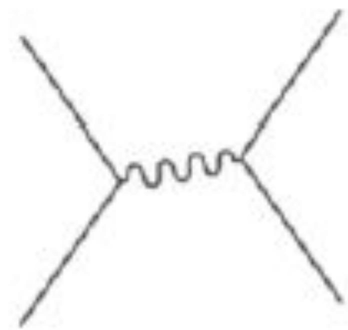
$S_n \approx \lambda$

$$S_n \approx \Delta + \lambda$$

The halo neutrons of ^{11}Li are bound only because of the extra pairing interaction mediated by the exchange of low-frequency surface vibrational modes.

F.Barranco, *et al*. Eur.Phys.J **A 11** 385 (2001)





NN

Essentially no role

Low lying phonons

Monopole, dipole and quadrupole

Mechanism analogous to the lattice phonon exchange responsible for the binding of electron Cooper pairs in a superconductor

⇨ ^{11}Li halo, an isolated Cooper pair?

PRL 100, 192502 (2008) PHYSICAL REVIEW LETTERS week ending 16 MAY 2008

Measurement of the Two-Halo Neutron Transfer Reaction $^{1}H(^{11}Li, ^{9}Li)^{3}H$ at 3A MeV

I. Tanihata,* M. Alcorta,† D. Bandyopadhyay, R. Bieri, L. Buchmann, B. Davids, N. Galinski, D. Howell, W. Mills, S. Mythili, R. Openshaw, E. Padilla-Rodal, G. Ruprecht, G. Sheffer, A.C. Shotter, M. Trinczek, and P. Walden
TRIUMF, 4004 Wesbrook Mall, Vancouver, BC, V6T 2A3, Canada

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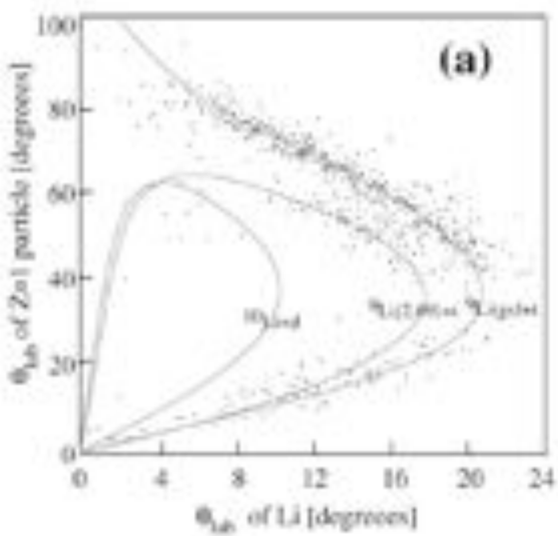
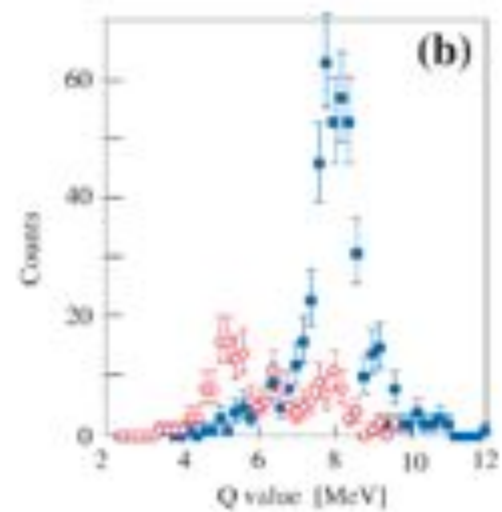
R. Kanungo and A. Gallant
Saint Mary's University, 923 Robie St., Halifax, Nova Scotia B3H 3C3, Canada

M. Notani and G. Savard
ANL, 9700 S. Cass Ave., Argonne, Illinois 60439, USA

I. J. Thompson
LLNL, L-414, P.O. Box 808, Livermore, California 94551, USA
(Received 22 January 2008; published 14 May 2008)





37MeV ^{11}Li from ISAC2 plus MAYA active target detector system

PRL 105, 172502 (2010) PHYSICAL REVIEW LETTERS week ending 22 OCTOBER 2010

Evidence for Phonon Mediated Pairing Interaction in the Halo of the Nucleus ^{11}Li

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Dipartimento di Fisica, Università di Milano, Via Celoria 16, 20133 Milano, Italy,
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and Departamento de Fisica Atomica, Molecular y Nuclear, Universidad de Sevilla,
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Sevilla, 41092 Camino de los Descubrimientos s/n, Spain

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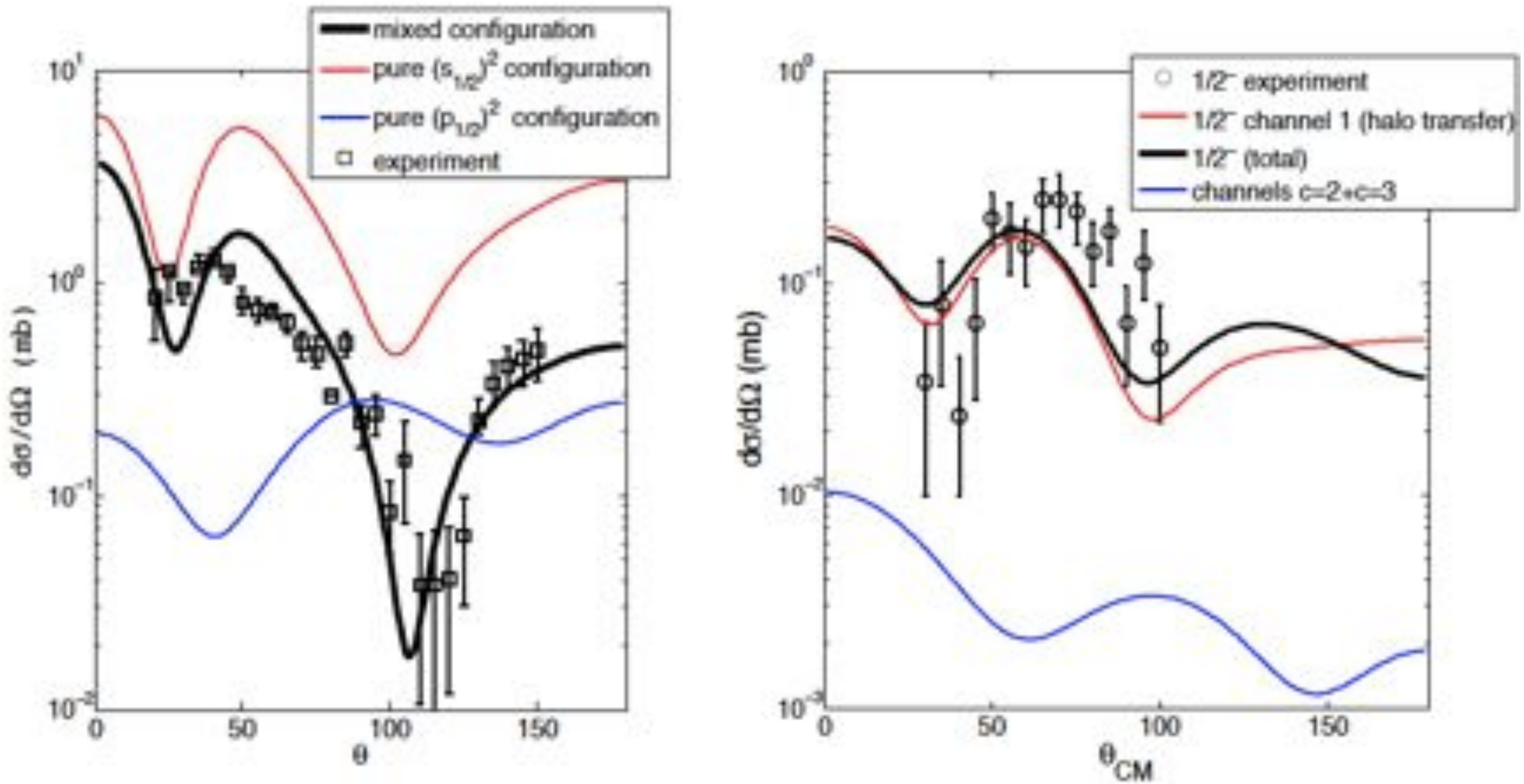
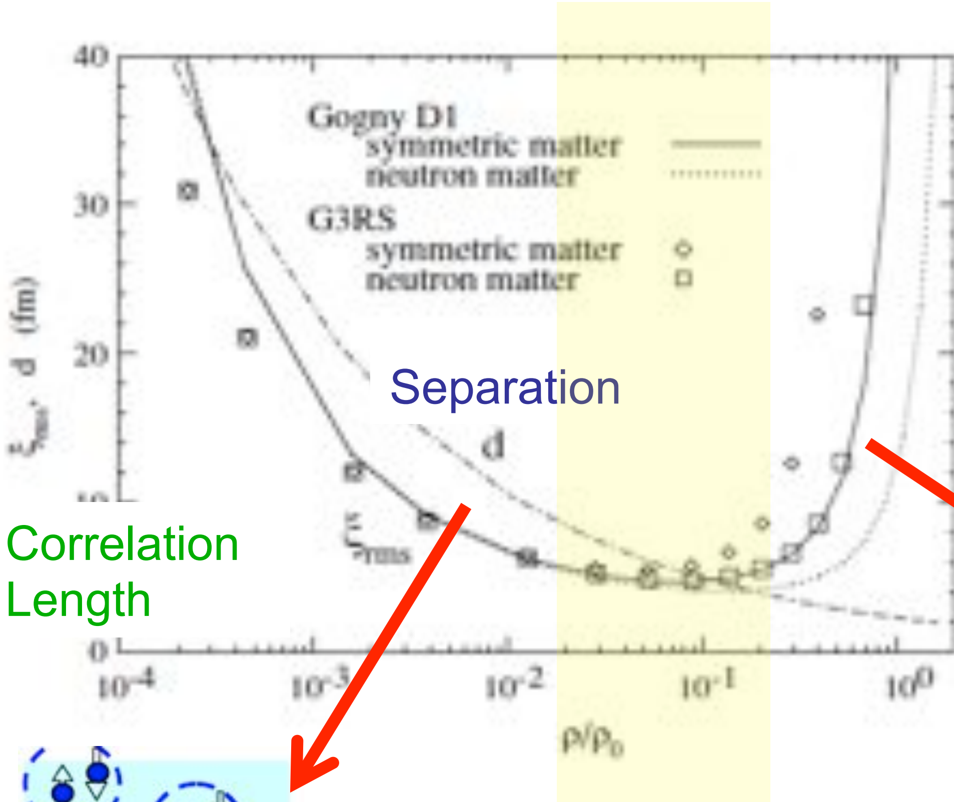
INFN, Sezione di Milano Via Celoria 16, 20133 Milano, Italy
and The Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, 2100 Copenhagen Ø, Denmark
(Received 16 December 2009; published 19 October 2010)

- Two particle transfer in second order DWBA
- Simultaneous and successive transfer
- Absolute normalization !!!



mixed configuration
pure $(s_{1/2})^2$ configuration
pure $(p_{1/2})^2$ configuration
experiment
dσ/dΩ (mb)
θ
1/2⁻ experiment
1/2⁻ channel 1 (halo transfer)
1/2⁻ (total)
channels c=2+c=3
dσ/dΩ (mb)
θ_{CM}

Pairing in weakly bound systems

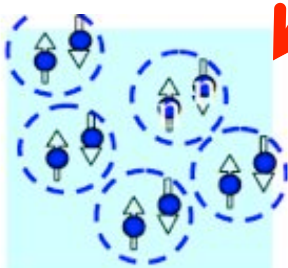


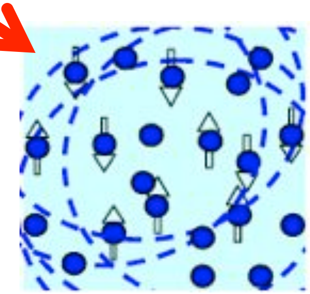
Matsuo PRC 73 (2006)044309

N. Pillet et al. PRC 76 (2007)024310

Separation

Correlation Length





Skin Di-neutrons

Effects on Two-neutron transfer reactions

Do we expect an enhancement of the cross-section ?

Pair and single neutron transfer with Borromean ^{8}He

Physics Letters B 697 (2011) 454–458

A. Lemasson[a,1], A. Navin[a,*], M. Rejmund[a], N. Keeley[b], V. Zelevinsky[c], S. Bhattacharyya[a,d], A. Shrivastava[a,e], D. Bazin[c], D. Beaumel[f], Y. Blumenfeld[f], A. Chatterjee[e], D. Gupta[f,2], G. de France[a], B. Jacquot[a], M. Labiche[g], R. Lemmon[g], V. Nanal[h], J. Nyberg[i], R.G. Pillay[h], R. Raabe[a,3], K. Ramachandran[e], J.A. Scarpaci[f], C. Schmitt[a], C. Simenel[j], I. Stefan[a,f,4], C.N. Timis[k]

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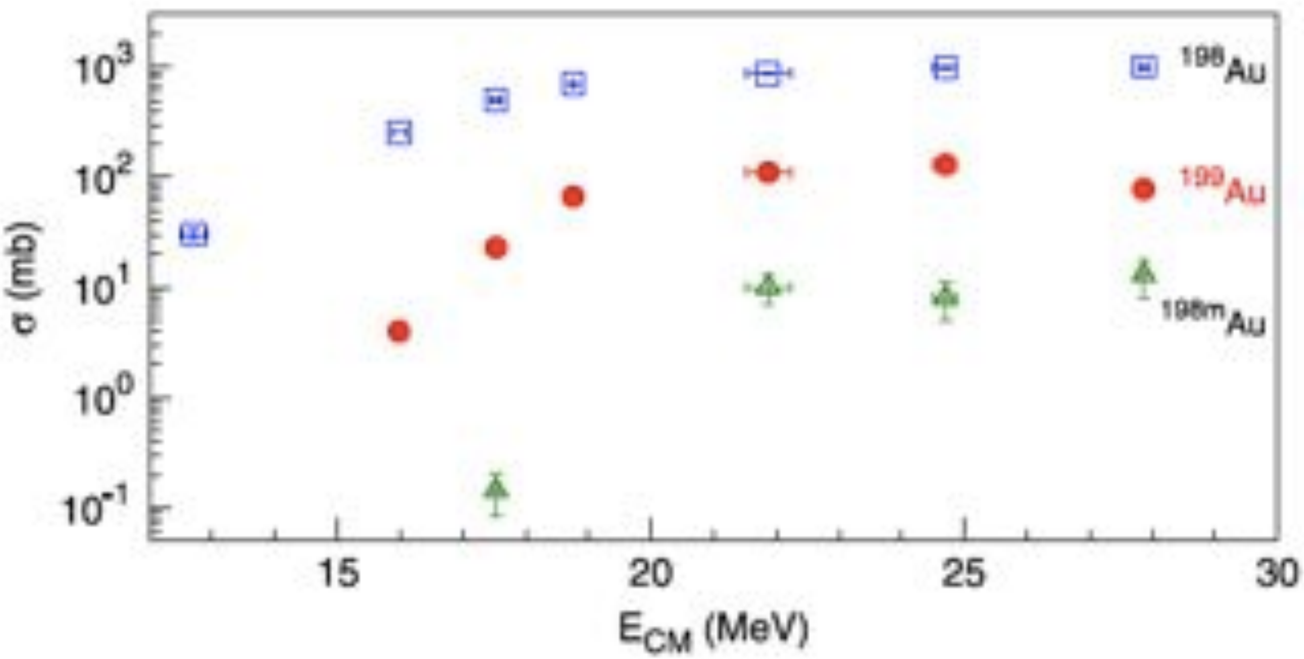


Pairing Phase Transition in Neutron Rich Nuclei

Properties of pairing phonons near $^{68,78}Ni$ and ^{132}Sn doubly magic nuclei, transition to superfluid.

Do we expect a different behavior ?

Opportunity to study the density dependence of nucleon pairing.

Cross sections to 0^+ and first excited 0+ and 2^+ show sensitivity to the volume/surface nature of pairing correlations.

(cf. M. Matsuo, Nuclear Structure 2010)

(t,p) and (p,t) reactions in reverse kinematics.

Expected reaccelerated beam intensities ~ 5 10^6 pps for ^{78}Ni and ^{132}Sn ✔

Efficient, high resolution light-particle detectors system (for example ANL - HELIOS)

Tritium targets for (t,p)

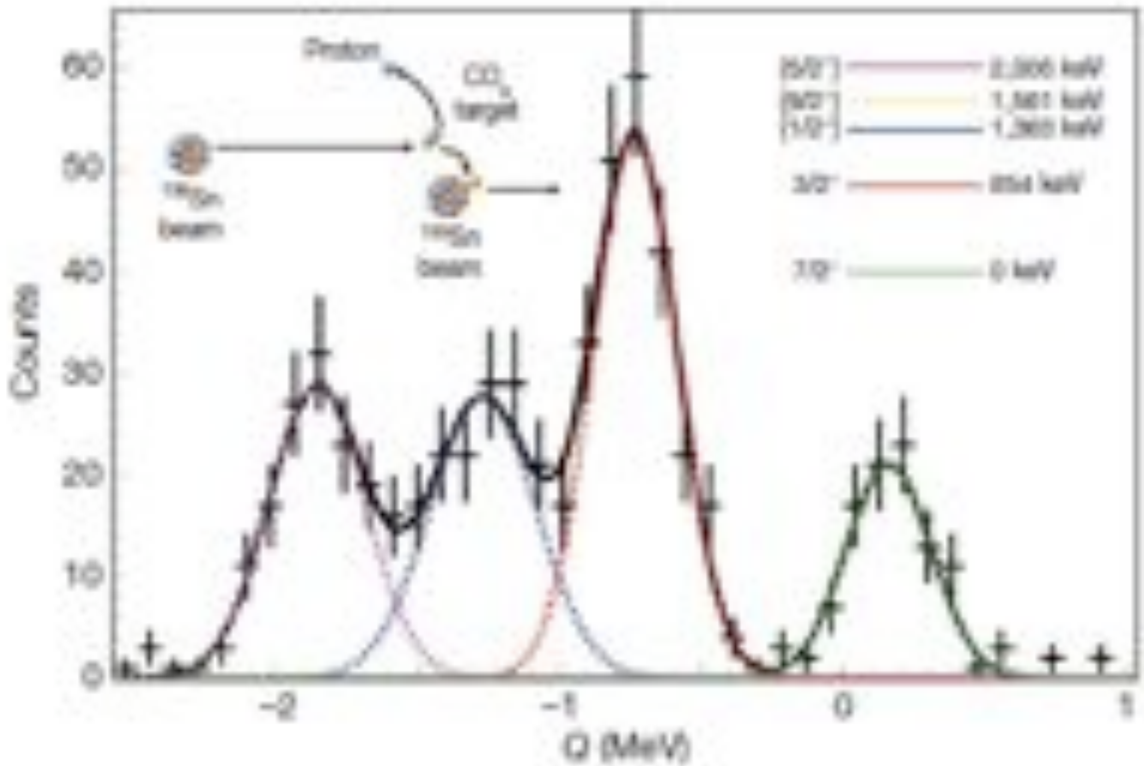
Ti loaded foils. Gas cell. $100\mu g/cm^2$ ~ 1Ci

Vol 465 | 27 May 2010 | doi:10.1038/nature09048

LETTERS

The magic nature of ^{132}Sn explored through the single-particle states of ^{133}Sn

K. L. Jones[1,2], A. S. Adekola[3], D. W. Bardayan[4], J. C. Blackmon[4], K. Y. Chae[1], K. A. Chipps[5], J. A. Cizewski[2], L. Erikson[5], C. Harlin[6], R. Hatarik[2], R. Kapler[1], R. L. Kozub[7], J. F. Liang[4], R. Livesay[5], Z. Ma[1], B. H. Moazen[1], C. D. Nesaraja[4], F. M. Nunes[8], S. D. Pain[2], N. P. Patterson[6], D. Shapira[4], J. F. Shriner Jr[7], M. S. Smith[4], T. P. Swan[2,6] & J. S. Thomas[6]



Thermal Properties of Pairing Correlations

Breaking of Cooper pairs with temperature. Phase transition.
Measurement of level densities with excitation energy. Oslo Group.

$$T^* \sim 0.7\Delta$$

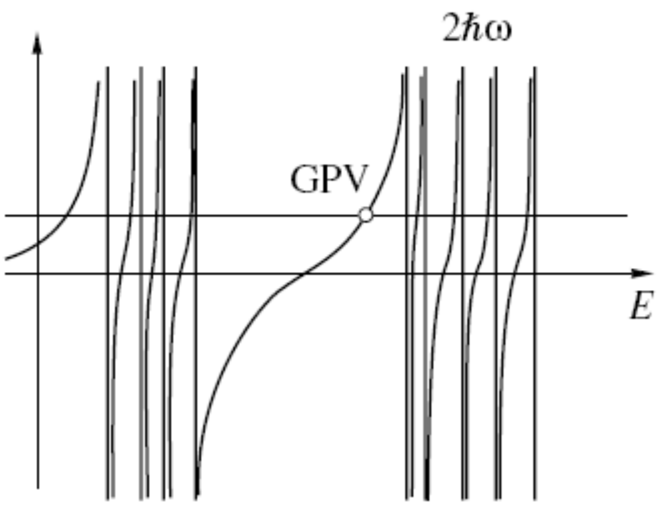
R. Chancova et al. Phys. Rev. C73 034311 (2006)

(^{3}He,α) (^{3}He,^{3}He') reactions in Mo -isotopes

Giant Pairing Vibration

Elementary mode of excitation, not yet discovered.

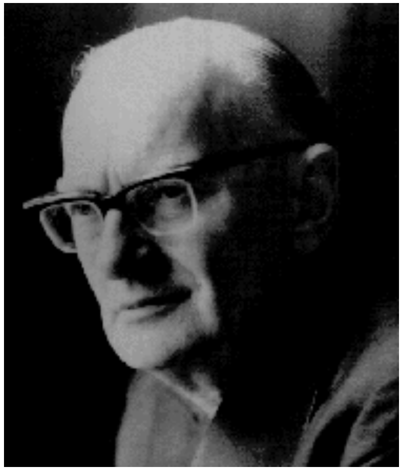
Use weakly bound projectiles such as ^{6}He to avoid Q-value mismatch.



$$\hbar\omega \sim 2\hbar\omega_0 - \Omega G \sim 60-70 MeV / A^{1/3}$$

“Prediction is very difficult, especially about the future.”

Niels Bohr



“The future isn’t what it used to be.”

Arthur C. Clarke

Augusto's Forecast

Sunny & Warm

I hope I did succeed in conveying to you the exciting physics of pairing phenomena in nuclei, and I trust you had as much fun as I did in preparing the lectures.

Merci Beaucoup !

Best wishes to you all!