Pairing and Two-nucleon Transfer reactions

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Interfaces between structure and reactions for rare isotopes and nuclear astrophysics

August 8 - September 2, 2011

INSTITUTE FOR NUCLEAR THEORY

Work supported by the US-DOE under contract number DE-AC02-05CH11231.

$$\langle \text{Jenny's Talk} \,|\, \text{Augusto's Talk} \rangle \sim 1$$

$$U^T |\, \text{Augusto's Talk} \rangle \rightarrow \widetilde{|\, \text{Augusto's Talk} \rangle}$$

Outline

Short Introduction

Two-nucleon transfer reactions

- Some examples

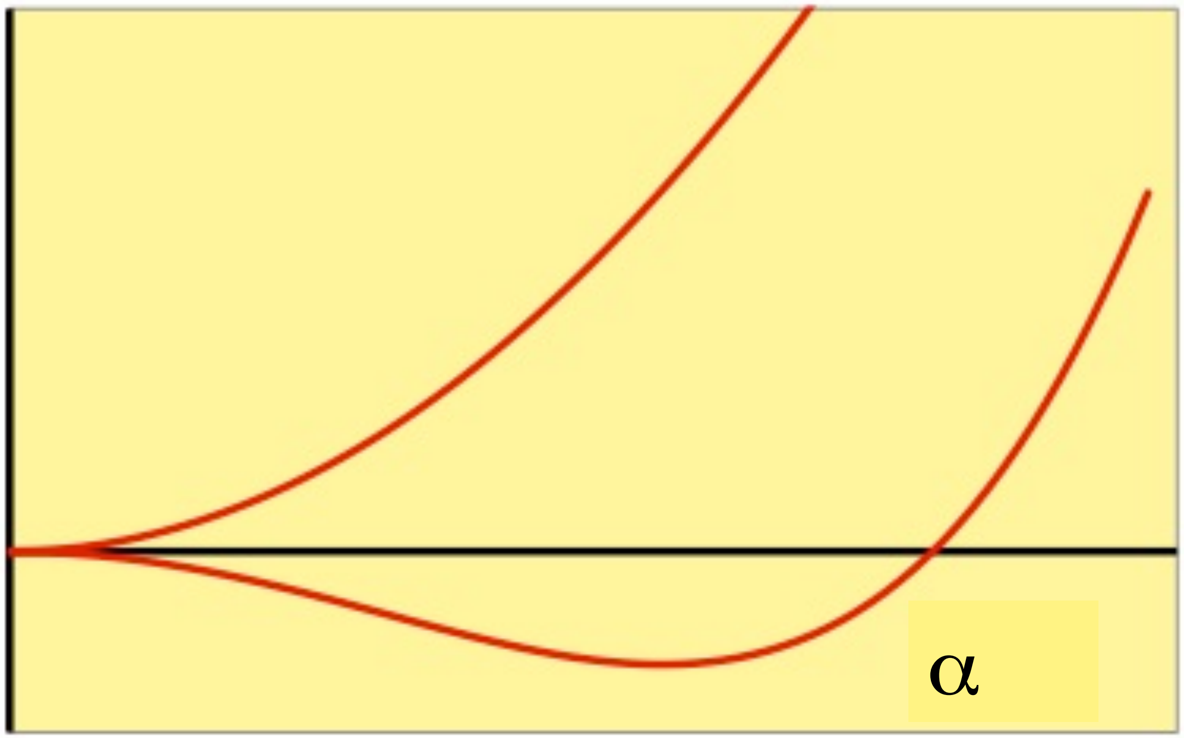
NP-Pairing and the (^{3}He,p) reaction

- Proof of principle
- A ^{44}Ti beam
- Next steps
- np knockout?

Other topics for discussion

- Giant Pairing Vibration
- Pairing in neutron rich nuclei

Conclusions

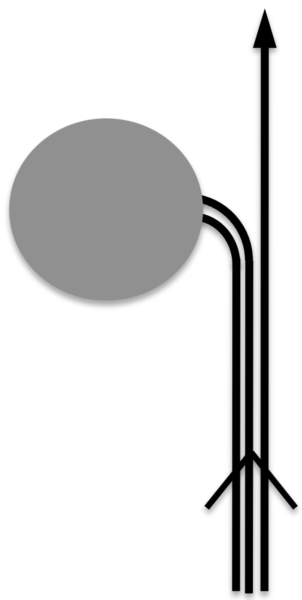


Deformation of the pair-field $\alpha = \frac{\Delta}{G} = < \Sigma a_{\nu}^{+} a_{\bar{\nu}}^{+} >$

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

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 $\langle f|a^+a^+|i\rangle$, $\langle f|aa|i\rangle$ are the analogous to the transition probabilities BE2's on the quadrupole case.

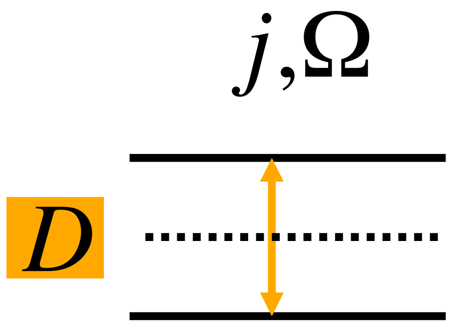


Process amplitude proportional to :

$$< A+2 \,|\, a^{+}a^{+} \,|\, A >$$

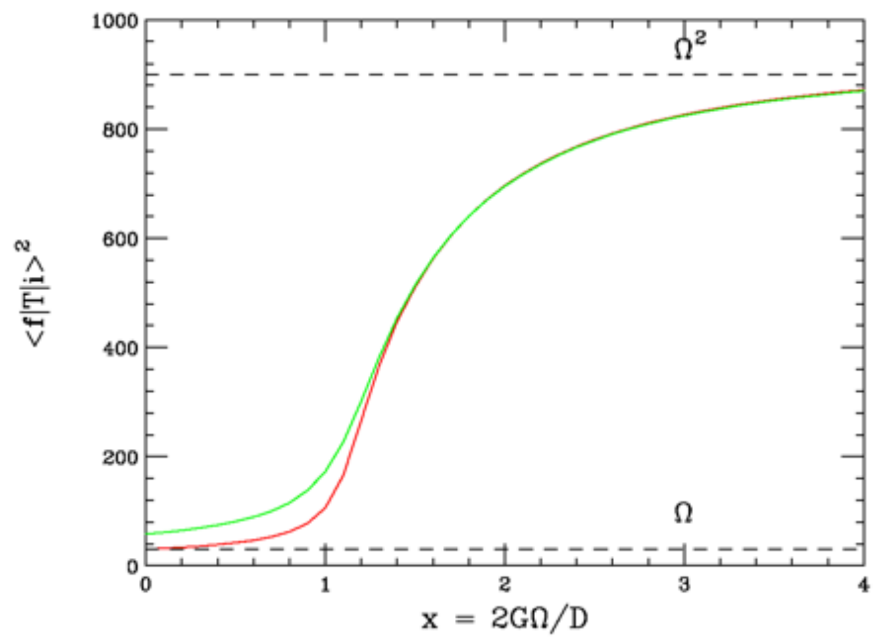
Pair correlations result in a constructive interference of reaction amplitudes giving a enhanced two-nucleon transfer.

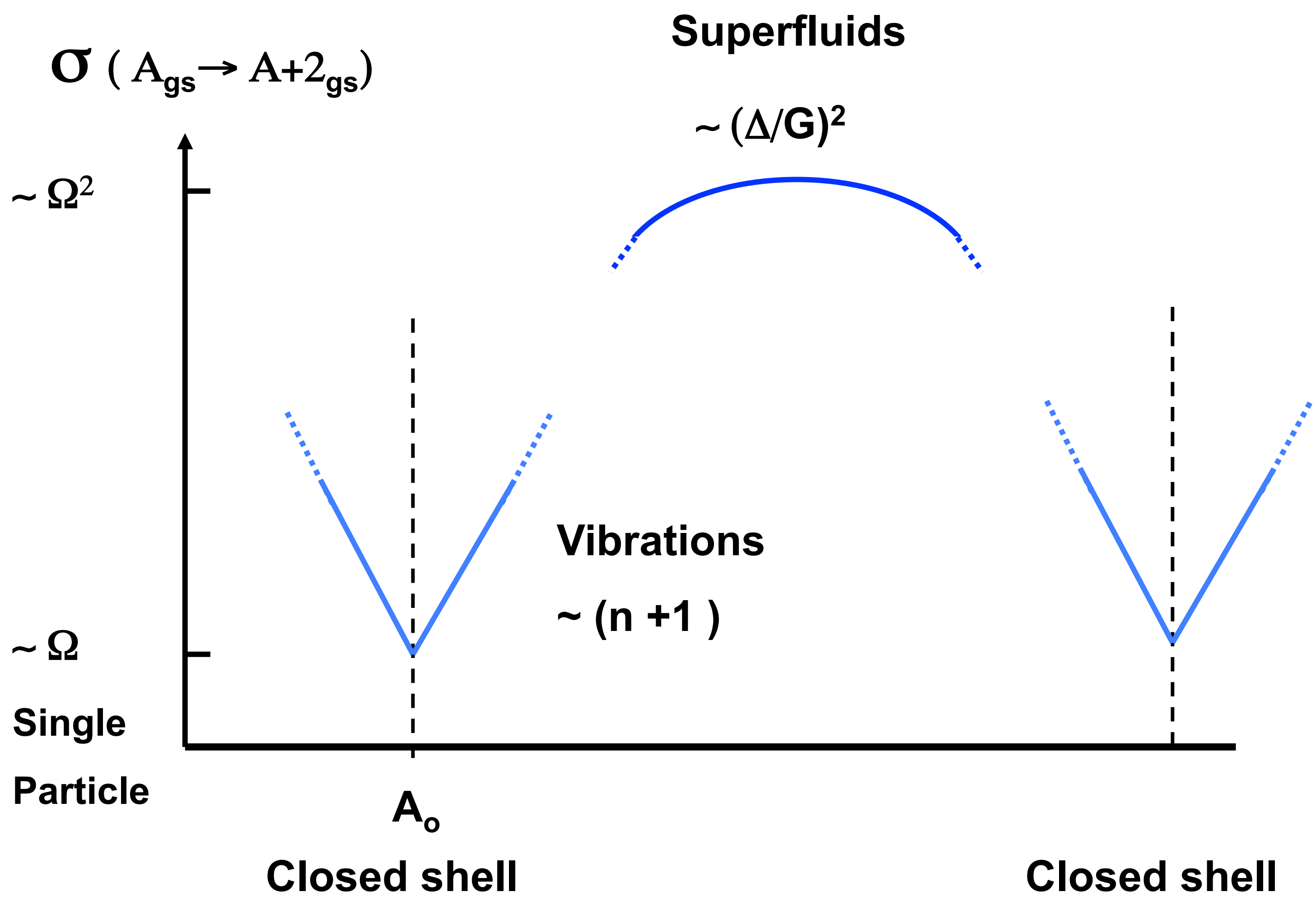
A simple microscopic model: Two j-shells



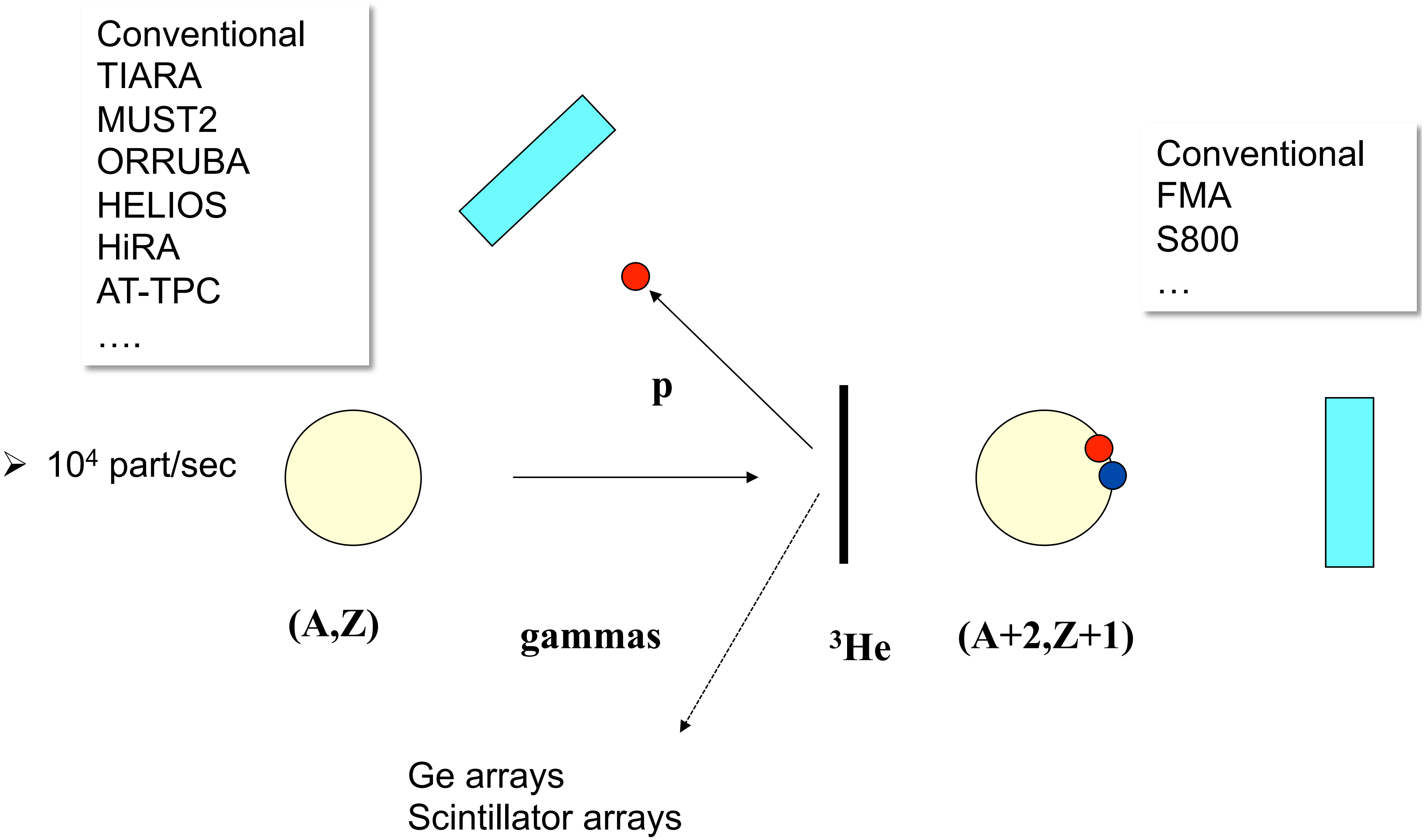
$$H = \frac{D}{2}(N_{j2} - N_{j1}) - \frac{1}{4}G(P^\dagger_{j1} + P^\dagger_{j2})(P_{j1} + P_{j2})$$

$$N_j = \sum_m a^\dagger_{jm} a_{jm} \qquad P^\dagger_j = \sum_{m>0} (-1)^{j+m} a^\dagger_{jm} a^\dagger_{j-m}$$

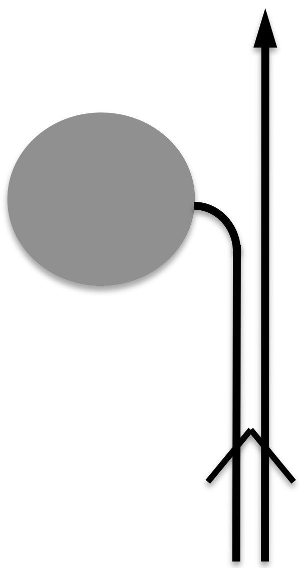




Systematic relative measurements and within a given nucleus.



Measure E(Θ), $d\sigma/d\Omega$ (Θ), σ



$$< A+1 \,|\, a^{+} \,|\, A >$$

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

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

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

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

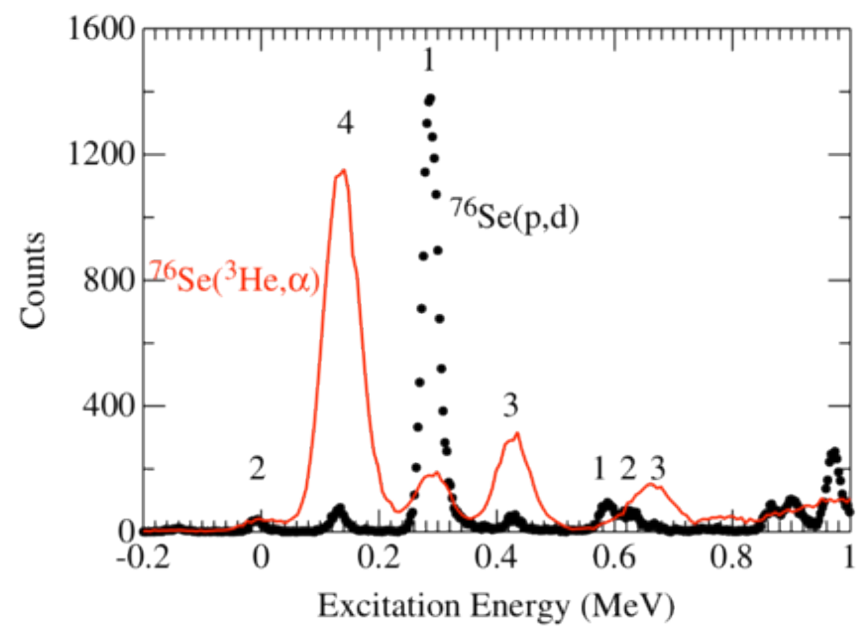
Single-particle occupancies are a measurable characteristic of a gs wave function that might help test input to DBBD matrix elements.

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)

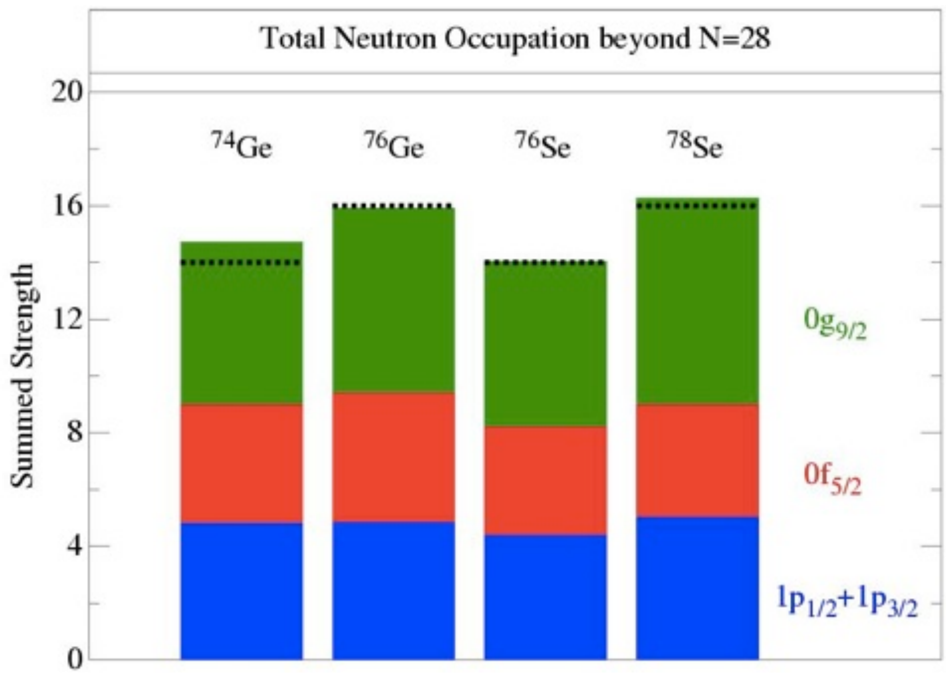
Reactions with different Q values to ensure observation across all L-transfers.

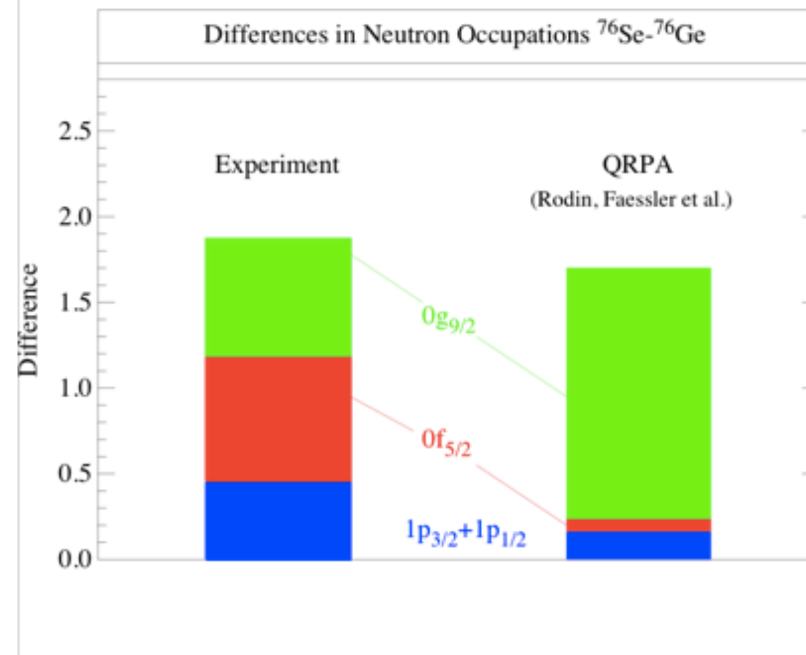
Neutron-adding AND neutron-removing reactions: mid-shell nuclei with partial occupancy of *fpg* orbitals.
Measurements of *occupancy **and** vacancy* in *removing **and** adding* reactions should add up to *(2j+1)*.



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

Courtesy of Sean Freeman





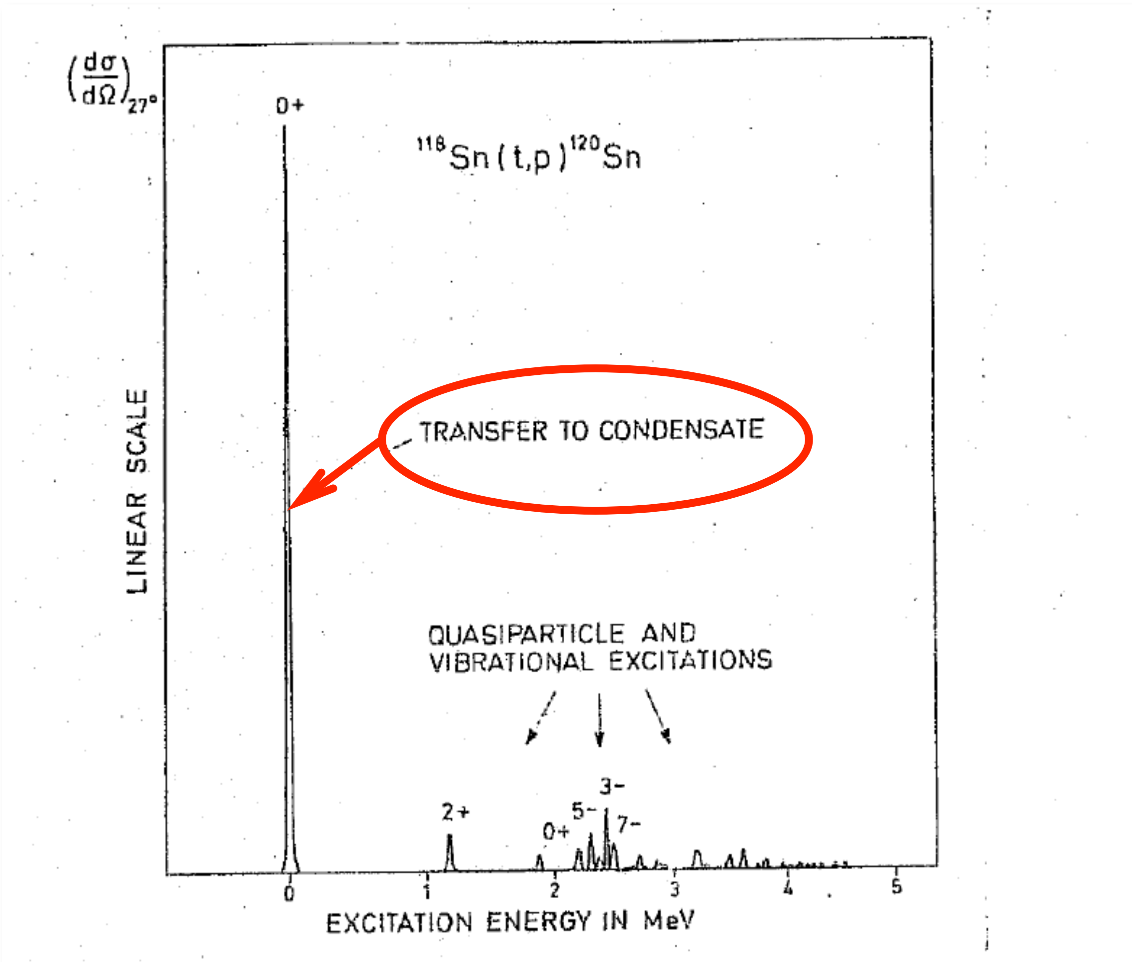
Fermi surface seems considerably more diffuse than QRPA.
Neutrons from three to four orbits are changing substantially between ^{76}Ge and ^{76}Se, while in QRPA the change is almost entirely in the $0g_{9/2}$.

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.

Courtesy of Sean Freeman

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

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)

PHYSICAL REVIEW C **78**, 064608 (2008)

^{118}Sn levels studied by the ^{120}Sn(p, t) reaction: High-resolution measurements, shell model, and distorted-wave Born approximation calculations

P. Guazzoni and L. Zetta
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School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA

T. Faestermann, G. Graw, R. Hertenberger, and H.-F. Wirth
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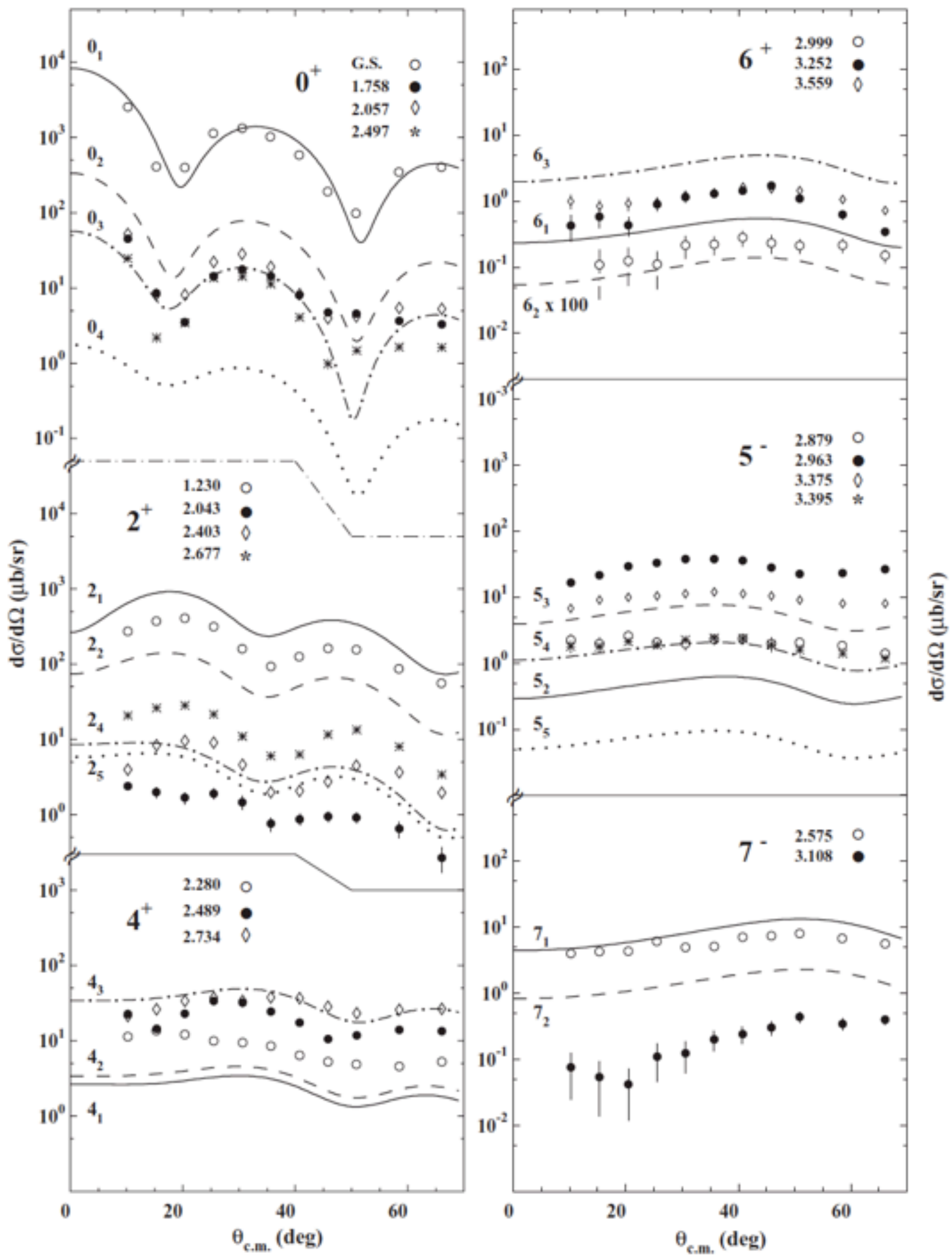
M. Jaskola
Soltan Institute for Nuclear Studies, Warsaw, Poland
(Received 17 September 2008; published 15 December 2008)

20Mev protons from LMU and TU – Munich Tandem and Q3D



One step DWBA
TWOFNR

Shell-model TNAs with CD-Bonn derived effective interaction

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
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[3]GANIL (IN2P3/CNRS-DSM/CEA), B. P. 55027 F-14076 Caen Cedex 5, France
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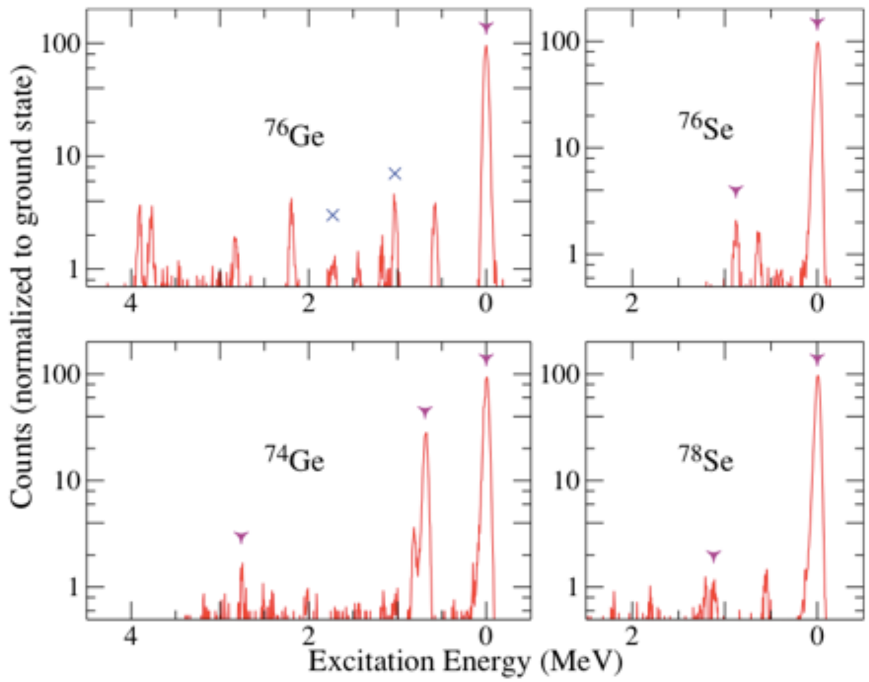
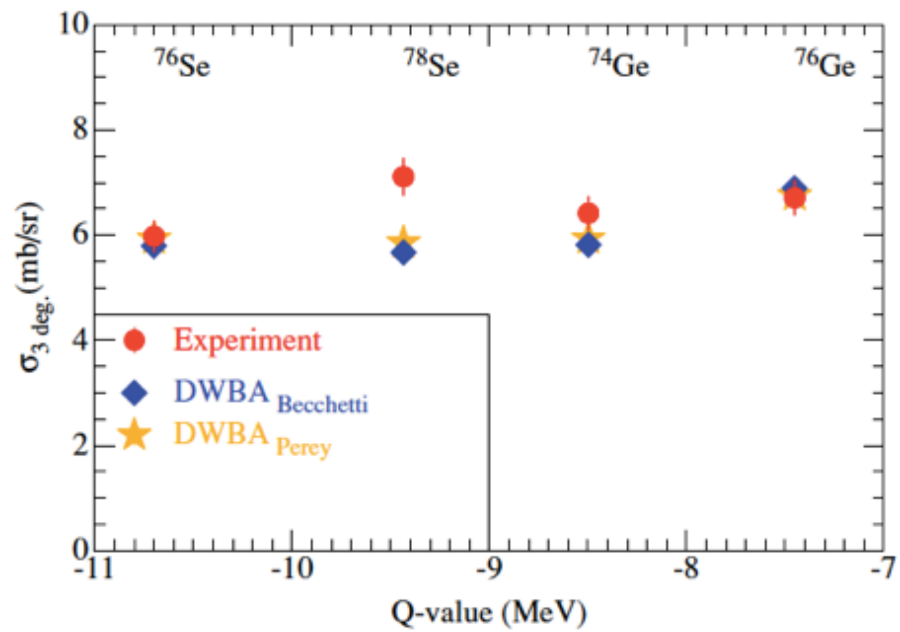
[5]The Open University, Dept. of Physics and Astronomy, Milton Keynes, MK7 6AA, United Kingdom

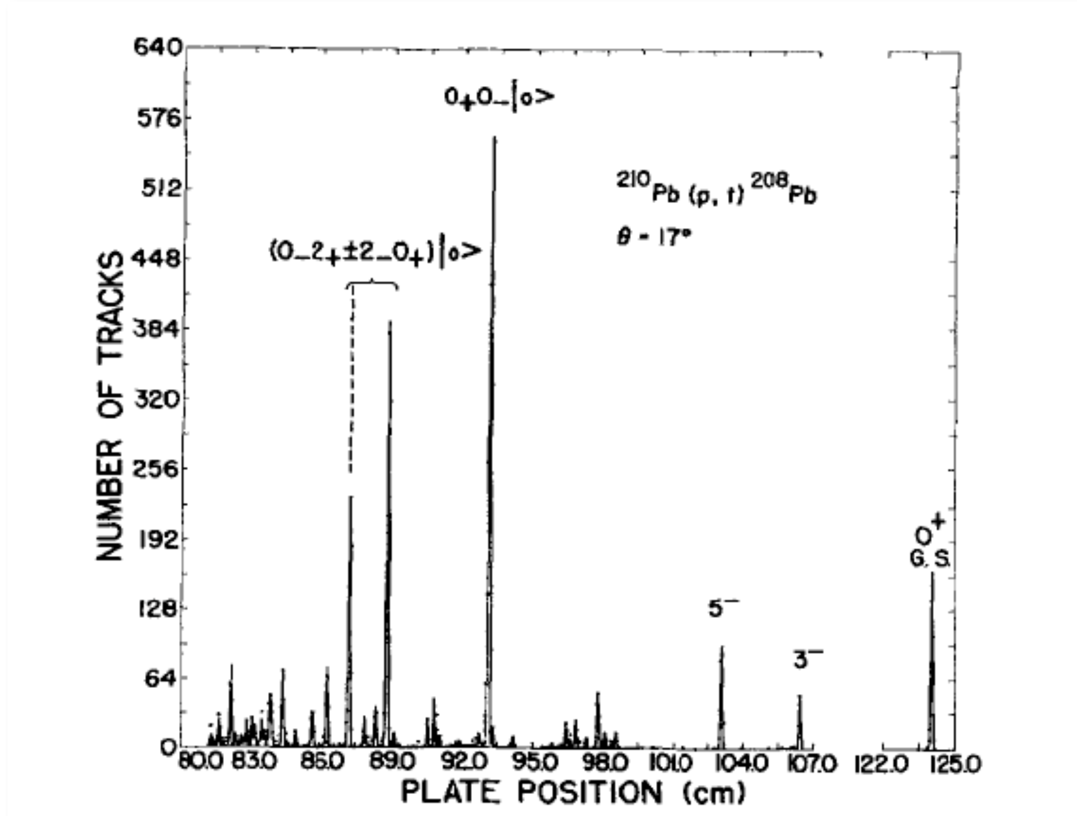
20MeV protons Yale Tandem. Split-pole spectrograph.

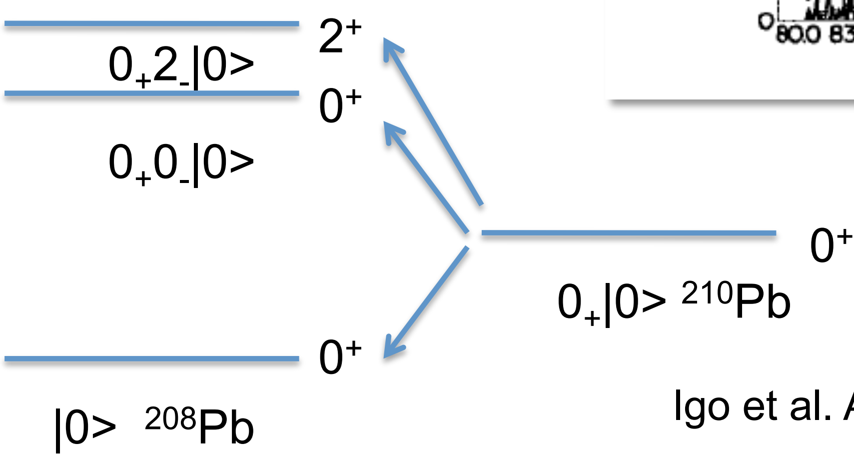




For ^{76}Ge and ^{76}Se (p,t) strength is predominately to the ground states, indicating they can be described as simple BCS paired states with quantitatively similar pair correlations.

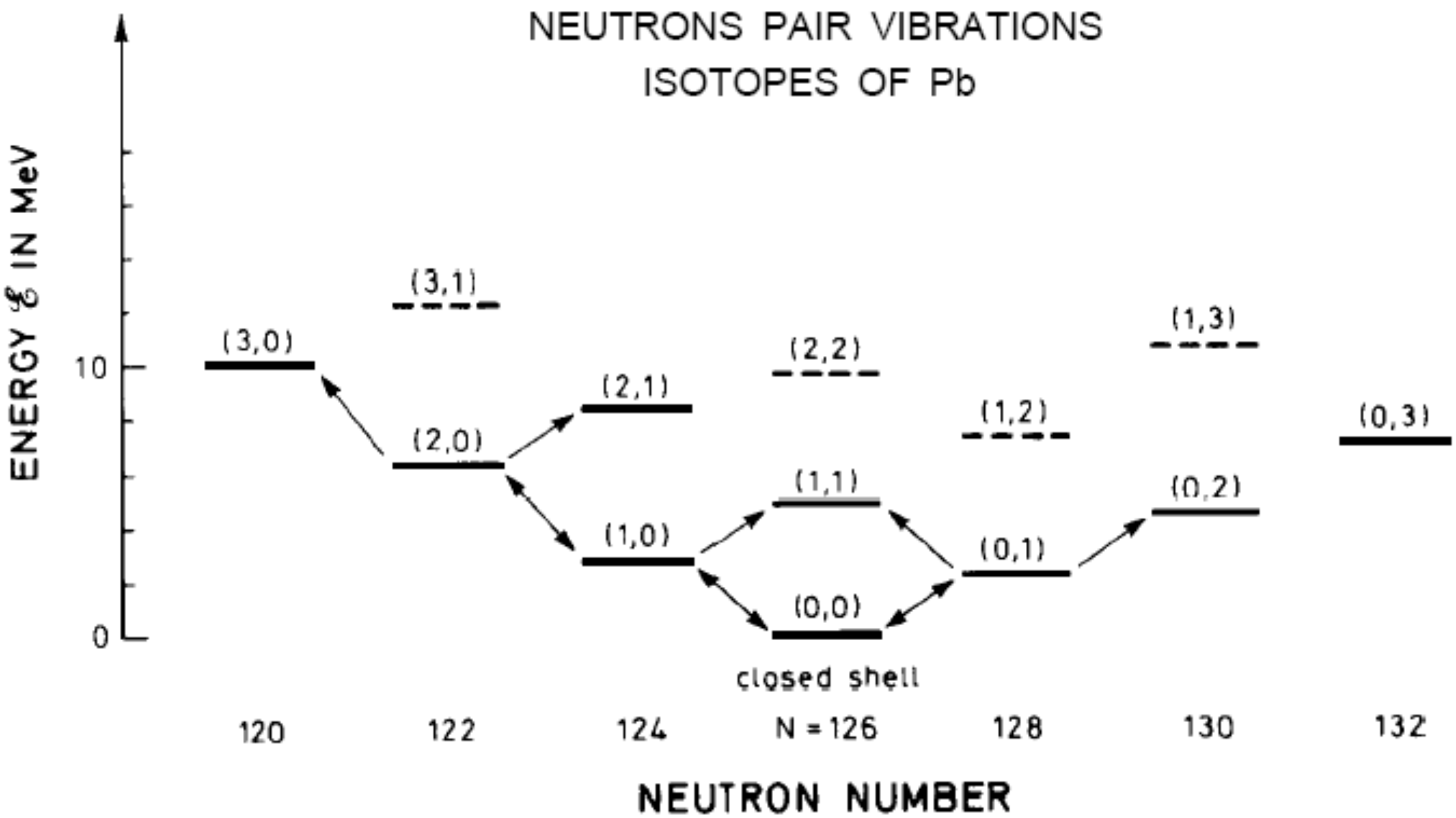
An example of pairing vibrations:





Igo et al. ANNALS OF PHYSICS: 66, 6O-116 (1971)

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

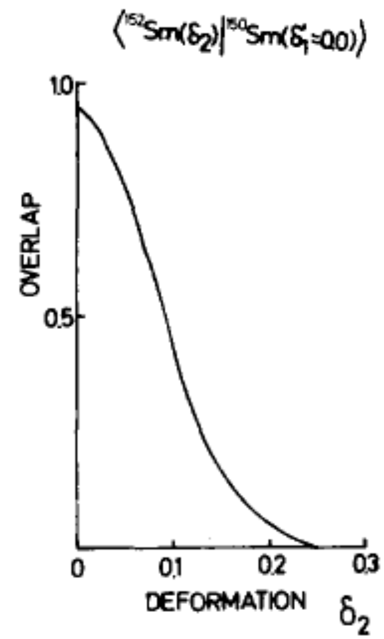


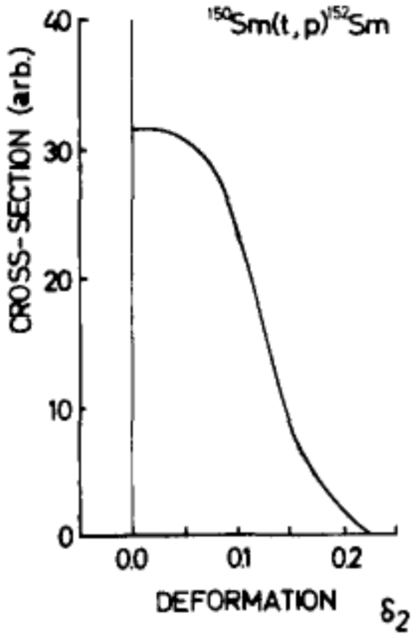
- Fluctuations give rise to a vibrational-like excitation spectrum.
- Enhanced pair-addition and pair-removal cross-sections seen in (t,p) and (p,t) reactions (indicated by arrows).
- Large anharmonicities in spectrum must be accounted for.

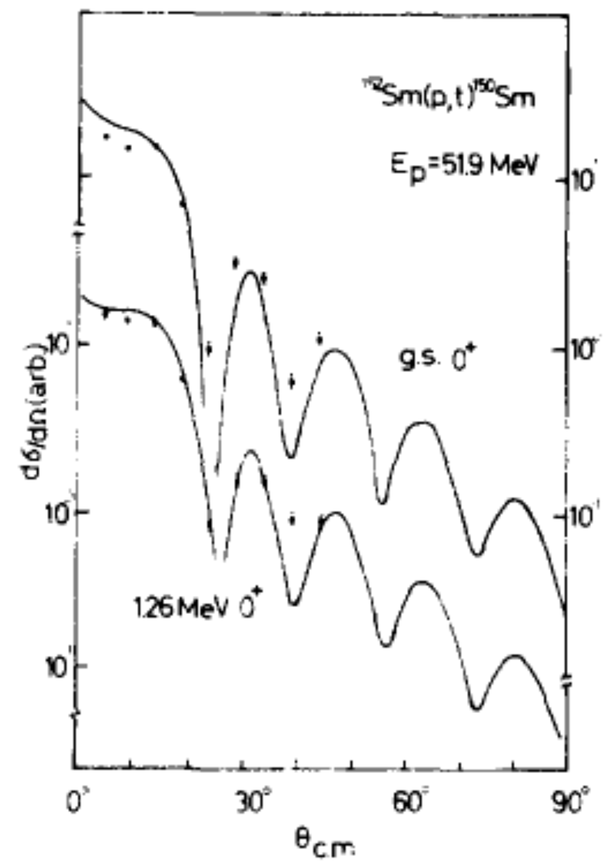
Volume 37, number 5 PHYSICS LETTERS 27 December 1971

TWO-NEUTRON TRANSFER REACTIONS ON NUCLEI IN THE TRANSITIONAL REGION

T. TAKEMASA, M. SAKAGAMI and M. SANO
Department of Physics, Osaka University, Osaka, Japan







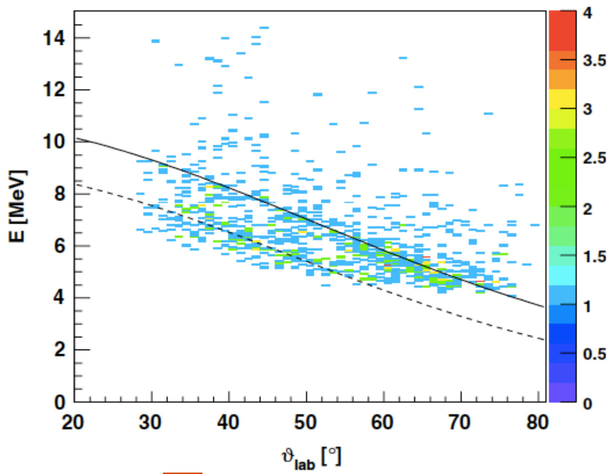
Nilsson/Collective Model framework. Should it be revisited theoretically?

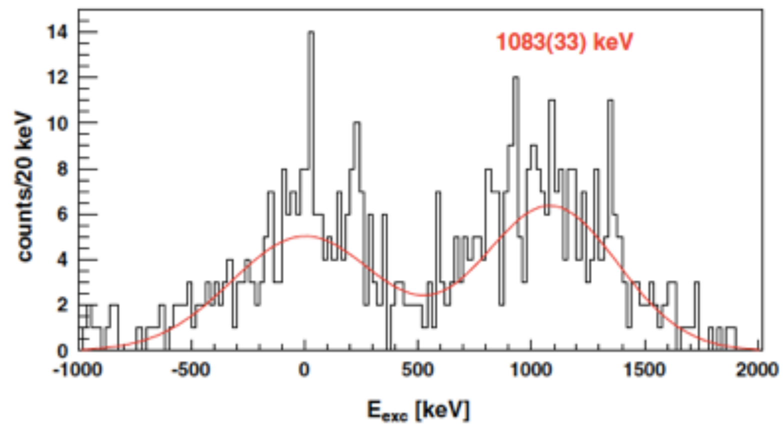
PRL 105, 252501 (2010)
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS
week ending 17 DECEMBER 2010

Discovery of the Shape Coexisting 0^+ State in ^{32}Mg by a Two Neutron Transfer Reaction

K. Wimmer,[1] T. Kröll,[1,*] R. Krücken,[1] V. Bildstein,[1] R. Gernhäuser,[1] B. Bastin,[2] N. Bree,[2] J. Diriken,[2] P. Van Duppen,[2] M. Huyse,[2] N. Patronis,[2,†] P. Vermaelen,[2] D. Voulot,[3] J. Van de Walle,[3] F. Wenander,[3] L. M. Fraile,[4] R. Chapman,[5] B. Hadinia,[5] R. Orlandi,[5] J. F. Smith,[5] R. Lutter,[6] P. G. Thirolf,[6] M. Labiche,[7] A. Blazhev,[8] M. Kalkühler,[8] P. Reiter,[8] M. Seidlitz,[8] N. Warr,[8] A. O. Macchiavelli,[9] H. B. Jeppesen,[9] E. Fiori,[10] G. Georgiev,[10] G. Schrieder,[11] S. Das Gupta,[12] G. Lo Bianco,[12] S. Nardelli,[12] J. Butterworth,[13] J. Johansen,[14] and K. Riisager[14]

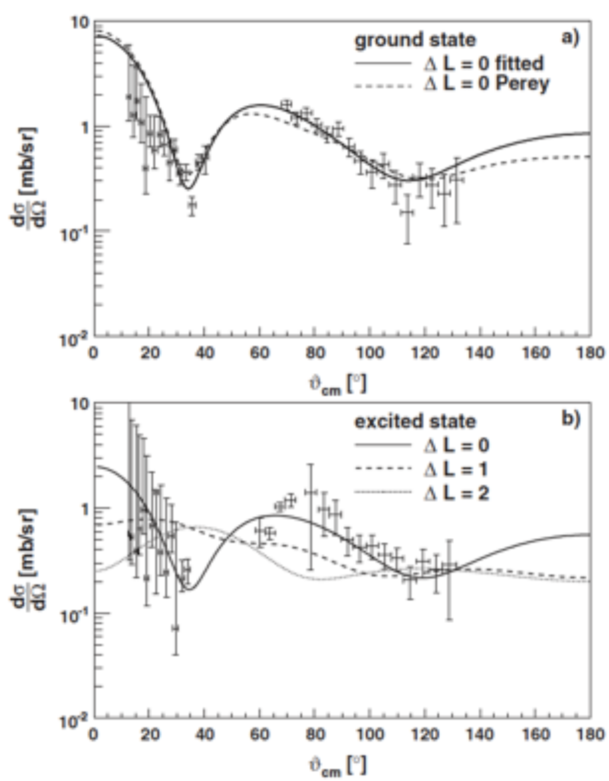
- REX-ISOLDE
- T-REX and MiniBall (gammas)
- Beam energy 1.8 MeV/A 30Mg
- Beam intensity $4 \cdot 10^4$ /s
- ~ 150 h of data with Tritium target
  (Titanium foil with 50 µg/cm2 Tritium)

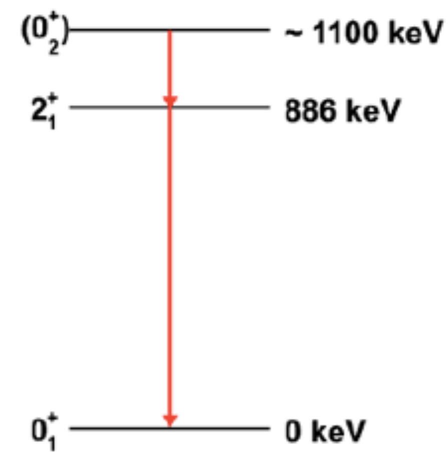




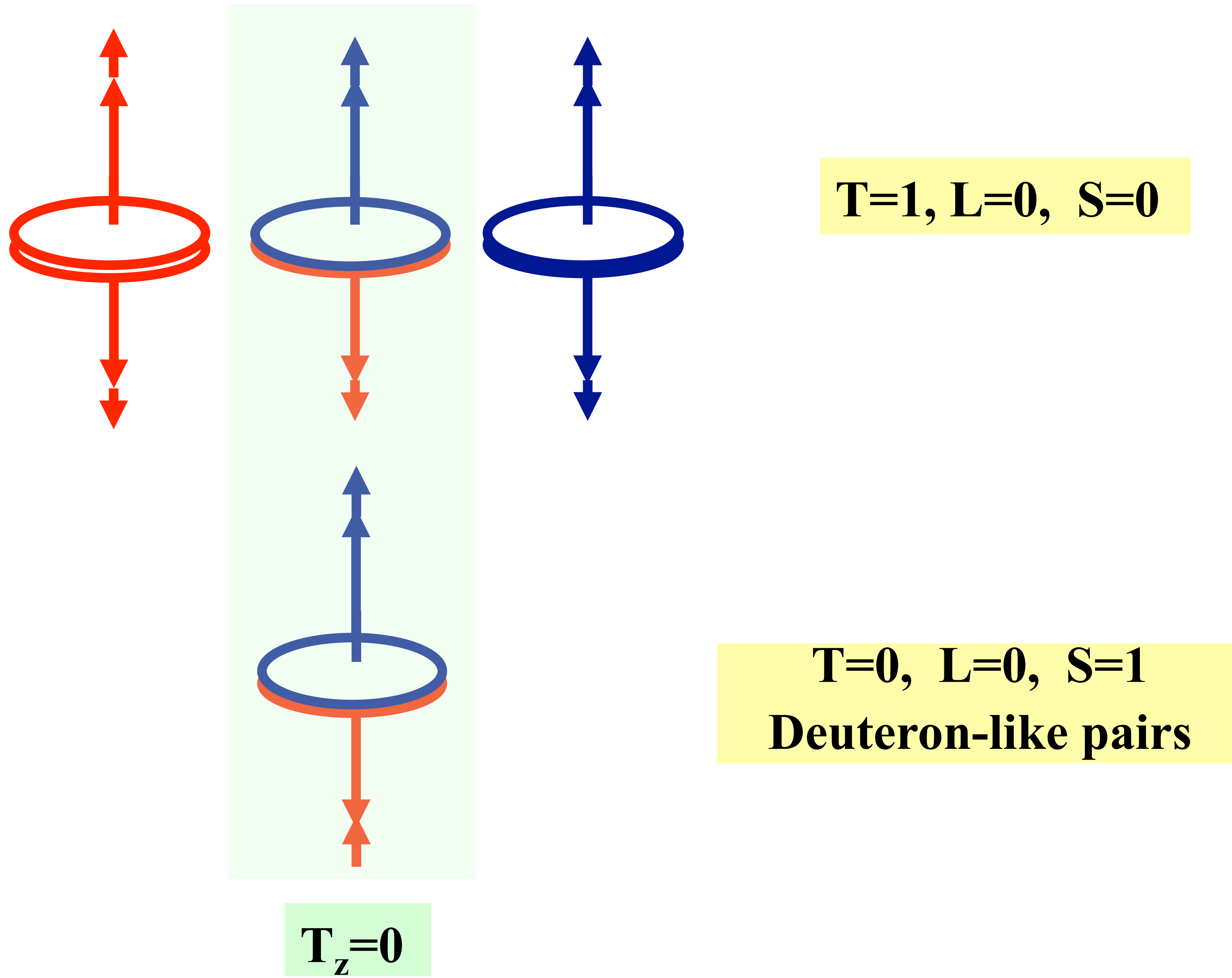
FRESCO

One step





Neutron-Proton Pairing



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.

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

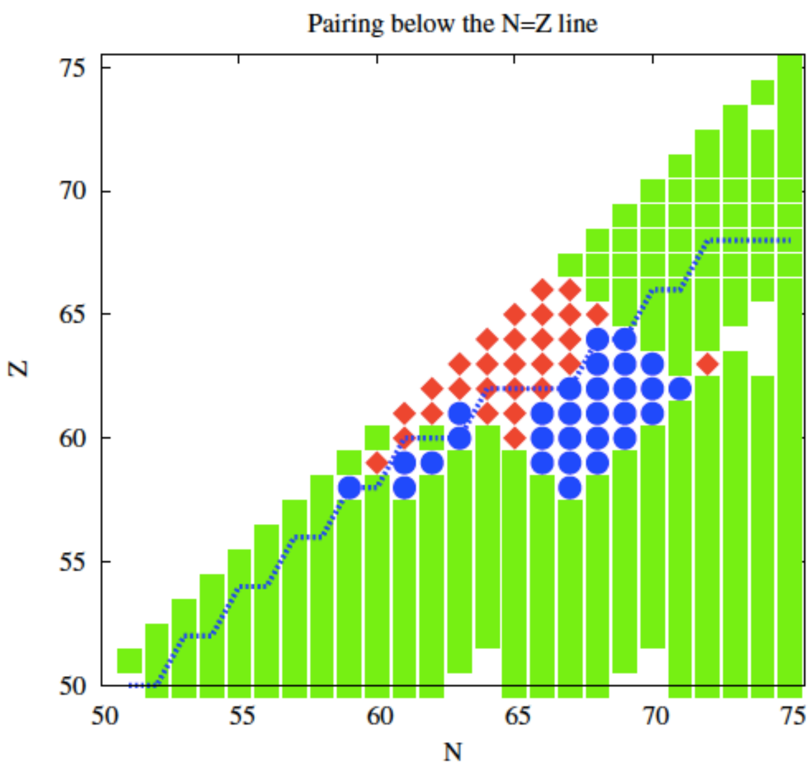
Beta Decay: Strong N=Z-2→ N=Z - 0^+ → 1^+ transition.
Gadea, Algora, et al.

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

PRL 106, 252502 (2011) PHYSICAL REVIEW LETTERS week ending 24 JUNE 2011

Mixed-Spin Pairing Condensates in Heavy Nuclei

Alexandros Gezerlis,[1] G. F. Bertsch,[1,2] and Y. L. Luo[1]
[1]Department of Physics, University of Washington, Seattle, Washington 98195-1560, USA
[2]Institute for Nuclear Theory, University of Washington, Seattle, Washington 98195-1560, USA
(Received 31 March 2011; published 23 June 2011)



Transfer reactions not likely.

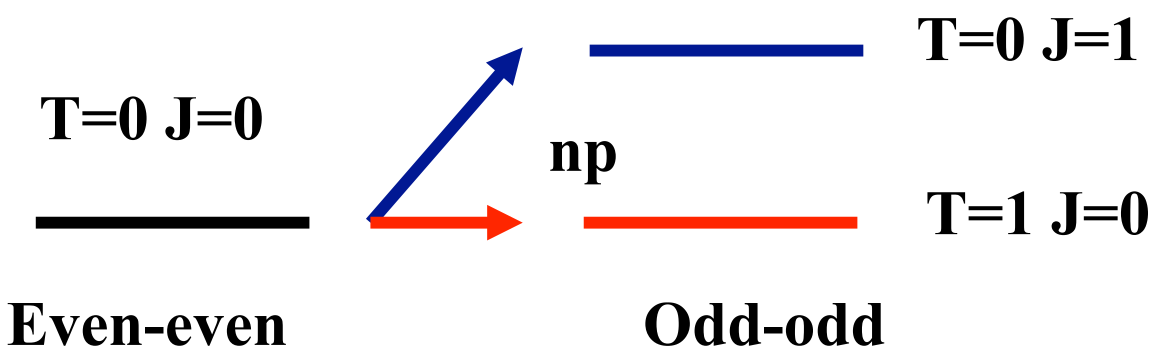
Detailed Spectroscopy following HI fusion.

Proton-decay tagging.

Deuteron decay??

(p, ^{3}He) (^{3}He,p)	ΔT=0,1
(d,α), (α,d)	ΔT=0
(α, ^{6}Li), (^{6}Li,α)	ΔT=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 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]
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[4]*Hebrew University, Jerusalem, Israel*
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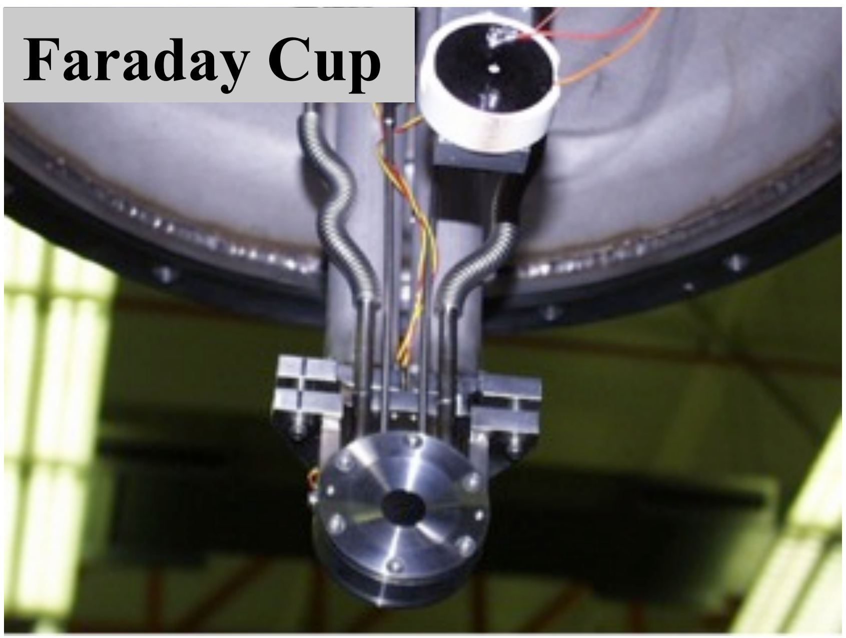
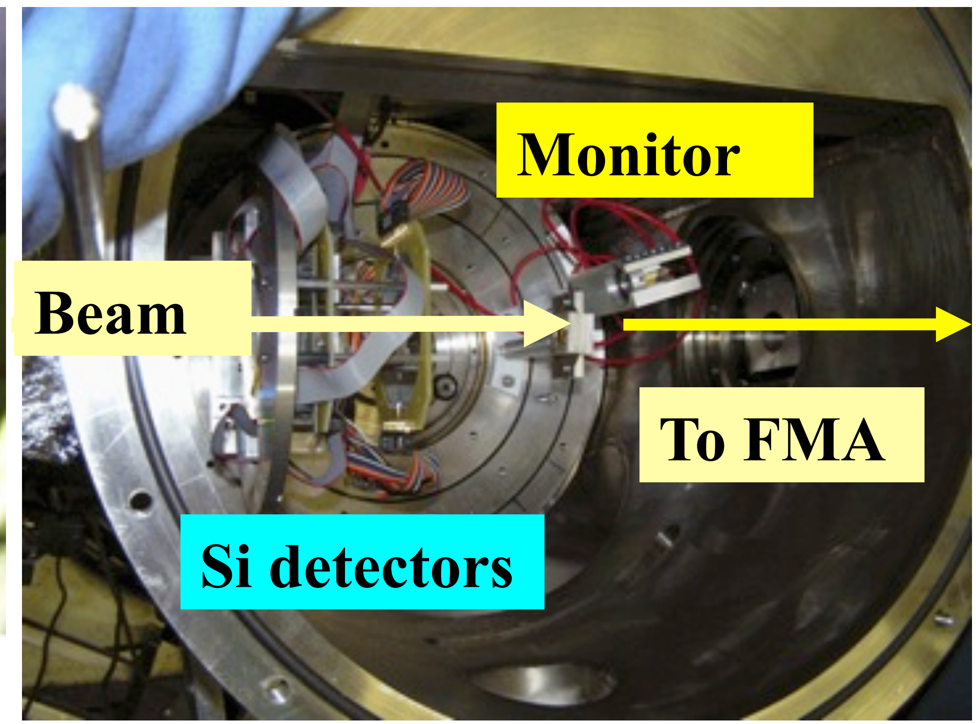
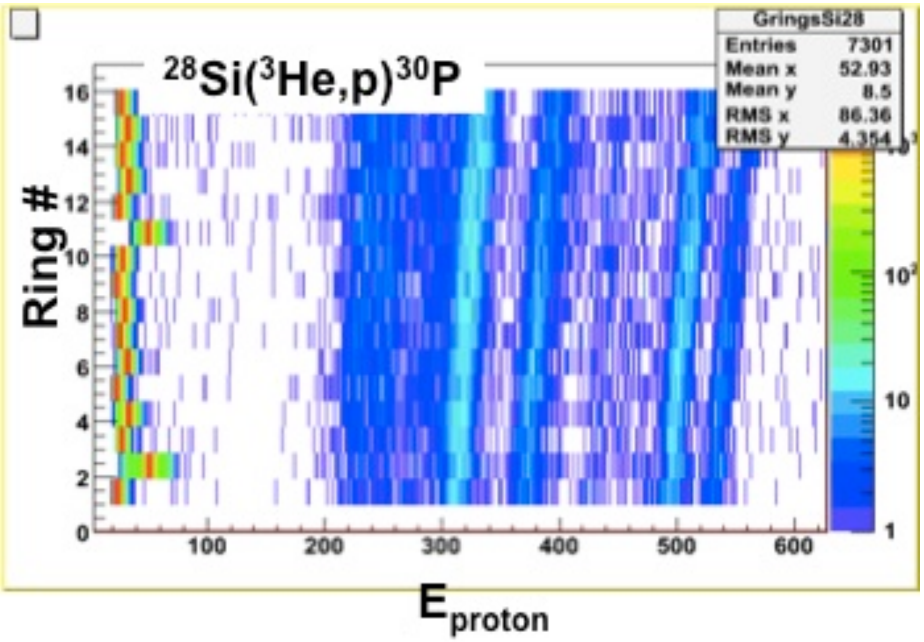


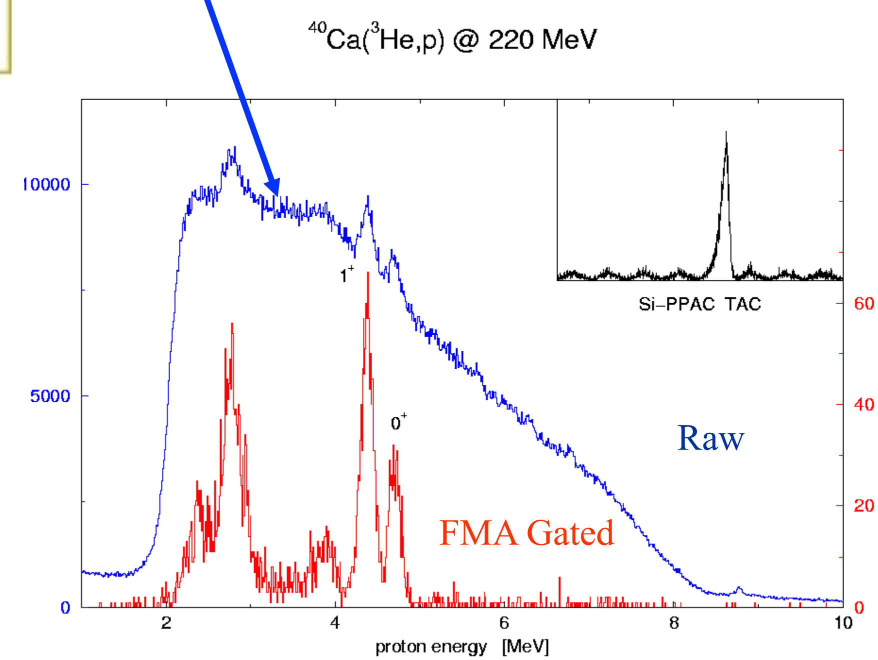
Gas Cell



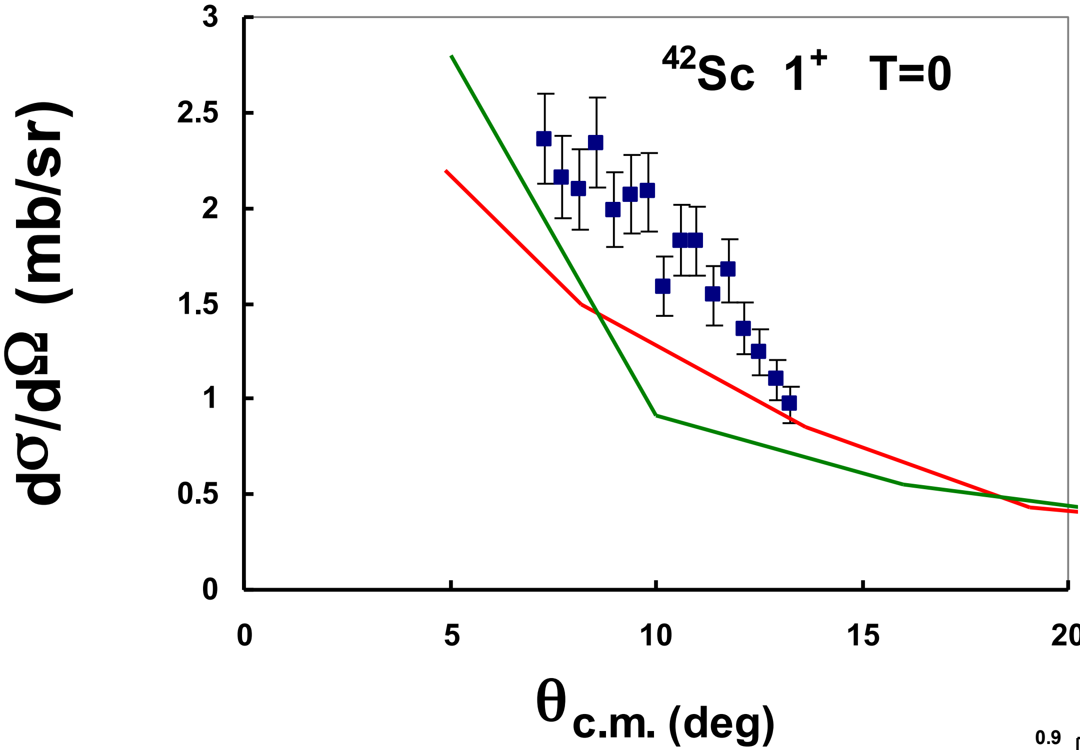
Proof of Principle



Evaporation protons

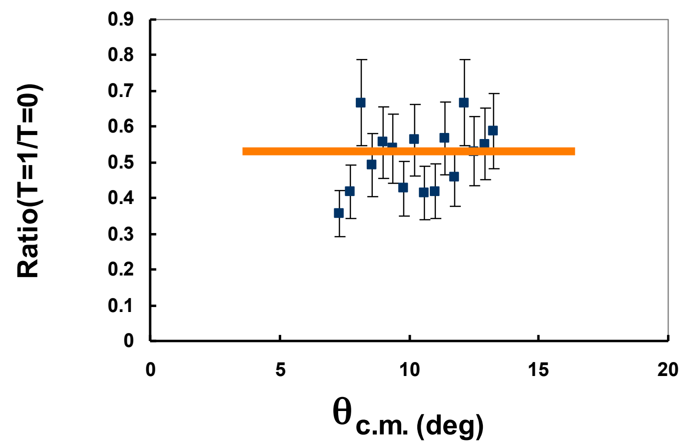


Proof of Principle



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

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



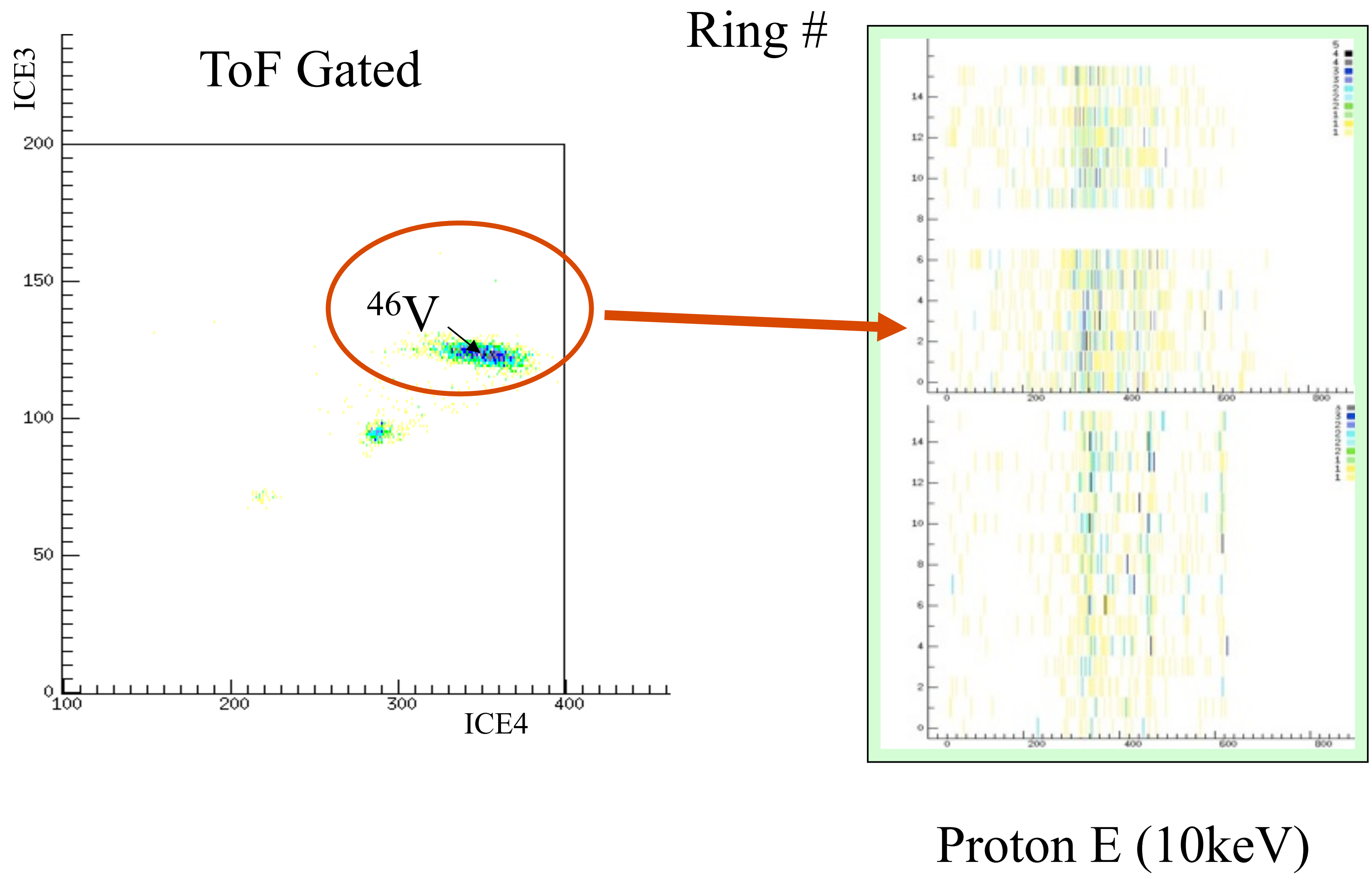
The ^{44}Ti Beam at ATLAS

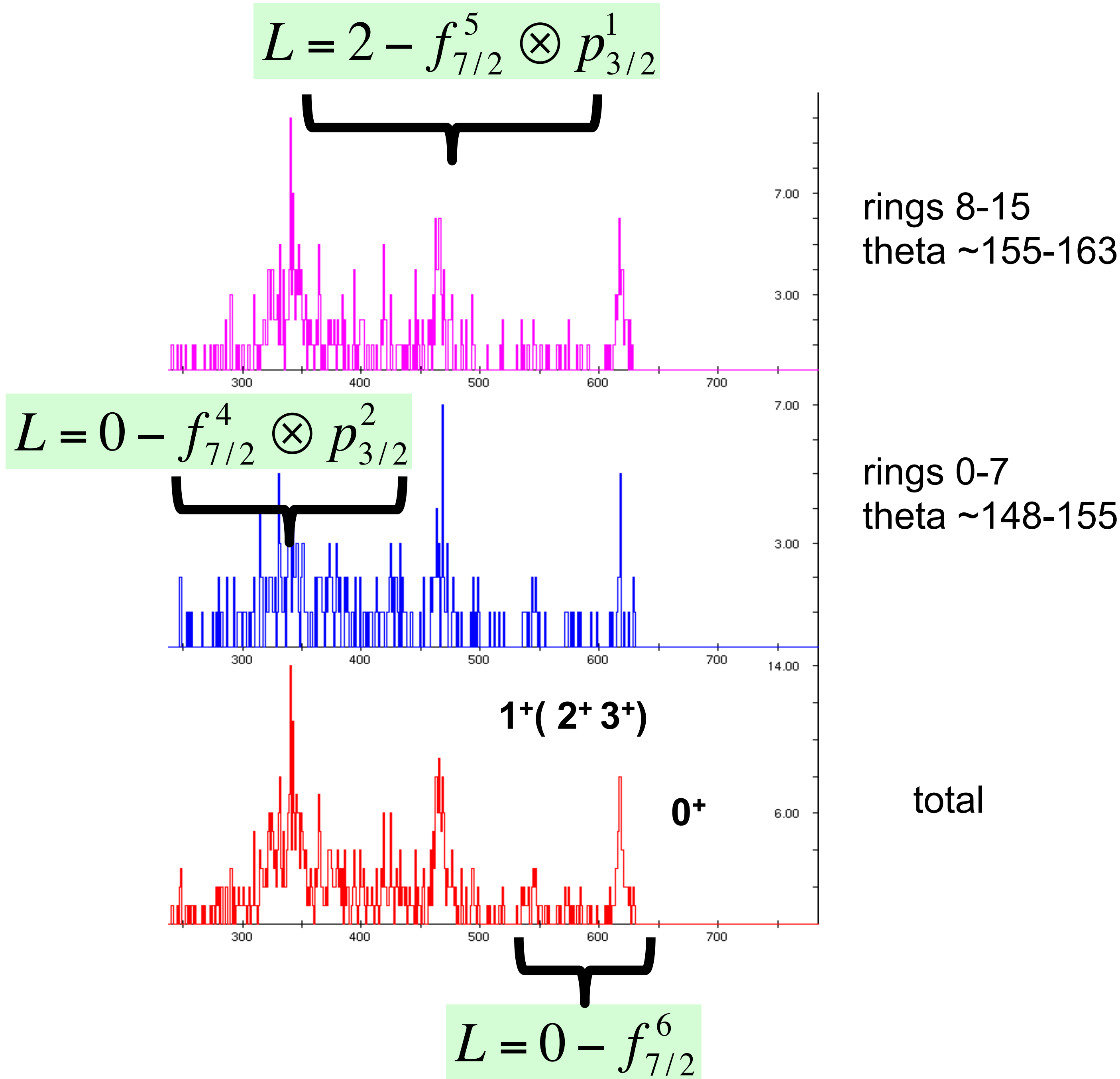
Purchased 100μCi of ^{44}Ti from LANL ~ 20k$

Some *"Nuclear"* Chemistry

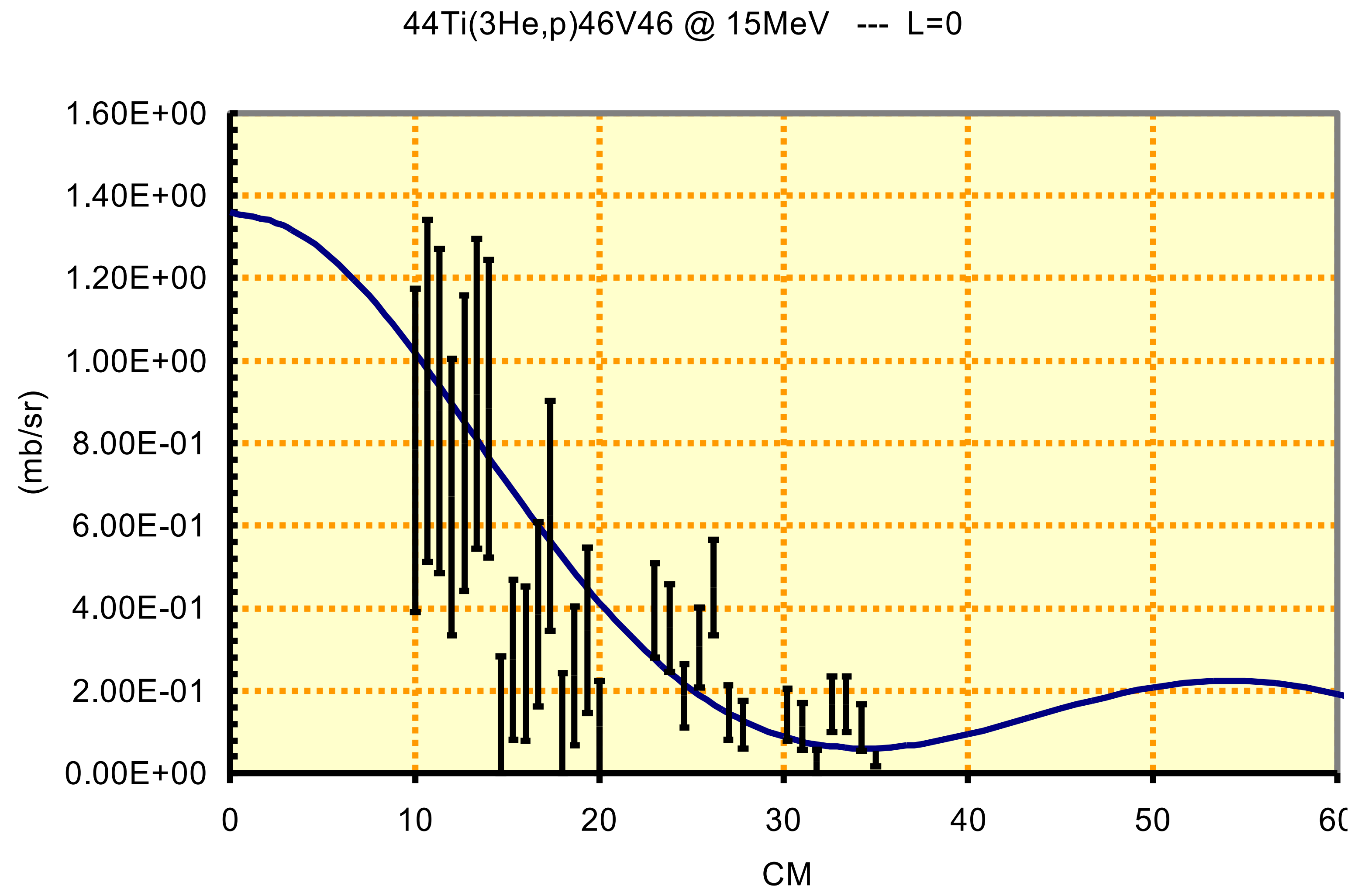
Tandem Ion-Source

A=46 (^{44}Ti, ^{3}He,p → ^{46}V)





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



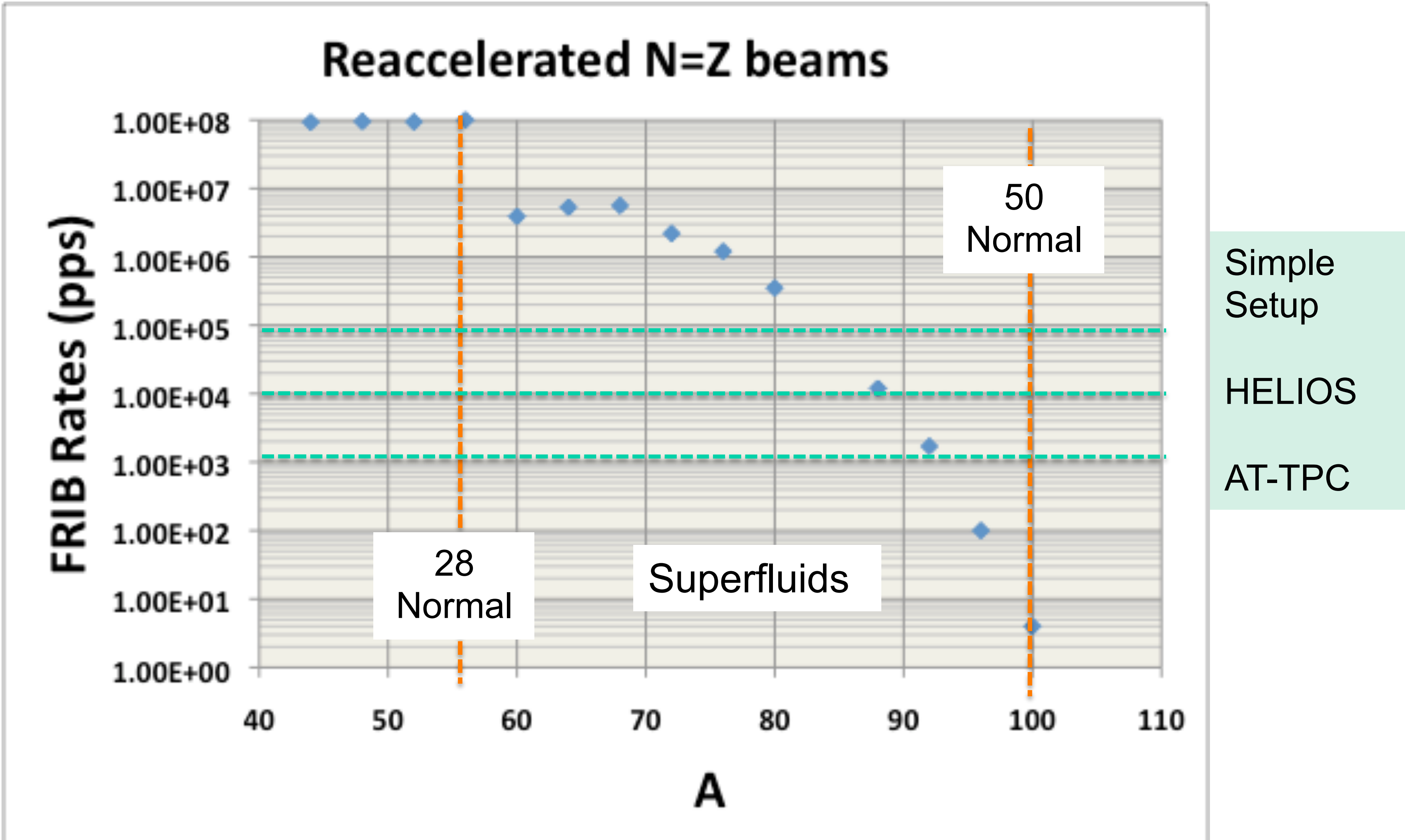
44Ti(3He,p)46V46 @ 15MeV --- L=0
1.60E+00
1.40E+00
1.20E+00
1.00E+00
8.00E-01
6.00E-01
4.00E-01
2.00E-01
0.00E+00
(mb/sr)
0
10
20
30
40
50
60
CM

Near term plans

^{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	discussions with *B.Tsang and W.Lynch*
Revisiting (p,^{3}He) and (^{3}He,p) reactions in stable targets	*J.Lee et al.*

Also (t,p) , (p,t) , charge exchange **cf. Following talks**

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

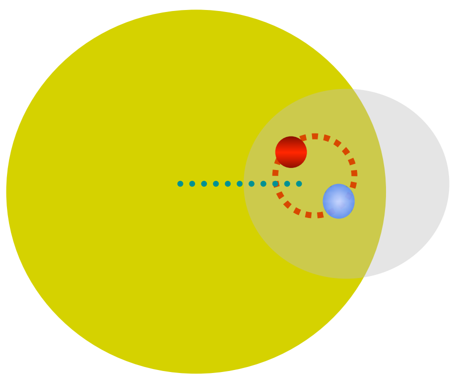


Reaccelerated N=Z beams
FRIB Rates (pps)
1.00E+08
1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
40
50
60
70
80
90
100
110
A
50 Normal
28 Normal
Superfluids
Simple Setup
HELIOS
AT-TPC

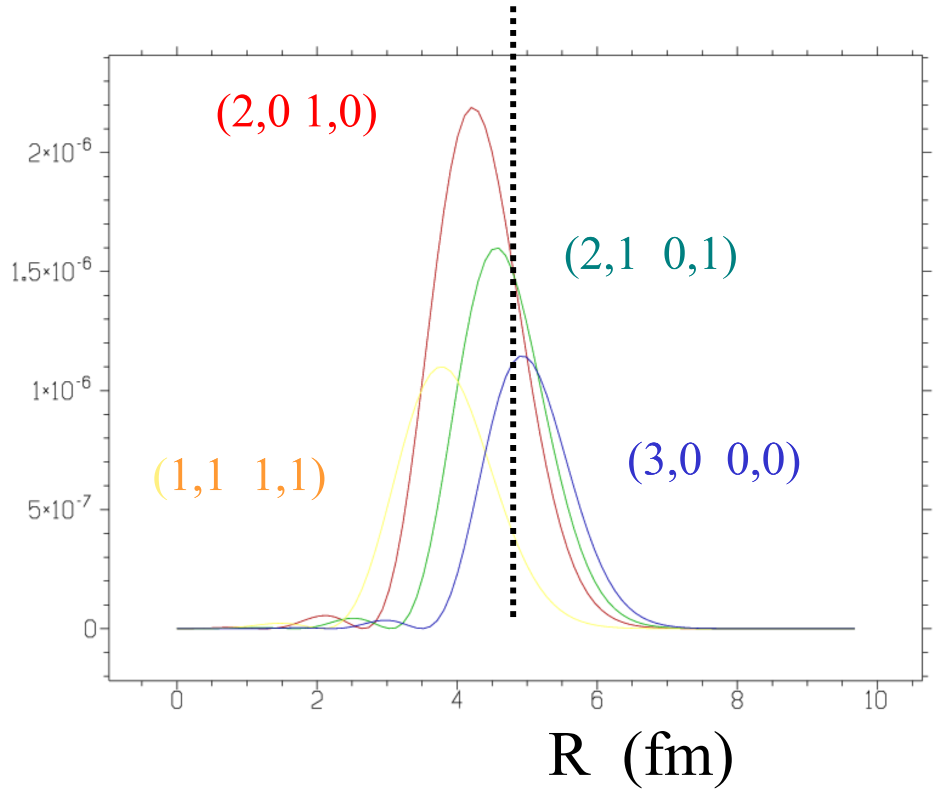
np Knockout reactions?

Exclusive measurement - Cross section and momentum distribution

Form factor for the KO of a J=0 pair



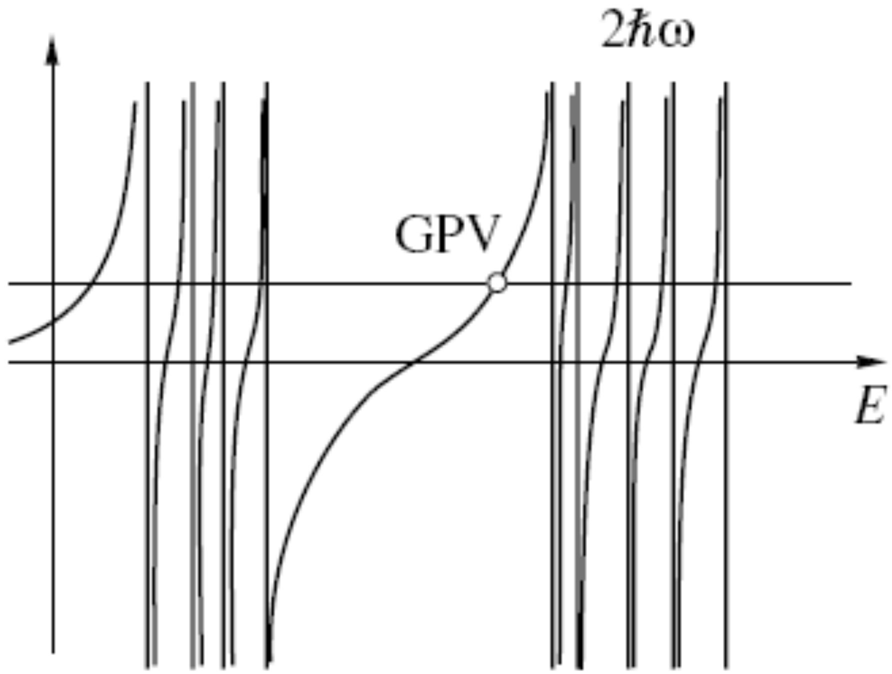
(N, Λ n, λ)



⇨ S- and P- waves

Other Topics for Discussion

Giant Pairing Vibration (Bes and Broglia)



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

Mode of excitation, not yet discovered.

PHYSICAL REVIEW C **83**, 037302 (2011)

Search for the giant pairing vibration through (*p*,*t*) reactions around 50 and 60 MeV

B. Mouginot,[1] E. Khan,[1] R. Neveling,[2] F. Azaiez,[1] E. Z. Buthelezi,[2] S. V. Förtsch,[2] S. Franchoo,[1] H. Fujita,[2,3] J. Mabiala,[2,4] J. P. Mira,[2,4] P. Papka,[4] A. Ramus,[1] J. A. Scarpaci,[1] F. D. Smit,[2] I. Stefan,[1] J. A. Swartz,[2,4] and I. Usman[2,3]
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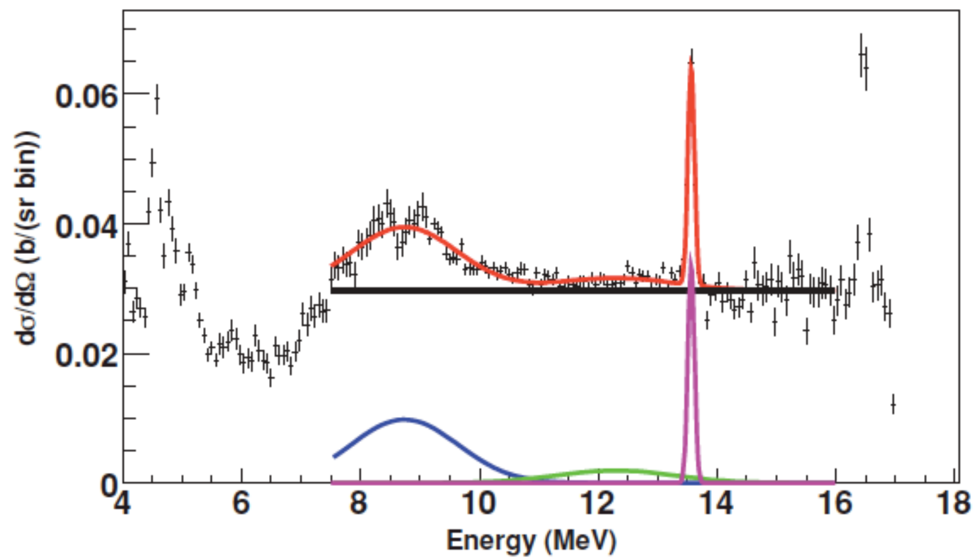


^{120}Sn and ^{208}Pb(p,t) at 50MeV - tritons at forward angles L=0 transfers

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

L. Fortunato *et al*., Eur. Phys. J. **A14** (2002) 37

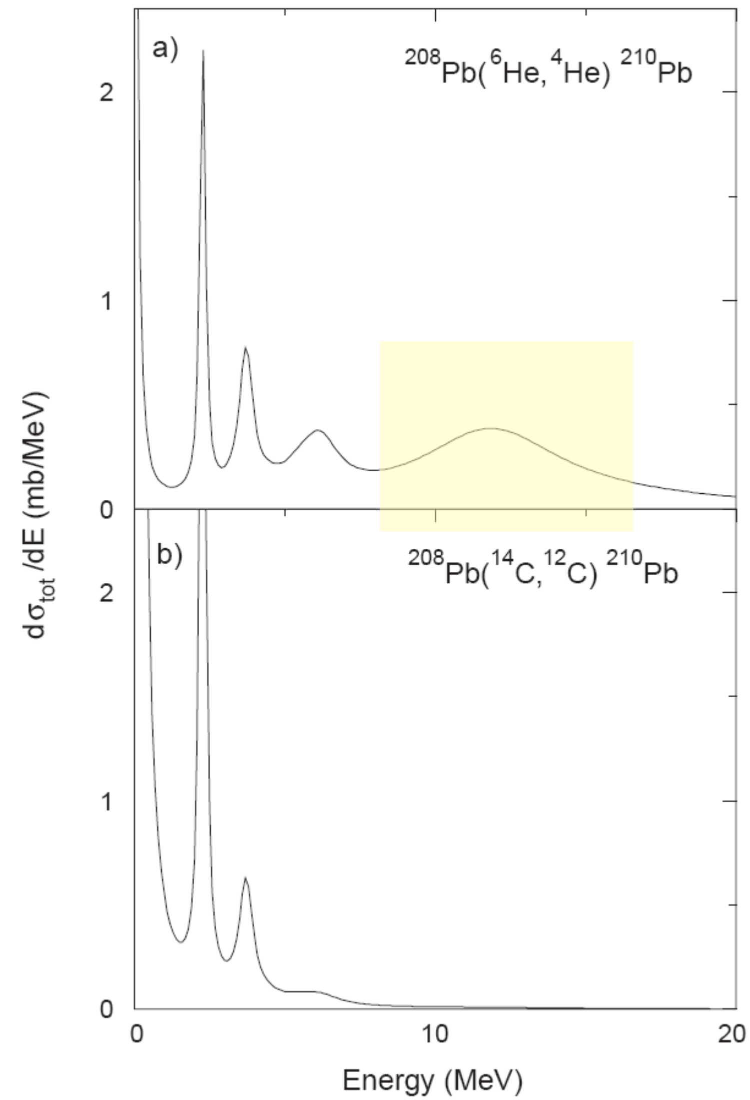
- *pp* RPA calculations on ^{208}Pb.
- Two-neutron transfer form factors from collective model

$$(\beta_P / 3A) R_0 \partial U(r) / \partial r$$

- DWBA (Ptolemy) calculation of σ_{GPV}

Table 2. Cross sections (in mb) for ground-state and GPV transitions obtained with the DWBA code Ptolemy [the target (column) and projectile (row) are specified]

	$^{14}C \rightarrow {}^{12}C$	$^{6}He \rightarrow {}^{4}He$
$^{116}Sn \rightarrow {}^{118}Sn_{g.s}$	19.4	0.4
$^{208}Pb \rightarrow {}^{210}Pb_{g.s}$	15.3	1.8
$^{116}Sn \rightarrow {}^{118}Sn_{GPV}$	0.14	2.4
$^{208}Pb \rightarrow {}^{210}Pb_{GPV}$	0.04	3.1



How good are these estimates using ^{6}He beams?

Do we expect to see GPV? Realistic calculations in the continuum.

PHYSICAL REVIEW C 80, 064311 (2009)

Collective excitations in the continuum

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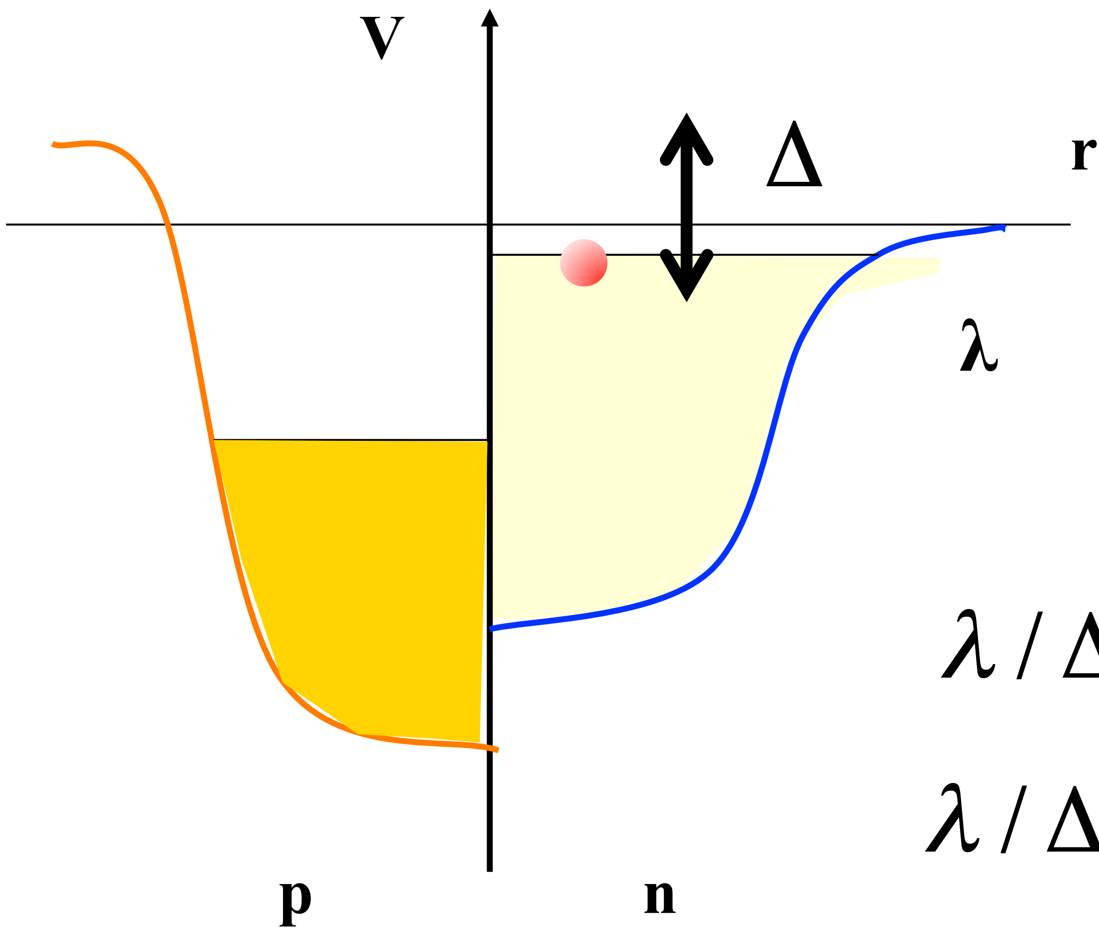
(Received 9 June 2009; revised manuscript received 2 September 2009; published 14 December 2009)

2p GPV is the one that survives in ^{208}Pb

(^{3}He,n)

Weakly bound systems

When do we expect to see effects due to continuum coupling?



$$\lambda / \Delta \approx 1$$

??

$$\lambda / \Delta << 1$$

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

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

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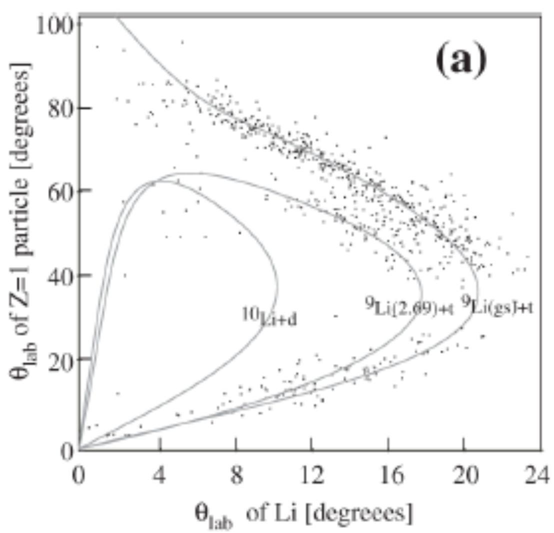
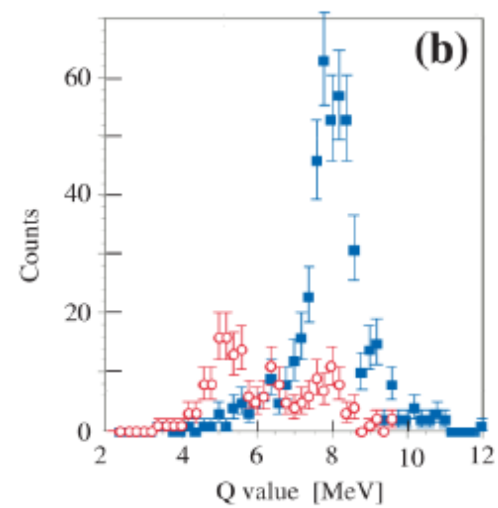
(Received 22 January 2008; published 14 May 2008)





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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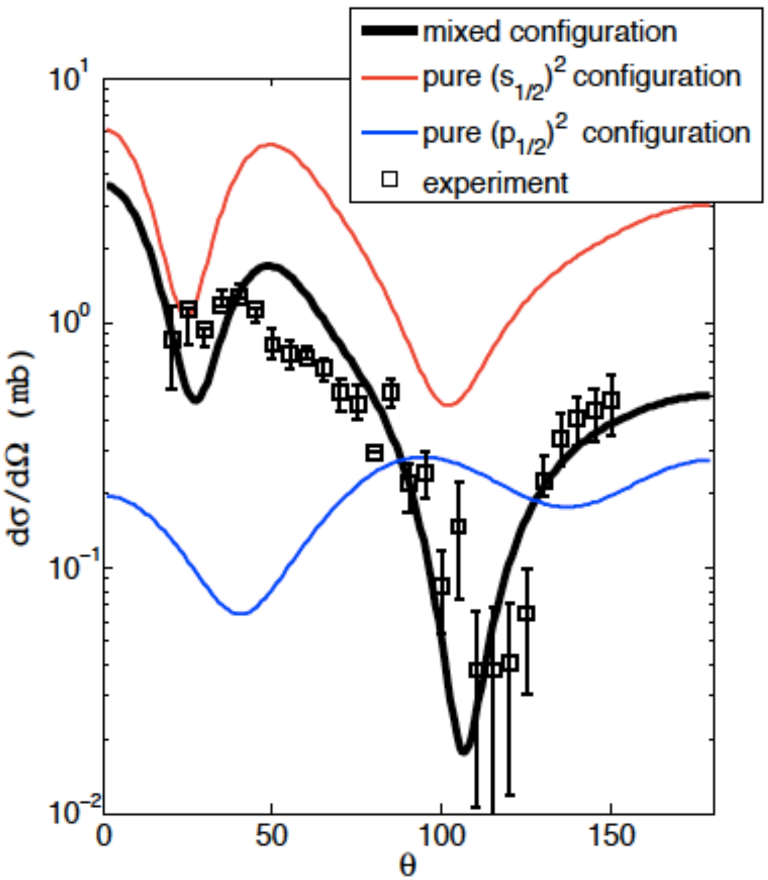
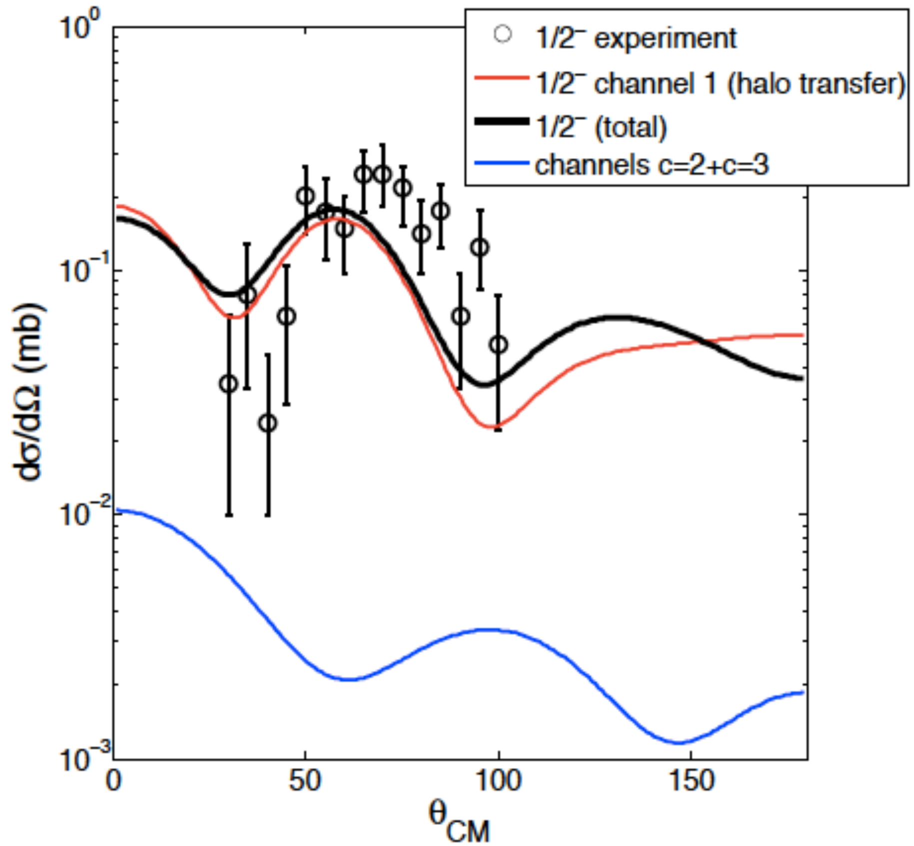
(Received 16 December 2009; published 19 October 2010)

- Two particle transfer in second order DWBA
- Simultaneous and successive transfer
- Non-orthogonality term
- Absolute normalization



mixed configuration
pure $(s_{1/2})^2$ configuration
pure $(p_{1/2})^2$ configuration
experiment
$d\sigma/d\Omega$ (mb)
θ
10^1
10^0
10^{-1}
10^{-2}
0
50
100
150



1/2⁻ experiment
1/2⁻ channel 1 (halo transfer)
1/2⁻ (total)
channels c=2+c=3
$d\sigma/d\Omega$ (mb)
θ_{CM}
10^0
10^{-1}
10^{-2}
10^{-3}
0
50
100
150

nature 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

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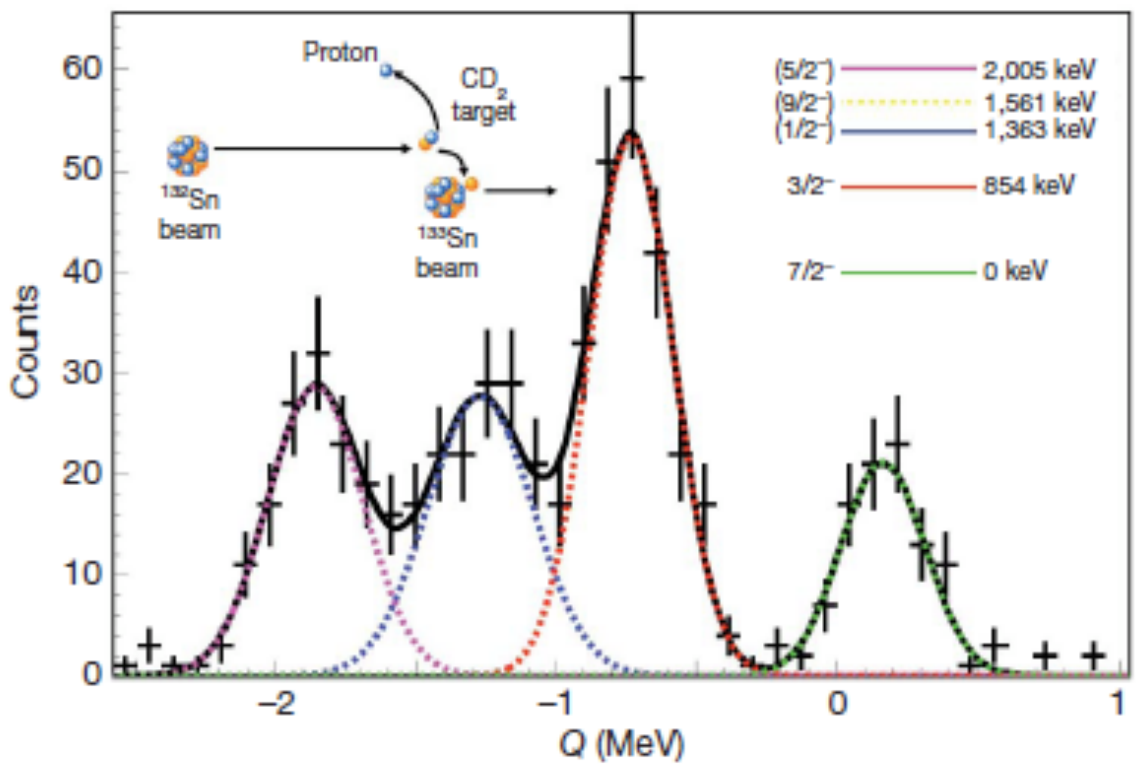

Pairing Phase Transition in Neutron Rich Nuclei

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 HELIOS)

Tritium targets for (t,p)

Ti loaded foils. Gas cell. 100μg/cm^2 ~ 1Ci

- Improve theoretical reaction models.

- Validation of common approximations.
  Two steps, Coupled-Channels.
  Absolute/Relative cross-sections

- Does theory need more data on stable nuclei ?

- Three-body effects.

- What can we learn from pair transfer about Volume vs. Surface Pairing?

- Do we expect to see GPV?

- Heavy-Ion Transfer 2N transfer.
  Semi-classical treatment. Josephson effect?

- Two-nucleon knock-out in the Nilsson and BCS models.

- Are transfer reactions the smoking gun for NP pairing?
  Knock-out reactions? Realistic theoretical estimates.

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