# The ($^3$He,p) Reaction to Study T=1 and T=0 Pairing in N=Z Nuclei

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Workshop on Pairing Degrees of Freedom in Nuclei and the Nuclear Medium

INT - University of Washington – November 14-17, 2005

Office of Science
U.S. Department of Energy

# Motivation

- 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

# The smoking gun?

2.G

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



## 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 pairing interaction model. The calculation also is applied to final states of collective type. For some types of reaction a collective enhancement of the reaction cross section is predicted.

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

# PAIR CORRELATIONS AND DOUBLE TRANSFER REACTIONS

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

PHYSICS REPORTS (Section C of Physics Letters) 34, No. 1 (1977) 1–53. NORTH-HOLLAND PUBLISHING COMPANY

# ISOVECTOR PAIRING VIBRATIONS

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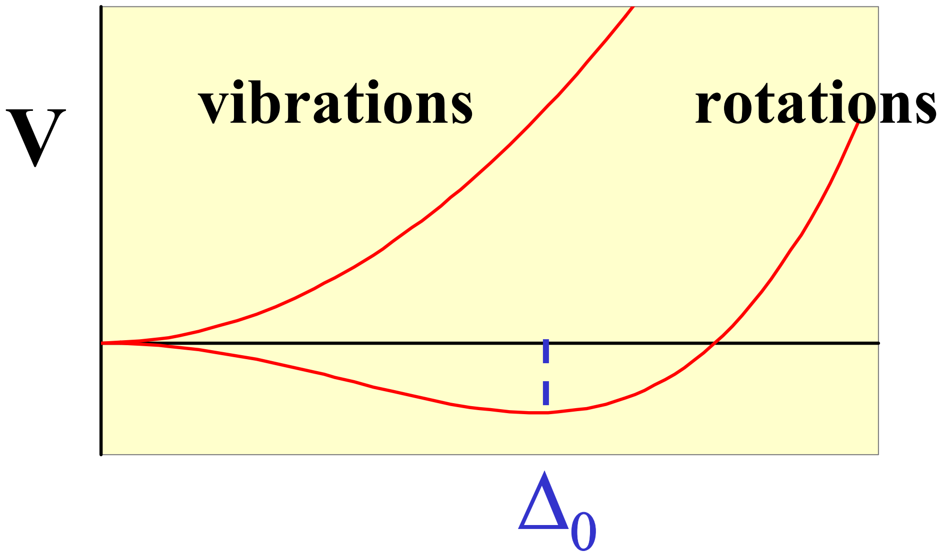
# Two nucleon transfer reactions

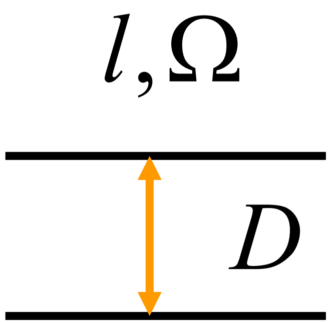
Generalized densities a+a+, aa represent the pair field and in close analogy to the collective excitations corresponding to the ordinary density, they can give rise to collective modes.



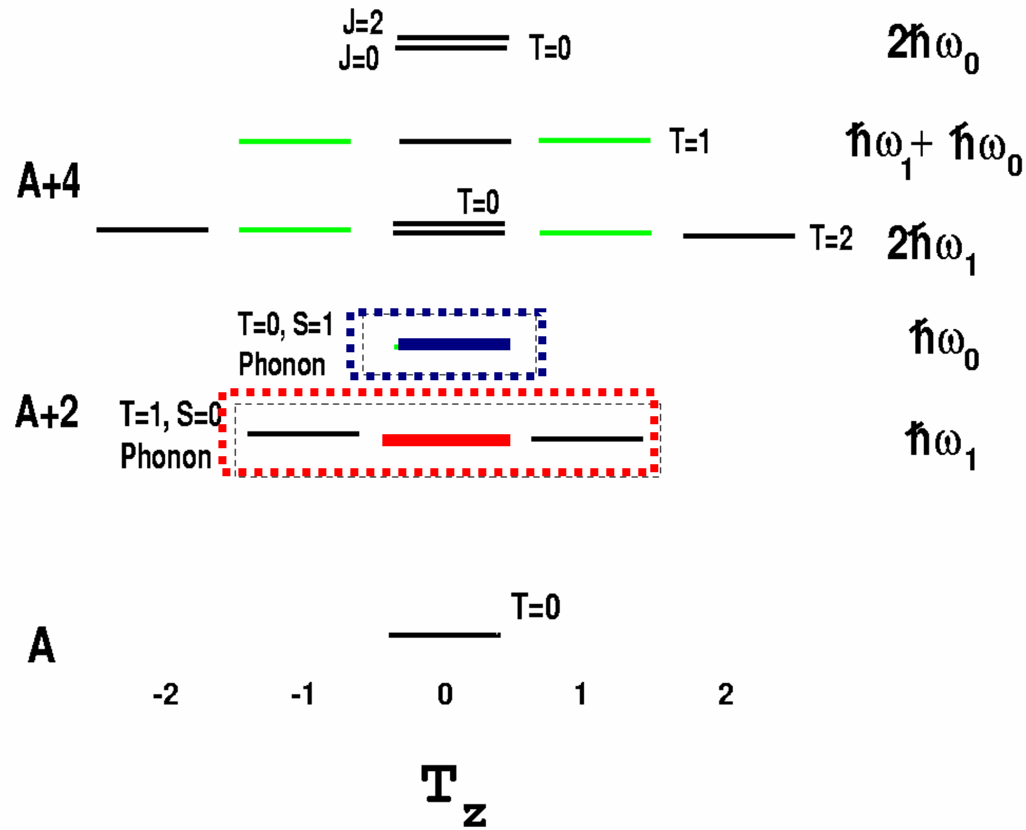

$$\Delta = G < \Sigma a_{\nu}^{+} a_{\bar{\nu}}^{+} >$$

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.

# Collective pairing vibrations near closed shells




$$\Omega G / D < 1$$




Collective excitations have a phonon-like spectrum

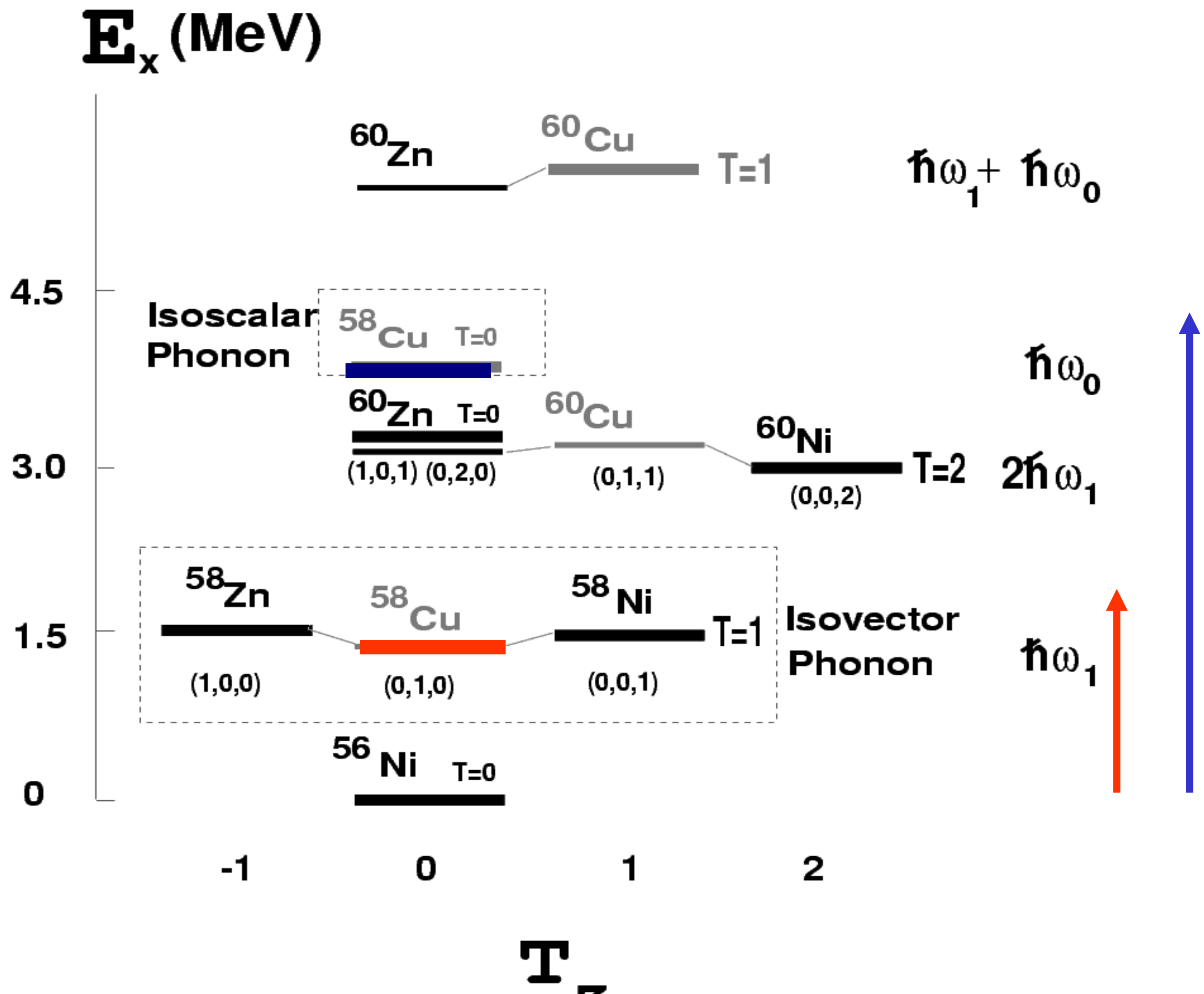
$$\hbar\omega \sim D(1-x)^{1/2}$$

$$x = G / G_{crit}$$

Study binding energies around closed shells ($^{56}$Ni)

T=0 Energy comparable with single particle separation - low collectivity.

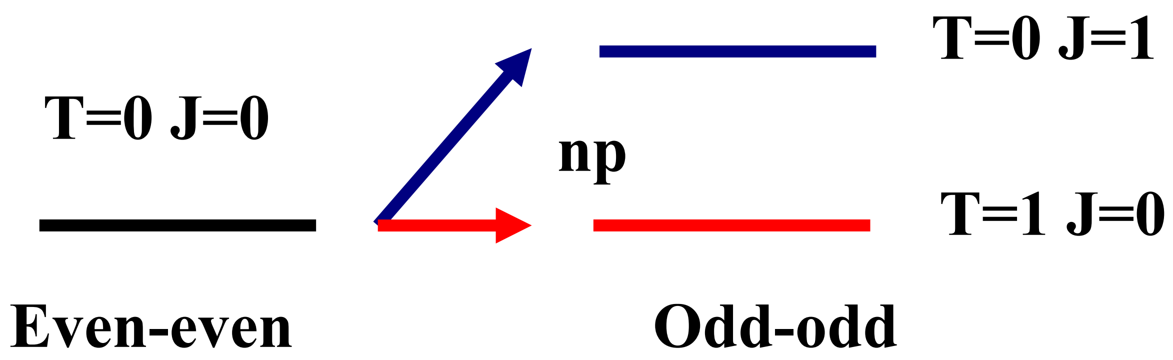
T=1 Energy consistent with collective excitations.



# ($^3$He,p) Transfer Reactions

σ ?

$$<1|T|0>^2 \propto 1/\hbar\omega$$



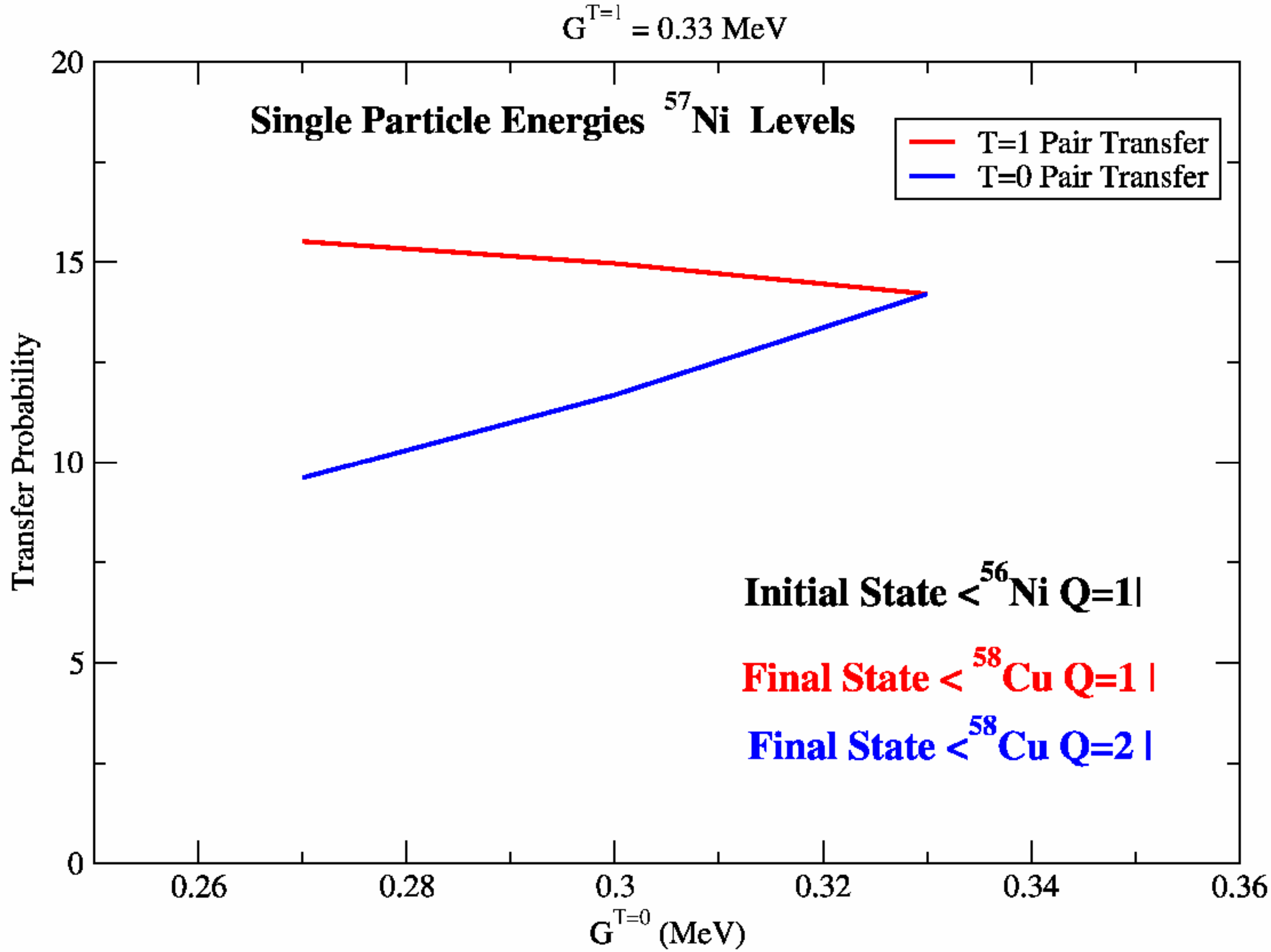

($^3$He,p)

L=0 transfer – forward peaked

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

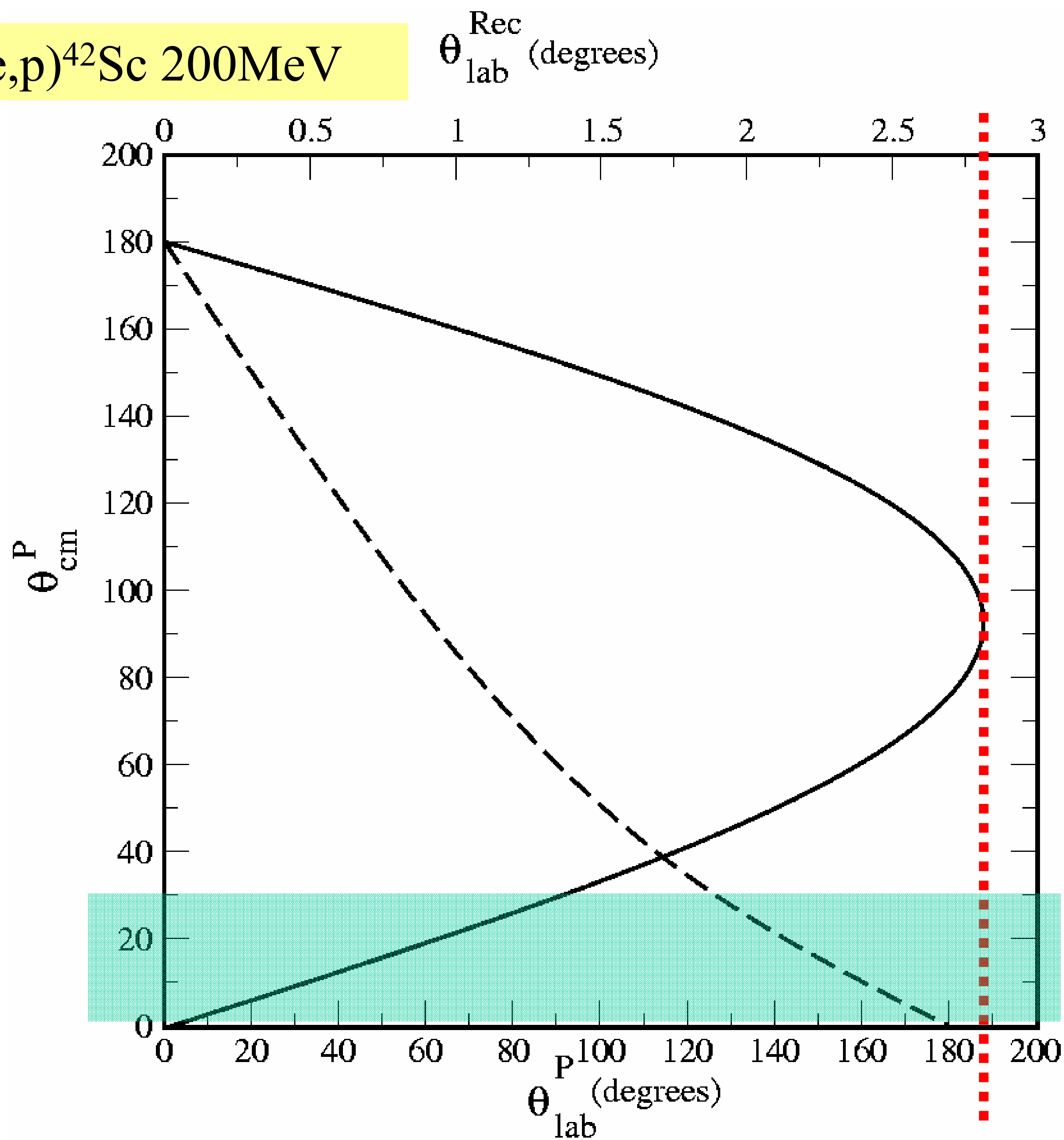
Both absolute σ(T=0) and σ(T=1) and relative σ(T=0) / σ(T=1) tell us about the character and strength of the correlations

# n-p Pair Transfer Probability




R.Chasman

$^{40}Ca(^3He,p)^{42}Sc$ 200MeV




**L=0 transfer**

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($p,\gamma$)$^{57}$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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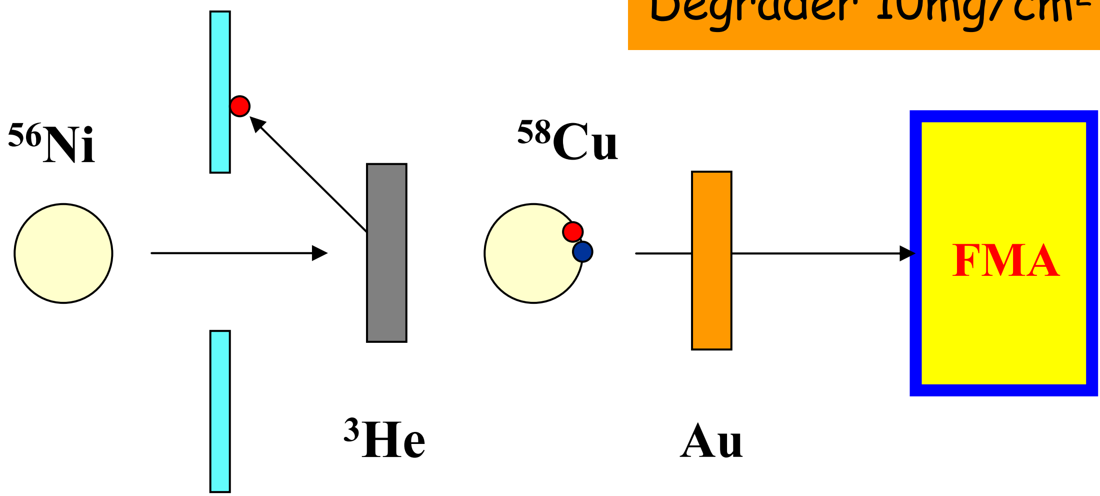
(Received 29 August 1997)

Degrader 10mg/cm$^2$

~10$^5$ /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], A.Görgen[1], P.Fallon[1], M.Cromaz[1], C.N.Davis[2], A.Heinz[2], R.V.F.Janssens[2],C.L.Jiang[2], E.F.Moore[2], G.Mukherjee[2], R.Pardo[2], D.Seweryniak[2], J.P.Schiffer[2], J.Cizewski[3], J.Thomas[3], M.Paul[4]

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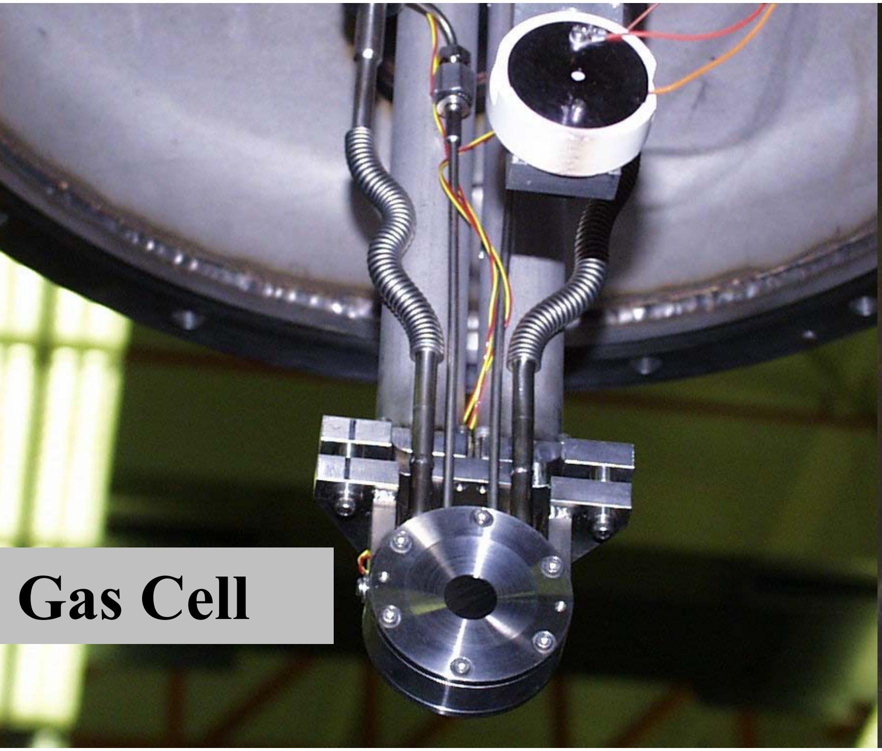
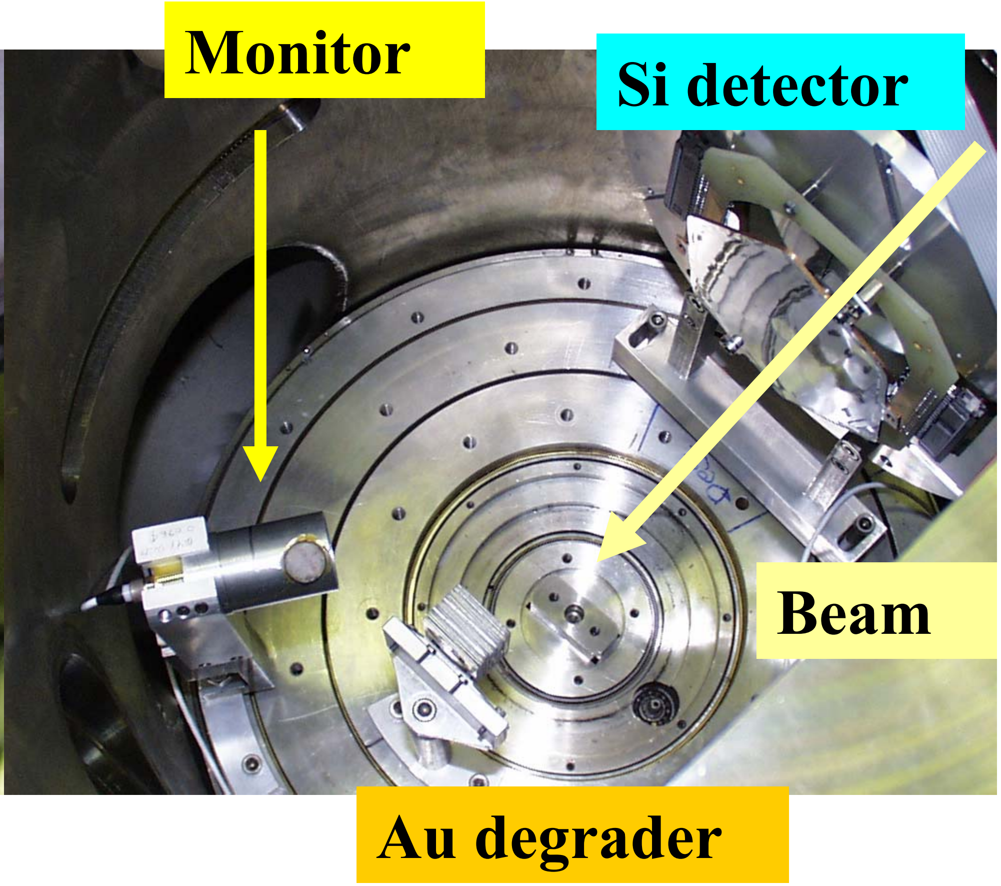
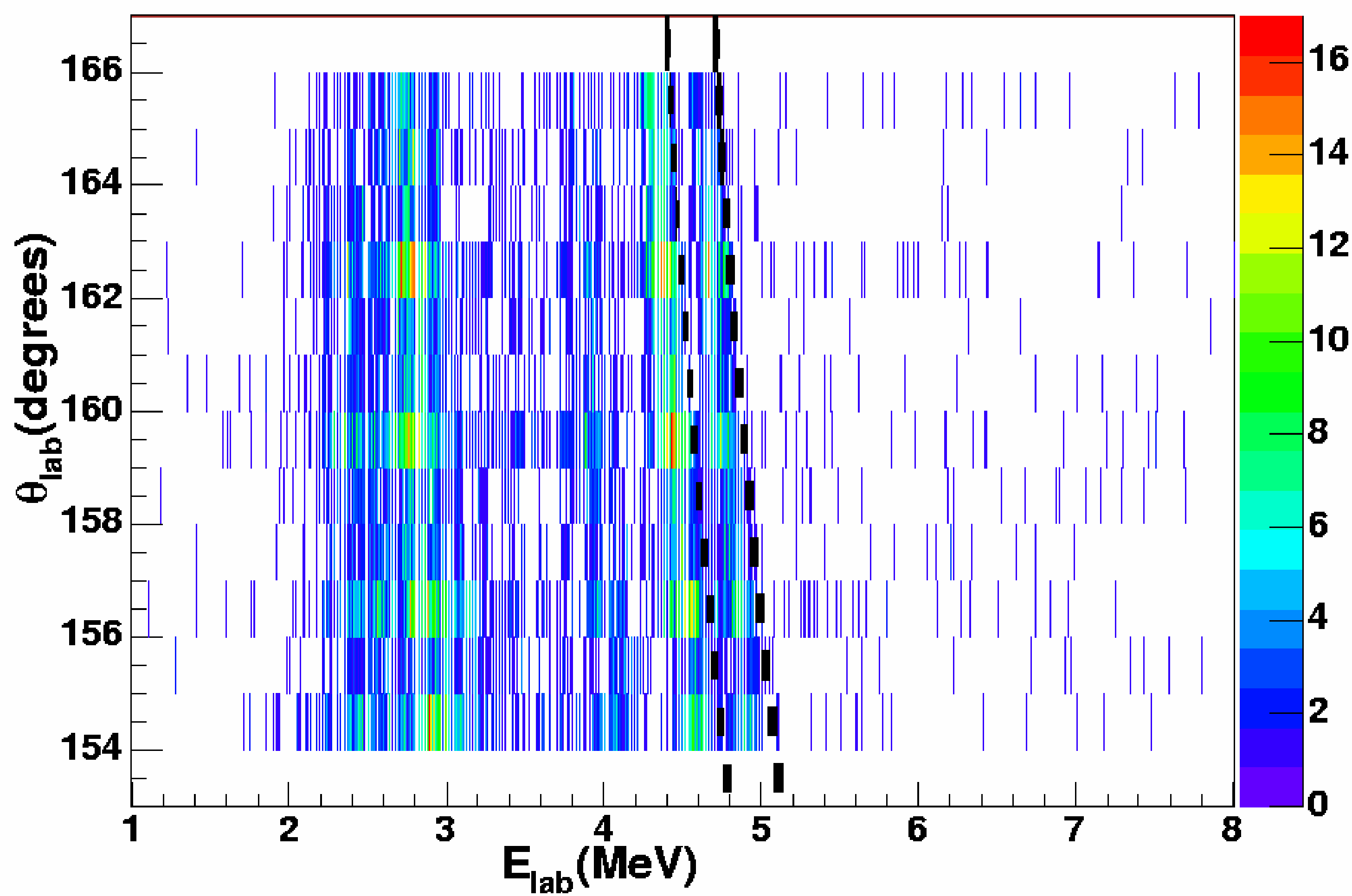
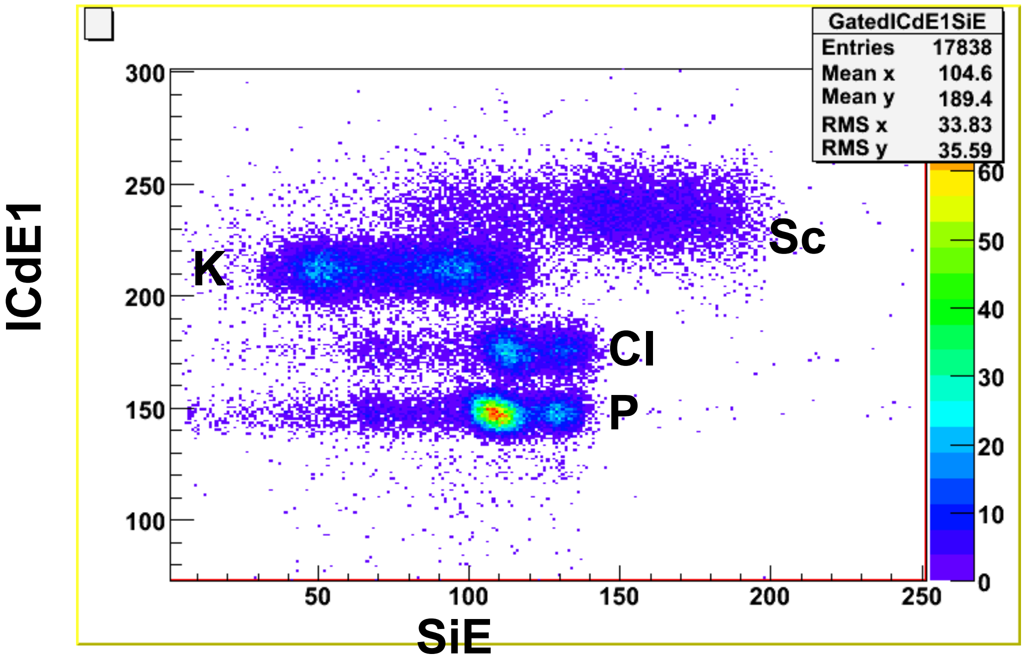
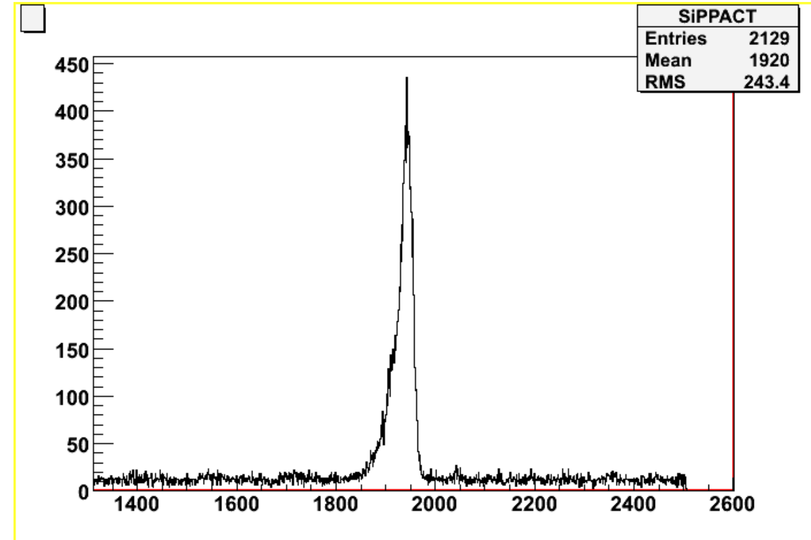




166
164
162
160
158
156
154
$\theta_{lab}$(degrees)
1
2
3
4
5
6
7
8
$E_{lab}$(MeV)
16
14
12
10
8
6
4
2
0



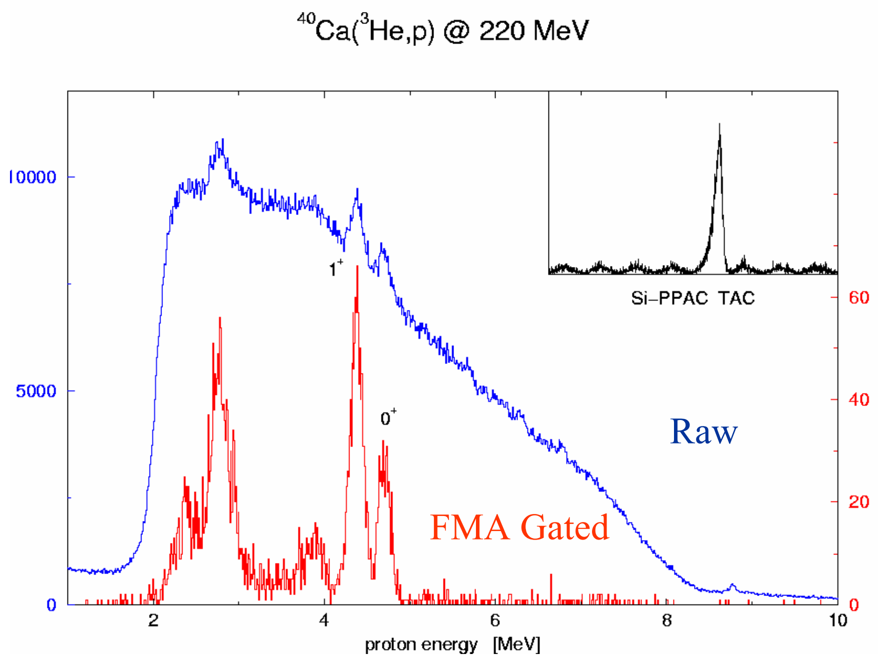




PPAC

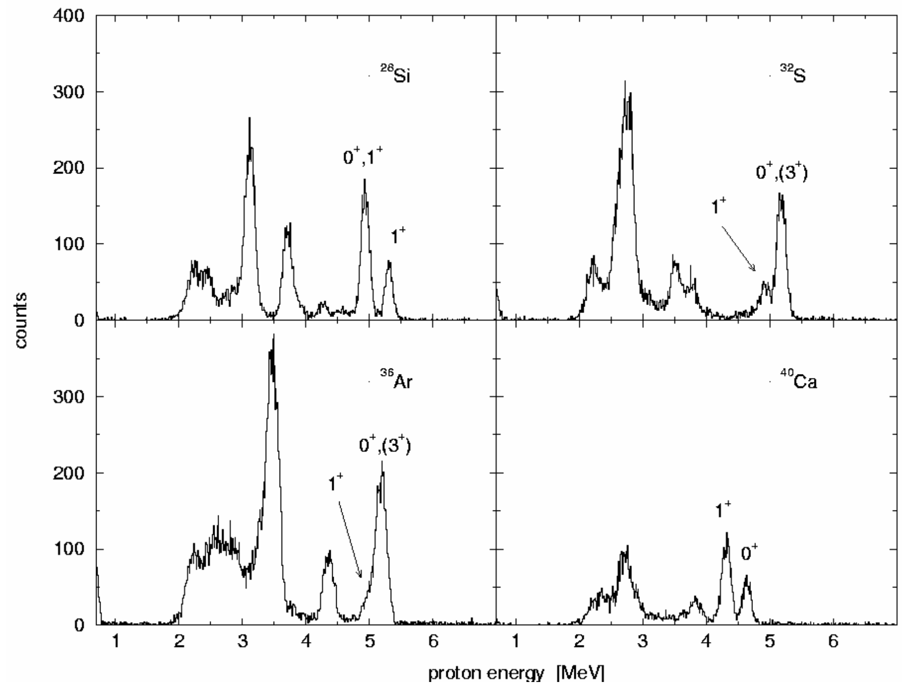
```
             W         C         X         A         Y         W
             (         |         |         |         |         )
 beam        (         |         |         |         |         )
 ---->       (         |         |         |         |         )
             (         |         |         |         |         )
             (         |         |         |         |         )
             (         |         |         |         |         )
```

IC

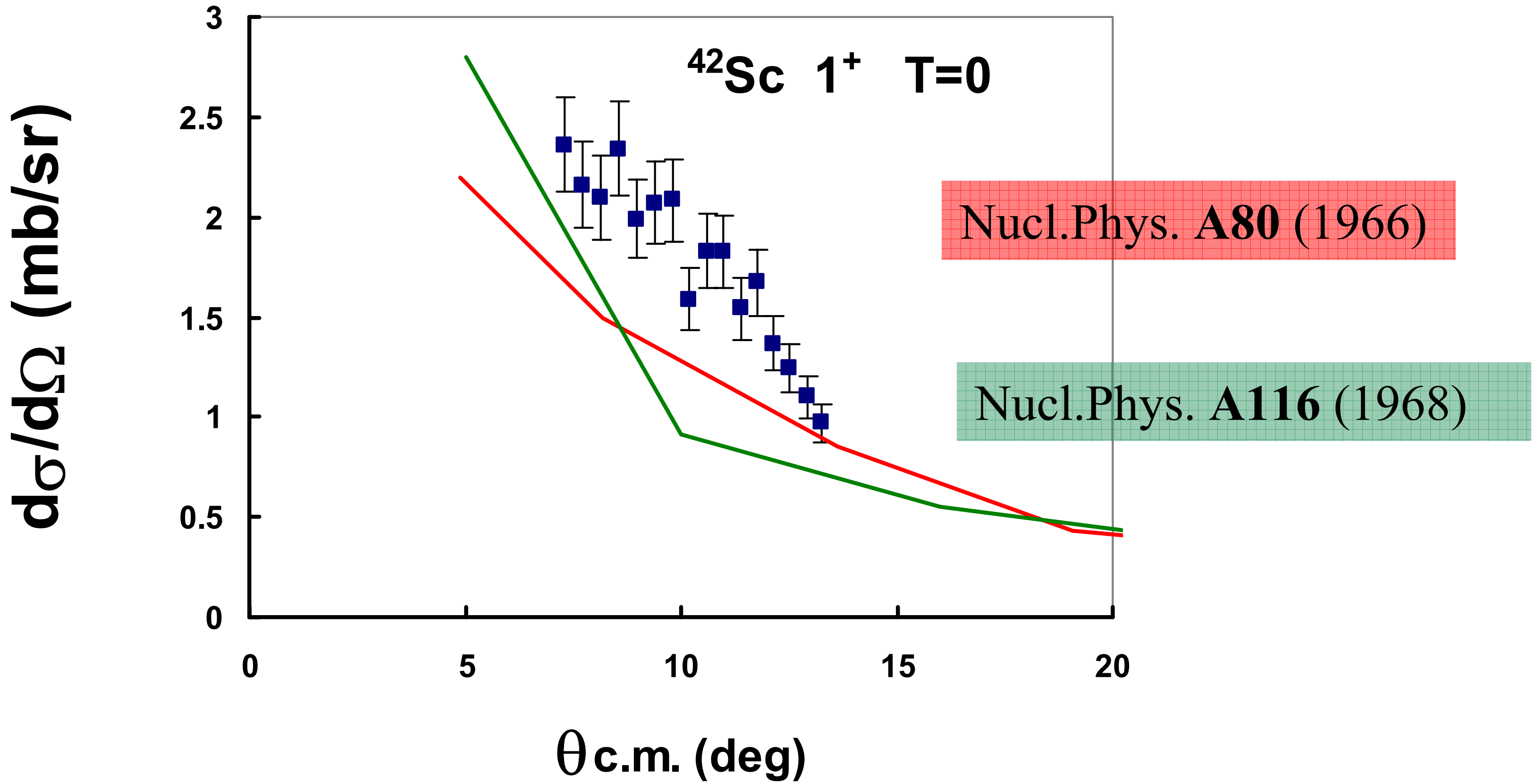
```
        DE1       DE2              DE3
     --------- -------- --------------------------

  X~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~X

  G..............................................G

  W                                              W
  (                                              )
 beam (                                          )
 ---> (                                          )
  (                                              )
  (                                              )
  (                                              )

  C----------------------------------------------C
```



$^{40}Ca(^{3}He,p)$ @ 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

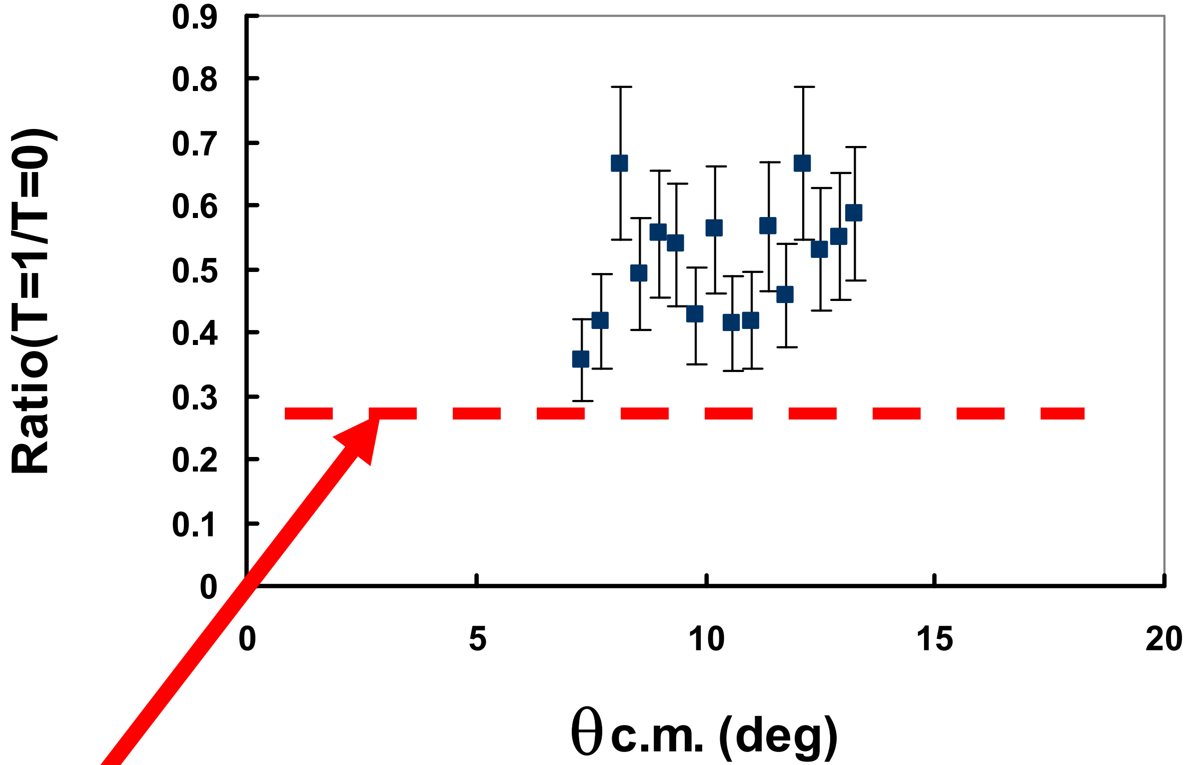



counts
400
300
200
100
0
$^{28}Si$
$0^+,1^+$
$1^+$
$^{32}S$
$0^+,(3^+)$
$1^+$
$^{36}Ar$
$0^+,(3^+)$
$1^+$
$^{40}Ca$
$1^+$
$0^+$
1
2
3
4
5
6
proton energy [MeV]



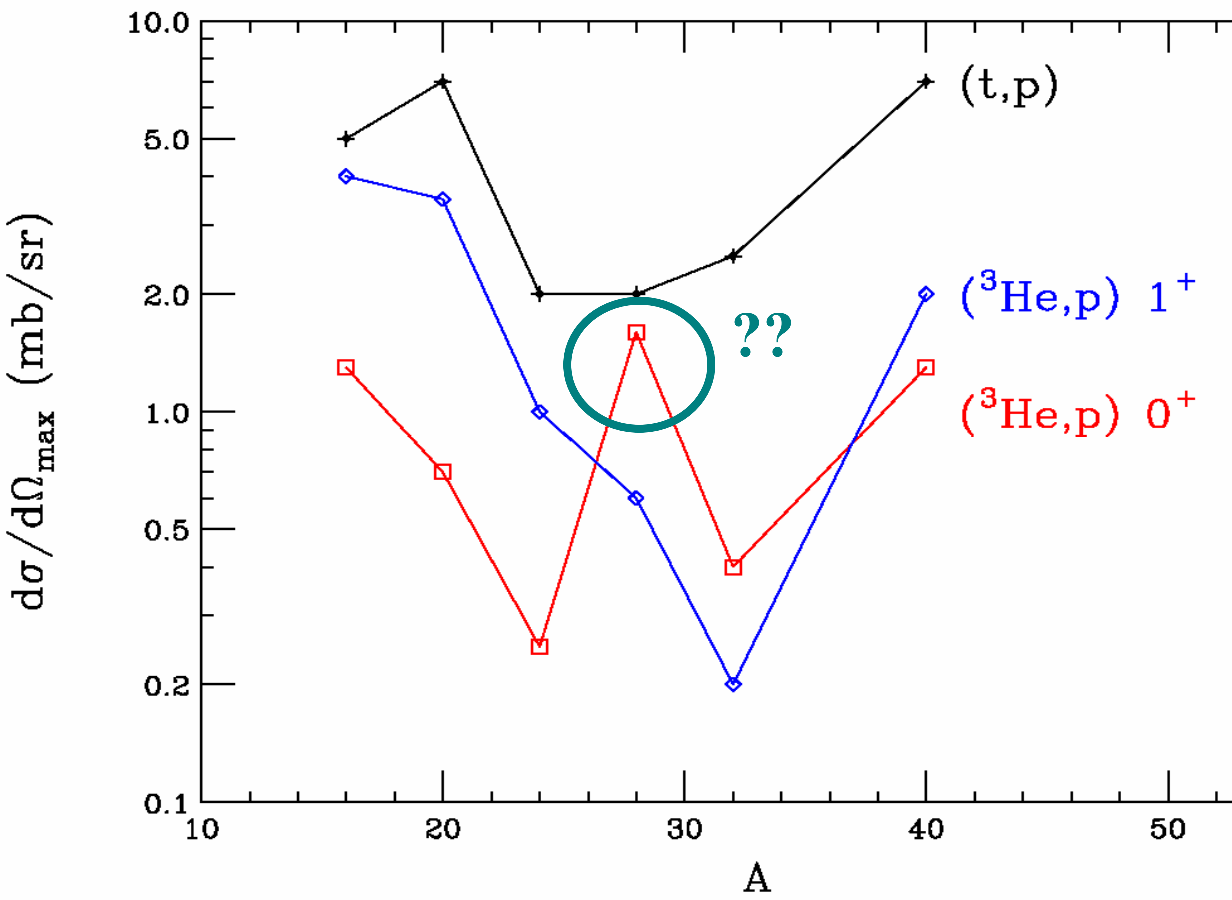
$^{42}$Sc 1$^+$ T=0
Nucl.Phys. **A80** (1966)
Nucl.Phys. **A116** (1968)
dσ/dΩ (mb/sr)
θ c.m. (deg)
0
0.5
1
1.5
2
2.5
3
0
5
10
15
20

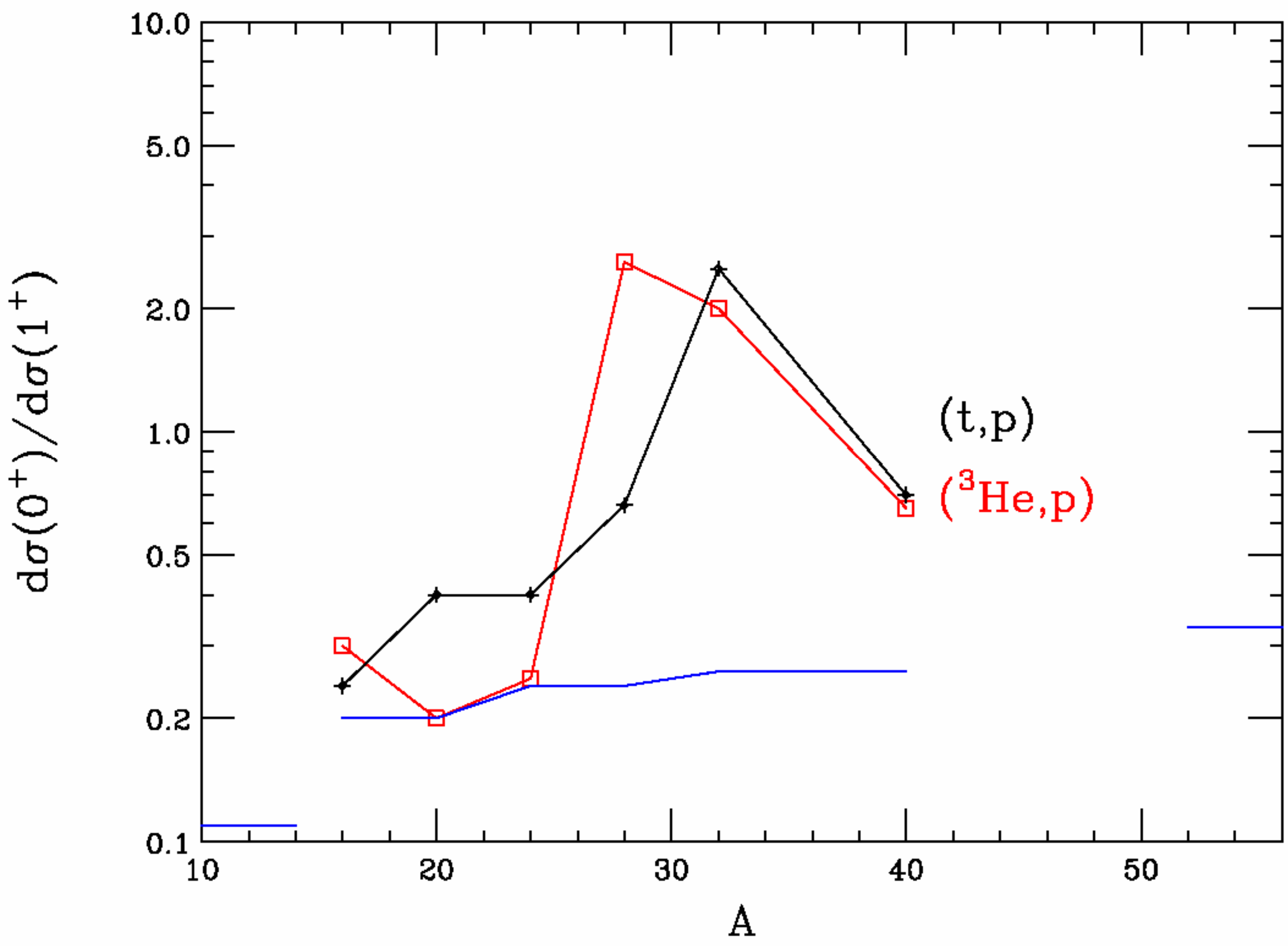
# What is our reference?




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

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






Ratios using both (t,p) and (3he,p). The blue line is the sp estimate assuming that the j2 configuration varies from an s1/2 to a j>>1

# Summary and Conclusions

Ground State Binding Energies (pair gaps)

Energies of T=0 T=1 in N=Z nuclei

Excitation spectra near shell gaps (pair vibrations)

Evidence for full isovector T=1 pairing (nn,np,pp) - charge independence.

BE differences can be described by an appropriate combination of the symmetry energy and the isovector pairing energy.

No evidence for a T=0 deuteron-like pairing condensate in N=Z nuclei. The T=0 states in an odd-odd N=Z nucleus can be characterized as a seniority 2 state (as in any other odd-odd nucleus).

Inverse kinematics - Successful test with stable beams

Next step - Measure "collectivity" with transfer reactions ($^{3}$He,p)

Approved ATLAS runs with $^{44}$Ti and $^{56}$Ni beams

"Role of pairing phonons near $^{40}$Ca and $^{56}$Ni"

# And looking ahead