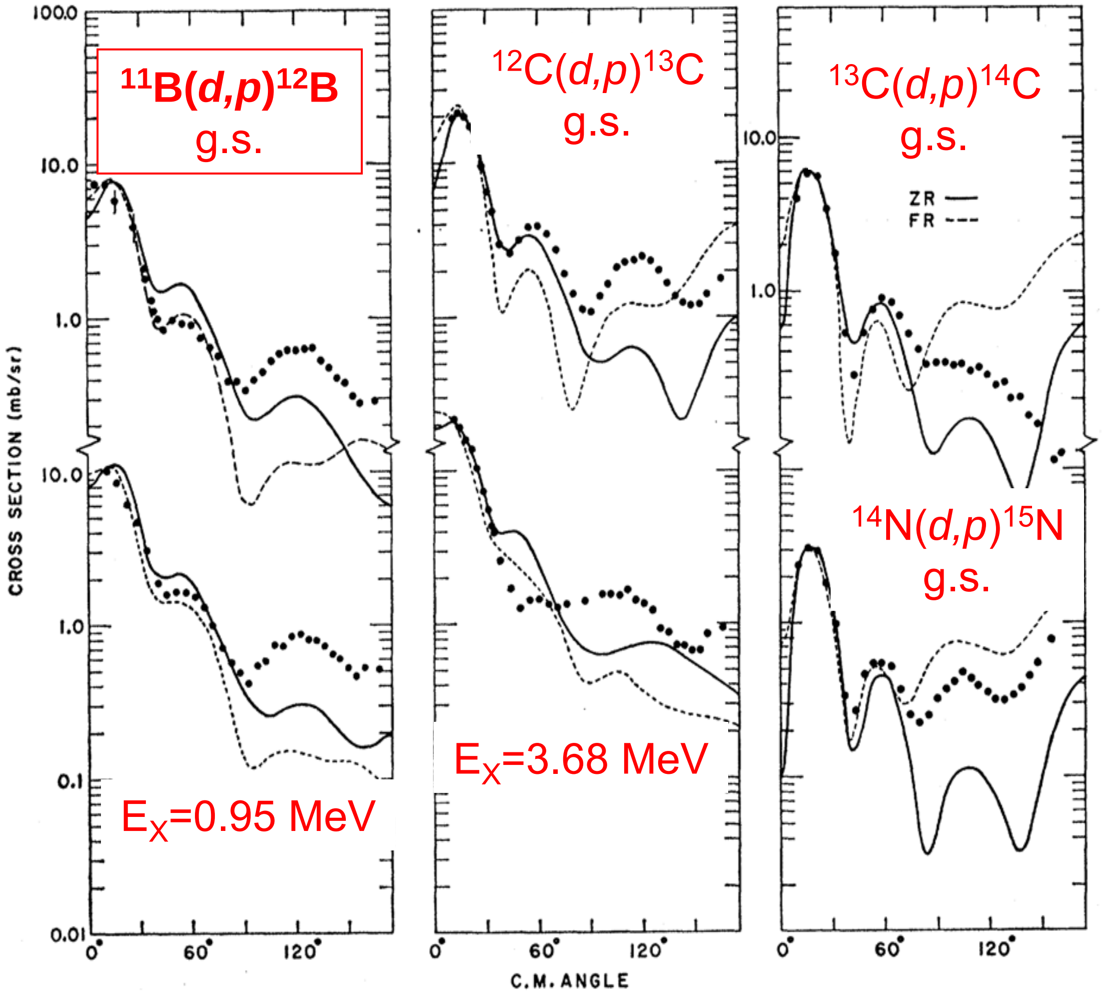
Transfer reactions before, and with, HELIOS

Or – "...seems like an awful lot of work just to do (d,p)..."

Congratulations ATLAS!
Happy 25th!

Prologue: Long before ATLAS...



Detailed survey of single-particle states in *p*-shell nuclei with (*d*,*p*).

Wouldn't it be nice to go *further* ?!

PHYSICAL REVIEW VOLUME 164, NUMBER 4 20 DECEMBER 1967

Study of the (*d*,*p*) Reaction in the 1*p* Shell*

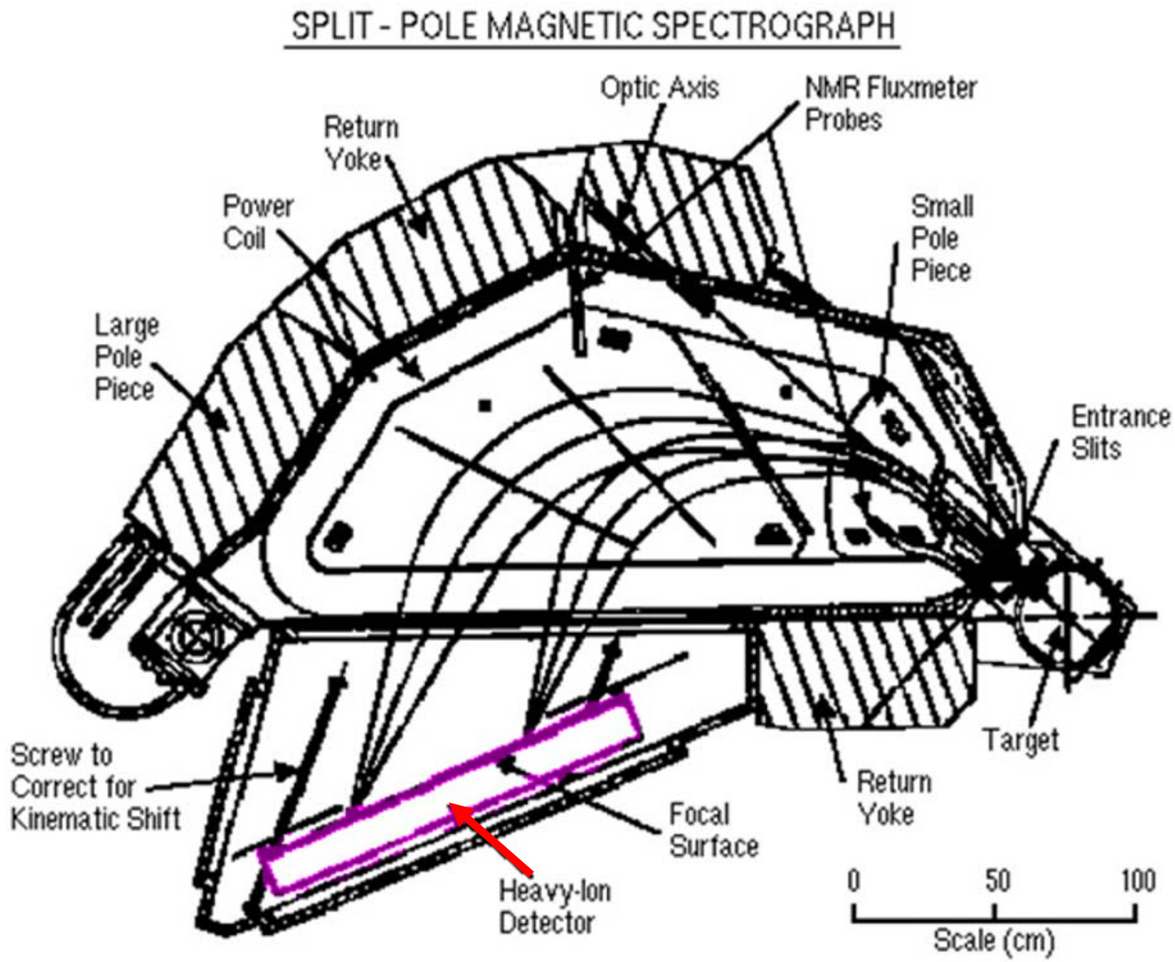
J. P. Schiffer, G. C. Morrison, R. H. Siemssen,† and B. Zeidman
Argonne National Laboratory, Argonne, Illinois

(Received 3 August 1967)

Two faces of transfer reactions- Facilitated by ATLAS

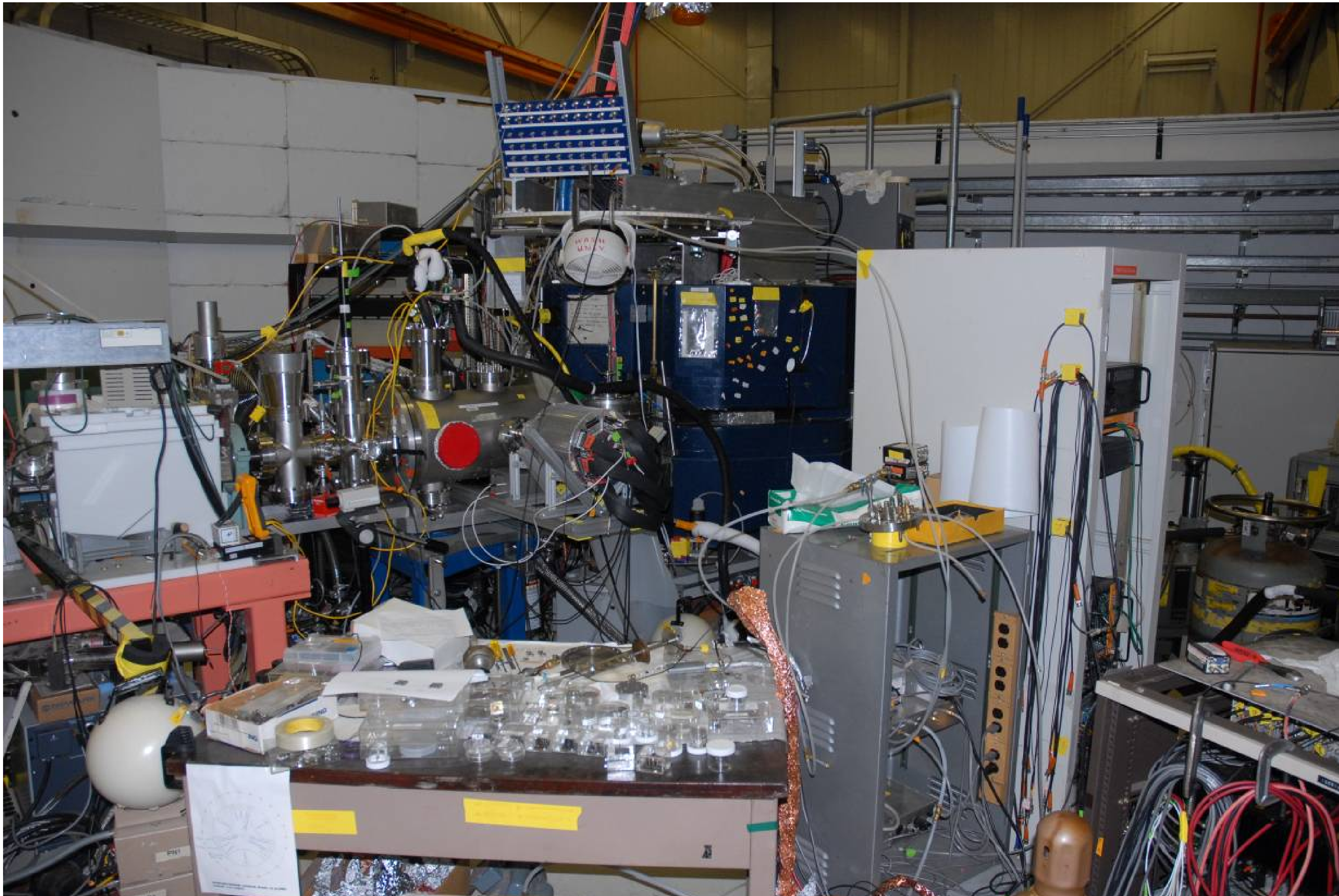
- Heavy-ion transfer
  – e.g.: (A+*n*,*p*) + B → A + (B+*n*,*p*) where A, B are heavy ions.
- Light-ion transfer
  – e.g.: (*d*,*p*) in inverse kinematics with RIBs
- Each demands:
  – High energies for heavy ions (E/A up to 10+ MeV)
  – Large variety of ions
  – High intensity and variability

The Enge Split-Pole spectrograph- The textbook picture



Dimensions of the Split-Pole Spectrograph are shown in the drawing where trajectories of particles with two different Bρ's are indicated

The experimentalist's view...

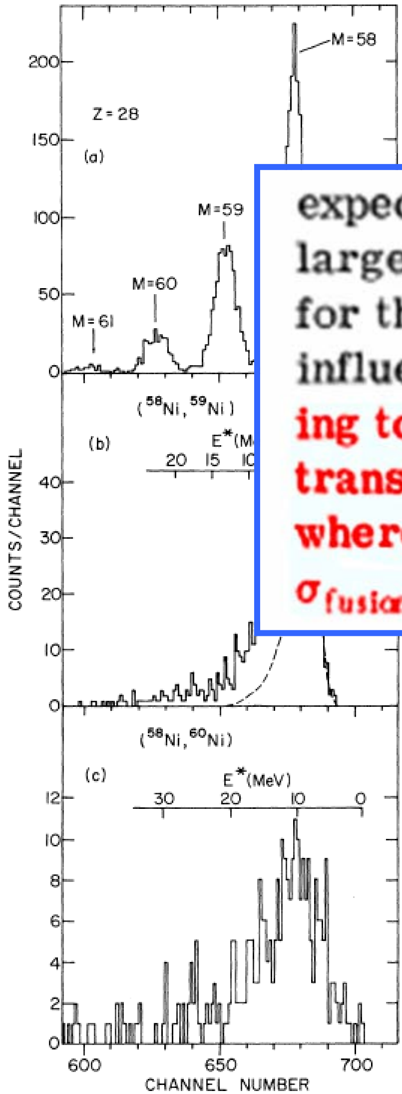


VOLUME 51, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1983

Large Cross Sections for Quasielastic Neutron-Pickup Reactions Induced by ^{37}Cl, ^{48}Ti, and ^{58}Ni on ^{208}Pb

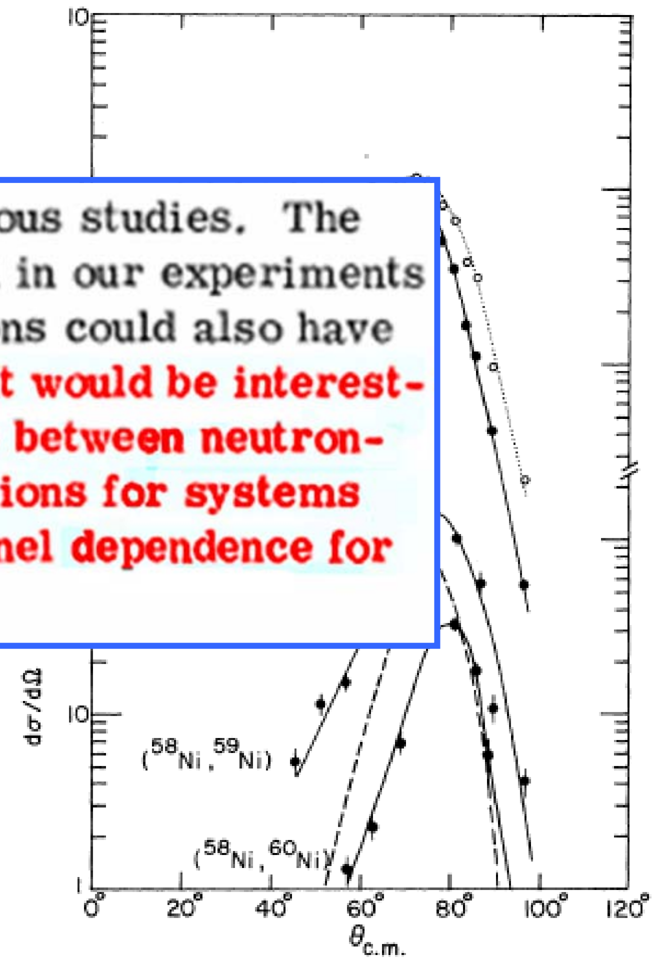
K. E. Rehm, D. G. Kovar, W. Kutschera, M. Paul,[a] G. Stephans, and J. L. Yntema
Argonne National Laboratory, Argonne, Illinois 60439

(Received 15 August 1983)



Mass resolution

expected on the basis of previous studies. The large cross sections observed in our experiments for the neutron-pickup reactions could also have influence on other channels. **It would be interesting to investigate correlations between neutron-transfer and fusion cross sections for systems where a strong entrance-channel dependence for σ_{fusion} has been observed.[15]**



Characteristic angular distributions for elastic, inelastic scattering, and transfer

Sub-barrier fusion enhancement

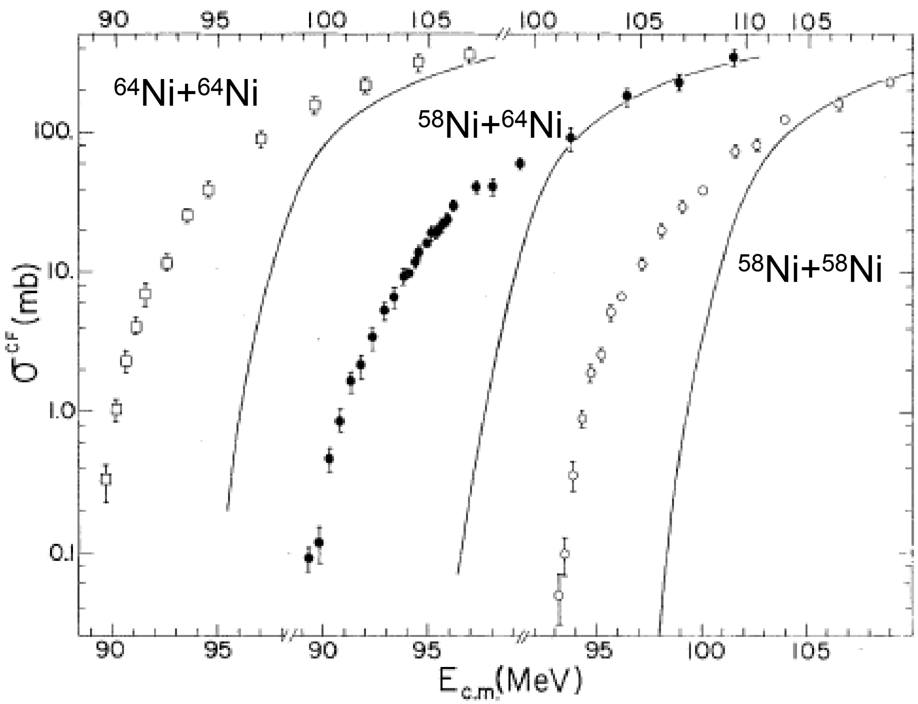


FIG. 2. Experimental and theoretical cross sections for complete fusion. Data symbols have the same meaning as in Fig. 1. Smooth curves represent generalized liquid-drop-model calculations (Ref. 15).

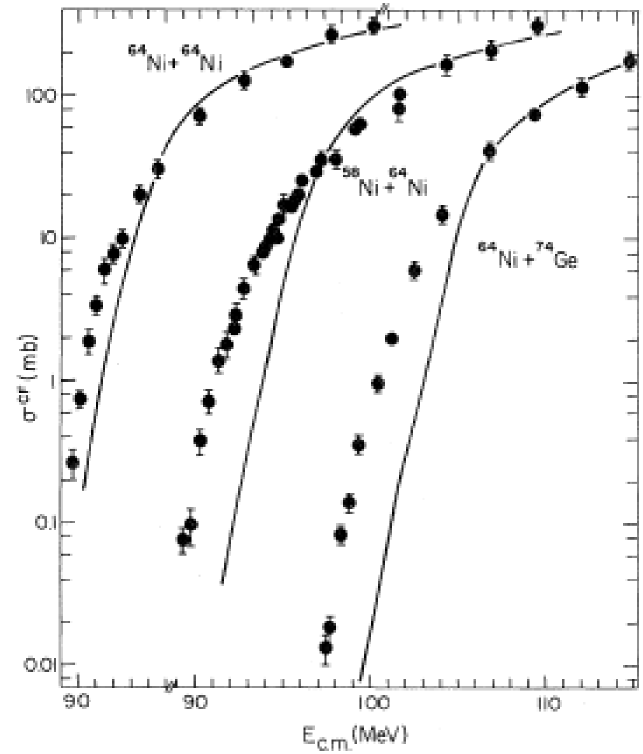


FIG. 11. Comparisons of experimental and phenomenological excitation functions for complete fusion. Filled circles represent the experimental results. Solid curves denote results of calculations performed using Eq. (3), as in Fig. 9.

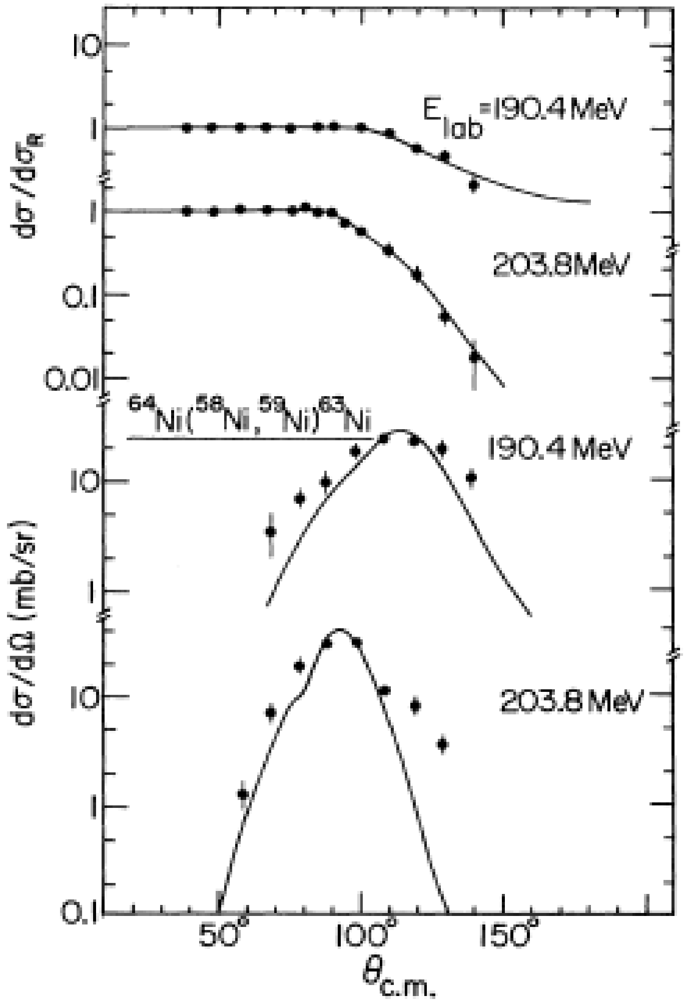
Strong entrance-channel dependence of fusion enhancement

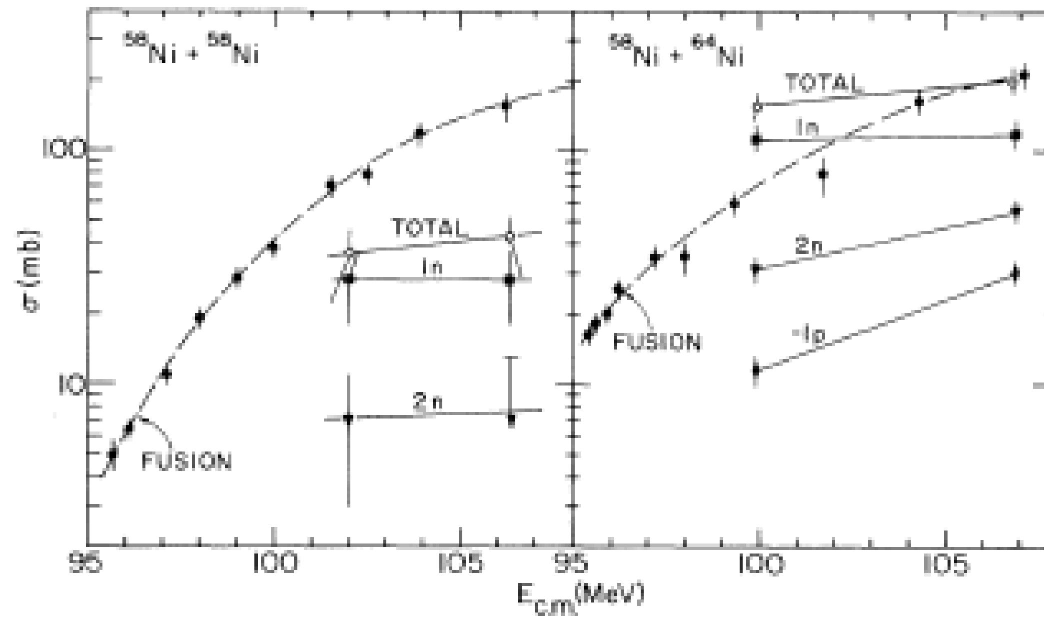
Beckerman et al., PRL **45**, 1472 (1980), PRC **25**, 837 (1982)

VOLUME 55, NUMBER 3 PHYSICAL REVIEW LETTERS 15 JULY 1985

Transfer Cross Sections for $^{58}Ni + ^{58}Ni$ and $^{58}Ni + ^{64}Ni$ in the Vicinity of the Fusion Barrier

K. E. Rehm, F. L. H. Wolfs, A. M. van den Berg, and W. Henning
Argonne National Laboratory, Argonne, Illinois 60439
(Received 25 February 1985)

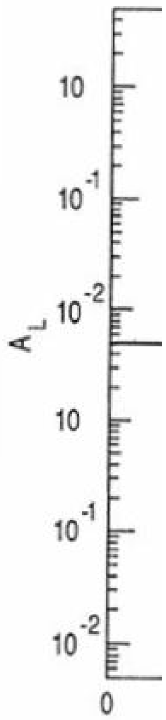


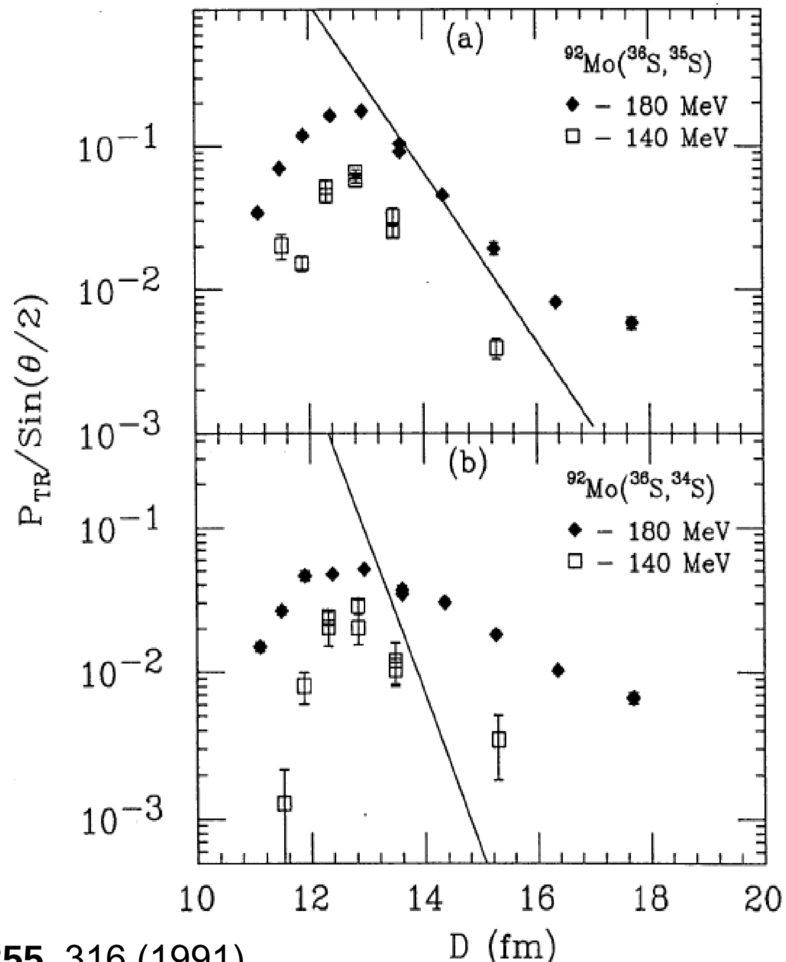


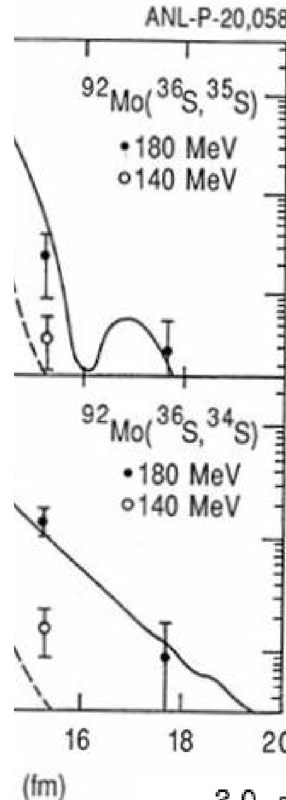
Coupling of transfer channels, in addition to inelastic excitations, is an essential key to understanding HI fusion enhancement (H. Esbensen and S. Landowne)

dP_{tr}/dD inconsistent with BE: "slope anomaly"

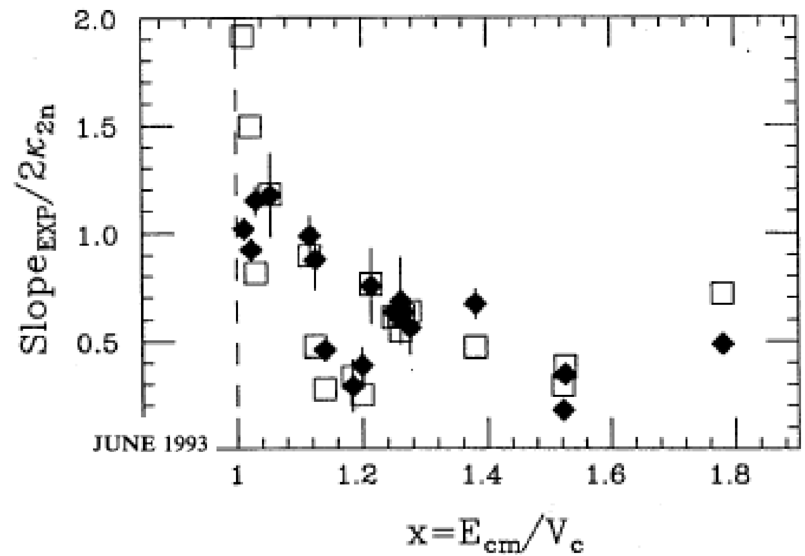
Expect $P_{TR} \sim e^{-2\alpha D}$







Prc
ser
PLB **255**, 316 (1991)
necessary, then everything
works!



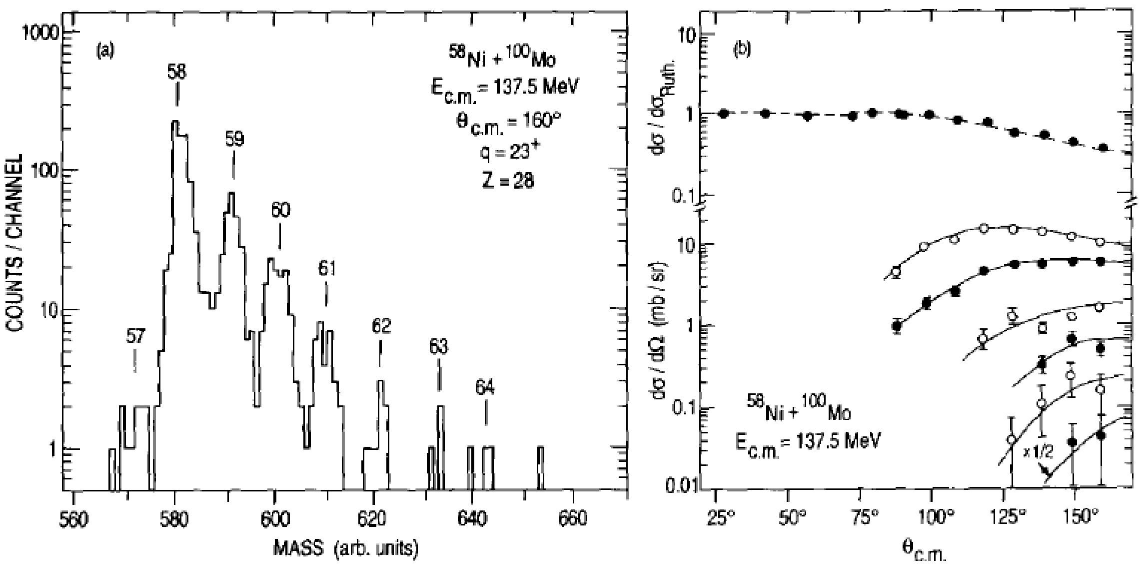
PHYSICAL REVIEW C VOLUME 47, NUMBER 6 JUNE 1993

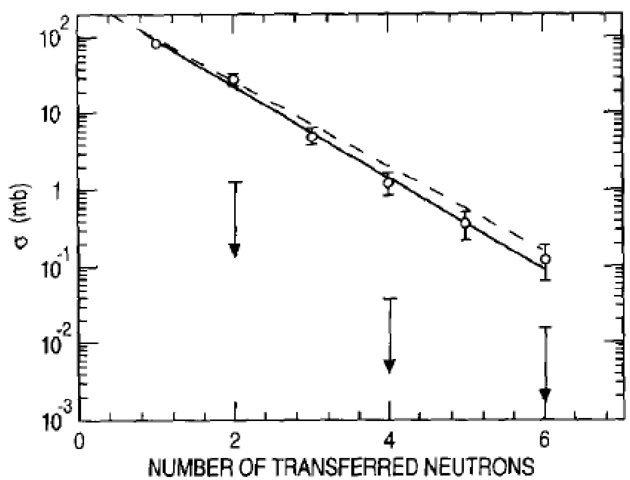
Neutron transfer reactions at large distances

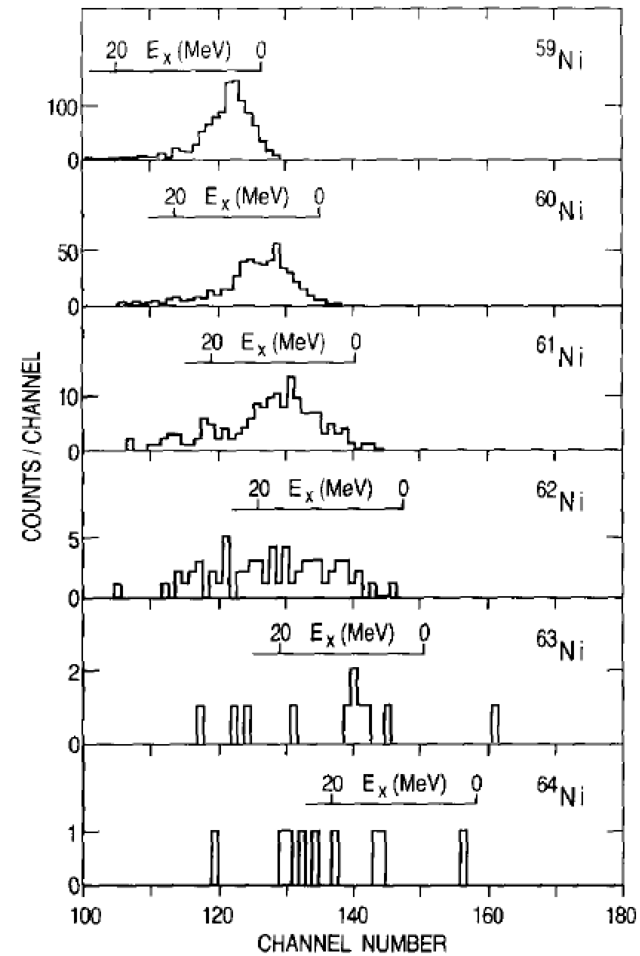
K. E. Rehm, B. G. Glagola, W. Kutschera, F. L. H. Wolfs,* and A. H. Wuosmaa
Argonne National Laboratory, Argonne, Illinois 60439
(Received 23 October 1992)

Why stop at 1 or 2n?!
6 (!) neutron transfer

C.L. Jiang et al. / Physics Letters B 337 (1994) 59–62







PHYSICAL REVIEW C VOLUME 17, NUMBER 6 JUNE 1978

Optimum Q value in heavy-ion-induced neutron transfer at the Coulomb barrier

W. Henning, Y. Eisen,[†] H.-J. Körner,[‡] D. G. Kovar, J. P. Schiffer, S. Vigdor,[§] and B. Zeidman
Argonne National Laboratory, Argonne, Illinois 60439
(Received 14 February 1978)

PHYSICAL REVIEW C VOLUME 30, NUMBER 1 JULY 1984

Quasielastic processes in the ^{28}Si + ^{208}Pb reaction at 8 MeV per nucleon

J. J. Kolata,* K. E. Rehm, D. G. Kovar, G. S. F. Stephans, G. Rosner,[†] and H. Ikezoe[‡]
Argonne National Laboratory, Argonne, Illinois 60439

R. Vojtech
Physics Department, University of Notre Dame, Notre Dame, Indiana 46556
(Received 27 March 1984)

VOLUME 51, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1983

Large Cross Sections for Quasielastic Neutron-Pickup Reactions Induced by ^{37}Cl, ^{48}Ti, and ^{58}Ni on ^{208}Pb

K. E. Rehm, D. G. Kovar, W. Kutschera, M. Paul,[(a)] G. Stephans, and J. L. Yntema
Argonne National Laboratory, Argonne, Illinois 60439
(Received 15 August 1983)

VOLUME 58, NUMBER 4 PHYSICAL REVIEW LETTERS 26 JANUARY 1987

Subbarrier Nucleon Transfer: Doorway to Heavy-Ion Fusion

W. Henning, F. L. H. Wolfs, J. P. Schiffer, and K. E. Rehm
Argonne National Laboratory, Argonne, Illinois 60439
(Received 20 October 1986)

PHYSICAL REVIEW C VOLUME 37, NUMBER 3

^{48}Ti + ^{104}Ru single-nucleon transfer at the barrier

S. J. Sanders, B. B. Back, R. R. Betts, D. Henderson, R. V. F. Janssens, K. E. Rehm, and F. Videbaek
Argonne National Laboratory, Argonne, Illinois 60439

VOLUME 56, NUMBER 6 PHYSICAL REVIEW LETTERS 10 FEBRUARY 1986

Quasielastic Nucleon Transfer and the Heavy-Ion Interaction Potential

A. M. van den Berg,[(a)] W. Henning, L. L. Lee, Jr.,[(b)] K. T. Lesko,[(c)] K. E. Rehm, J. P. Schiffer, G. S. F. Stephans,[(d)] and F. L. H. Wolfs
Argonne National Laboratory, Argonne, Illinois 60439

and

W. S. Freeman
Fermi National Accelerator Laboratory, Batavia, Illinois 60510
(Received 2 December 1985)

PHYSICAL REVIEW C VOLUME 26, NUMBER 3 SEPTEMBER 1982

Inelastic scattering and one-neutron-transfer reactions of ^{18}O + ^{40}Ca

K. E. Rehm, W. Henning, J. R. Erskine,* and D. G. Kovar
Argonne National Laboratory, Argonne, Illinois 60439
(Received 15 March 1982)

PHYSICAL REVIEW C VOLUME 47, NUMBER 6 JU

Neutron transfer reactions at large distances

K. E. Rehm, B. G. Glagola, W. Kutschera, F. L. H. Wolfs,* and A. H. Wuosmaa
Argonne National Laboratory, Argonne, Illinois 60439
(Received 23 October 1992)

AL REVIEW C VOLUME 57, NUMBER 5 MAY 1998

Multineutron transfer in ^{58}Ni + ^{124}Sn collisions at sub-barrier energies

C. L. Jiang, K. E. Rehm, H. Esbensen, D. J. Blumenthal, B. Crowell, J. Gehring, B. Glagola, J. P. Schiffer, and A. H. Wuosmaa
Physics Division, Argonne National Laboratory, Argonne, Illinois 60439
(Received 10 December 1997)

PHYSICAL REVIEW C VOLUME 33, NUMBER 4 APRIL 1986

Quasi-elastic processes in the ^{28}Si + ^{40}Ca reaction at 225 MeV

M. F. Vineyard, D. G. Kovar, G. S. F. Stephans,* K. E. Rehm, G. Rosner,[†] and H. Ikezoe[‡]
Argonne National Laboratory, Argonne, Illinois 60439

J. J. Kolata and R. Vojtech
Physics Department, University of Notre Dame, Notre Dame, Indiana 46556
(Received 13 November 1985)

VOLUME 55, NUMBER 3 PHYSICAL REVIEW LETTERS 15 JULY 1985

Transfer Cross Sections for ^{58}Ni + ^{58}Ni and ^{58}Ni + ^{64}Ni in the Vicinity of the Fusion Barrier

K. E. Rehm, F. L. H. Wolfs, A. M. van den Berg, and W. Henning
Argonne National Laboratory, Argonne, Illinois 60439
(Received 25 February 1985)

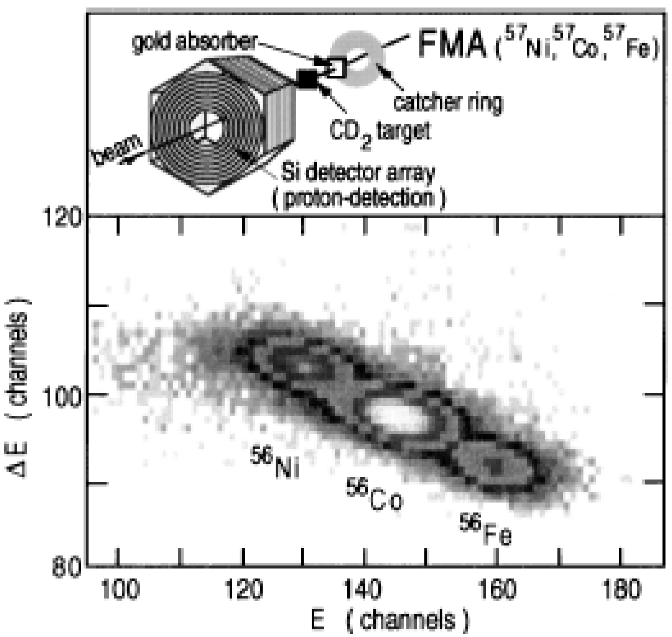
Just some of the many papers!

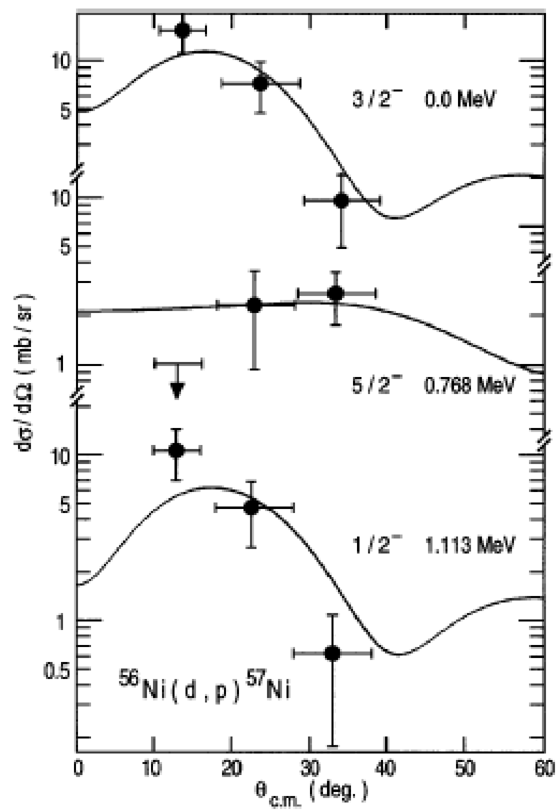
RIBS at ATLAS and nucleon transfer

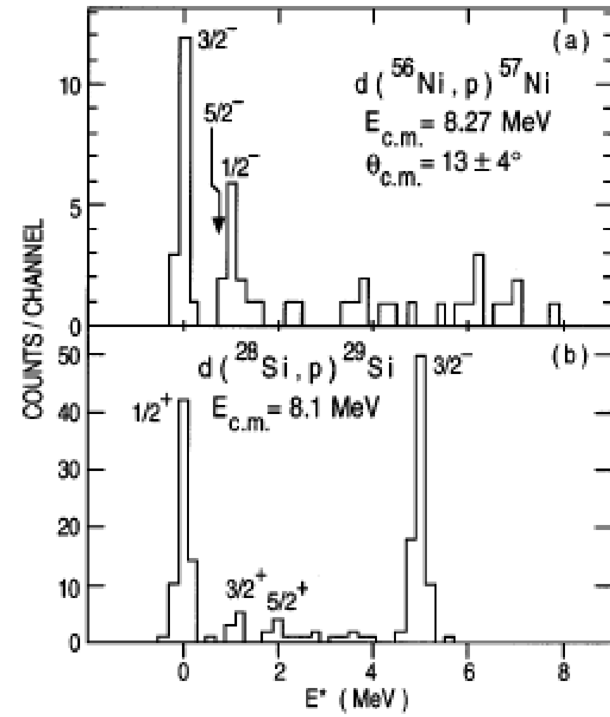
- Problem: how do we study single-particle states via (*d*,*p*) with unstable nuclei?
- Exchange light beam, heavy target, work in inverse kinematics
- RIBS at ATLAS to the rescue!
  - Two-accelerator method
  - In-Flight beams
  - Need the energy and intensity of ATLAS

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]

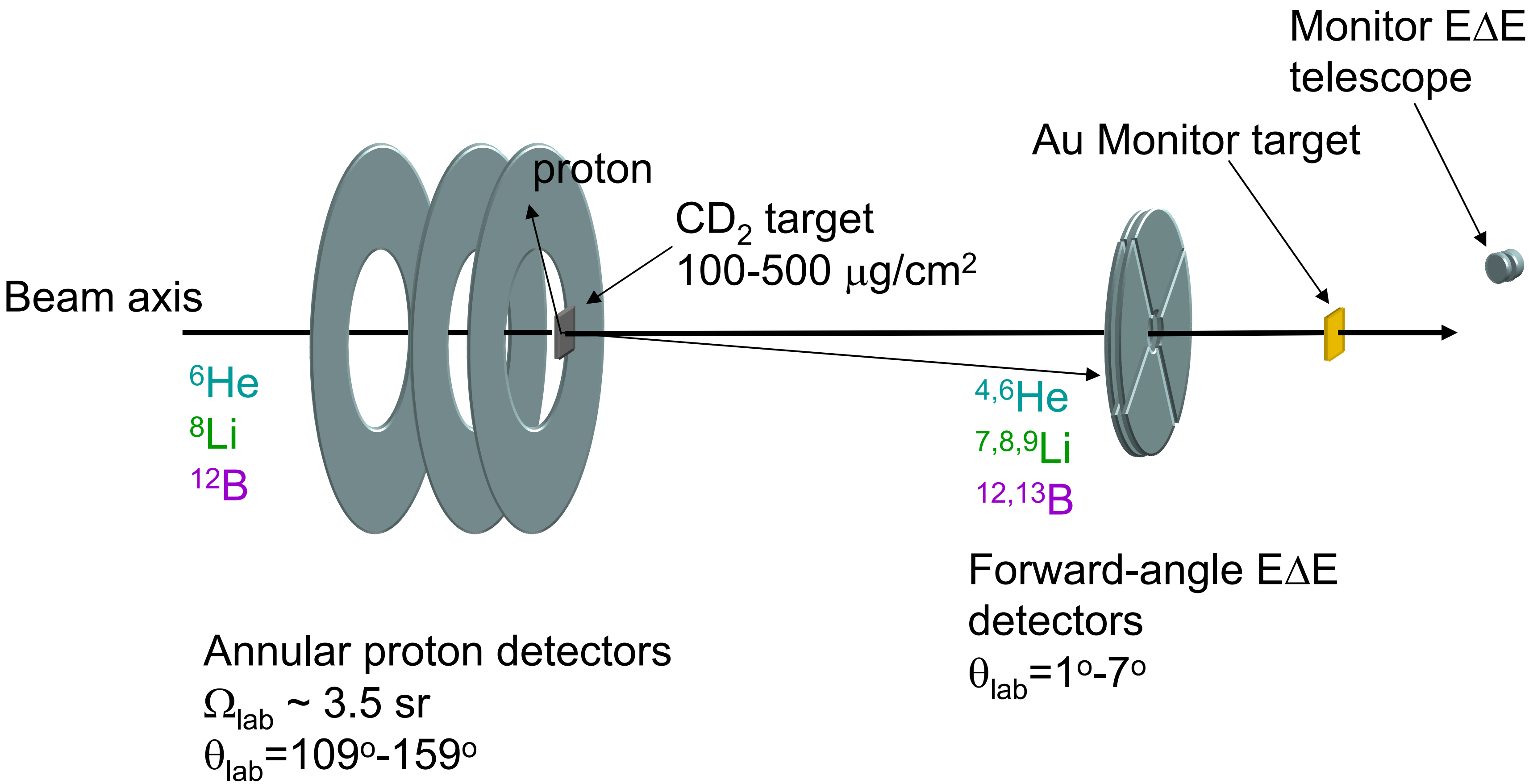






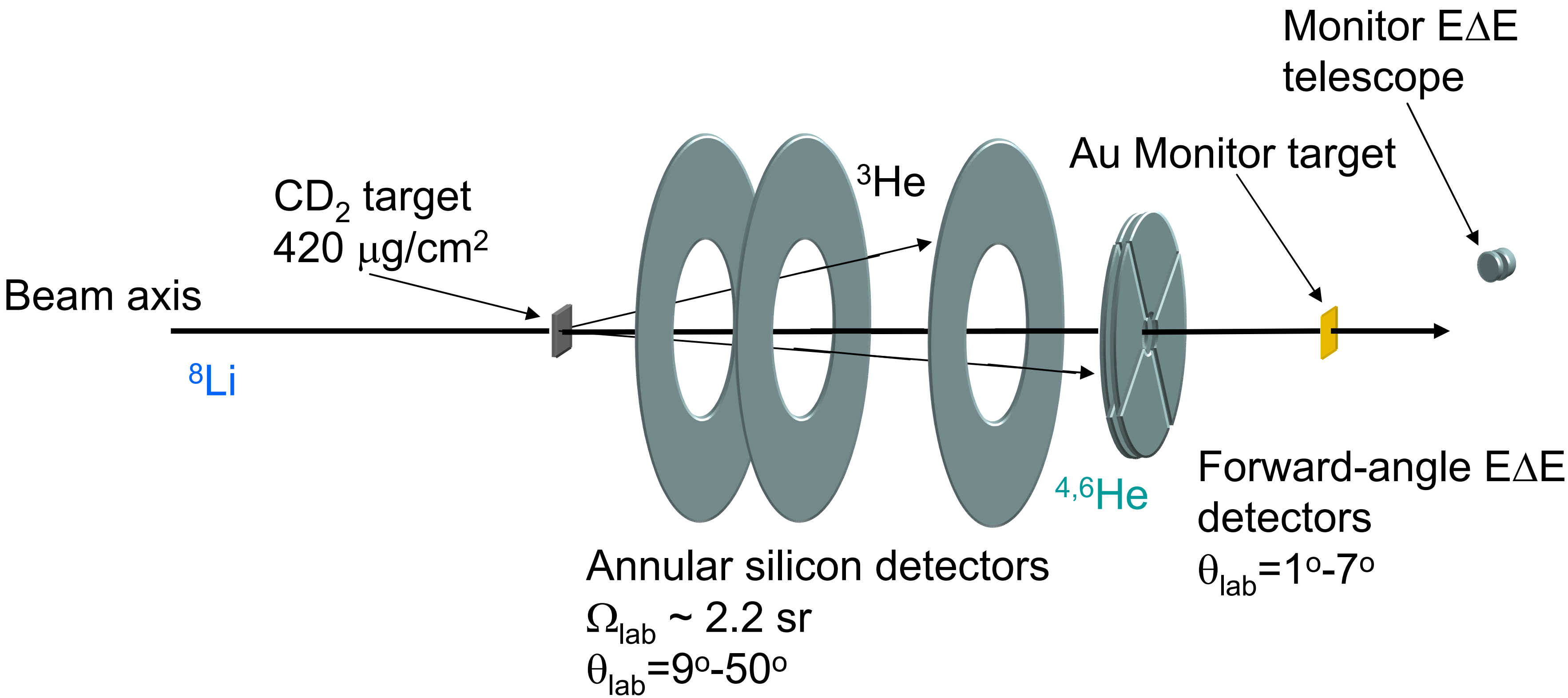
You heard yesterday-

Experiments with light nuclei: (*d,p*)

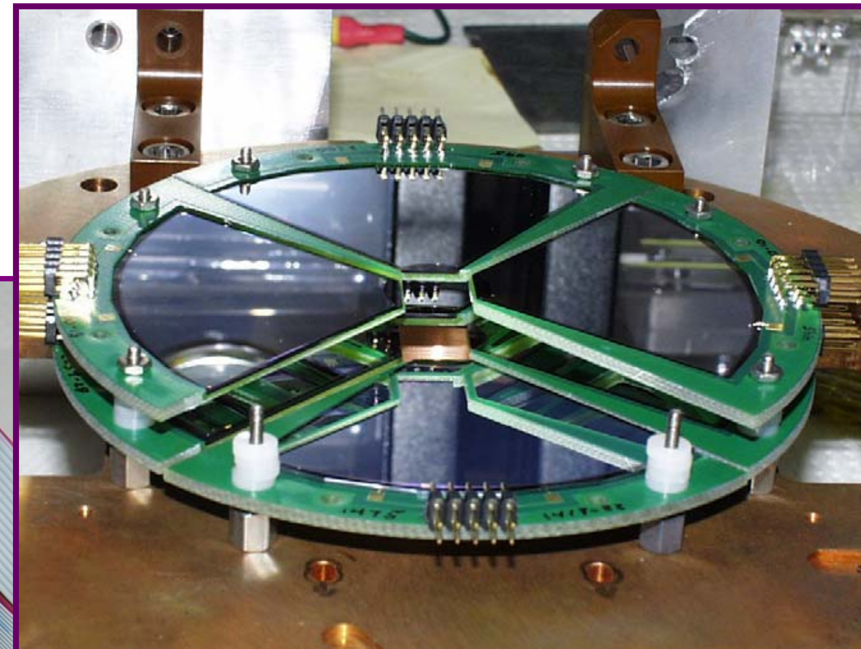


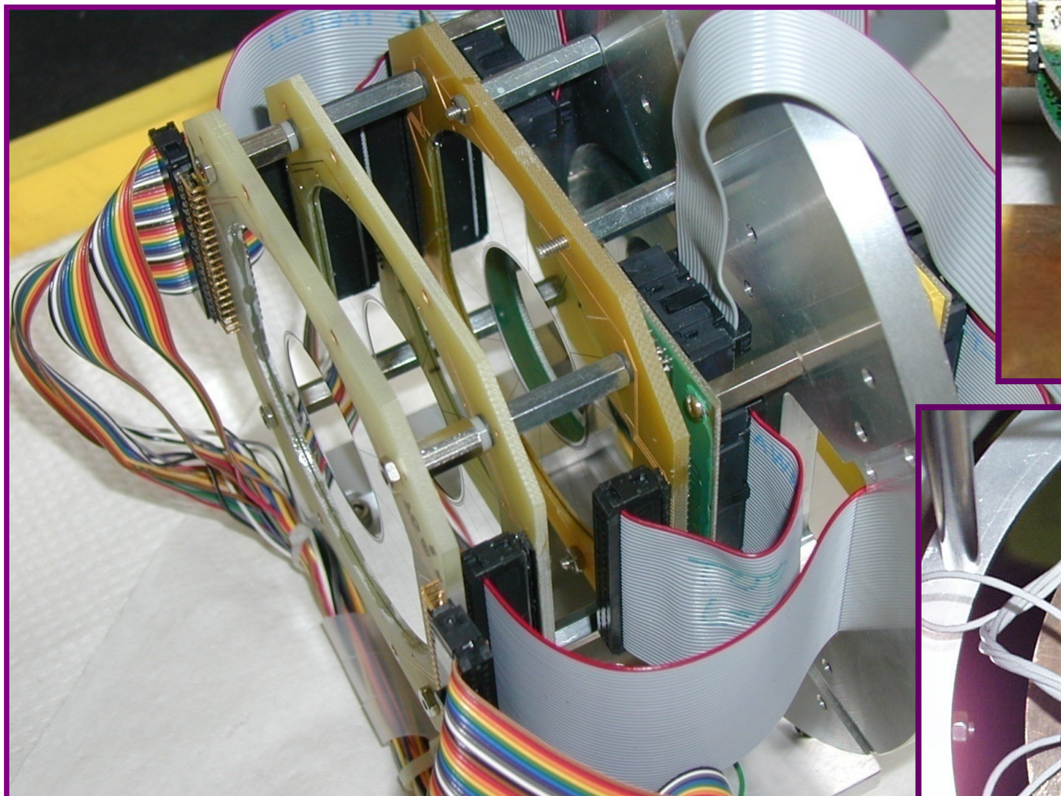
Secondary-beam intensities are ~1-5X10^4 particles/sec
Event rate for 10 mb/sr ~ 10-50 counts/hour

(d,^{3}He) Experimental setup

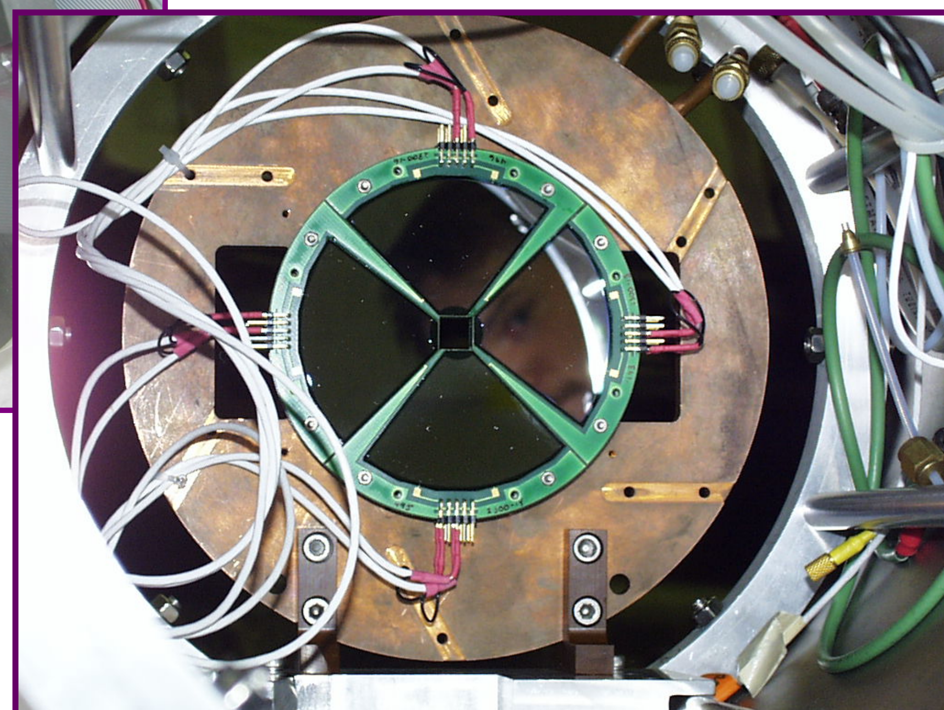


Detectors



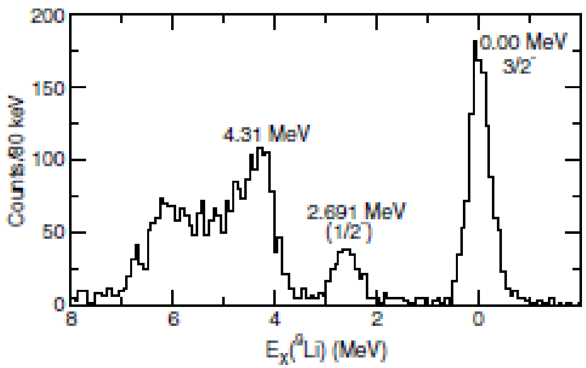


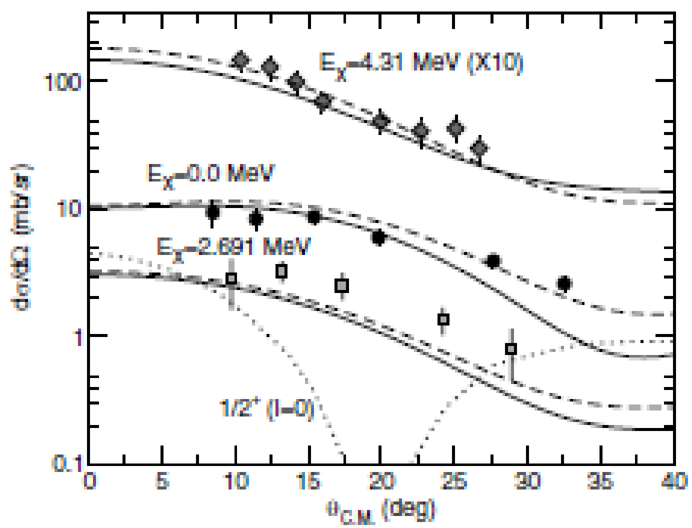
Segmented proton detectors



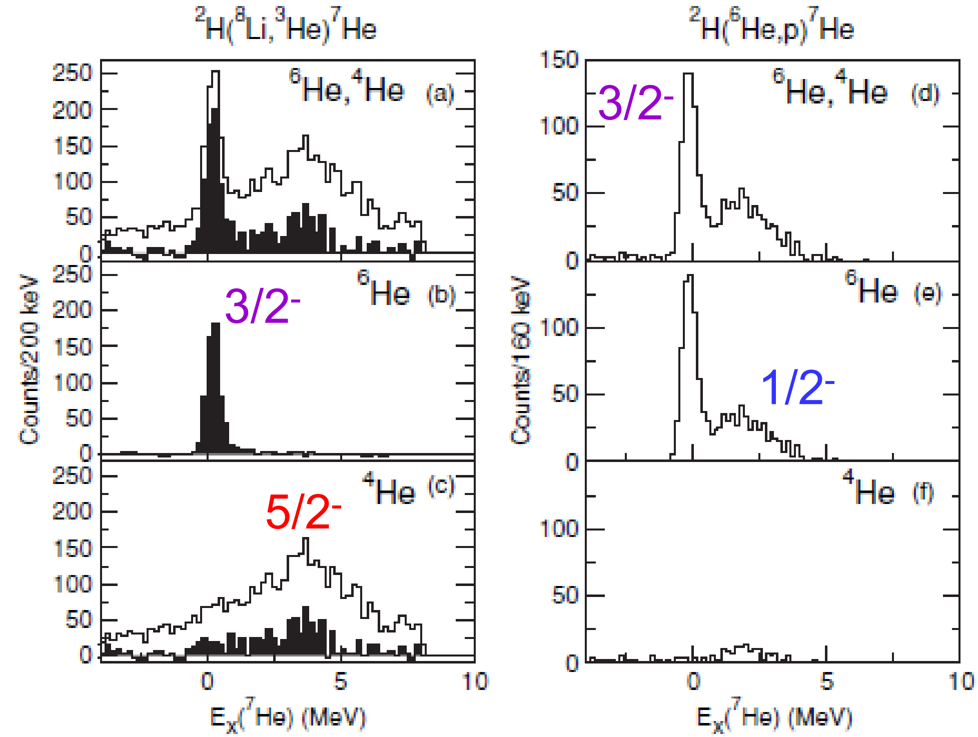
500μm/1000μm silicon EΔE telescope

In-flight RIBS – light nuclei – testing QMC calculations





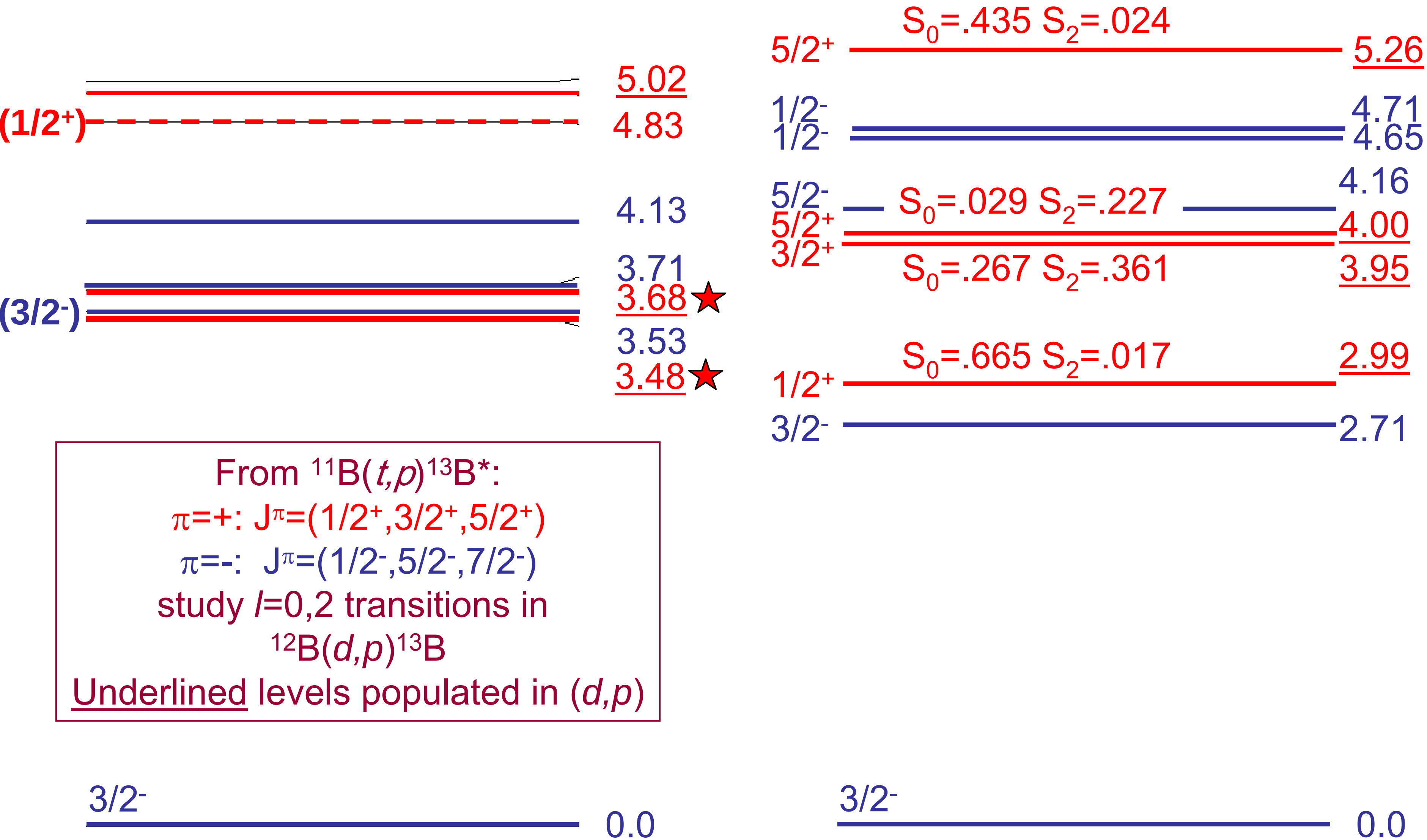
^{9}Li from ^{8}Li(*d,p*)
Test of QMC –
angular distributions with DWBA +
QMC overlap functions



Pickup and stripping to ^{7}He-
Broad, resonant excited states identified by cross-reaction analysis, decay properties are in agreement with QMC predictions

PRL 94, 082502 (2005), PRC 061301R (2005)
PRC 78, 041302R (2008)

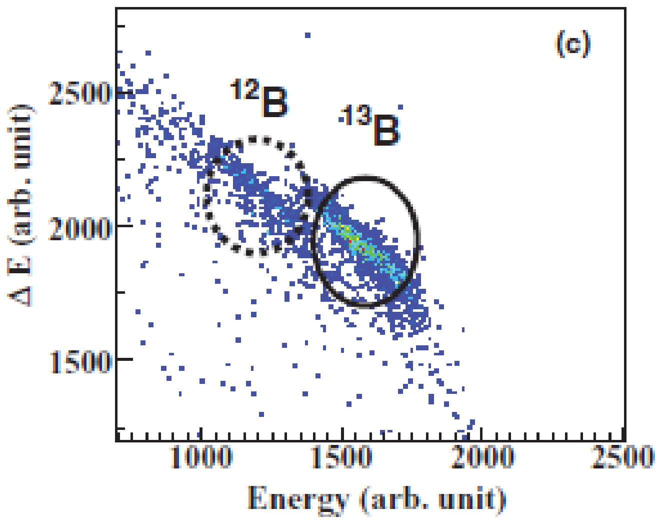
^{13}B(N=8) via ^{12}B(*d,p*)^{13}B: Experiment vs. shell model

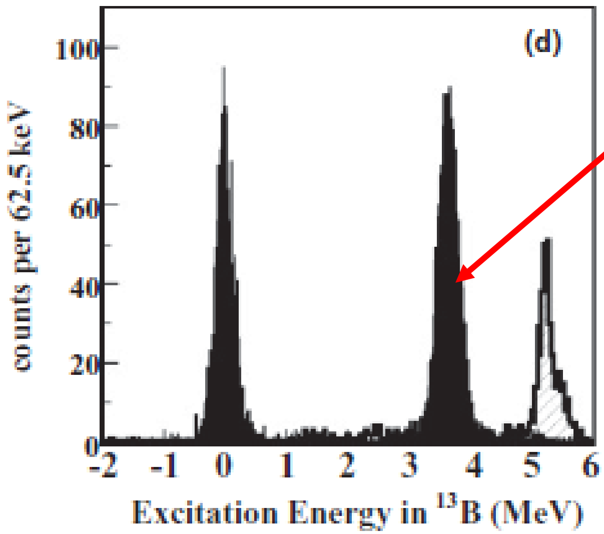


*^{13}B(Experiment)
(*t,p*): Middleton and Pullen, NP **50**, 1964

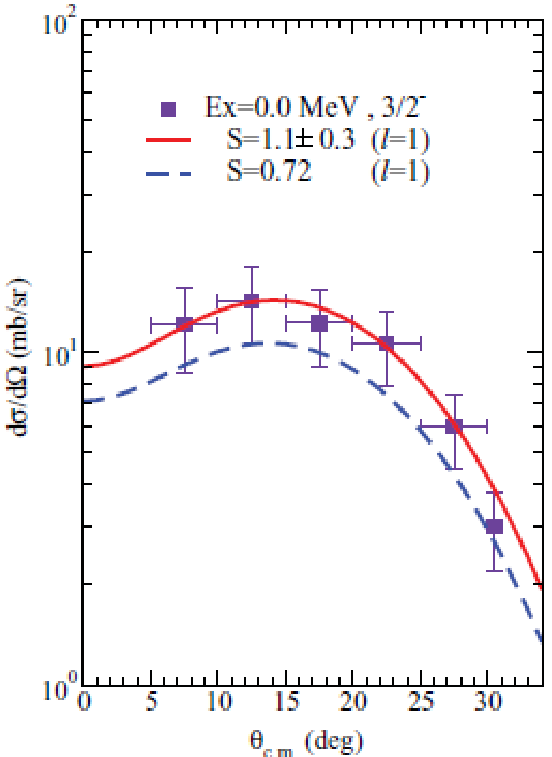
^{13}B(Shell Model π=+,-)
(B. A. Brown, WBP interaction)

Approaching full circle... $^{12}B(d,p)^{13}B$ with Si detector array





Two unresolved positive parity states here – separation 200 keV

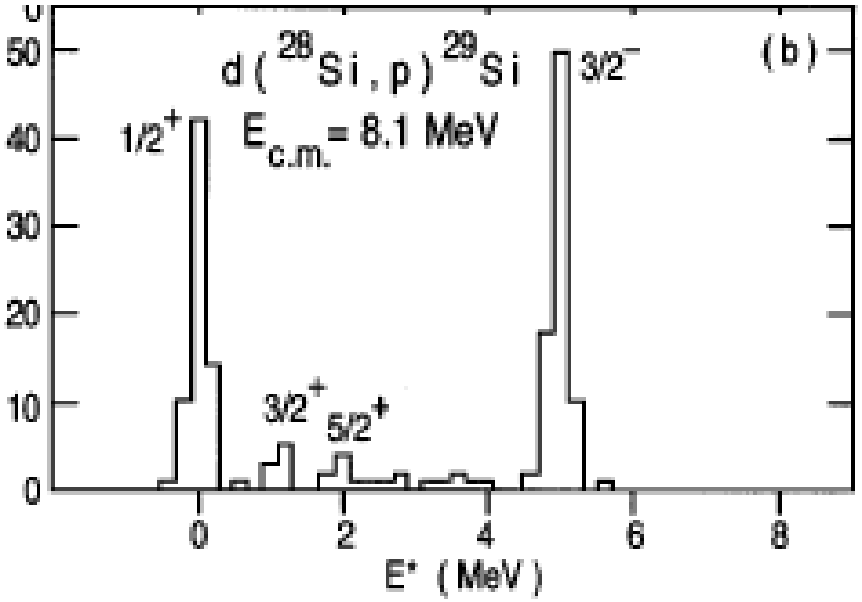


Can answer some questions about astrophysical reaction rates

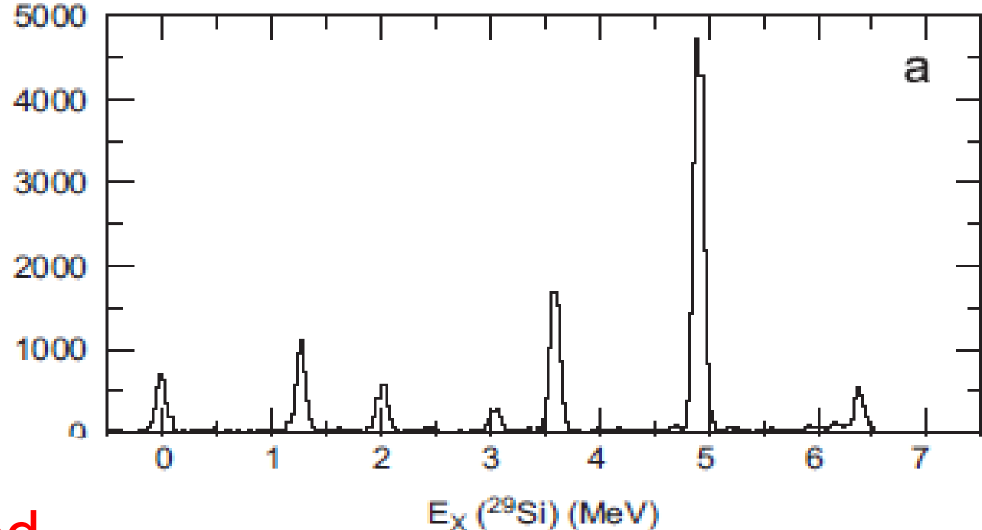
BUT – resolution insufficient to get at the interesting question of the re-ordering of *s* and *d* orbitals in neutron-rich light nuclei. **Need better resolution!!**

H. Y. Lee et al., PRC **81**, 015802 (2010)

And then a miracle occurs…



d(^{28}Si,p)^{29}Si
with HELIOS



HELIOS provides vastly improved excitation-energy resolution

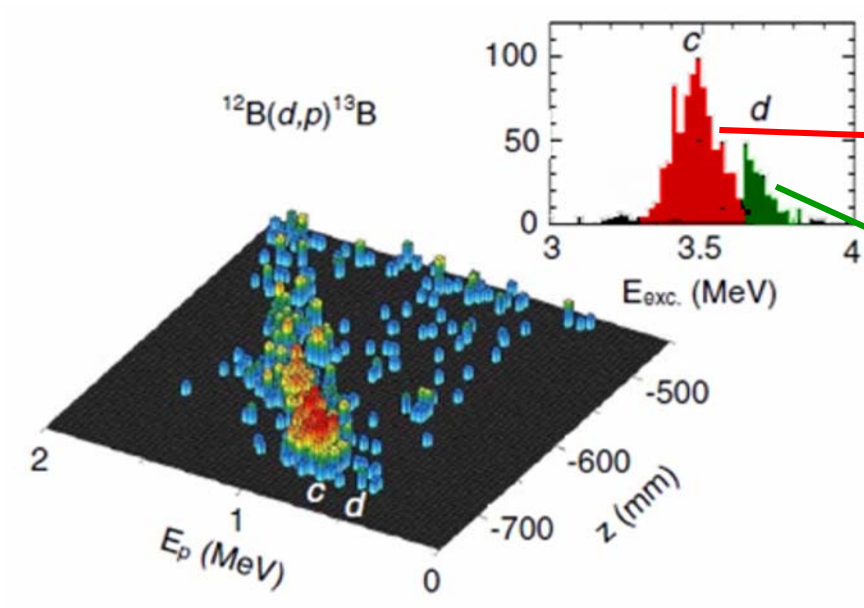
J. C. Lighthall et al., NIMPRA **622**, 97 (2010)

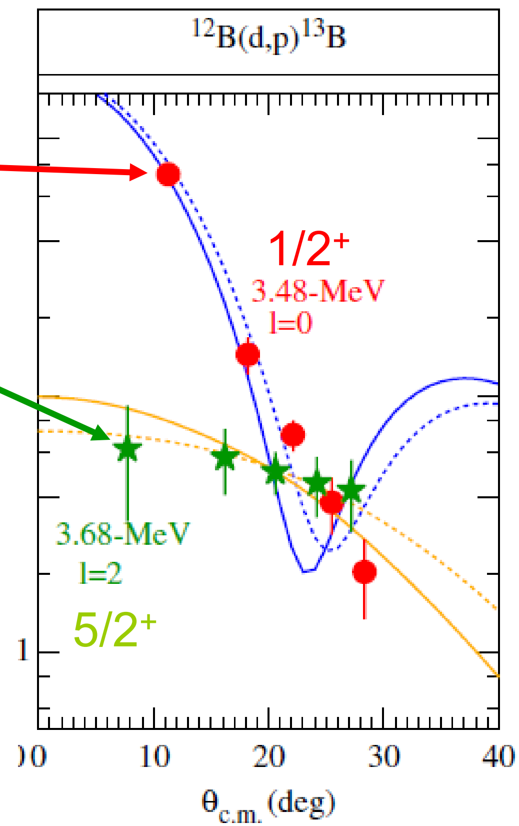
Now... with HELIOS

PRL **104,** 132501 (2010) PHYSICAL REVIEW LETTERS week ending 2 APRIL 2010

First Experiment with HELIOS: The Structure of ^{13}B

B. B. Back,[1] S. I. Baker,[1] B. A. Brown,[2] C.M. Deibel,[1,3] S. J. Freeman,[4] B. J. DiGiovine,[1] C. R. Hoffman,[1] B. P. Kay,[1] H. Y. Lee,[1] J. C. Lighthall,[5] S. T. Marley,[5] R. C. Pardo,[1] K.E. Rehm,[1] J. P. Schiffer,[1,*] D. V. Shetty,[5] A. W. Vann,[5] J. Winkelbauer,[5] and A.H. Wuosmaa[5]

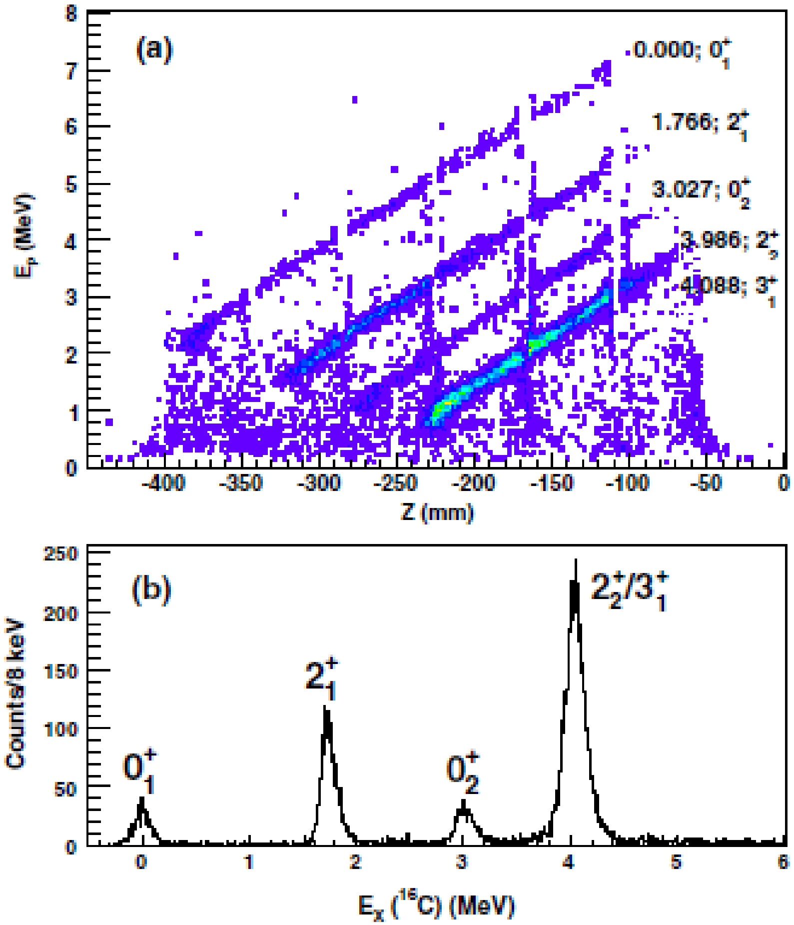


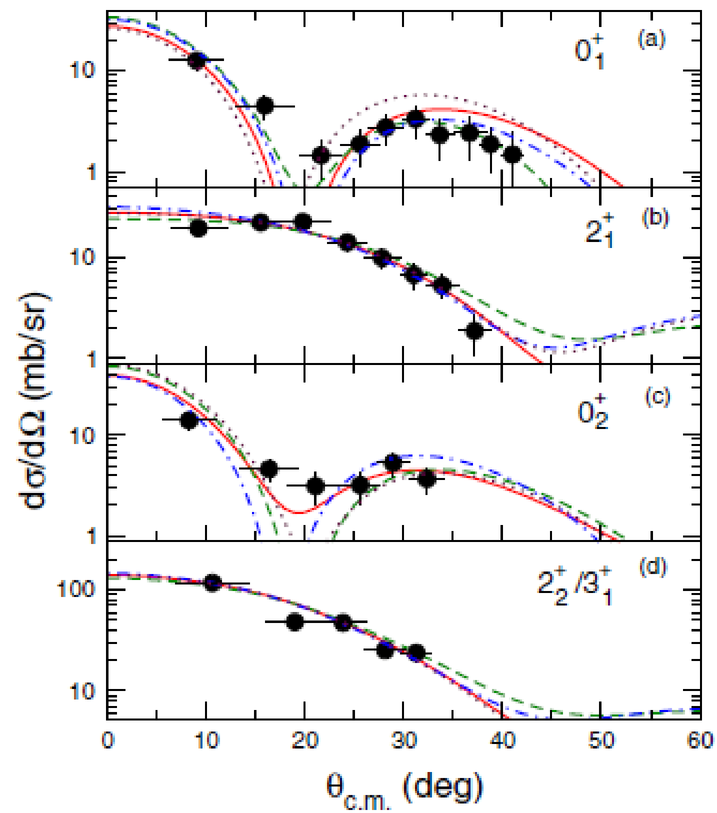


John returns to the *p* shell – inversion of *s* and *d* orbitals in ^{13}B confirmed !

$^{15}C(d,p)^{16}C$ Reaction and Exotic Behavior in ^{16}C

A. H. Wuosmaa,[1] B. B. Back,[2] S. Baker,[2] B. A. Brown,[3] C. M. Deibel,[2,4] P. Fallon,[5] C. R. Hoffman,[2] B. P. Kay,[2] H. Y. Lee,[6] J. C. Lighthall,[1,2] A. O. Macchiavelli,[5] S. T. Marley,[1,2] R. C. Pardo,[2] K. E. Rehm,[2] J. P. Schiffer,[2] D. V. Shetty,[1] and M. Wiedeking[7]





Funny business in ^{16}C?

Study wave functions of low-lying 2*n* states in ^{16}C

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

LETTERS

The future – the Holy Grail of ^{132}Sn(d,p)^{133}Sn

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]

E(^{132}Sn)=4.8 MeV/u

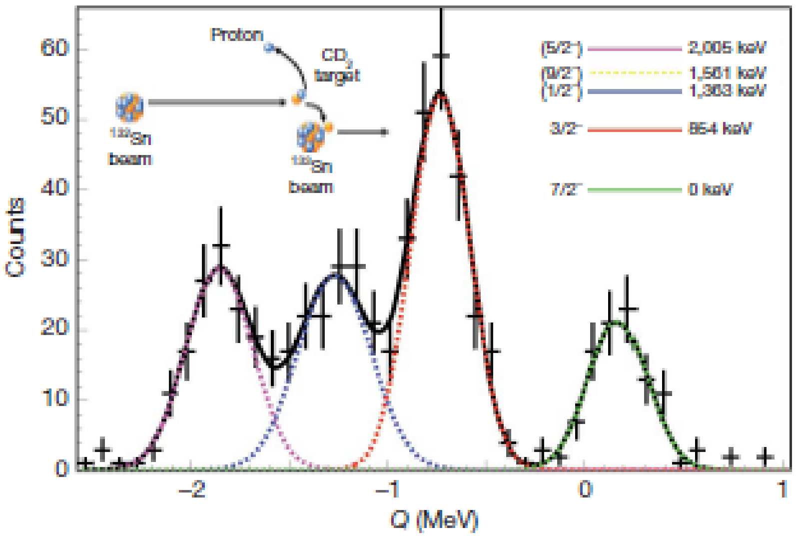
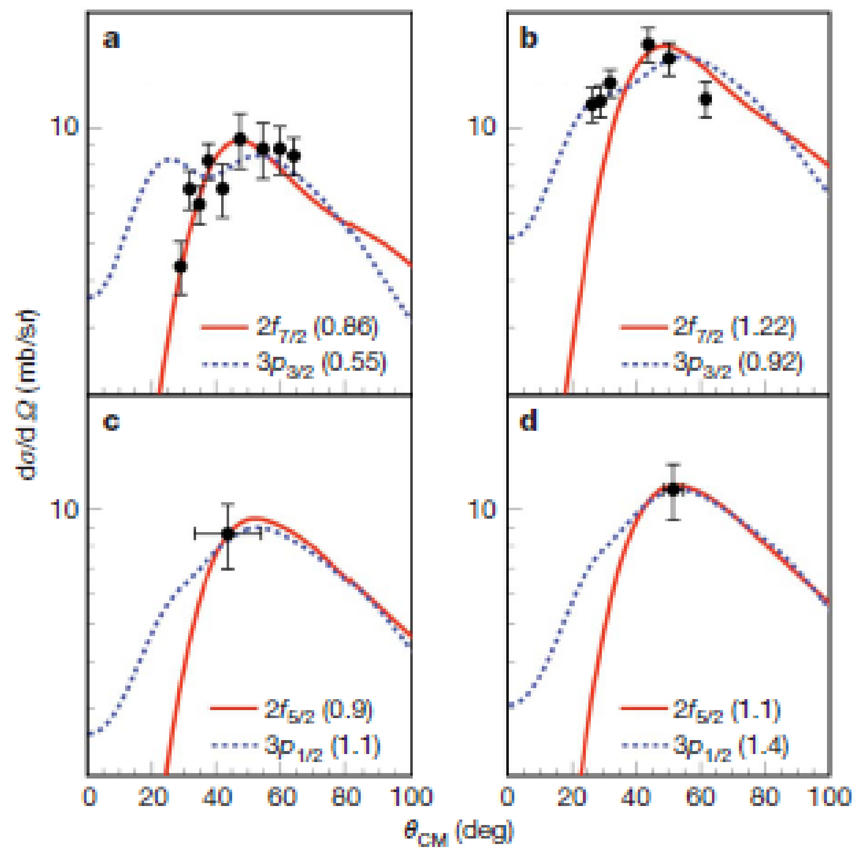
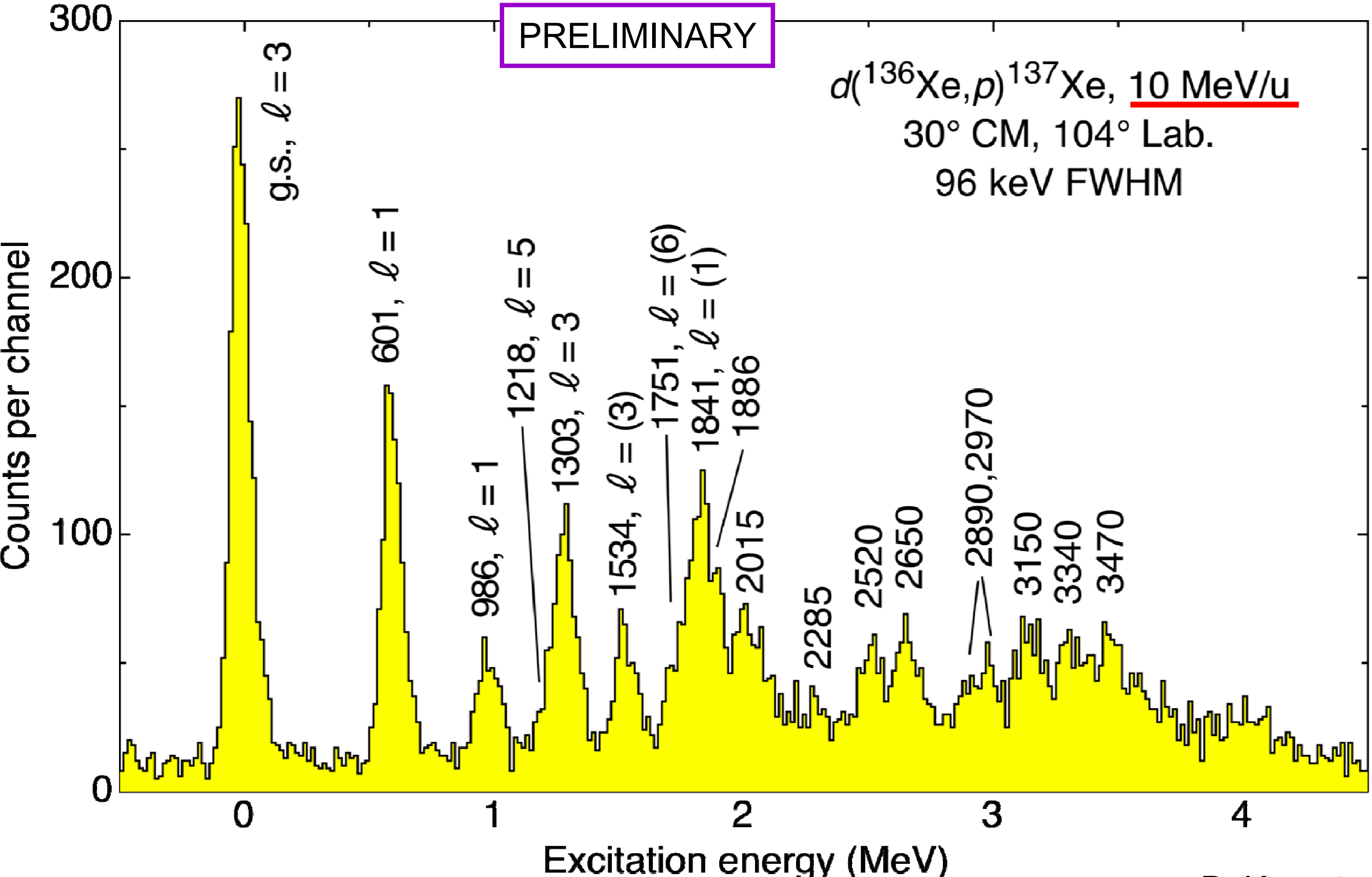


Figure 2 | Q-value spectrum for the ^{132}Sn(d,p)^{133}Sn reaction at 54° in the centre of mass. Error bars are statistical, shown as a standard deviation in the number of counts. The black solid line shows a fit to four peaks: the ground state (green), the 854-keV state (red), the first observation of the 1,363-keV state (blue), and the 2,005-keV state (magenta). The top left inset displays a diagram of the (d,p) reaction in inverse kinematics. The top right inset shows the level scheme of ^{133}Sn. The 1,561-keV state, expected to be the 9/2⁻ $h_{9/2}$ state, was not significantly populated in this reaction and therefore was not included in the fit.



HELIOS with beams near ^{132}Sn



First heavy-beam data

B. Kay et al.

HELIOS Experiments to date:

- ^{28}Si(*d*,*p*)^{29}Si
- ^{12}B(*d*,*p*)^{13}B
- ^{17}O(*d*,*p*)^{18}O
- ^{15}C(*d*,*p*)^{16}C
- ^{130,136}Xe(*d*,*p*)^{131,137}Xe
- ^{86}Kr(*d*,*p*)^{87}Kr
- ^{14}C(^{6}Li,*d*)^{18}O
- ^{19}O(*d*,*p*)^{20}O

Stable

With In-Flight RIB

We anticipate with CARIBU:
^{134}Te(*d*,*p*)^{135}Te, ^{132}Sn(*d*,*p*)^{133}Sn, many others

Quite a story

- Transfer reactions and ATLAS (really PHY) have gone hand in hand for 30+ years
- Capabilities provided by ATLAS enabled entirely new fields of research
- New accelerator (upgrades + CARIBU) and detector capabilities paint a very bright future: (d,p), (d,^{3}He), (α,t) etc. with fission-fragment beams + HELIOS

THANKS!

and ONWARD!

Multineutron transfer in ^{58}Ni+^{124}Sn collisions at sub-barrier energies

C. L. Jiang, K. E. Rehm, H. Esbensen, D. J. Blumenthal, B. Crowell, J. Gehring, B. Glagola, J. P. Schiffer, and A. H. Wuosmaa
Physics Division, Argonne National Laboratory, Argonne, Illinois 60439

(Received 10 December 1997)

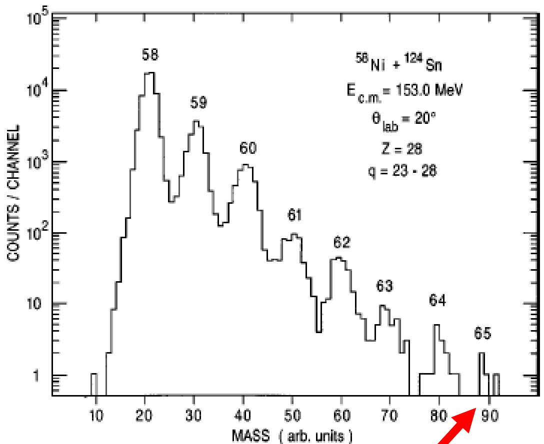


FIG. 1. Mass spectrum for $Z=28$ isotopes measured at $E_{c.m}=153.0$ MeV, $\theta_{lab}=20°$, and integrated over the charge states $q=23-26$ in the system ^{58}Ni+^{124}Sn.

7 neutrons!

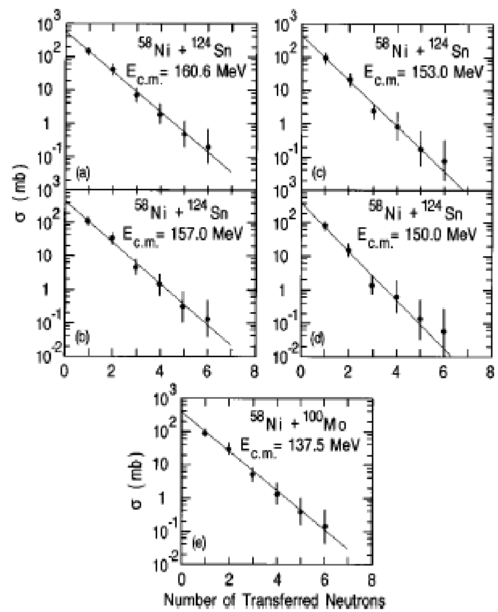
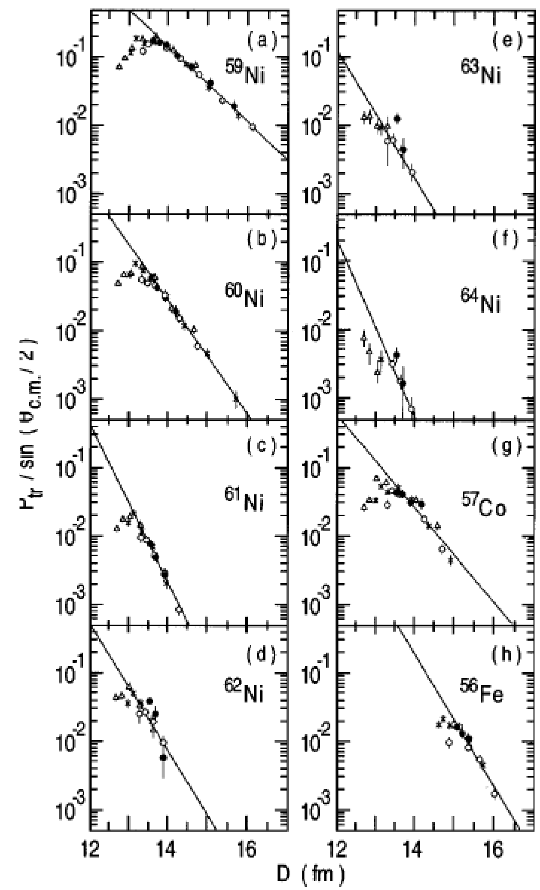


FIG. 8. Angle- and energy-integrated cross sections as a function of the number of transferred neutrons for the system ^{58}Ni + ^{124}Sn at four incident energies, together with data for the system ^{100}Mo+^{58}Ni [4]. The solid lines are least-squares fits to the data. The reduction factors for each transferred neutron are given in Table IV.




CAREFUL
HOT

What do we learn from nucleon transfer?

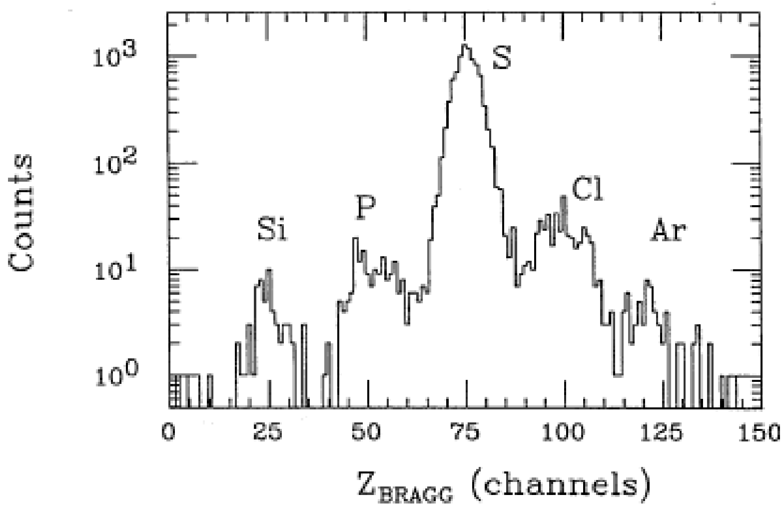
- Nuclear structure
  - Properties of single-particle states
  - Test/Tune shell-model interactions
  - Success of DWBA analyses
  - Spectroscopic factors
- The meat and potatoes of nuclear physics for many decades

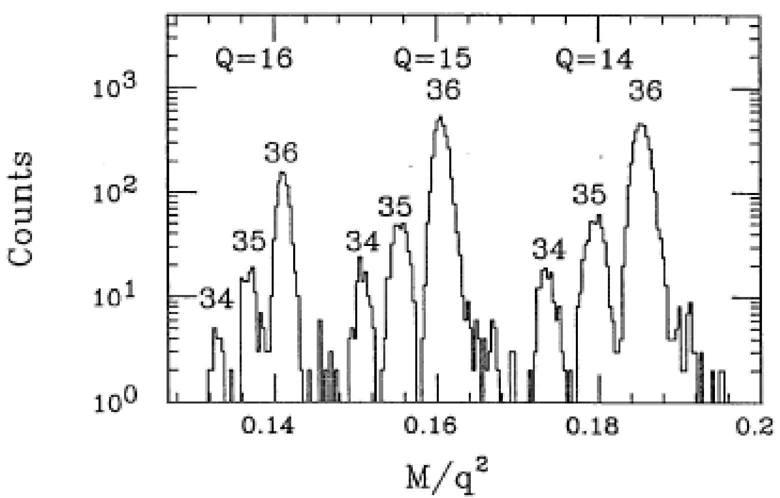
What was new with ATLAS?

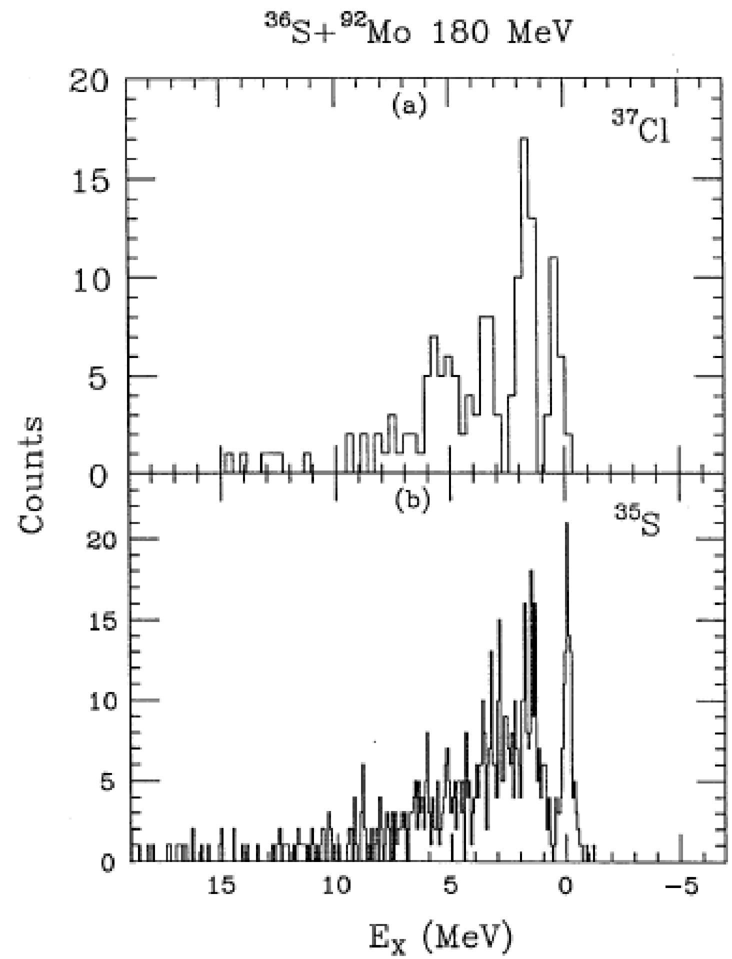
- What about nucleon transfer between heavy ions?
- Need:
  - Higher bombarding energies (E_{CM}~V_c)
  - High resolution (high-quality HI beams)
  - Systematics – a variety of HI beams throughout the periodic table
  - High-resolution experimental devices (Split-Pole spectrograph)

All become available with the development of ATLAS!

High-resolution ATLAS data







$^{92}Mo(^{36}S,X)$ data from ATLAS + SPS:
Good resolution in Z, M/q, and E_X

Slope anomalies...

Volume 192, number 3,4 PHYSICS LETTERS B 2 July 1987

ANOMALOUS TWO-NEUTRON TRANSFER CROSS SECTIONS AT LARGE SEPARATION IN HEAVY ION REACTIONS

S. JUUTINEN [a,b,1], X.T. LIU [a,b], S. SØRENSEN [a,b], B. COX [a,b,2], R.W. KINCAID [a,b], C.R. BINGHAM [a,b], M.W. GUIDRY [a,b], W.J. KERNAN [c], C.Y. WU [c,3], E. VOGT [c], T. CZOSNYKA [c], D. CLINE [c], M.L. HALBERT [b], I.Y. LEE [b] and C. BAKTASH [b]

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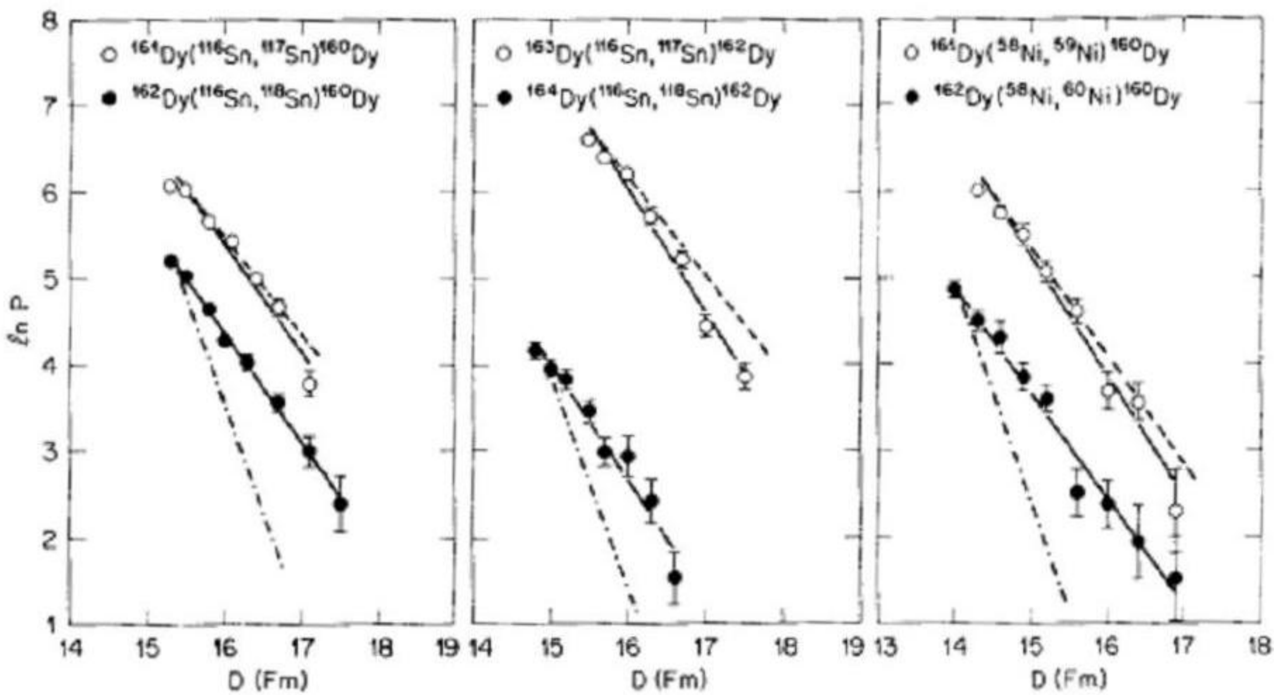
[c] *Nuclear Structure Research Laboratory, University of Rochester, Rochester, NY 14627, USA*



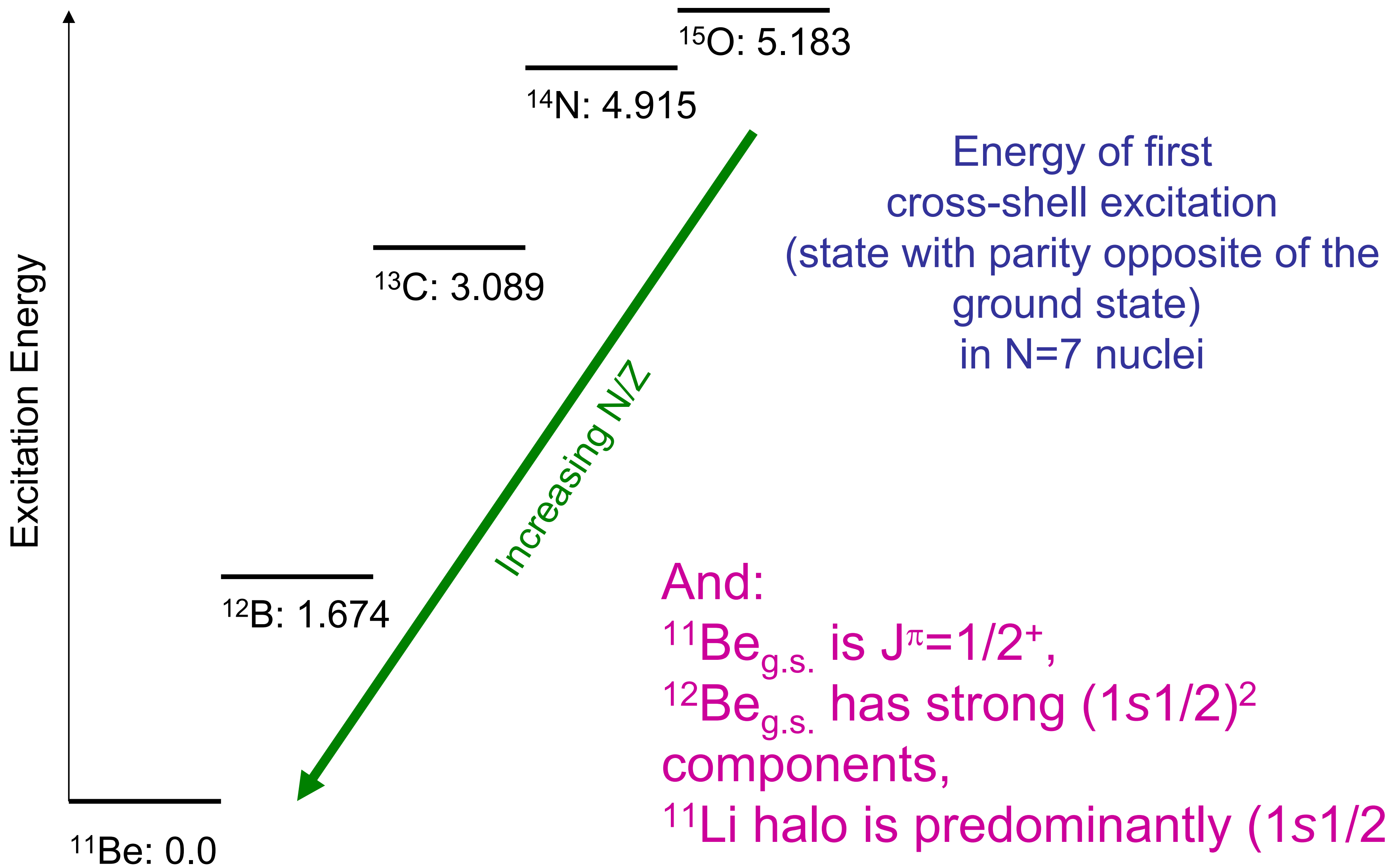
Expect: $P_t \sim e^{-2\alpha D}$
Observe: NOT!

Nucleon transfer and total reaction cross section

- Assumption was that transfer is a small fraction of total σ_R for heavy projectiles; (based on limited, poor resolution data)
- Observation was that transfer is large fraction and increases with projectile mass
- Unexpected result.
- Influence on other channels (e.g. fusion) – suggests further investigation of that relationship...

> The large cross sections observed in our experiments for the neutron-pickup reactions could also have influence on other channels. **It would be interesting to investigate correlations between neutron-transfer and fusion cross sections for systems where a strong entrance-channel dependence for σ_{fusion} has been observed.**[15]

sd states in light nuclei



And:

^{11}Be$_{g.s.}$ is $J^{\pi}=1/2^{+}$,

^{12}Be$_{g.s.}$ has strong $(1s1/2)^2$ components,

^{11}Li halo is predominantly $(1s1/2)^2$

The (short) story of ^{16}C...

VOLUME 92, NUMBER 6 PHYSICAL REVIEW LETTERS week ending 13 FEBRUARY 2004

Anomalously Hindered $E2$ Strength $B(E2; 2_1^+ \rightarrow 0^+)$ in ^{16}C

Big hindrance!

N. Imai,[1,*] H. J. Ong,[2] N. Aoi,[1] H. Sakurai,[2] K. Demichi,[3] H. Kawasaki,[3] H. Baba,[3] Zs. Dombrádi,[4] Z. Elekes,[1,†] N. Fukuda,[1] Zs. Fülöp,[4] A. Gelberg,[5] T. Gomi,[3] H. Hasegawa,[3] K. Ishikawa,[6] H. Iwasaki,[2] E. Kaneko,[3] S. Kanno,[3] T. Kishida,[1] Y. Kondo,[6] T. Kubo,[1] K. Kurita,[3] S. Michimasa,[7] T. Minemura,[1] M. Miura,[6] T. Motobayashi,[1] T. Nakamura,[6] M. Notani,[7] T. K. Onishi,[2] A. Saito,[3] S. Shimoura,[7] T. Sugimoto,[6] M. K. Suzuki,[2] E. Takeshita,[3] S. Takeuchi,[1] M. Tamaki,[7] K. Yamada,[3] K. Yoneda,[1,‡] H. Watanabe,[1] and M. Ishihara[1]

Physics Letters B 586 (2004) 34–40

Decoupling of valence neutrons from the core in ^{16}C

Exotic behavior!

Z. Elekes[a,1], Zs. Dombrádi[b], A. Krasznahorkay[b], H. Baba[c], M. Csatlós[b], L. Csige[b], N. Fukuda[a], Zs. Fülöp[b], Z. Gácsi[b], J. Gulyás[b], N. Iwasa[d], H. Kinugawa[c], S. Kubono[e], M. Kurokawa[e], X. Liu[e], S. Michimasa[e], T. Minemura[e], T. Motobayashi[a], A. Ozawa[a], A. Saito[c], S. Shimoura[e], S. Takeuchi[a], I. Tanihata[a], P. Thirolf[f], Y. Yanagisawa[a], K. Yoshida[a]

PRL 100, 152501 (2008) PHYSICAL REVIEW LETTERS week ending 18 APRIL 2008

Lifetime Measurement of the First Excited 2^+ State in ^{16}C

M. Wiedeking, P. Fallon, A. O. Macchiavelli, J. Gibelin, M. S. Basunia, R. M. Clark, M. Cromaz, M.-A. Deleplanque, S. Gros, H. B. Jeppesen, P. T. Lake, I.-Y. Lee, L. G. Moretto, J. Pavan, L. Phair, and E. Rodriguez-Vietiez
Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

L. A. Bernstein, D. L. Bleuel, J. T. Burke, S. R. Lesher, B. F. Lyles, and N. D. Scielzo
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(Received 20 November 2007; published 16 April 2008)

No hindrance, and no exotic behavior.

Measured spectroscopic factors and predictions

Nucleus	State	E_{exp}(MeV)	E_{LSF}(MeV)	E_{WBP}(MeV)	S_{exp}	S_{LSF}	S_{WBP}
^{16}C	0_1^+	0.000	0.000	0.000	0.60(.13)	1.071	0.601
^{16}C	2_1^+	1.766	2.354	2.385	0.52(.12)	0.630	0.581
^{16}C	0_2^+	3.027	3.448	3.581	1.40(.31)	0.929	1.344
^{16}C	2_2^+	3.986	4.052	4.814	≤0.34[a]	0.397	0.329
^{16}C	3_1^+	4.088	–	5.857	0.82-1.06[a]	–	0.918
^{15}C	$1/2^+$	0.000	–	0.000	0.88(.18)[b]	–	0.980
^{15}C	$5/2^+$	0.740	–	0.380	0.69(.14)[b]	–	0.943

Data normalization: $\Sigma S(0^+) = 2.0$

LSF: interaction only from ^{18}O

WBP: Warburton-Brown, PRC **46**, 923 (1992).

[b] ^{14}C(*d*,*p*) Goss et al, PRC **12** 1730 (1975).

Consistency test:

$\Sigma S(\mathbf{l}=2)/\Sigma S(\mathbf{l}=0)$ for ^{15}C and ^{16}C should be equal

Result:

R(^{15}C)=.78(.15) R(^{16}C)=.84(.10)

PHYSICAL REVIEW C VOLUME 35, NUMBER 6 JUNE 1987

Higher-order coupling effects in low energy heavy-ion fusion reactions

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(Received 8 January 1987)

Higher-order couplings to inelastic excitations of surface vibrations can strongly affect the enhancement of heavy-ion fusion cross sections at sub-barrier energies. Detailed second-order calculations are presented for reactions between different nickel isotopes. The agreement with measured fusion cross sections is considerably improved with respect to conventional coupled channels calculations based on linear couplings.

PHYSICAL REVIEW C VOLUME 40, NUMBER 5 NOVEMBER 1989

Fusion calculations for $^{40}Ca + ^{40,44,48}Ca$

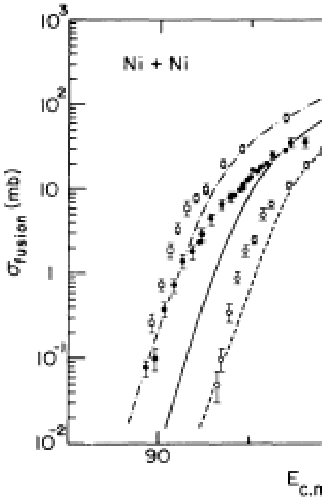


FIG. 5. Comparison of secon
with the fusion data of Ref. 18
and $^{64}Ni + ^{64}Ni$ reactions. The pa

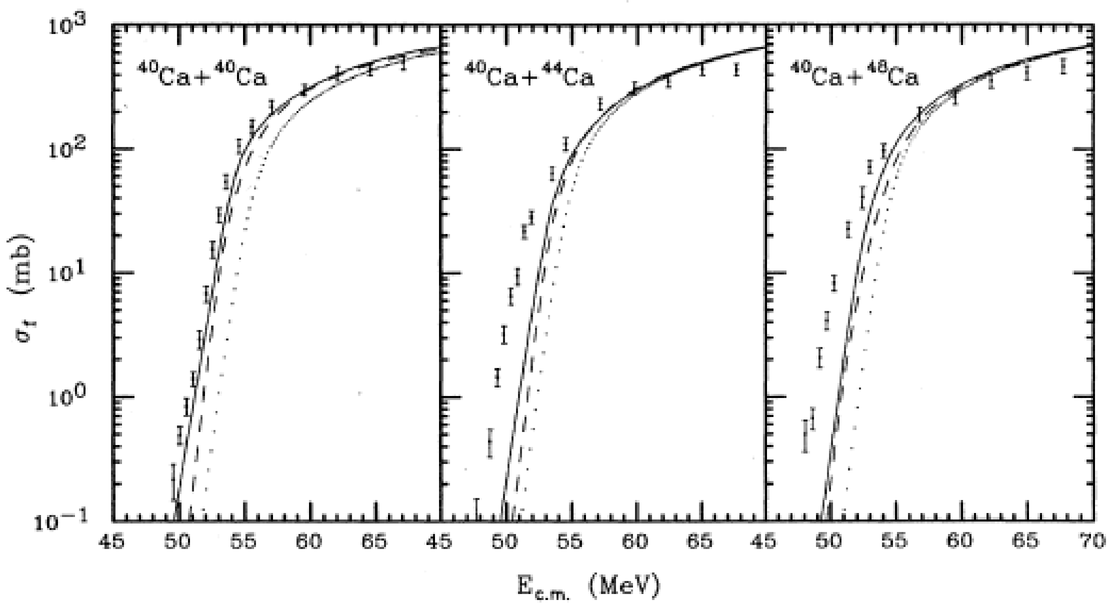


FIG. 2. Fusion cross sections resulting from including both vibrational and single-nucleon transfer channels. Shown are the no-coupling result (dotted line), the transfer only result (dashed line), and the result of the full calculation (solid line) compared to the data from Ref. 3.

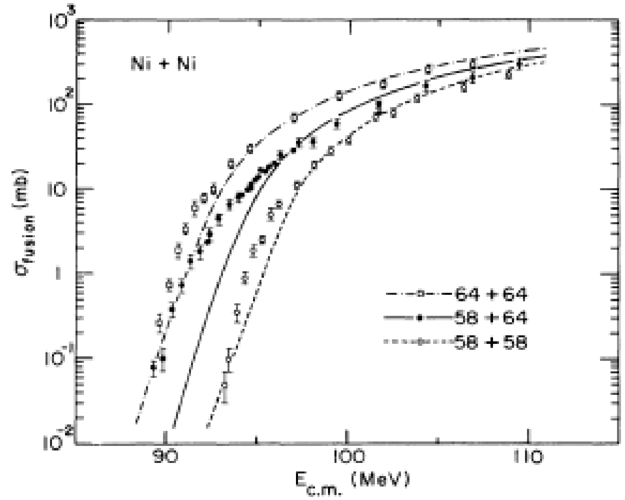


FIG. 5. Comparison of second-order vibrational calculations with the fusion data of Ref. 18 for the $^{58}Ni+^{58}Ni$, $^{58}Ni+^{64}Ni$, and $^{64}Ni+^{64}Ni$ reactions. The parameters are given in Table I.

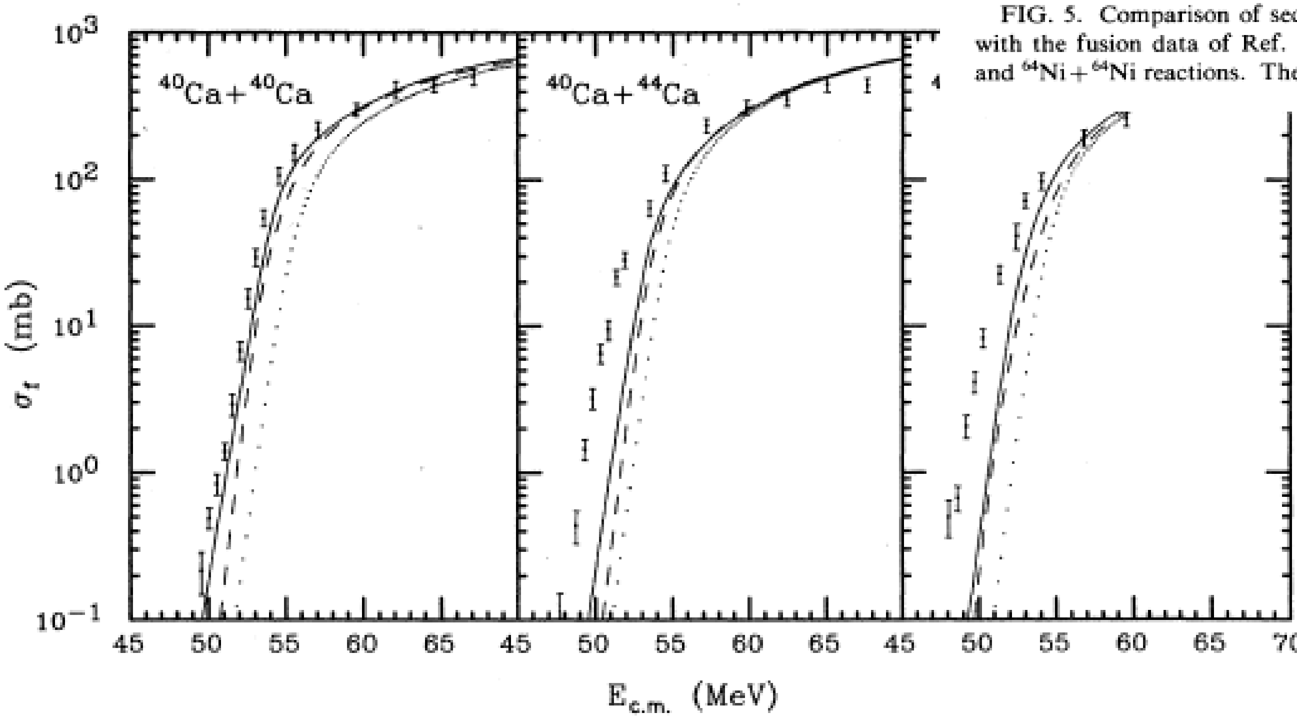
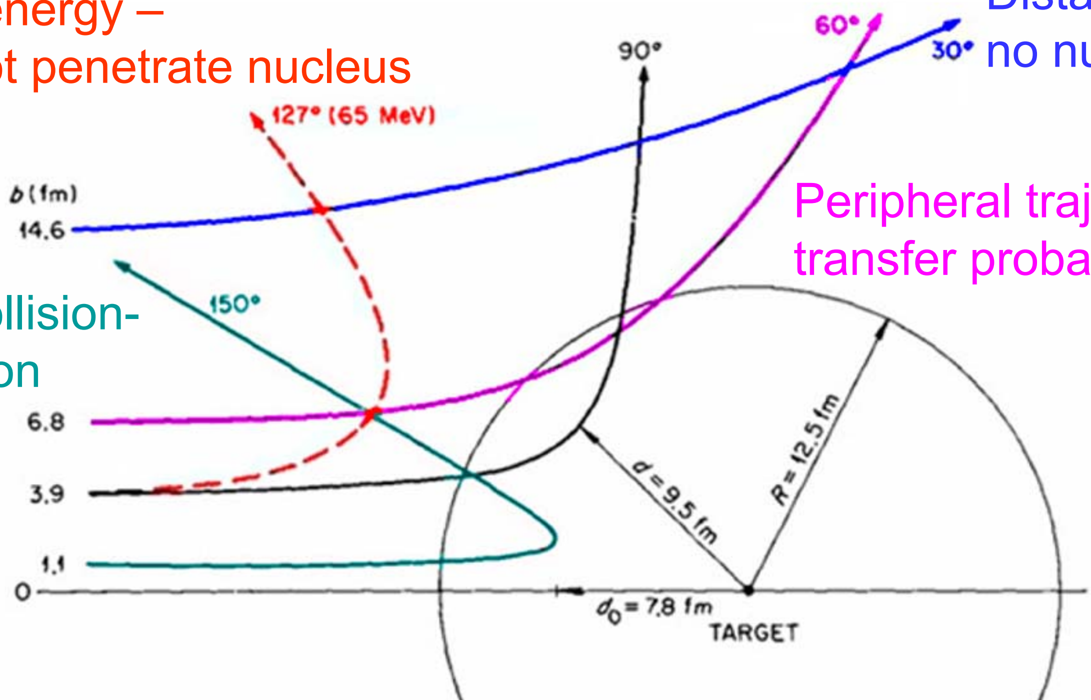


FIG. 2. Fusion cross sections resulting from including both vibrational and single-nucleon transfer channels. Shown are the no-coupling result (dotted line), the transfer only result (dashed line), and the result of the full calculation (solid line) compared to the data from Ref. 3.

Characteristics of HI transfer

Lower energy –
does not penetrate nucleus

Distant trajectory-
no nucleons to transfer



Peripheral trajectory –
transfer probability peaks

Close collision-
absorption

Transfer probability is peaked at
the angle corresponding to the trajectory
for which the two nuclei are the closest

P_{TR} falls off
exponentially with
D (distance of closest
approach)

$^{16}O + ^{208}Pb$ $E(^{16}O)$=130 MeV, V_C~93 MeV

(Satchler 1980, pp 36)