Angular momentum in projectile fragmentation

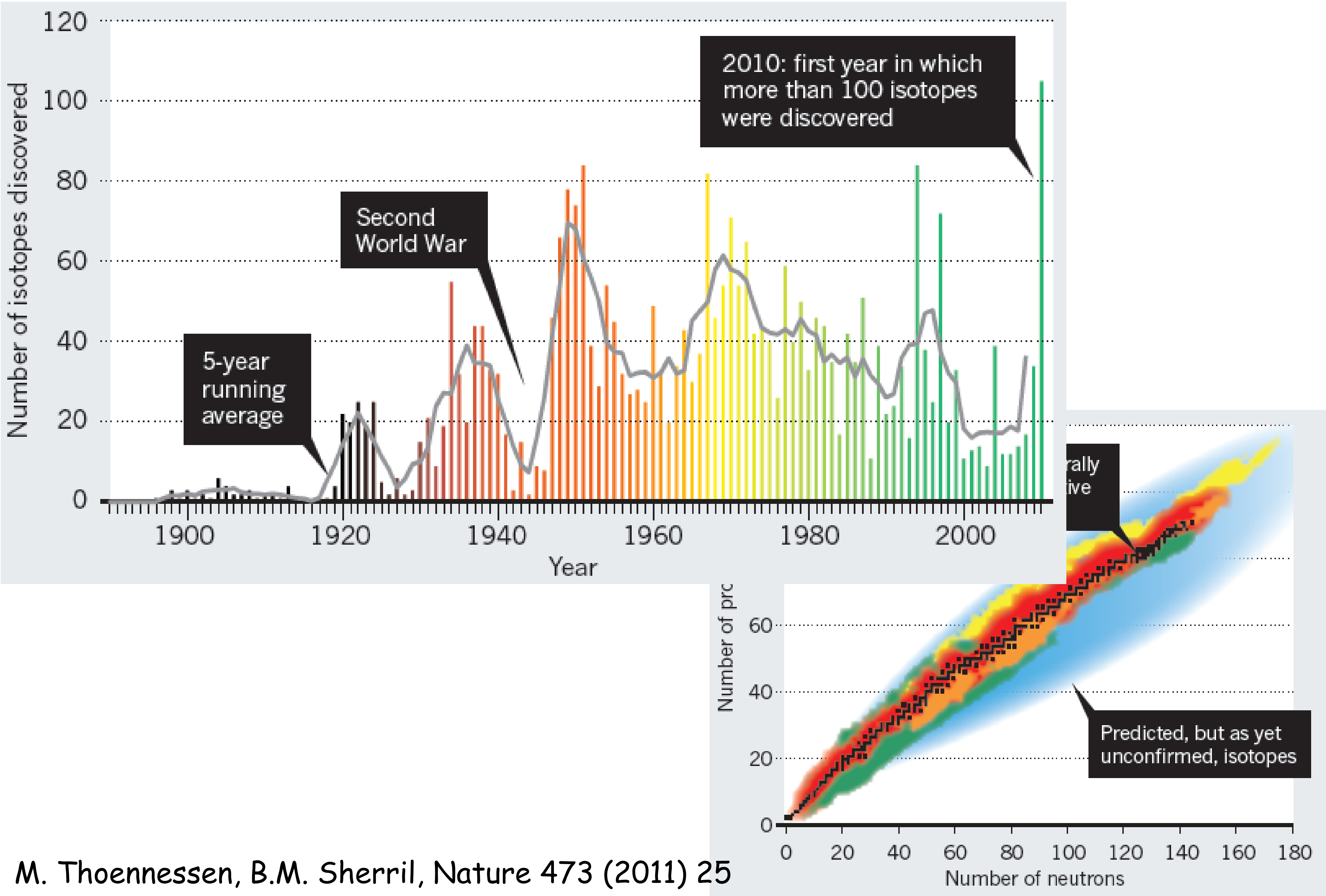
High-spin states

Isomeric beams

Zsolt Podolyák

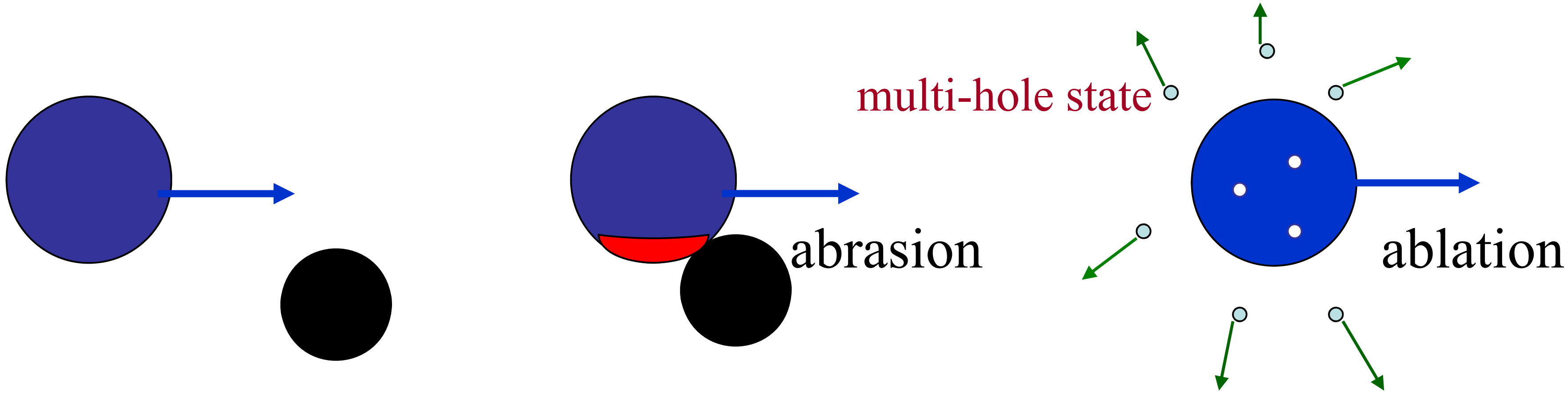
University of Surrey

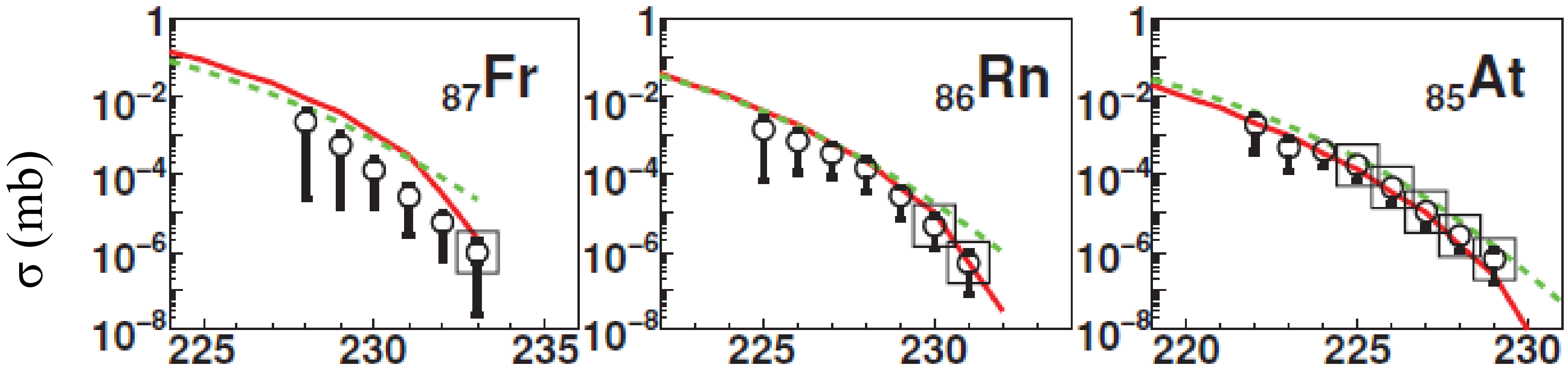
Fragmentation



M. Thoennessen, B.M. Sherril, Nature 473 (2011) 25

Fragmentation (spallation) reactions at relativistic energies:





H. Alvarez-Pol et al., Phys. Rev. C 82, 041602(R) (2110)

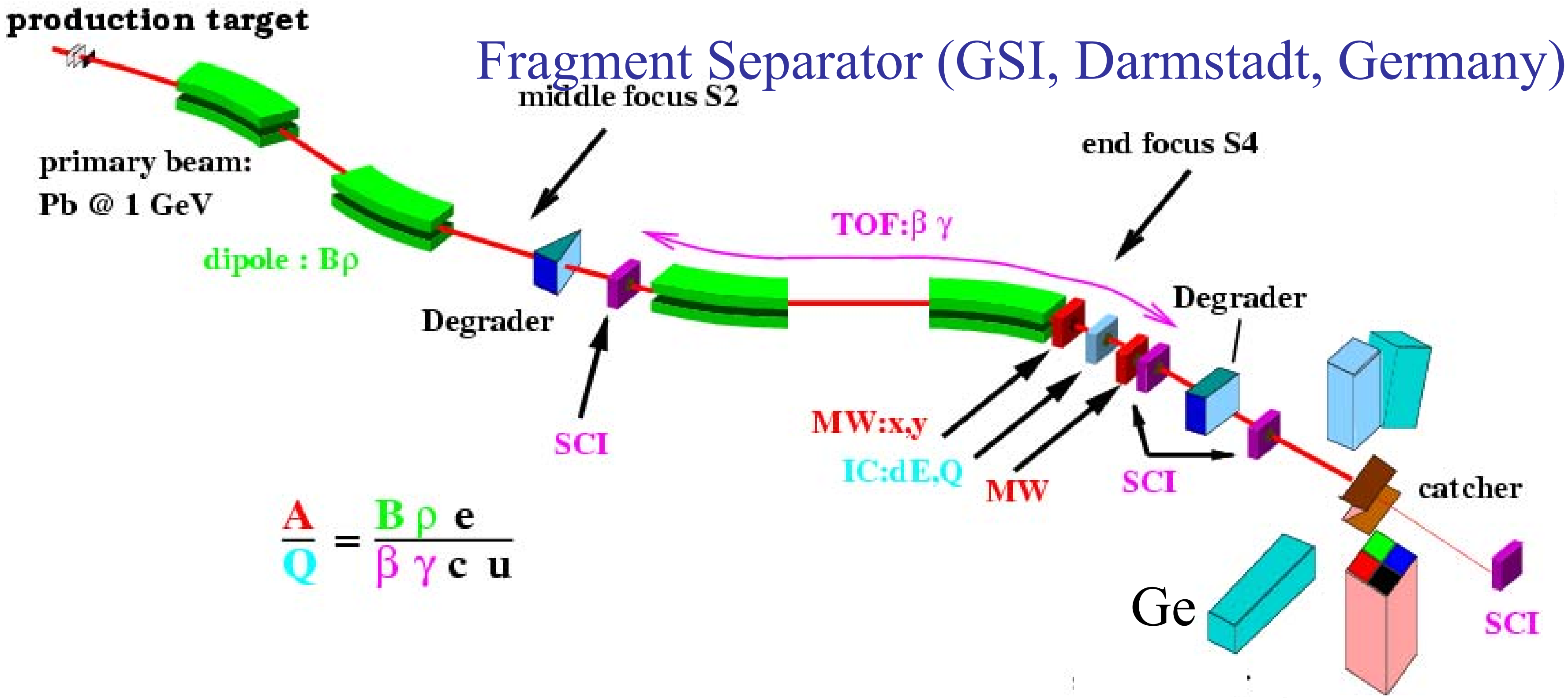
Cross section: measures the end product

What would give information about abrasion?

<u>Angular</u> (and linear) momentum

In flight fragmentation (and fission): separation and identification

Fragment Separator (GSI, Darmstadt, Germany)



$$\frac{A}{Q} = \frac{B \rho e}{\beta \gamma c u}$$

Relativistic energy fragmentation: => heavy ions

Isomeric decay spectroscopy:

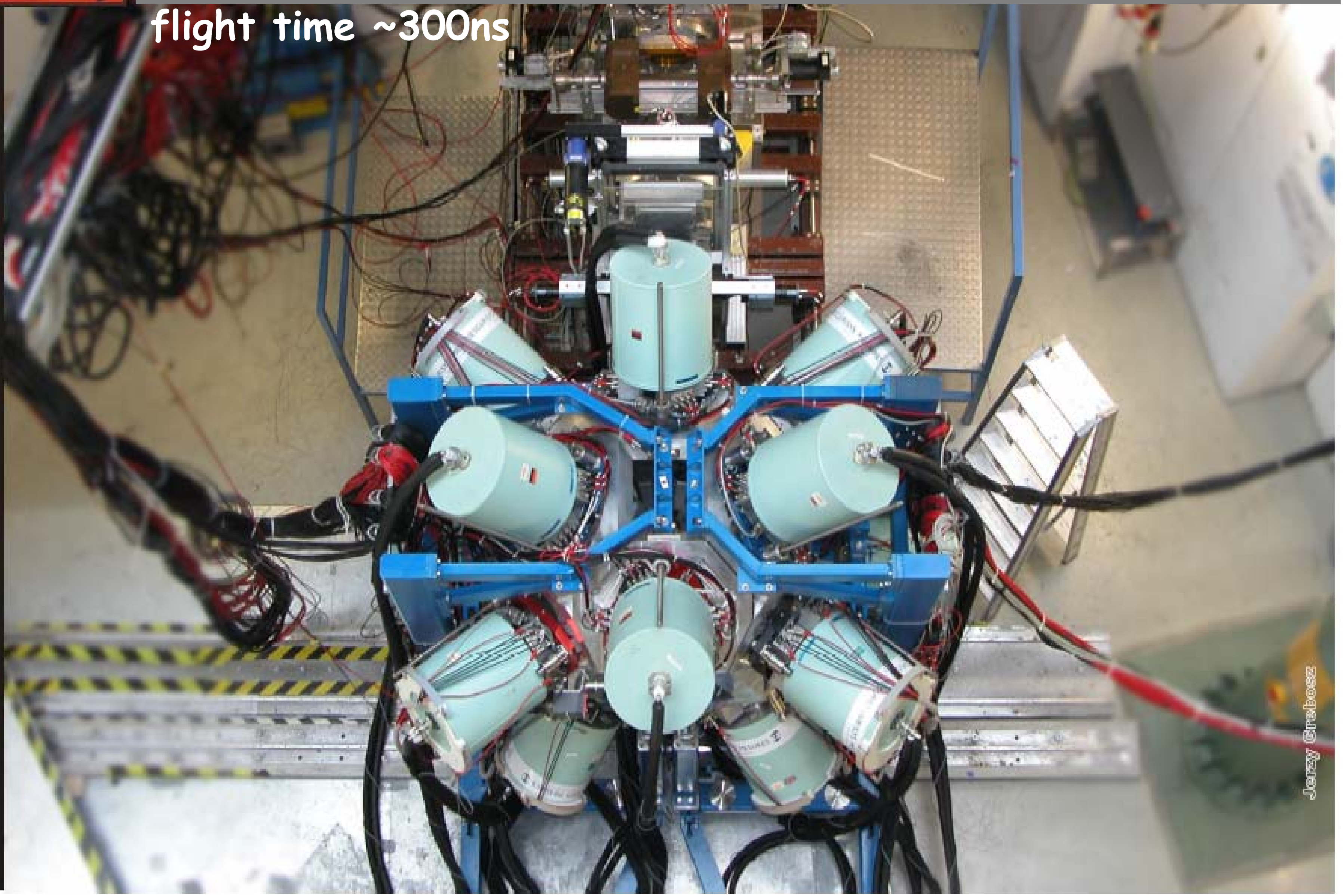
- decay correlated with the fragment
- ***very sensitive***

stopped beam setup

Stopped Rising Array @ GSI: 15 x 7 element CLUSTERs

ε_γ =11% at 1.3 MeV, 20% at 550 keV, 35% at 100 keV

flight time ~300ns



Highest spin from fragmentation: I=(55/2) isomer in ^{213}Rn

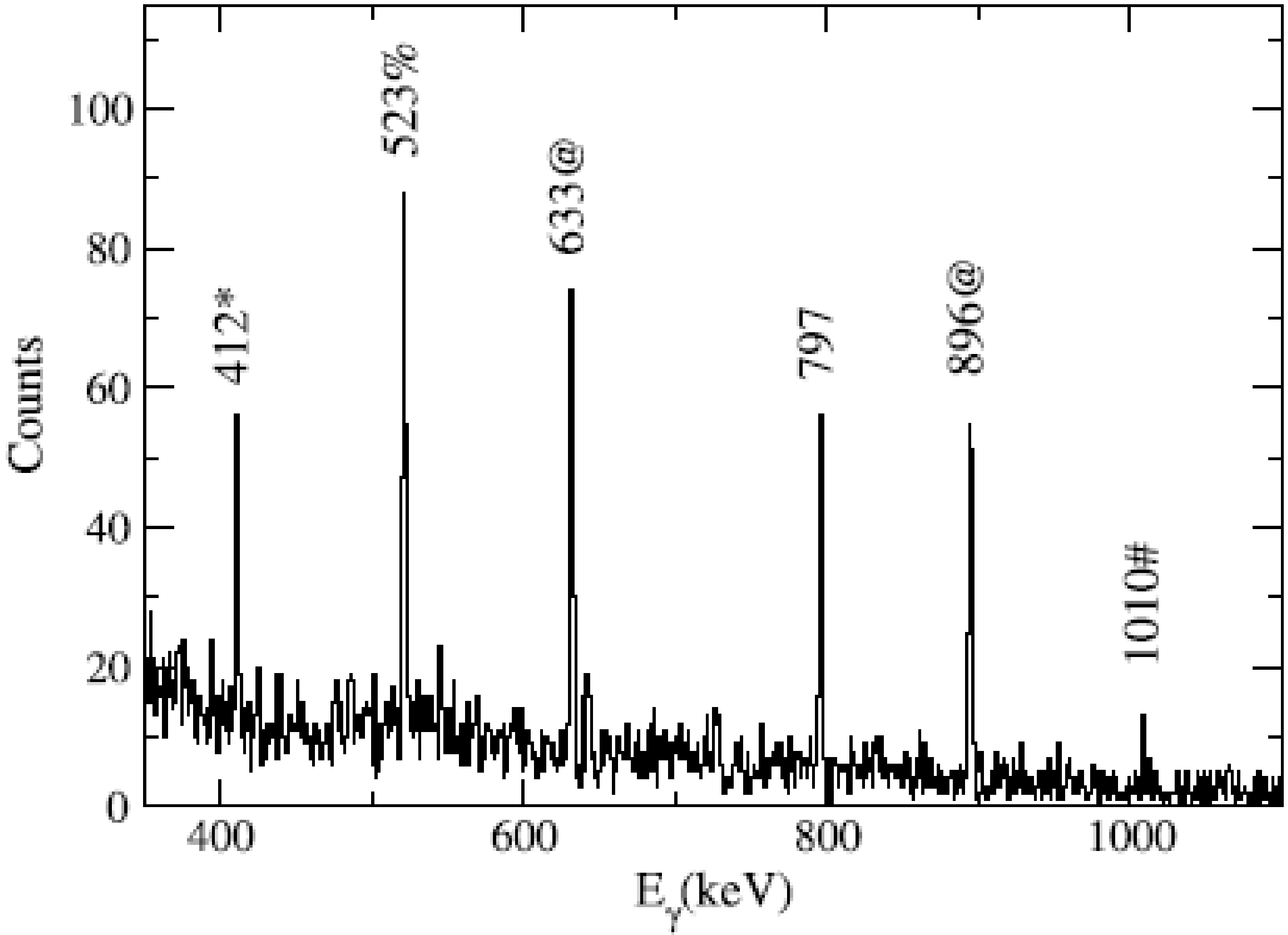
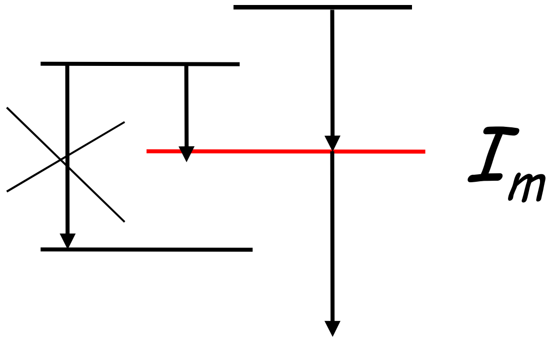


Fig. 1. Gamma-ray energy spectrum obtained in coincidence with ^{213}Rn ions using a time gate of width 1.4 μs starting ~50 ns after the prompt flash. The transitions used to obtain the isomeric ratios for the $(55/2)^+$, $43/2^-$, $31/2^-$ and $25/2^+$ levels are denoted #, *, % and @ respectively.

A.M. Denis Bacelar et al., Phys. Lett. B 723, 302 (2012)

Isomeric ratio

$$R_{\exp} = \frac{N_{isomer}}{N_{total}}$$



$$P(I) = \frac{2I+1}{2\sigma_f^2}\exp\left(-\frac{I(I+1)}{2\sigma_f^2}\right)$$

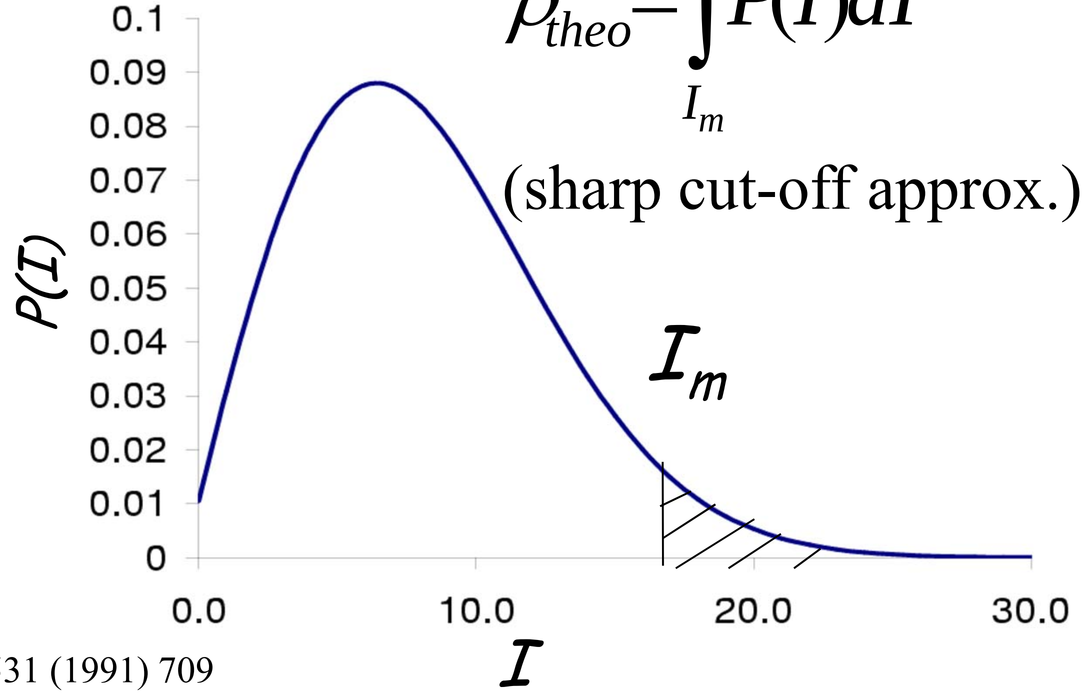
$$\rho_{theo} = \int_{I_m}^{\infty} P(I)\,dI$$

(sharp cut-off approx.)

Spin-cutoff parameter:

$$\sigma_f^2 = 0.16A_p^{2/3}\frac{(A_p - A_f)(\nu A_p + A_f)}{(\nu+1)^2(A_p - 1)}$$

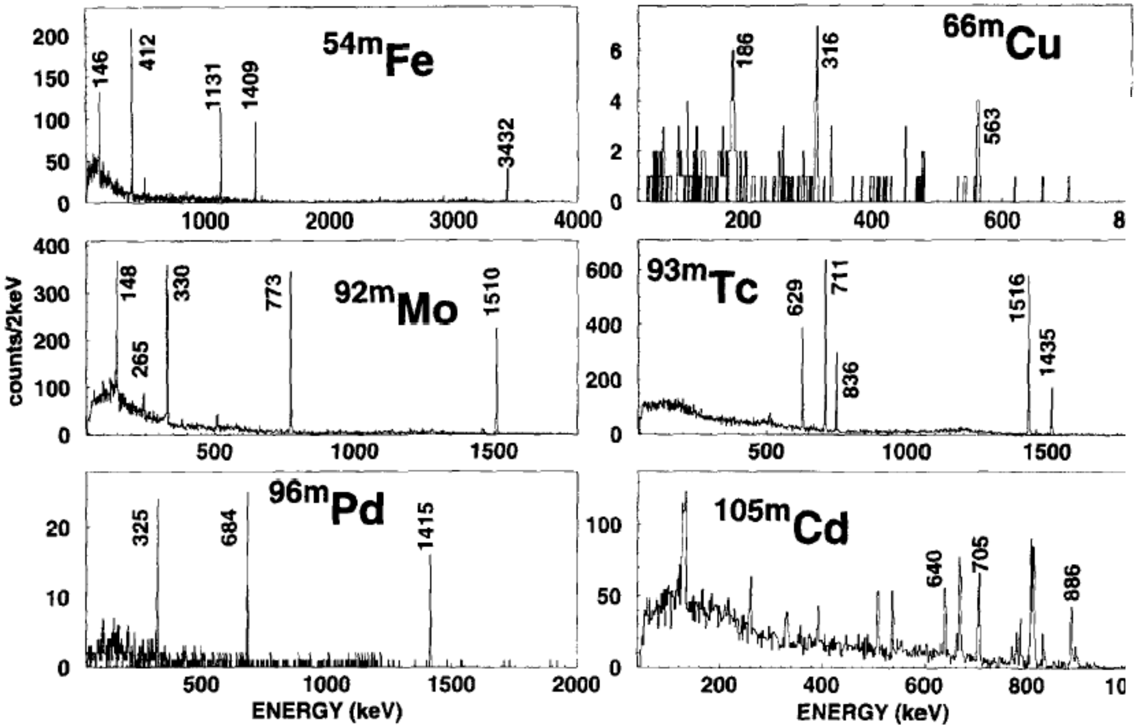
$\langle j_z^2 \rangle$



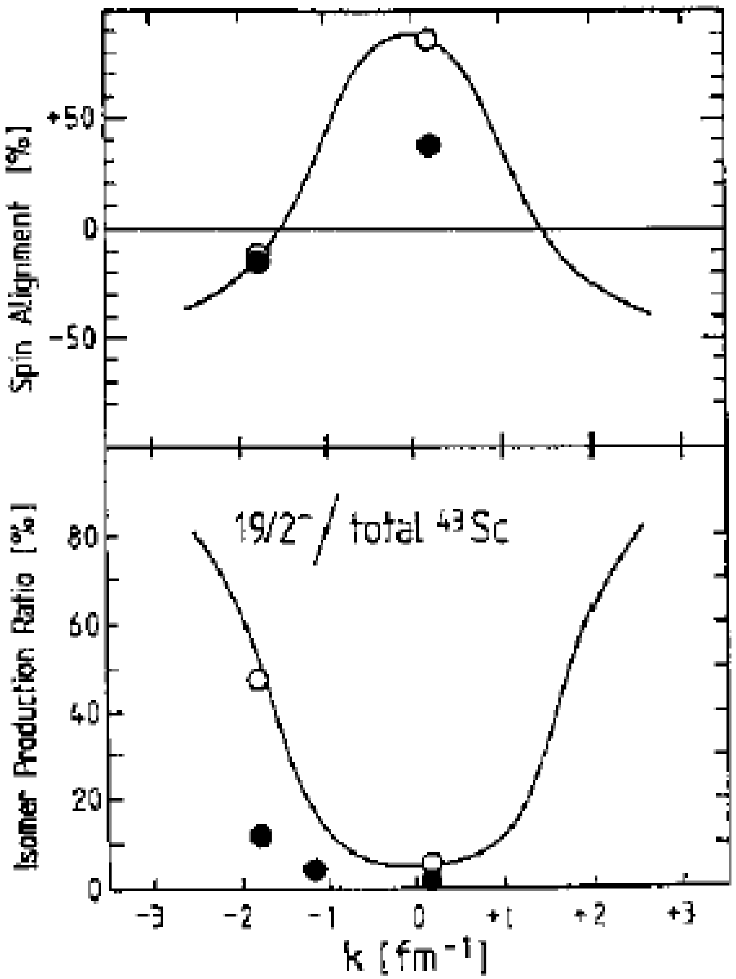
J.-J. Gaimard and K.-H. Schmidt, Nucl. Phys. A 531 (1991) 709

M. De Jong, A.V. Ignatyuk and K.-H. Schmidt, Nucl. Phys. A 613 (1997) 435

Isomers are special

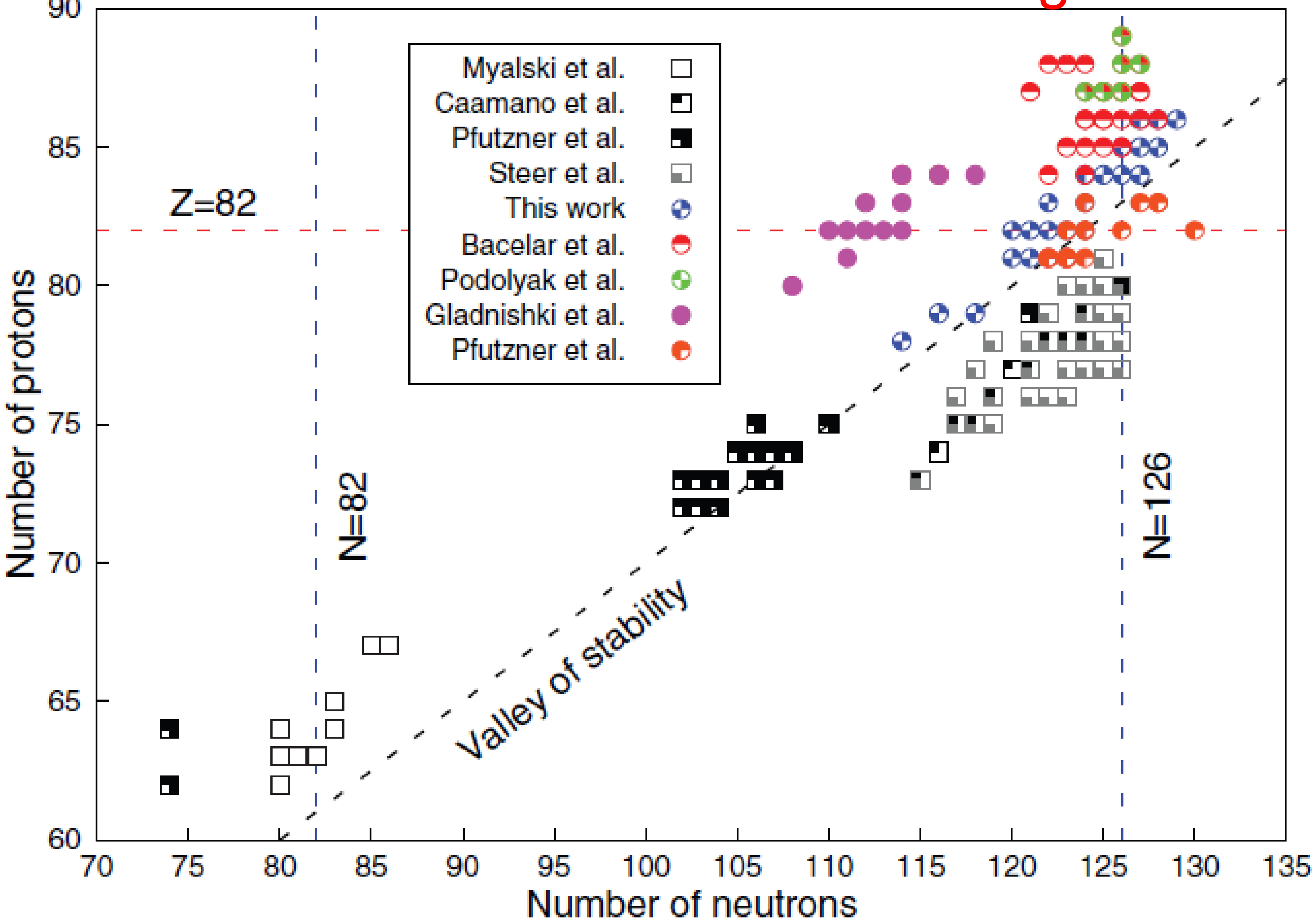


R. Grzywacz et al., Phys. Lett. B 355 (1995) 439.



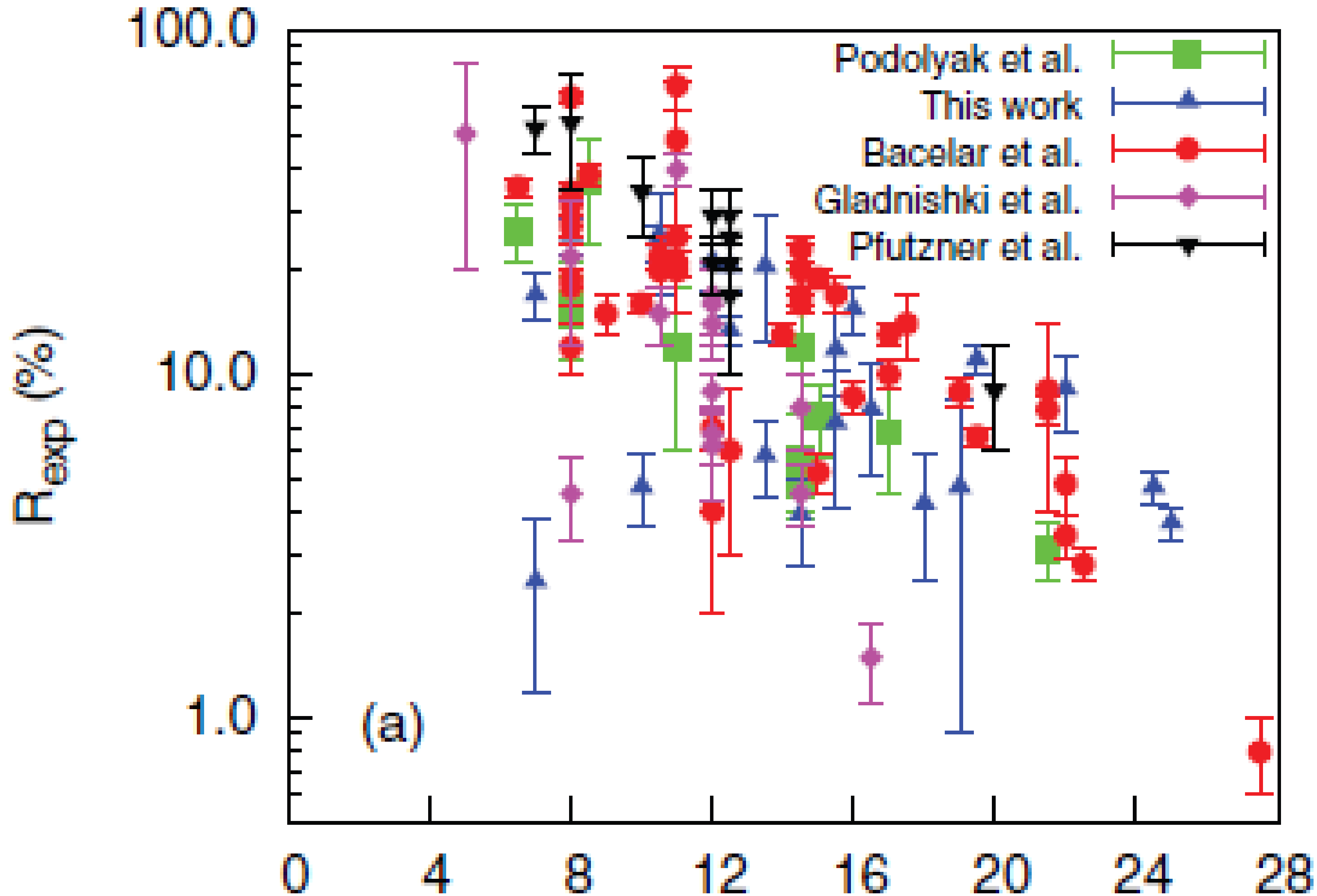
W.-D. Schmidt-Ott et al., Z. Phys. A 350 (1994) 215.

Isomeric ratios from ^{208}Pb and ^{238}U fragmentation



M. Bowry et al., Phys. Rev. C 88, 024611 (2013)

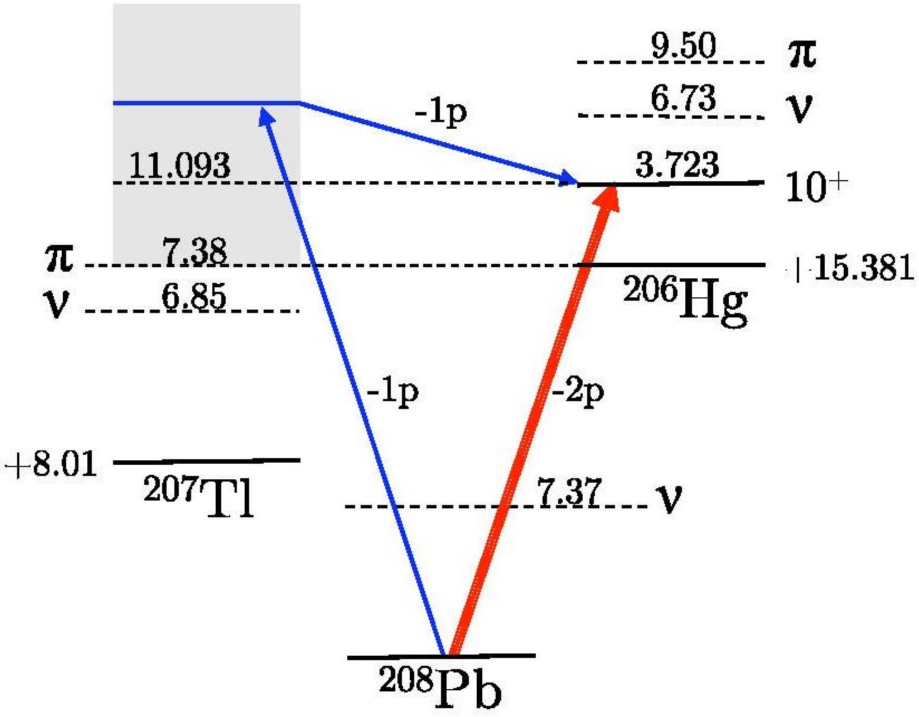
Isomeric ratio vs spin

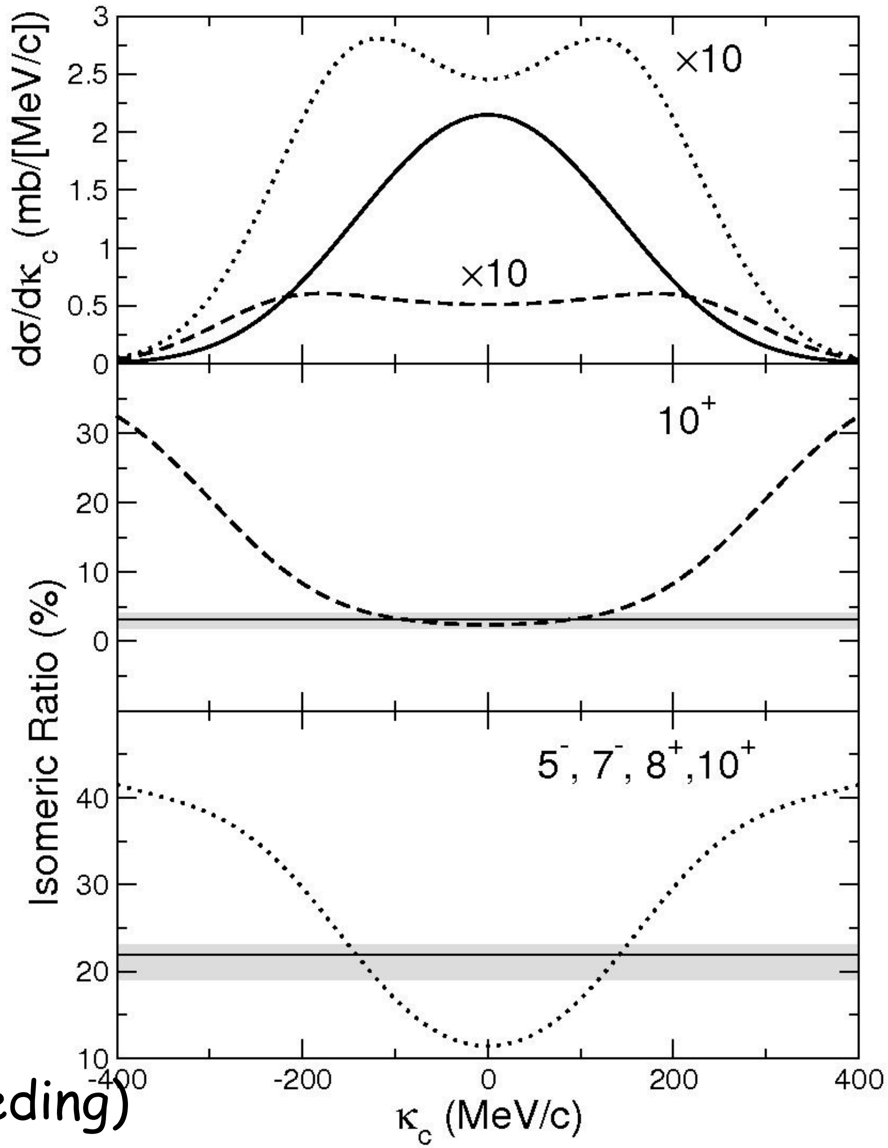


^{238}U beam

M. Bowry et al., Phys. Rev. C 88, 024611 (2013)

Population of isomers by ***two-proton knockout*** reaction in ^{206}Hg





Isomeric ratios

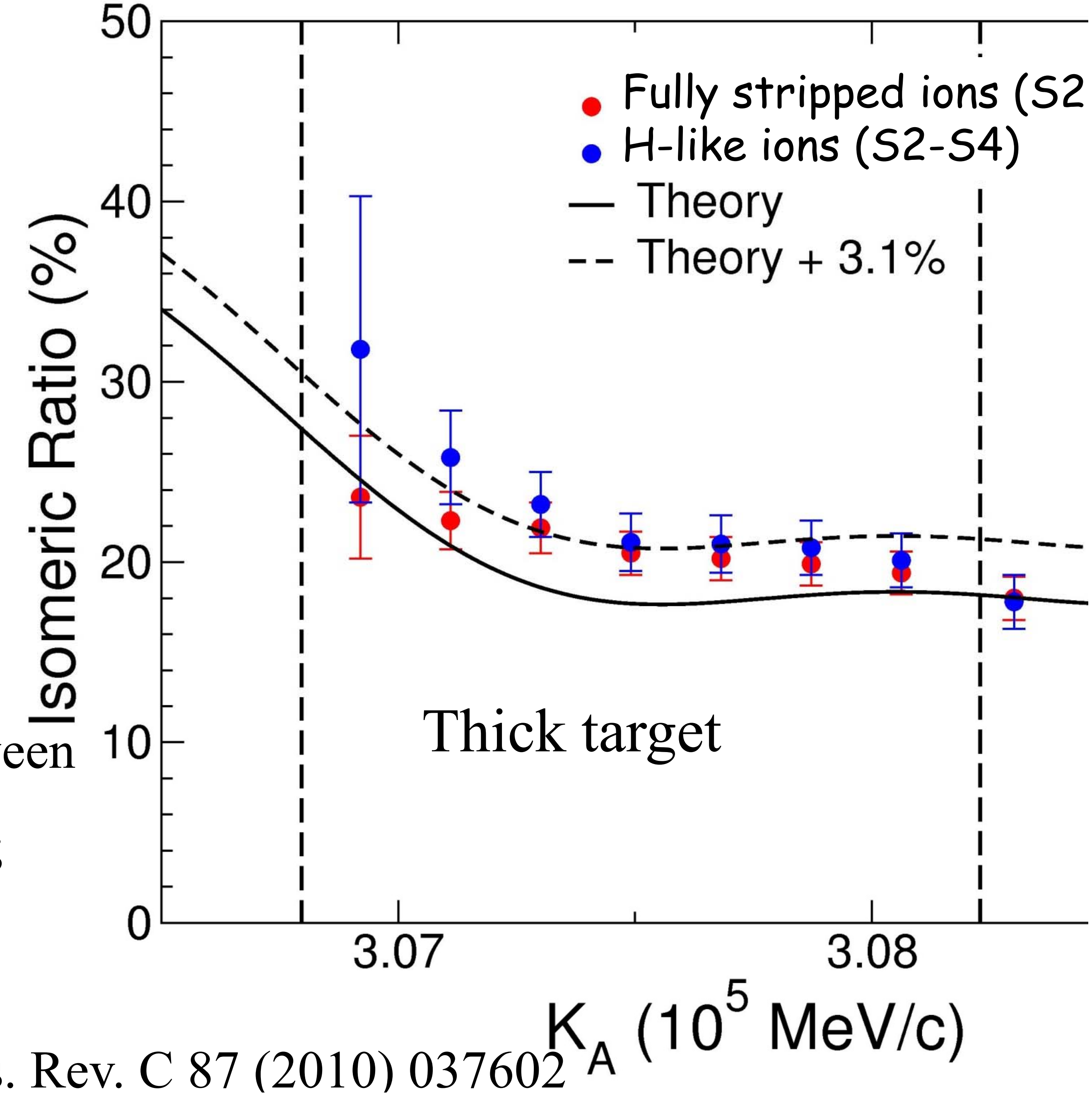
Exp.	Theory	fig.
		—— Total
3(1)%	4.7	- - - - 10+
22(+1-2)%	18.8	·········· 5- (with feeding)

E.Simpson *et al.*, Phys. Rev. C 80 (2009) 064608.

Isomeric ratio as function of longitudinal momentum

5- isomer

— Theory
-- Theory + 3.1%



(3.1%=difference between experiment and theory; additional feeding?)

E. Simpson et al., Phys. Rev. C 87 (2010) 037602 *if $A_{projectile}-A_{fragment}$~large*

Statistical abrasion-ablasion model (ABRABLA code)

Excitation energy

~27 MeV/abrated nucleon=

=2 x single particle (holes) energy

Angular momentum

from single particle

states only

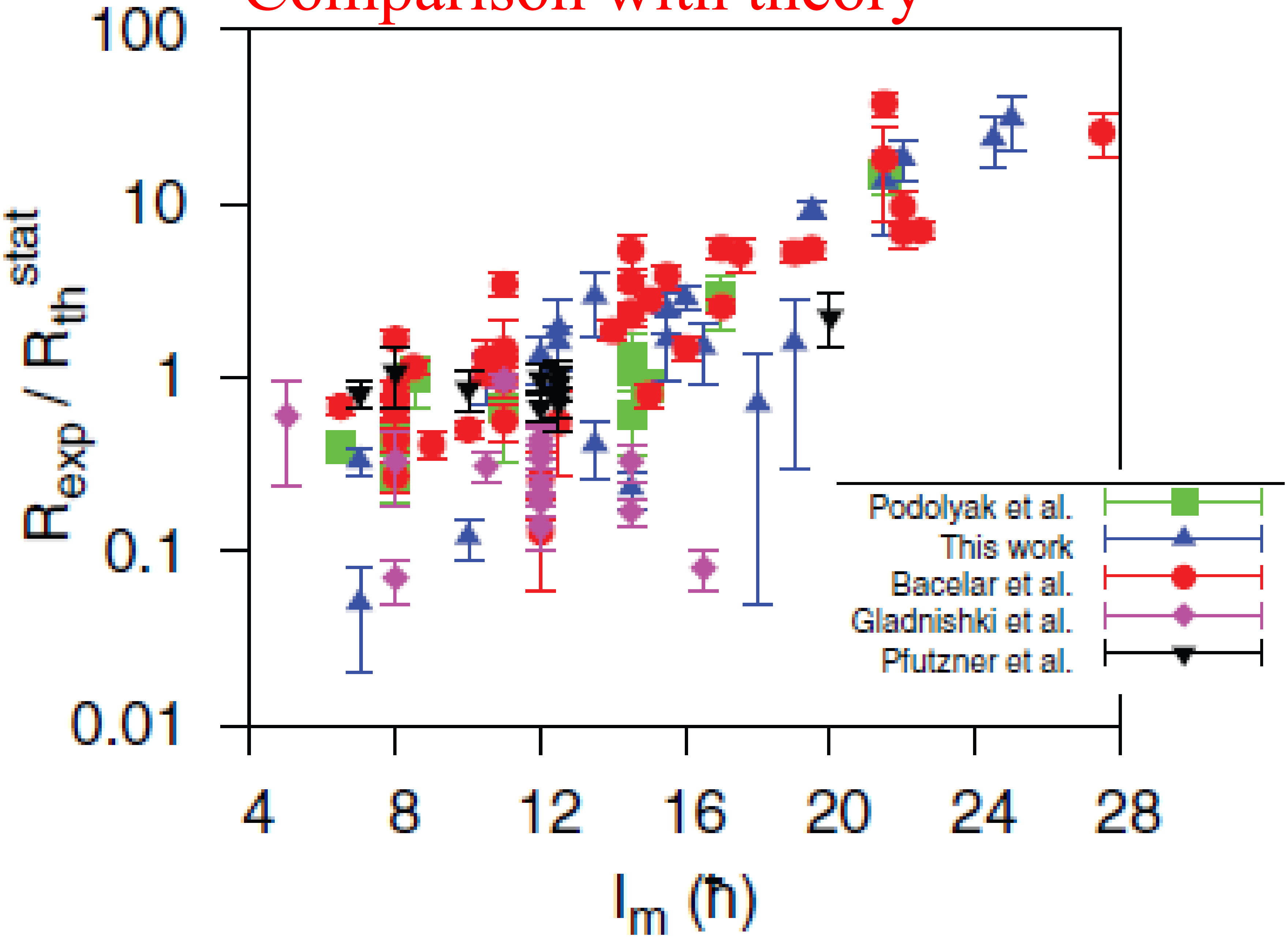
Is this good enough?

Ablated nuclei/abraded nuclei ~2

Good cross sections

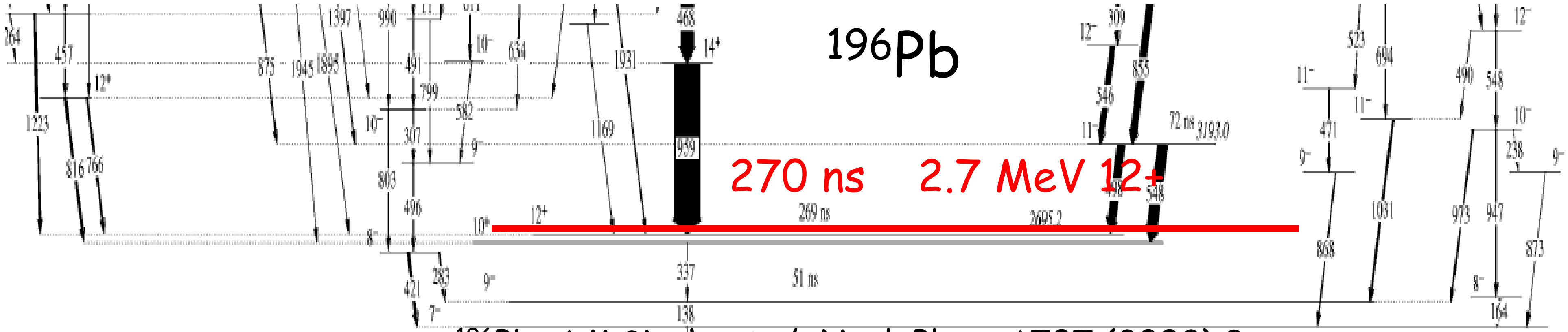
M. De Jong, A.V. Ignatyuk and K.-H. Schmidt, Nucl. Phys. A 613 (1997) 435

Comparison with theory



M. Bowry et al., Phys. Rev. C 88, 024611 (2013)

Nuclear structure has to be considered



^{196}Pb: A.K.Singh *et al.*, Nucl. Phys. A707 (2002) 3

$^{186}W(^{16}O,6n)$ at 110 MeV; $^{170}Er(^{30}Si,4n)$ at 144 MeV

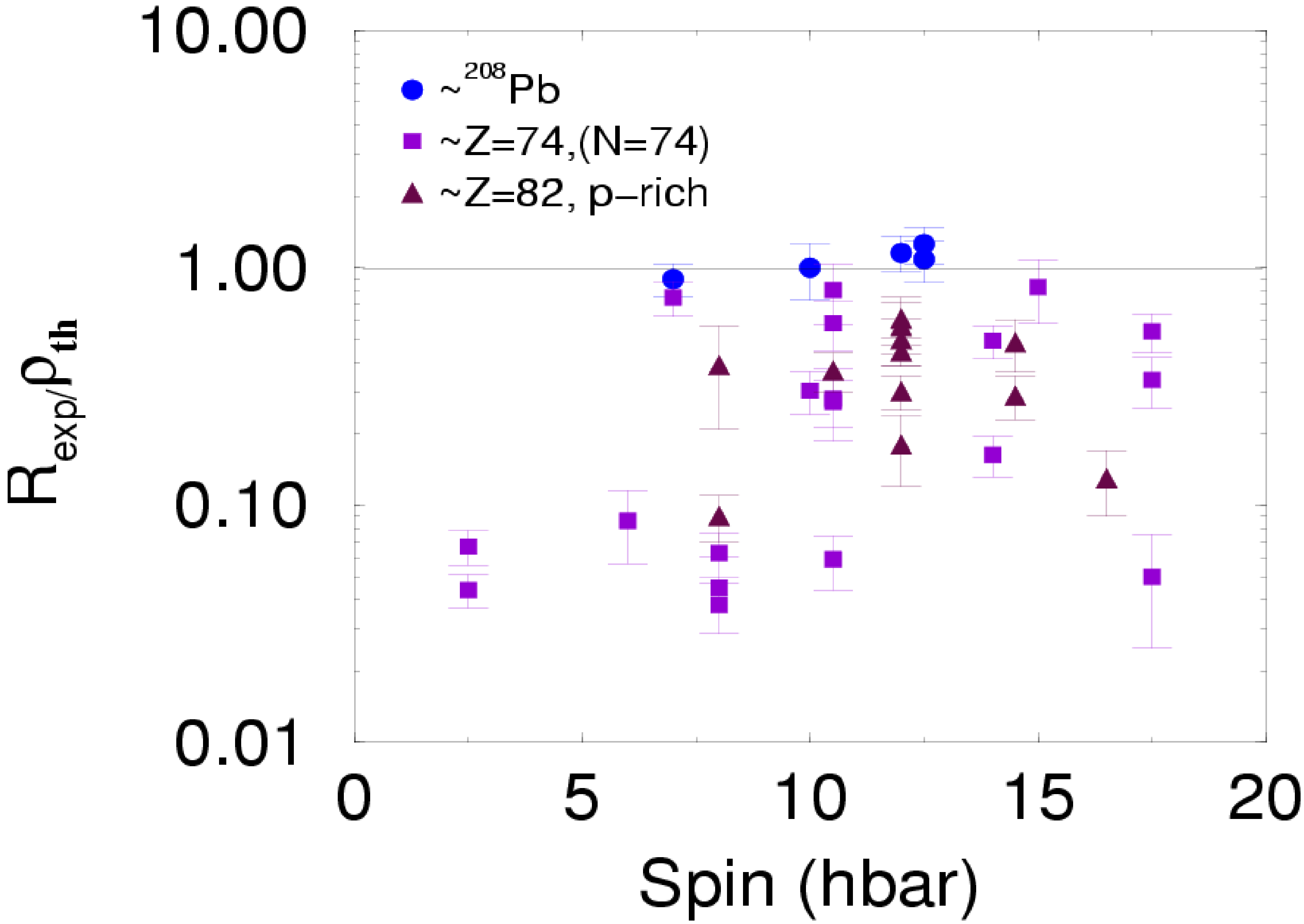
fusion-evaporation reaction!

$$\varphi = I_{isomer}/(I_{parallel}+I_{isomer}) = I_{isomer} / I_{total}$$

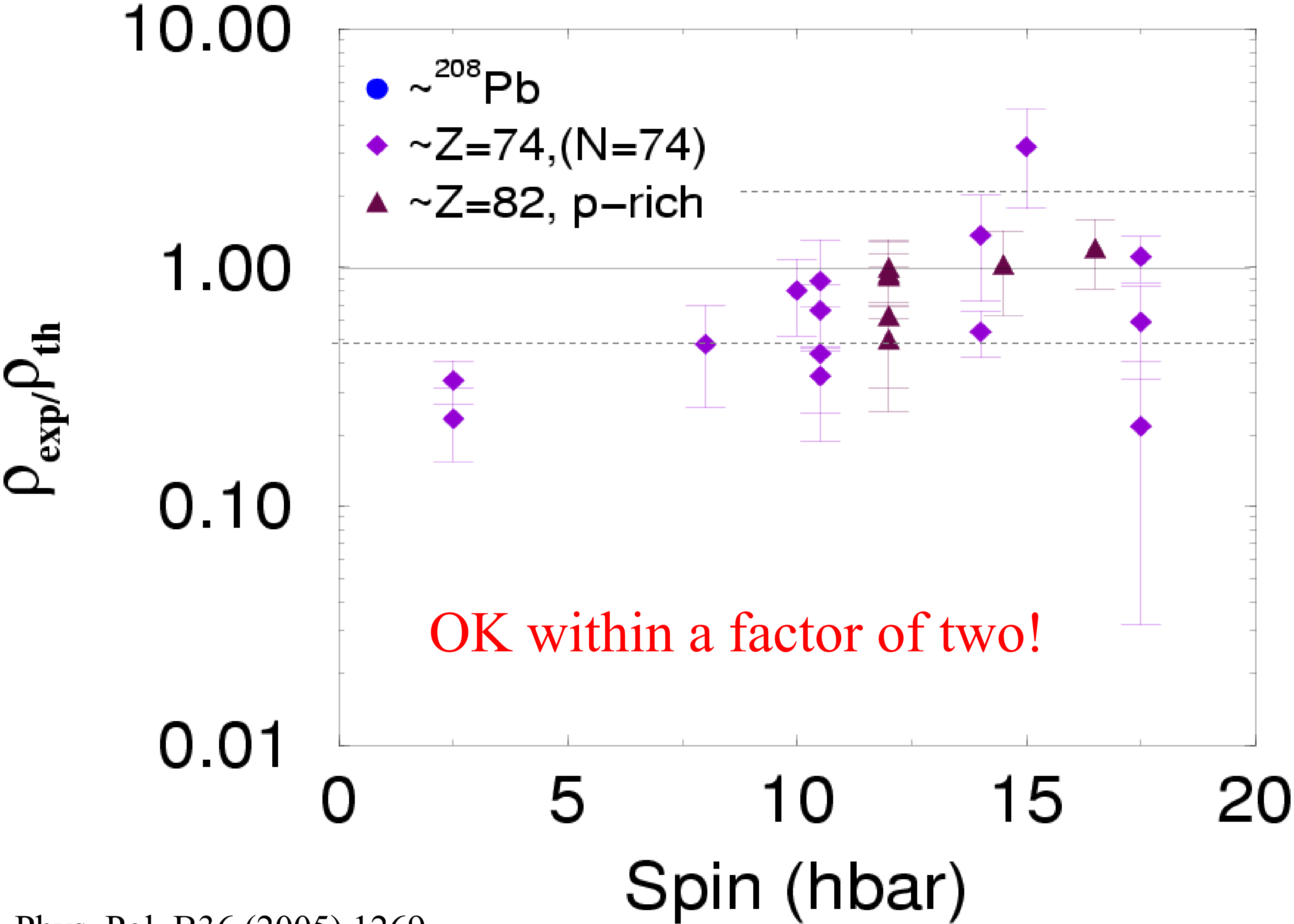
$$\rho_{exp}=R_{exp}/\varphi$$

ρ_{exp} - the probability of populating states with higher spin than the isomer – can be compared with theory!

Without structure considerations

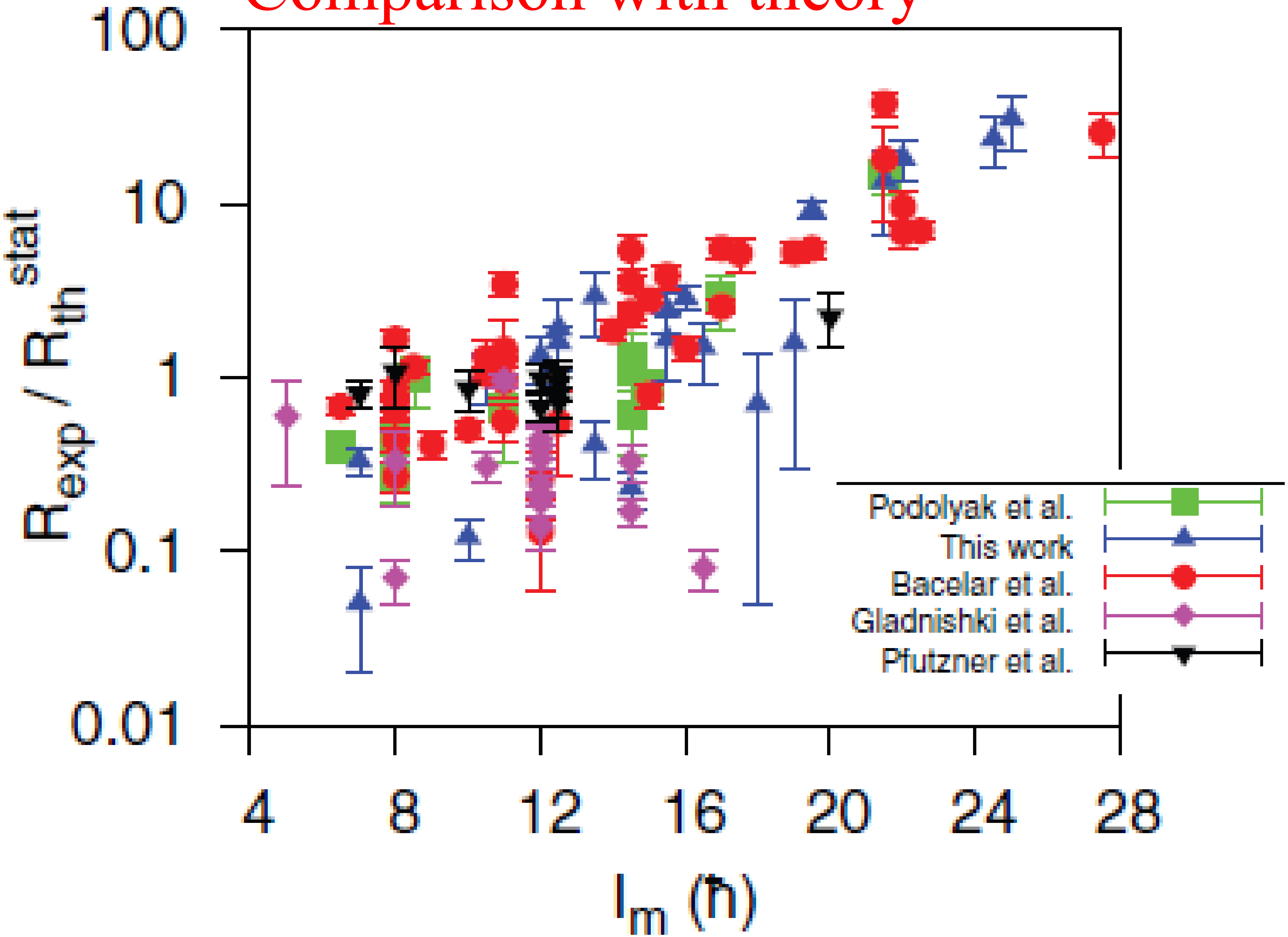


With structure considerations



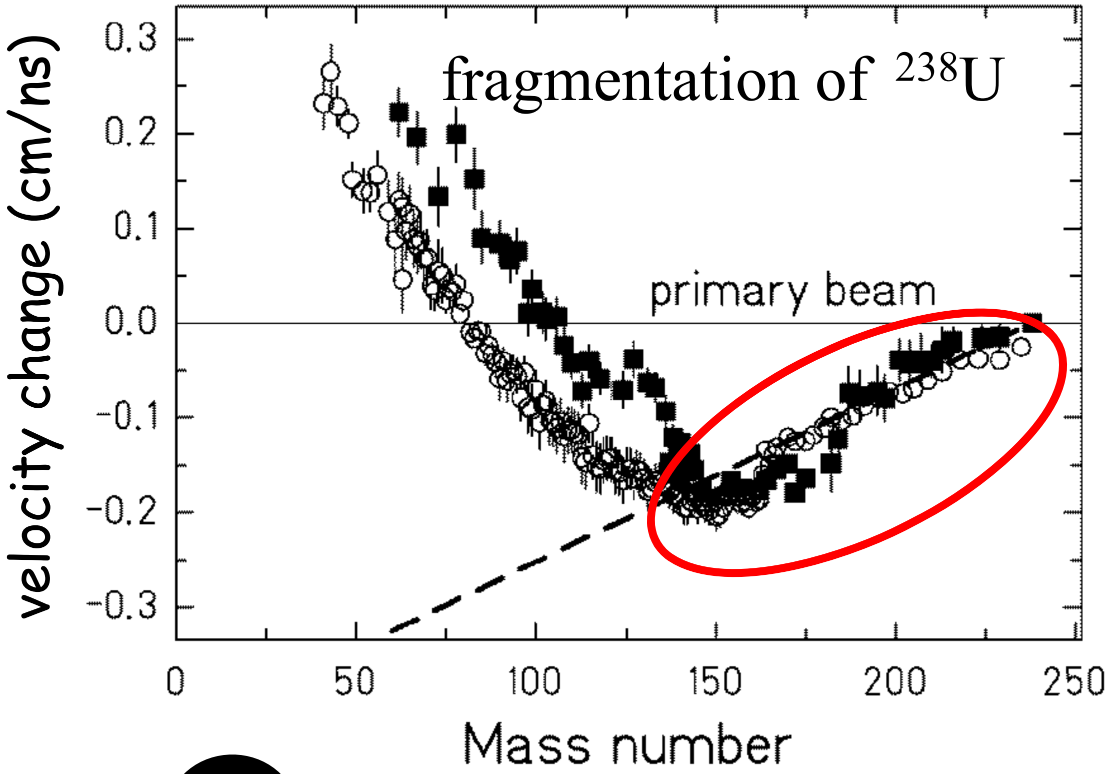
Zs. P. , Acta Phys. Pol. B36 (2005) 1269

Comparison with theory

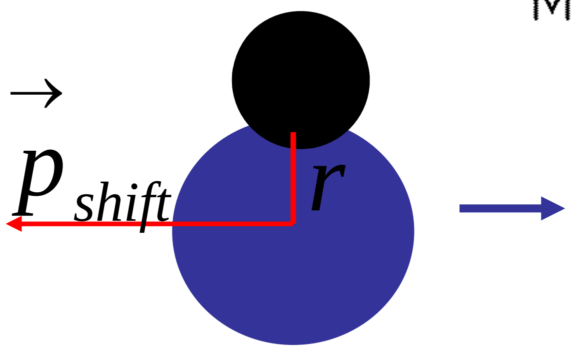


M. Bowry et al., Phys. Rev. C 88, 024611 (2013)

Fragments are slower than projectile: momentum shift (friction)



M.V. Ricciardi et al., PRL 90 (2003) 212302



$$\vec{I} = \vec{r} \times \vec{p}_{shift}$$

⇨ angular momentum produced

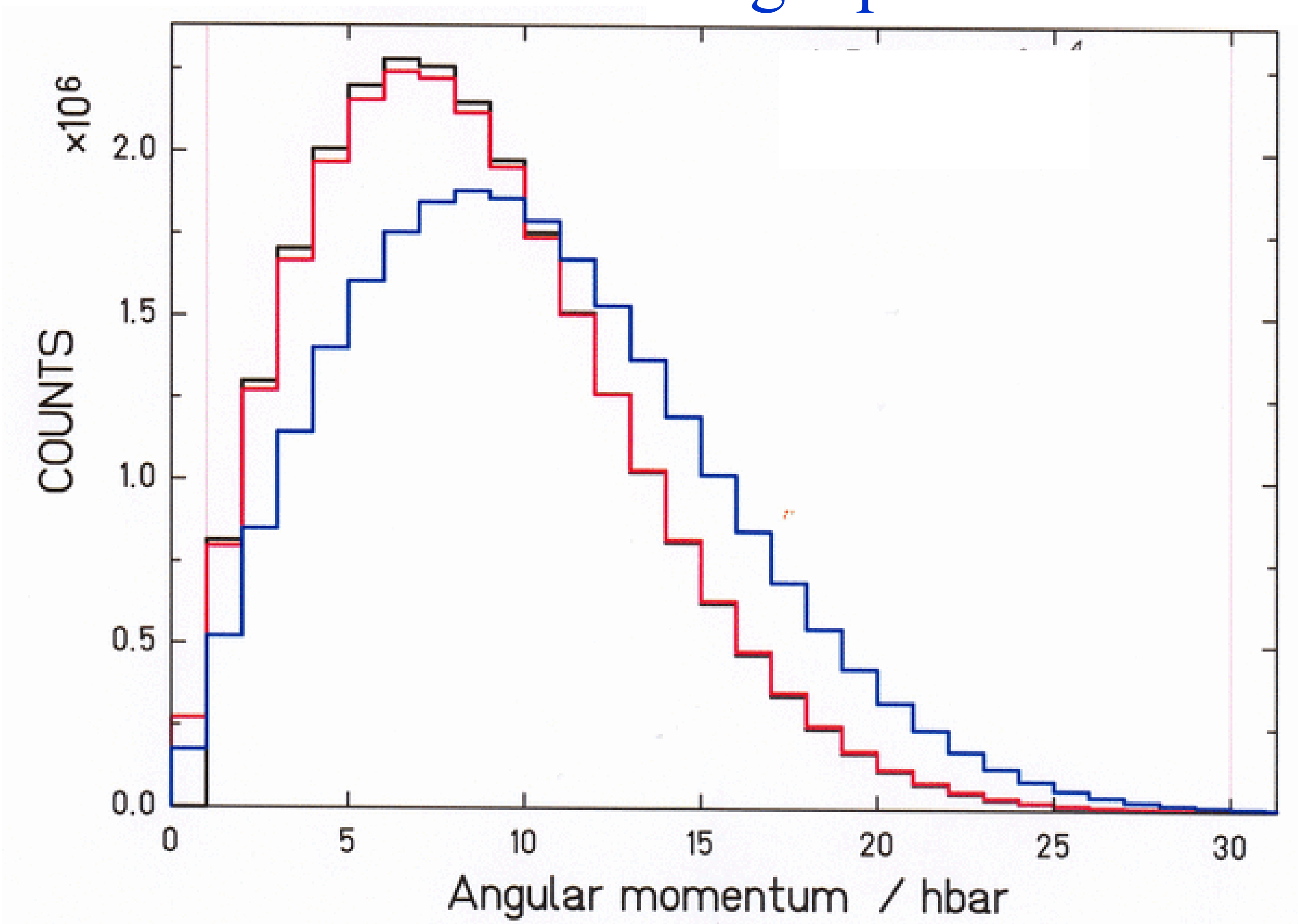
(collective)

I perpendicular to the beam

We need to couple: single particle holes *I* (any direction in 3D)
collective *I* (2D)

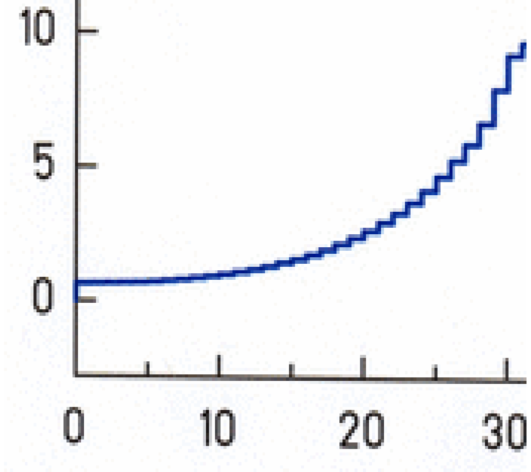
single particle only (Analytical)

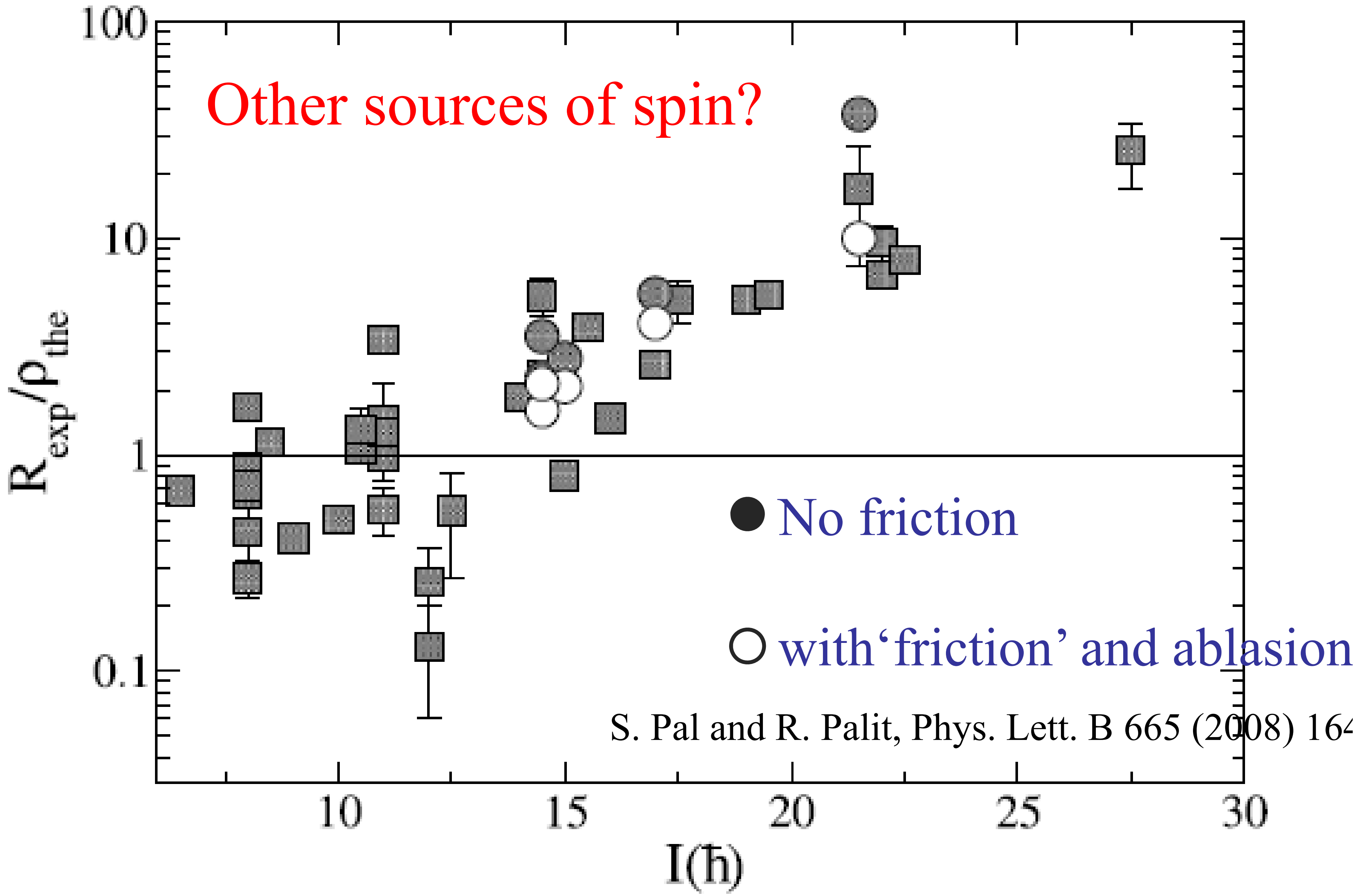
single particle + collective



increased high-spin population due

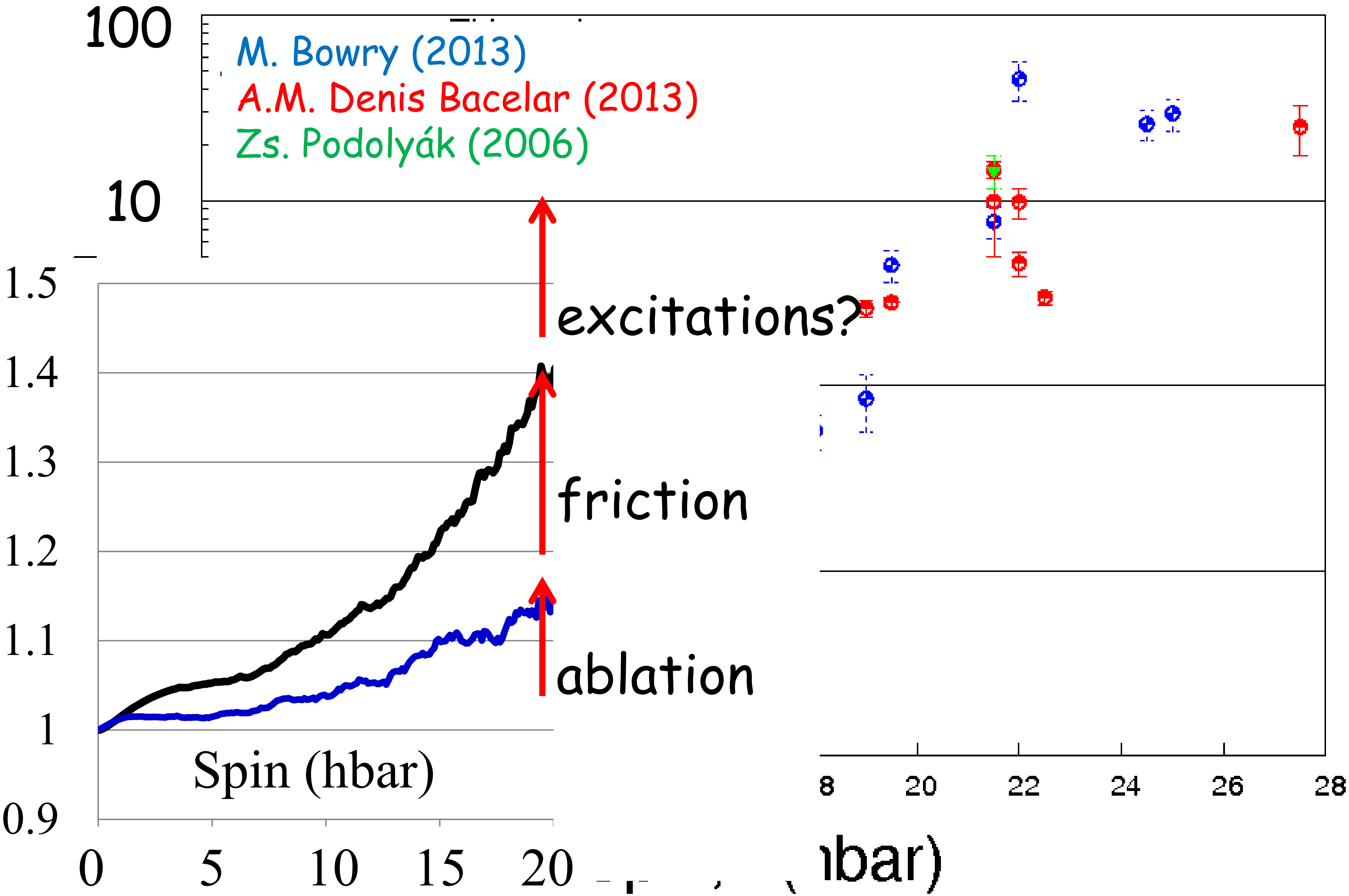
to **collective *I***





A.M. Denis Bacelar et al., Phys. Lett. B 723, 302 (2012)

Comparison with theory (sharp cut-off approx.)



Simplified theory (analytical formula)

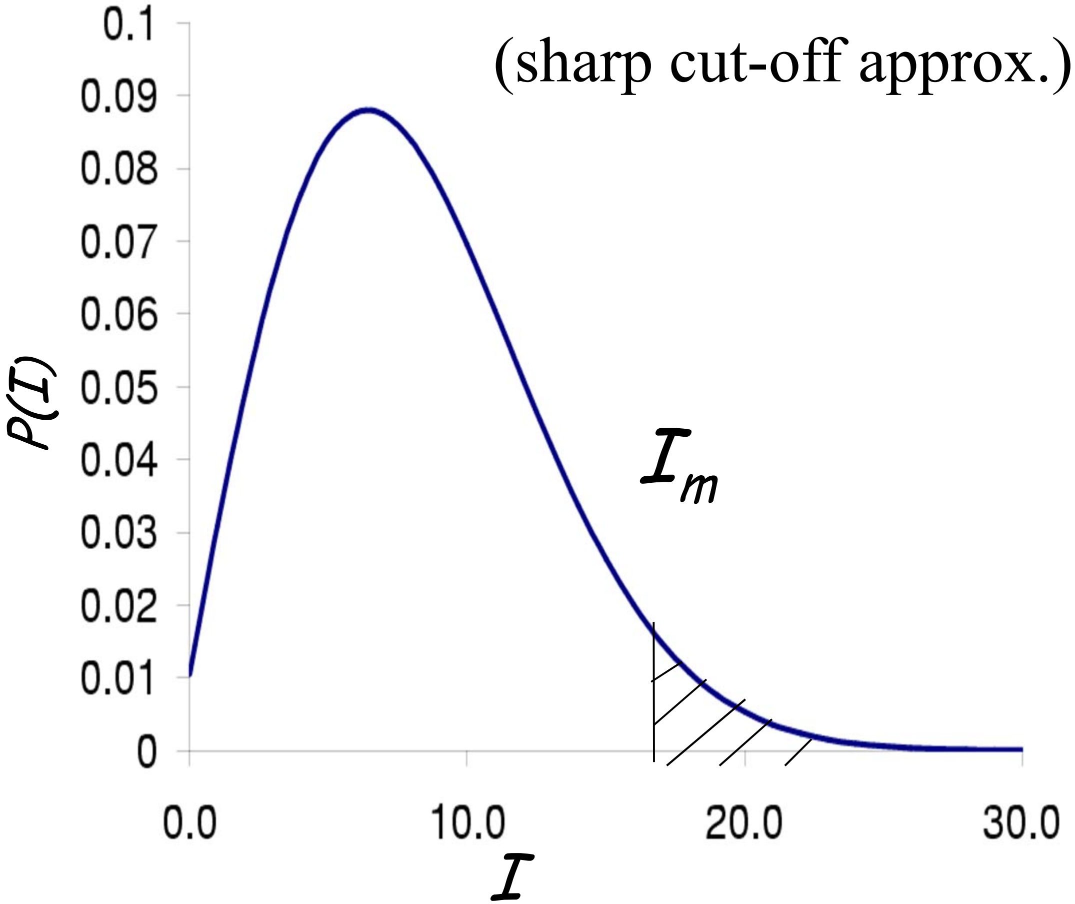
$$P(I) = \frac{2I+1}{2\sigma_f^2}\exp\left(-\frac{I(I+1)}{2\sigma_f^2}\right) \quad \Rightarrow \quad \rho_{theo} = \int_{I_m}^{\infty} P(I)\,dI$$

(sharp cut-off approx.)

Spin-cutoff parameter:

$$\sigma_f^2 = 0.16 A_p^{2/3} \frac{(A_p - A_f)(\nu A_p + A_f)}{(\nu+1)^2 (A_p - 1)}$$

$\langle j_z^2 \rangle$



J.-J. Gaimard and K.-H. Schmidt, Nucl. Phys. A 531 (1991) 709

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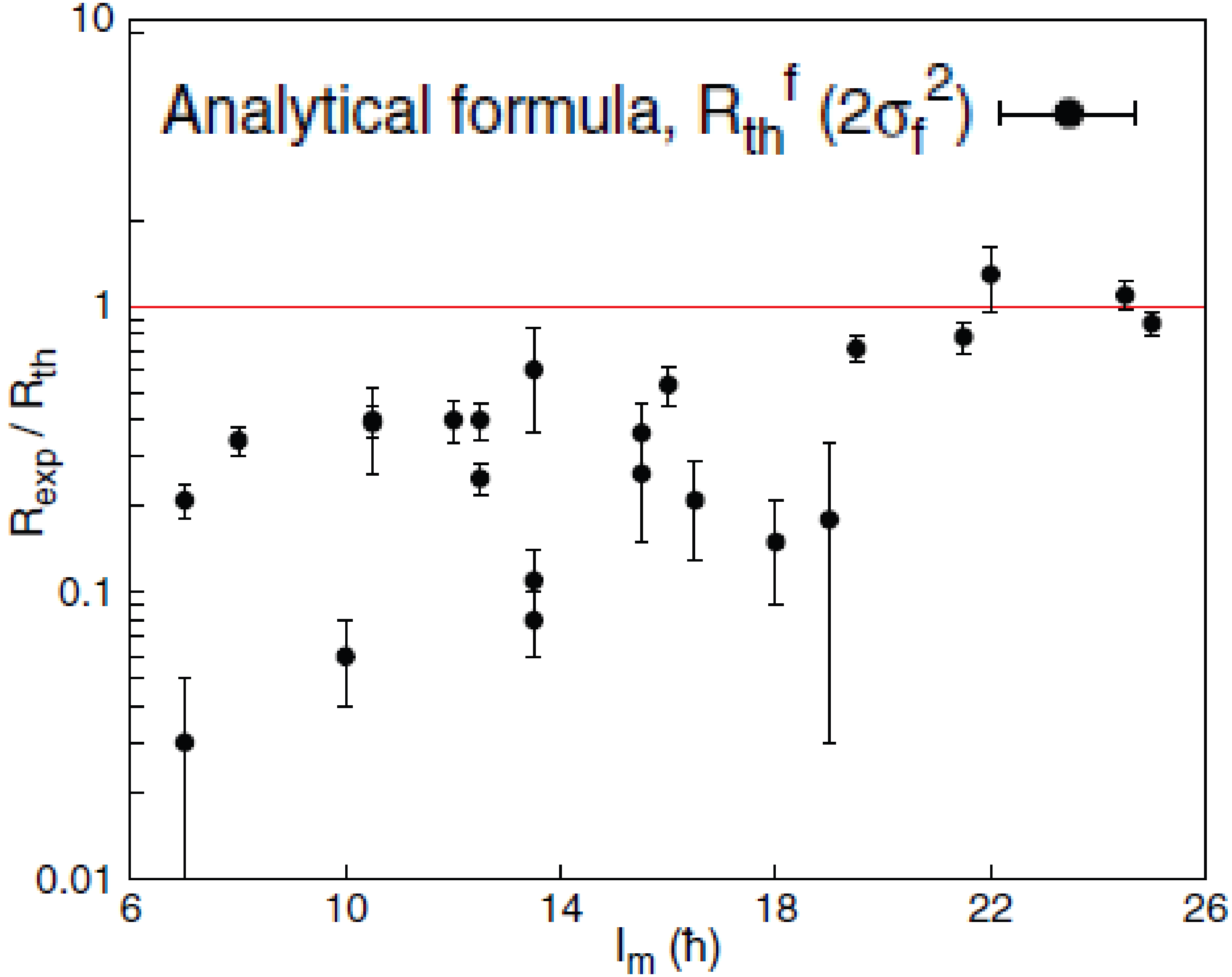

FIG. 8. (Color online) Isomeric ratios determined in the current study (see Table I) compared with the theoretical population predicted by the analytical formula only [Eq. (3)] plotted as a function of angular momentum of the isomeric state. The spin-cutoff parameter in Eq. (3) was multiplied by a factor of 2.

M. Bowry et al., Phys. Rev. C 88, 024611 (2013)

Conclusions

Isomeric ratios from two-particle removal understood

High-spin states are produced with higher probability
than expected (isomeric beams)

At high-spins the angular momentum from abraded nuclei
are not enough: contributions from
evaporation, friction, excitations

Reasonable predictability for isomer production
-factor of two *if* structure is known (I<15hbar)

RISING

Thanks!

Collaborators

PHYSICAL REVIEW C 88, 024611 (2013)

Population of high-spin isomeric states following fragmentation of ^{238}U

M. Bowry,[1] Zs. Podolyák,[1] S. Pietri,[2] J. Kurcewicz,[2] M. Bunce,[1] P. H. Regan,[1] F. Farinon,[2] H. Geissel,[2,3] C. Nociforo,[2] A. Prochazka,[2] H. Weick,[2] N. Al-Dahan,[1] N. Alkhomashi,[1] P. R. P. Allegro,[4] J. Benlliure,[5] G. Benzoni,[6] P. Boutachkov,[2] A. M. Bruce,[7] A. M. Denis Bacelar,[7] G. F. Farrelly,[1] J. Gerl,[2] M. Górska,[2] A. Gottardo,[8] J. Grębosz,[9] N. Gregor,[2] R. Janik,[10] R. Knöbel,[2] I. Kojouharov,[2] T. Kubo,[11] N. Kurz,[2] Yu. A. Litvinov,[2] E. Merchan,[2] I. Mukha,[2] F. Naqvi,[12] B. Pfeiffer,[2,3] M. Pfützner,[13] W. Plaß,[3] M. Pomorski,[13] B. Riese,[2] M. V. Ricciardi,[2] K.-H. Schmidt,[2] H. Schaffner,[2] C. Scheidenberger,[2,3] E. C. Simpson,[1] B. Sitar,[10] P. Spiller,[2] J. Stadlmann,[2] P. Strmen,[10] B. Sun,[2,14] I. Tanihata,[15] S. Terashima,[14] J. J. Valiente Dobón,[8] J. S. Winfield,[2] H.-J. Wollersheim,[2] and P. J. Woods[16]

[1]*Department of Physics, University of Surrey, Guildford GU2 7XH, United Kingdom*
[2]*GSI, Planckstrasse 1, D-64291 Darmstadt, Germany*
[3]*IInd Physical Institute, Justus-Liebig University Giessen, D-35392 Giessen, Germany*
[4]*University of São Paulo, São Paulo 05508-900, Brazil*
[5]*University Santiago de Compostela, 15706 Santiago de Compostela, Spain*
[6]*INFN Sezione di Milano, Dipartimento di Fisica, Via Celoria 16, 20133 Milano, Italy*
[7]*School of Computing Engineering and Mathematics, University of Brighton, Brighton BN2 4GJ, United Kingdom*
[8]*INFN, Laboratori Nazionali di Legnaro, Legnaro (Padova), Italy*
[9]*The Henryk Niewodniczański Institute of Nuclear Physics, PL-31-342 Kraków, Poland*
[10]*Department of Nuclear Physics and Biophysics, Comenius University, Mlynská dolina, 842 48 Bratislava, Slovakia*
[11]*RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[12]*Department of Physics, University of Yale, New Haven, Connecticut 06511-8499, USA*
[13]*Faculty of Physics, University of Warsaw, PL-00-681 Warsaw, Poland*
[14]*School of Physics and Nuclear Energy Engineering, Beihang University, Beijing 100191, China*
[15]*Research Center for Nuclear Physics, 10-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan*
[16]*School of Physics and Astronomy, University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom*

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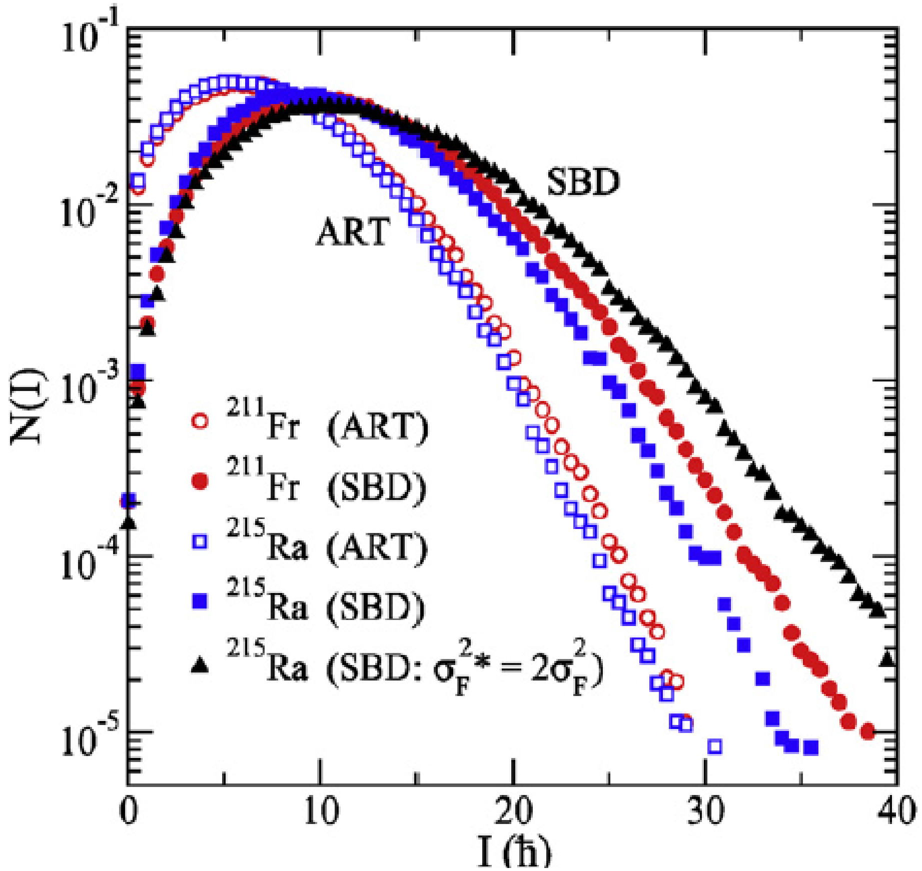
Thanks!



Abrasion (incl. friction)

(relativistic transport model)

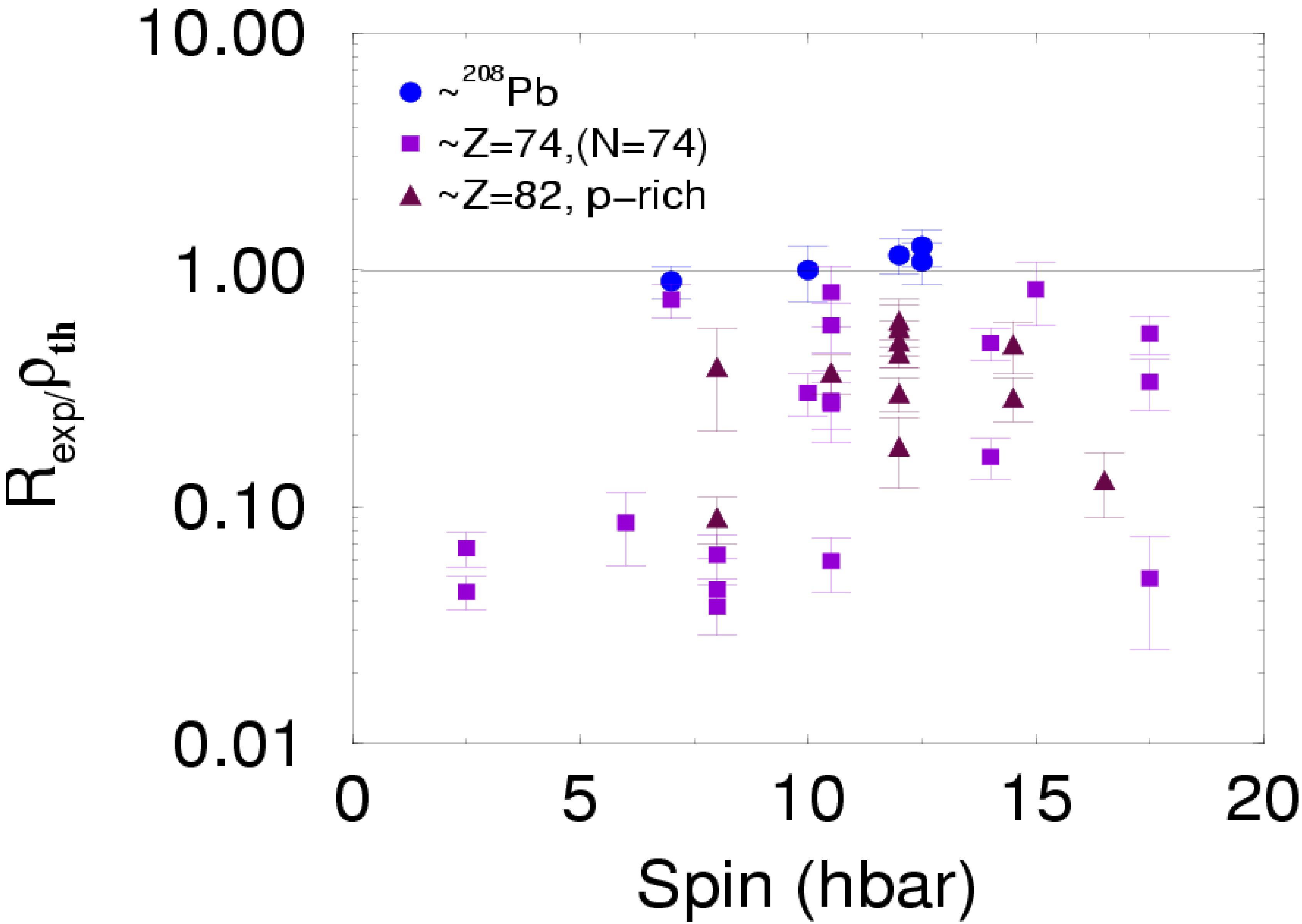
Abrasion+ablation

(+sequential binary decay)

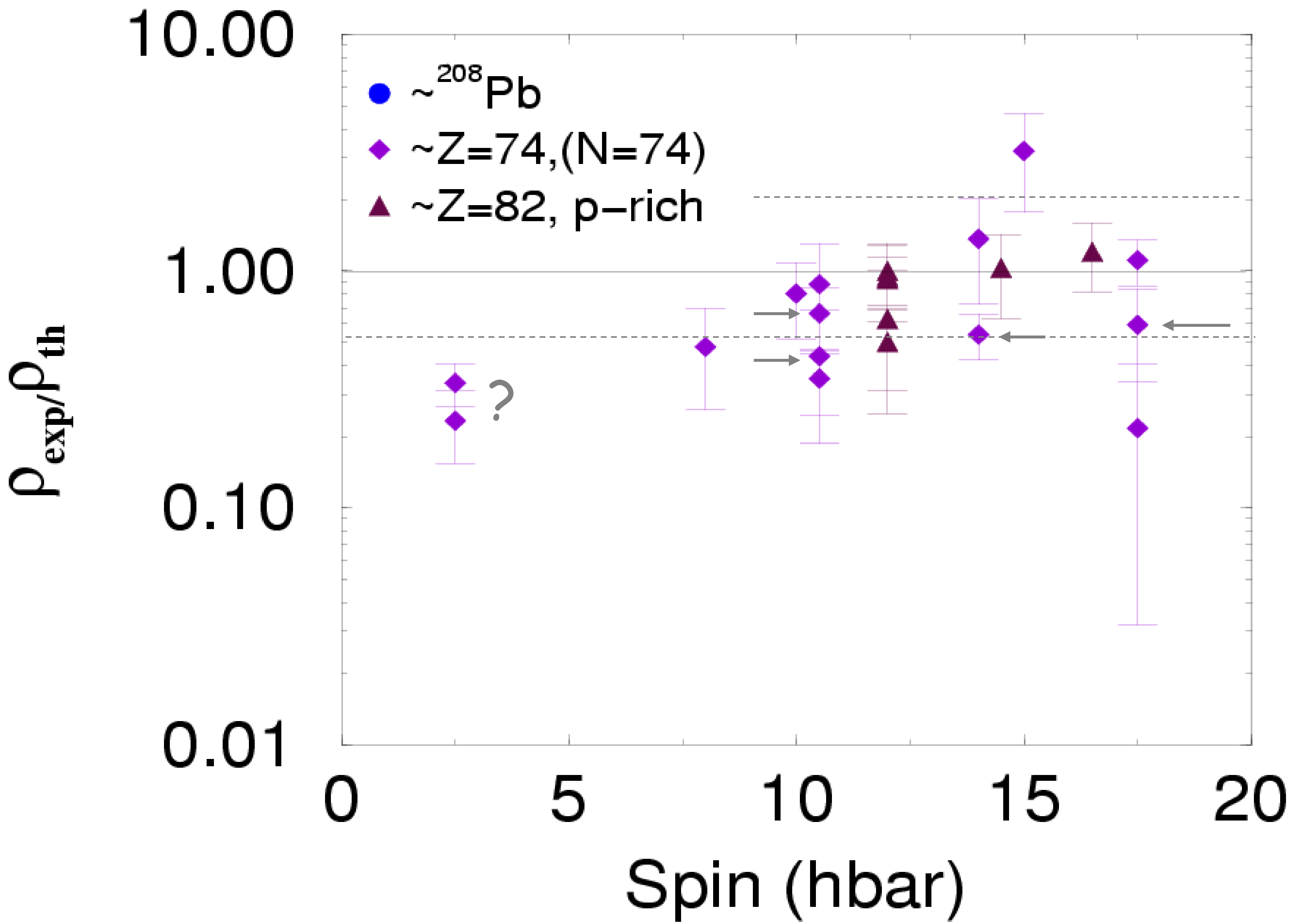
Ion	I^{π}	E (keV)	R_{exp} [%]	R_{the}^{ART} [%]	R_{the}^{SBD} [%]
^{211}Fr	$29/2^+$	2423	5.7(19)	2.59	10.03
^{212}Fr	15^-	2492	7.5(18)	2.24	9.15
^{213}Fr	$29/2^+$	2538	12(8)	2.65	10.82
^{214}Ra	17^-	4147	6.8(23)	0.58	3.20
^{215}Ra	$43/2^-$	$3757 + \Delta$	3.1(6)	0.07	0.82

Better agreement

S. Pal and R. Palit, Phys. Lett. B 665 (2008) 164.

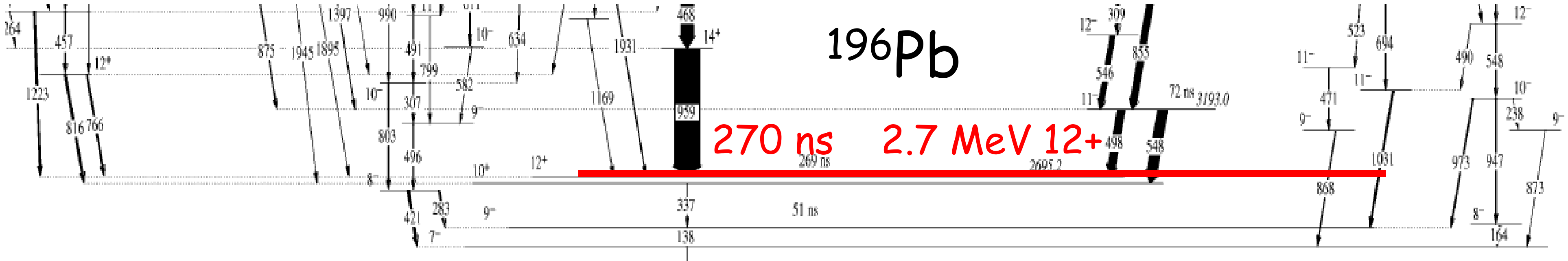


10.00
1.00
0.10
0.01
R_{exp}/ρ_{th}
~^{208}Pb
~Z=74,(N=74)
~Z=82, p-rich
0
5
10
15
20
Spin (hbar)



The highlighted points: higher lying isomers decay int

Nuclear structure has to be considered



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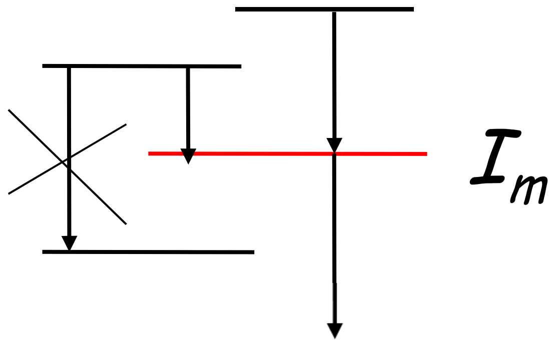

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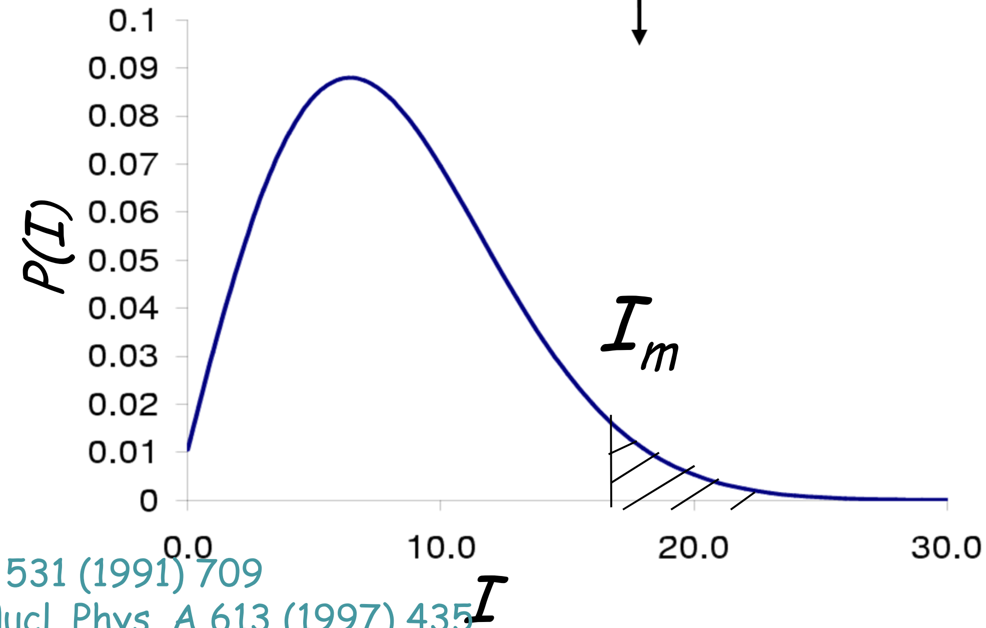
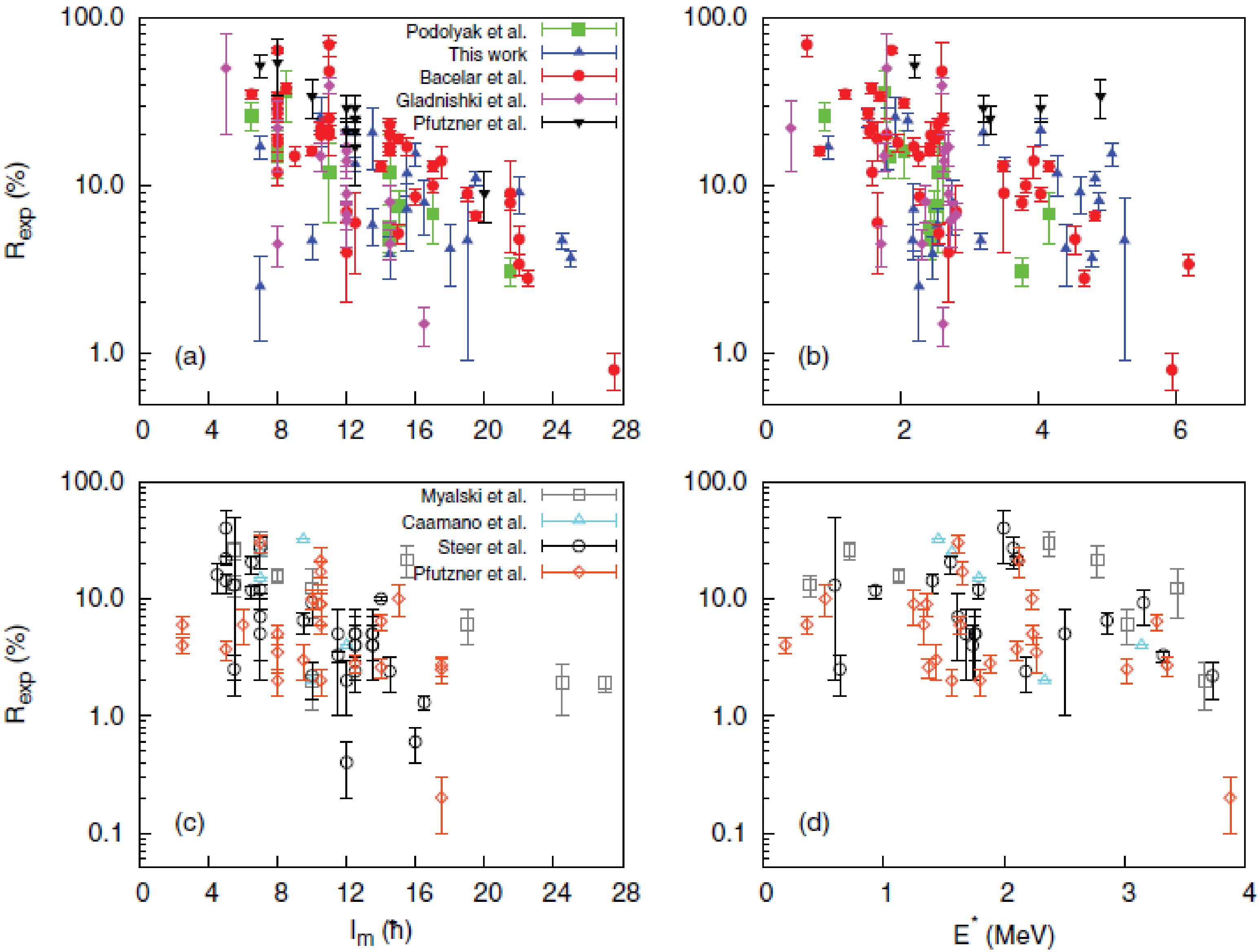
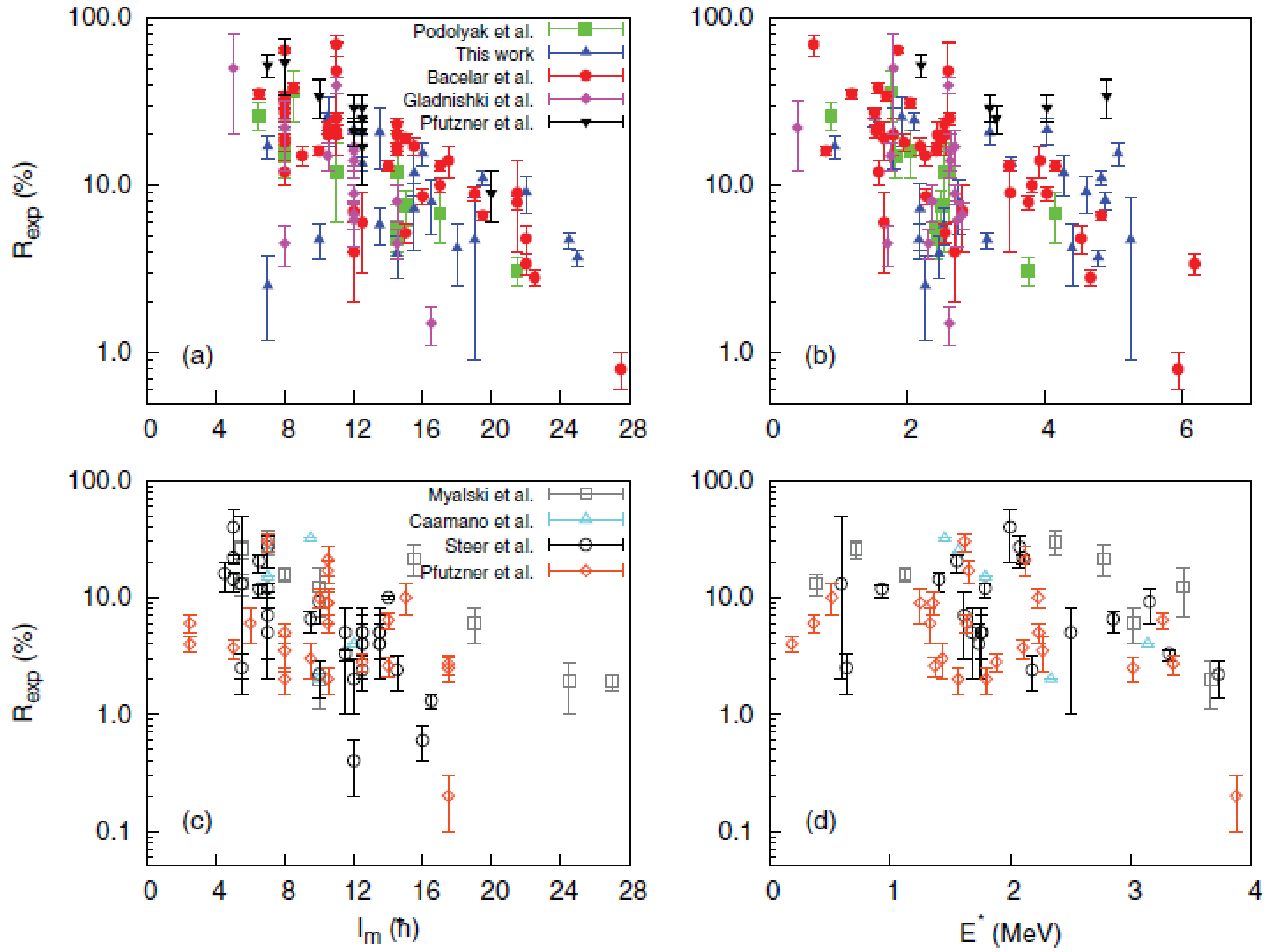


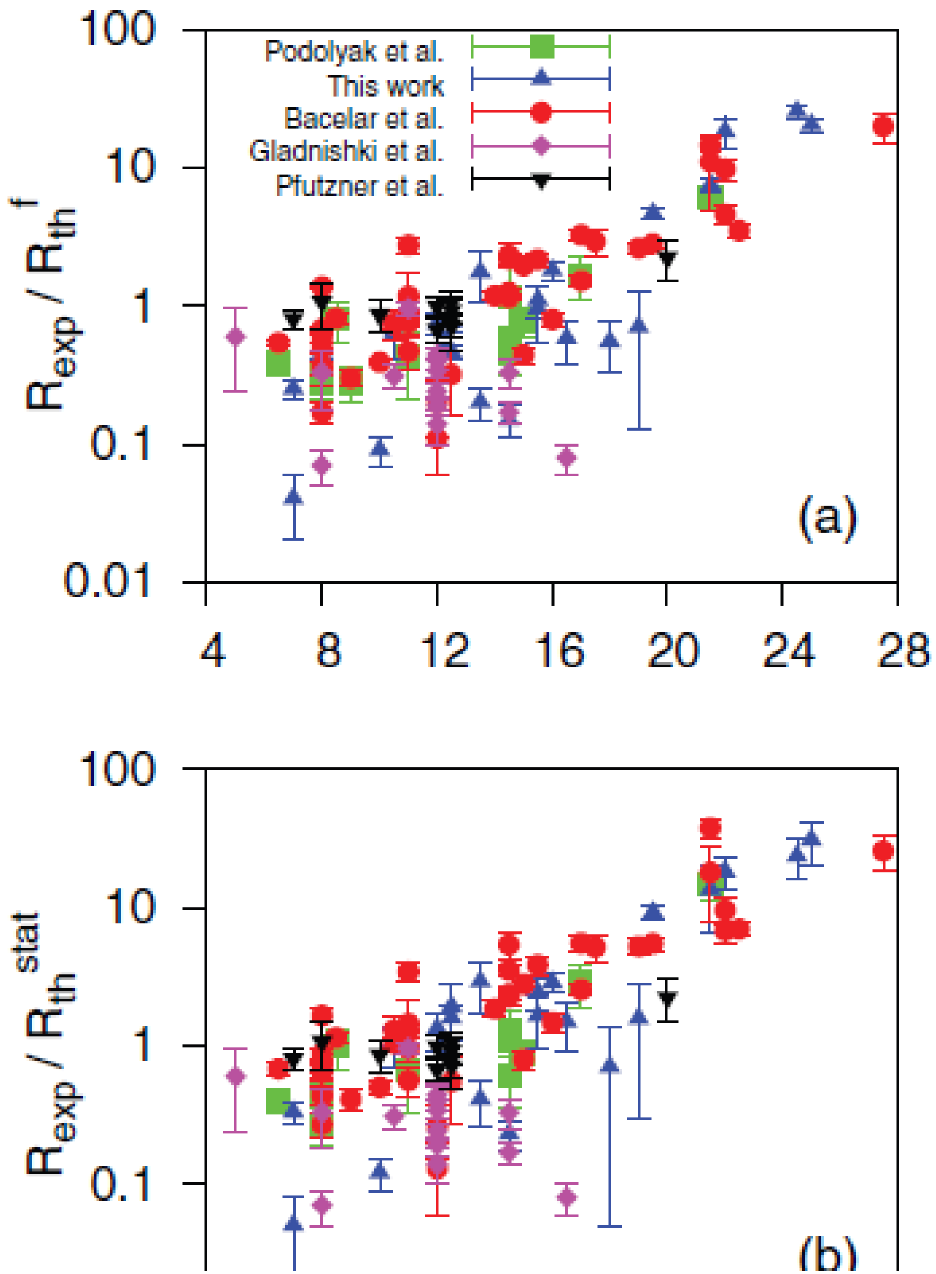
J.-J. Gaimard and K.-H. Schmidt, Nucl. Phys. A 531 (1991) 709
M. De Jong, A.V. Ignatyuk and K.-H. Schmidt, Nucl. Phys. A 613 (1997) 435



M. Bowry et al., Phys. Rev. C 88, 024611 (2013)



M. Bowry et al., Phys. Rev. C 88, 024611 (2013)



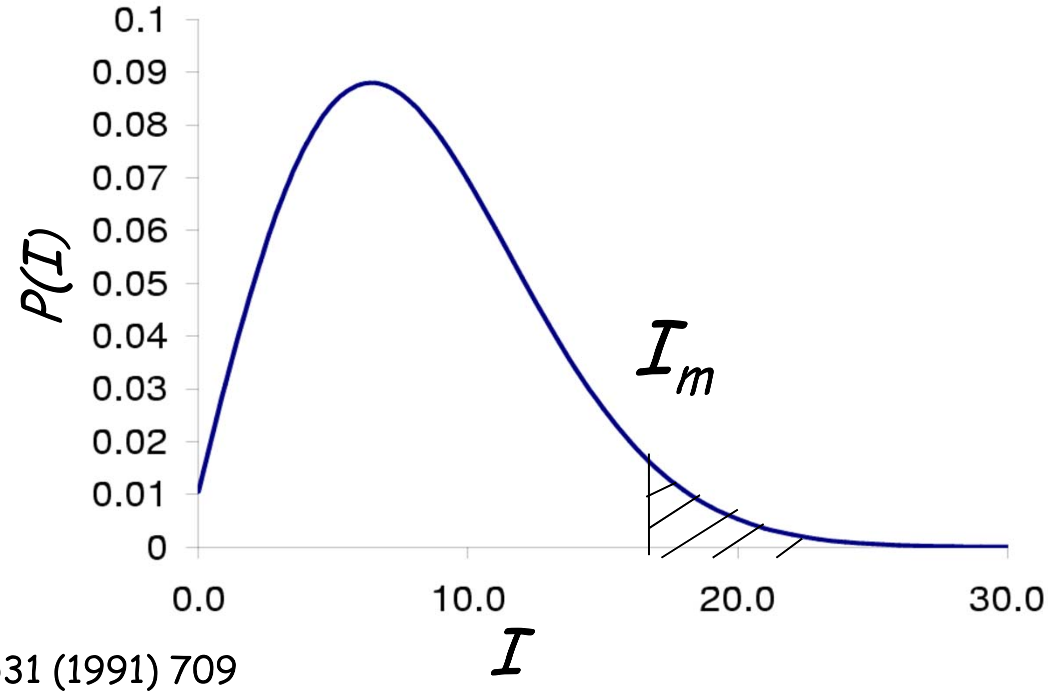
Podolyak et al.
This work
Bacelar et al.
Gladnishki et al.
Pfutzner et al.
R_{exp} / R_{th}^{f}
(a)
R_{exp} / R_{th}^{stat}
(b)
100
10
1
0.1
0.01
4
8
12
16
20
24
28

$$P_I = \frac{2I+1}{2\sigma_f^2}\exp\left(\frac{-I(I+1)}{2\sigma_f^2}\right) \quad \Rightarrow \quad R_{th}^f = \exp\left(\frac{-I_m(I_m+1)}{2\sigma_f^2}\right)$$

$$\sigma_f^2 = \langle j_z^2 \rangle \frac{(A_p - A_f)(\nu A_p + A_f)}{(\nu+1)^2(A_p - 1)}$$

$\nu=2$

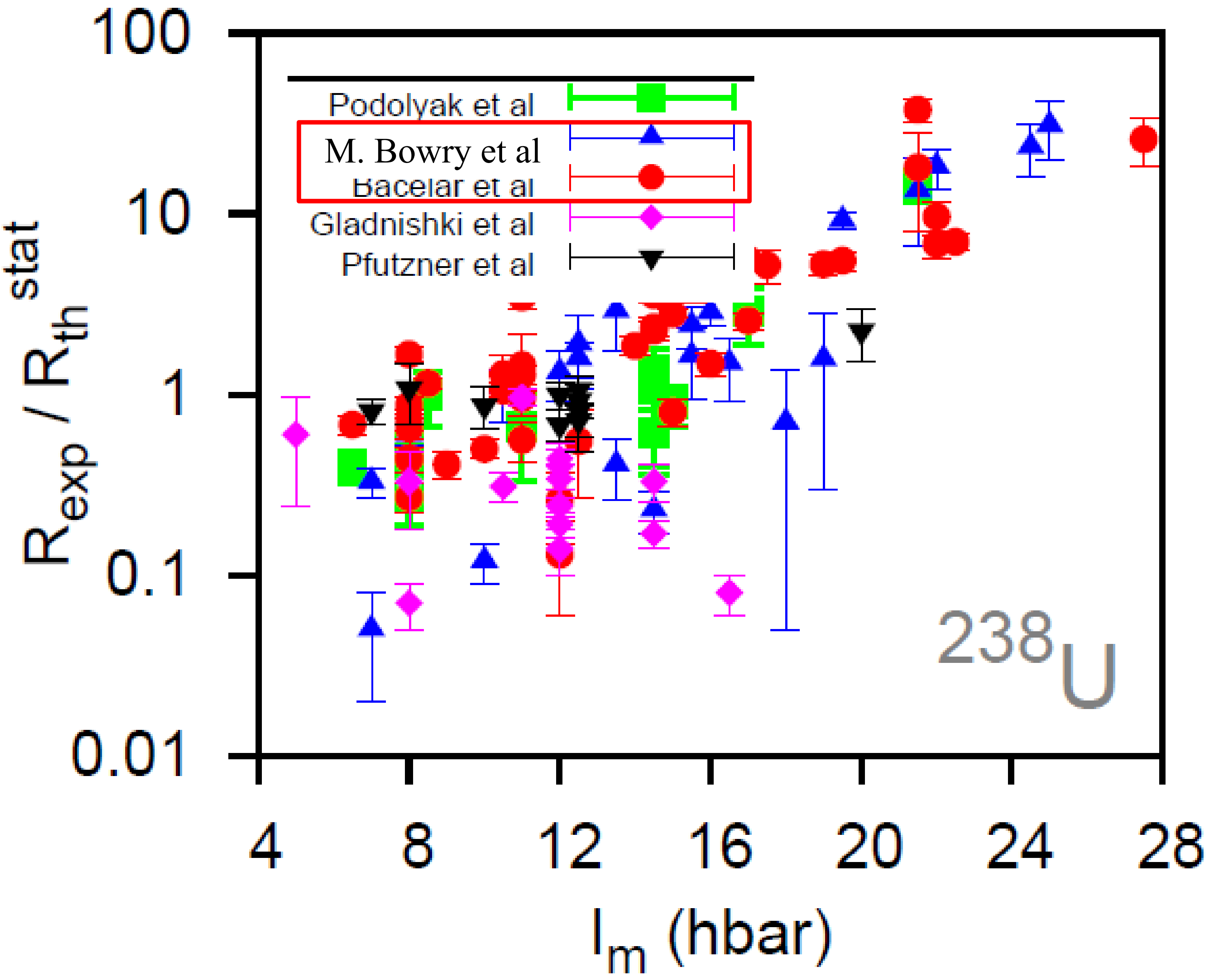
$$\langle j_z^2 \rangle = k\, A_p^{\frac{2}{3}}\left(1 - \frac{2\beta}{3}\right)$$



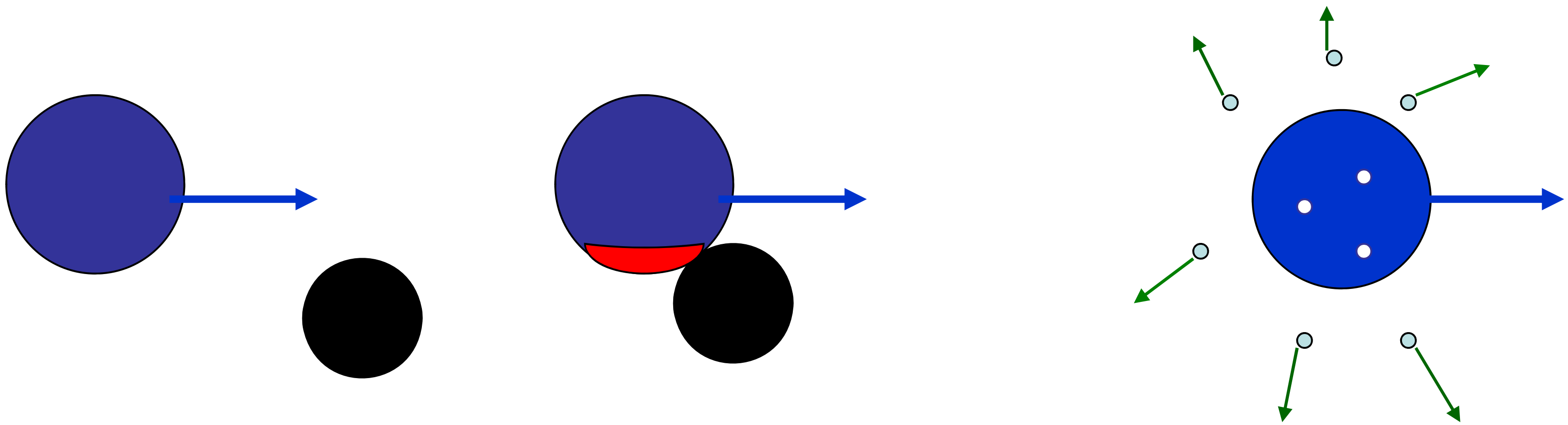
J.-J. Gaimard and K.-H. Schmidt, Nucl. Phys. A 531 (1991) 709

M. De Jong, A.V. Ignatyuk and K.-H. Schmidt, Nucl. Phys. A 613 (1997) 435

Comparison with theory



Fragmentation/spallation is (one of the) main source(s) of radioactive beams/exotic nuclei



abrasion

ablation

multi-hole state

Fragmentation reaction at relativistic energies

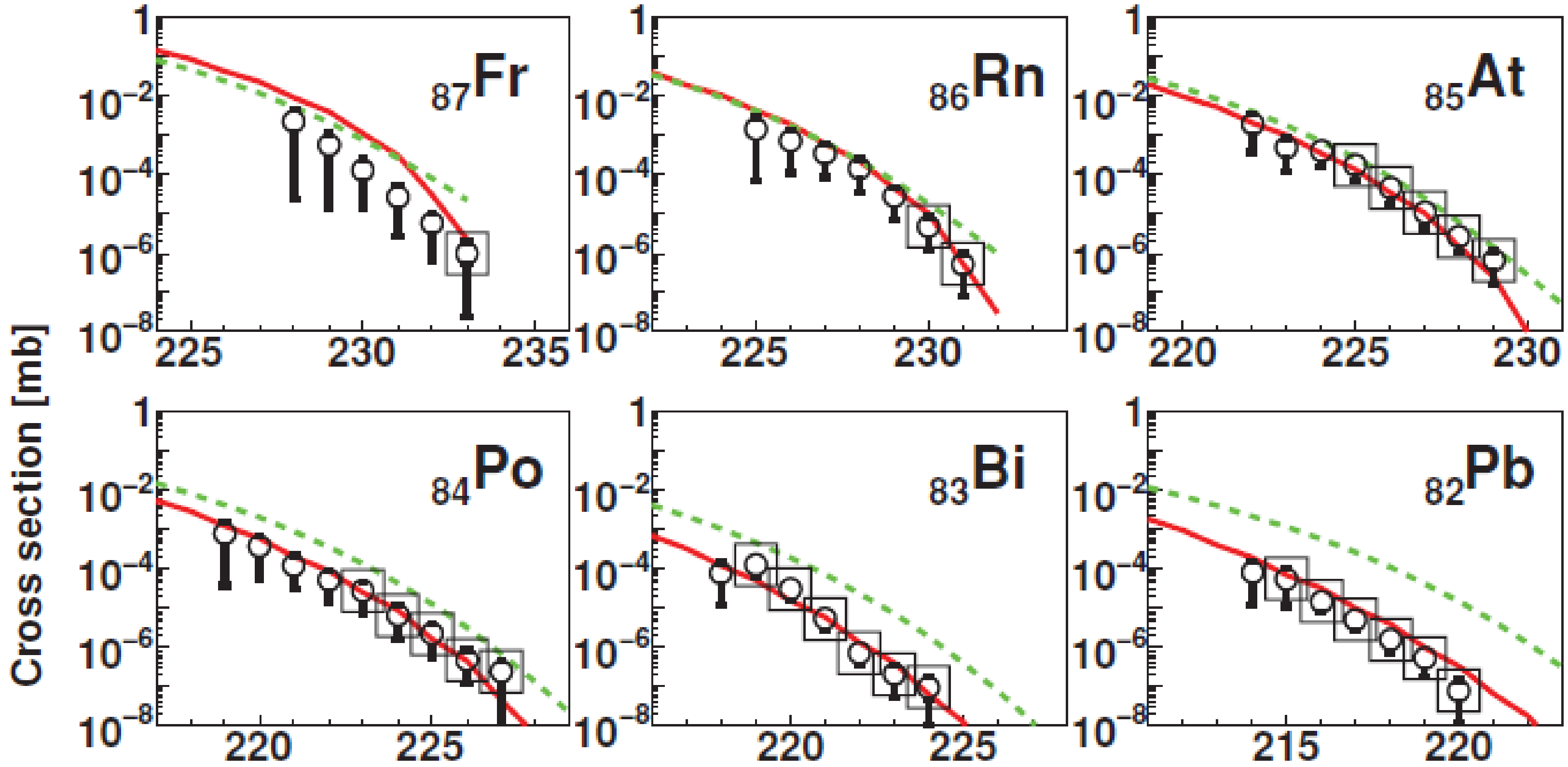
How to study fragmentation?

Cross section: measures the end product

What would give information about abrasion?

Angular (and linear) momentum

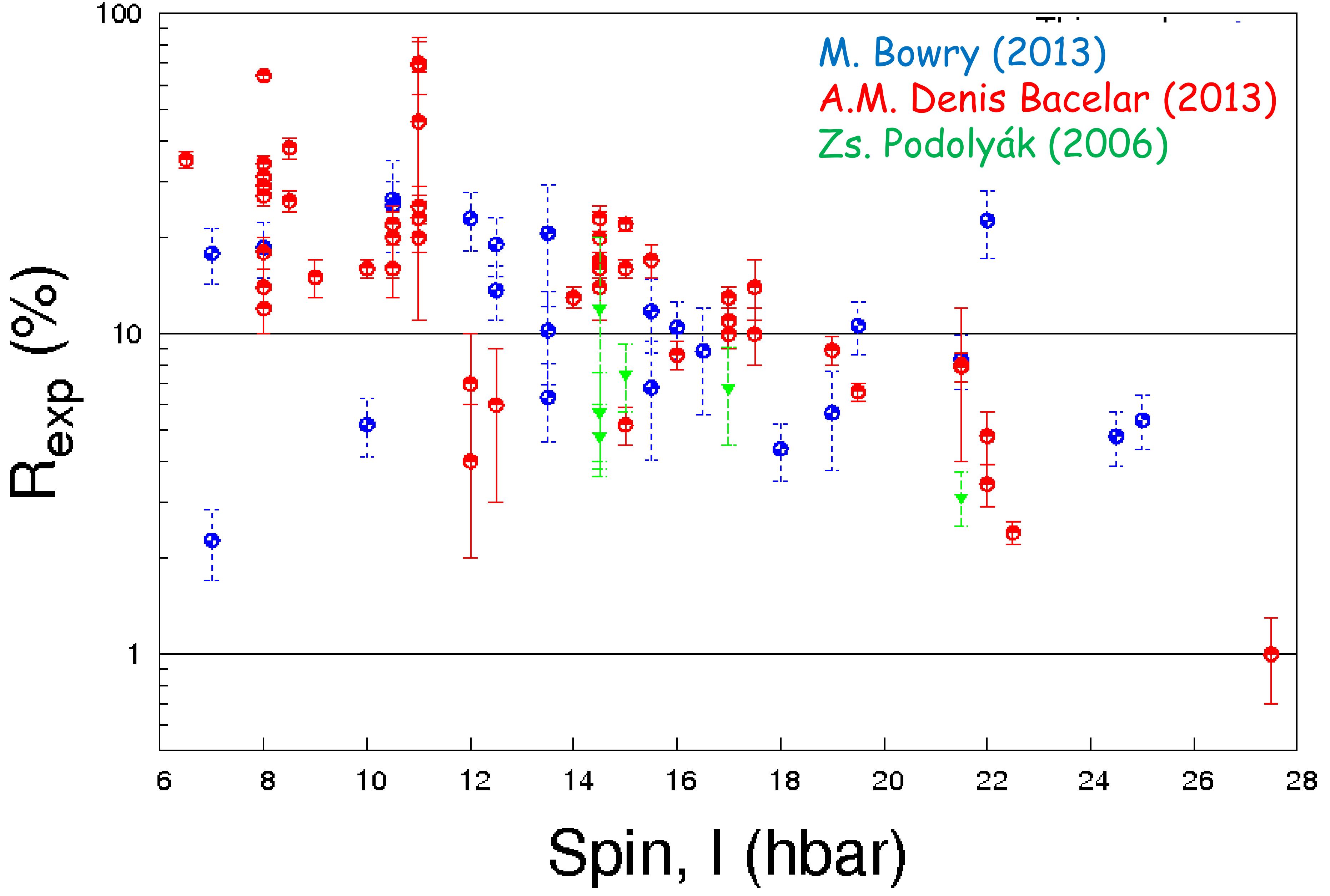
↘ from isomers

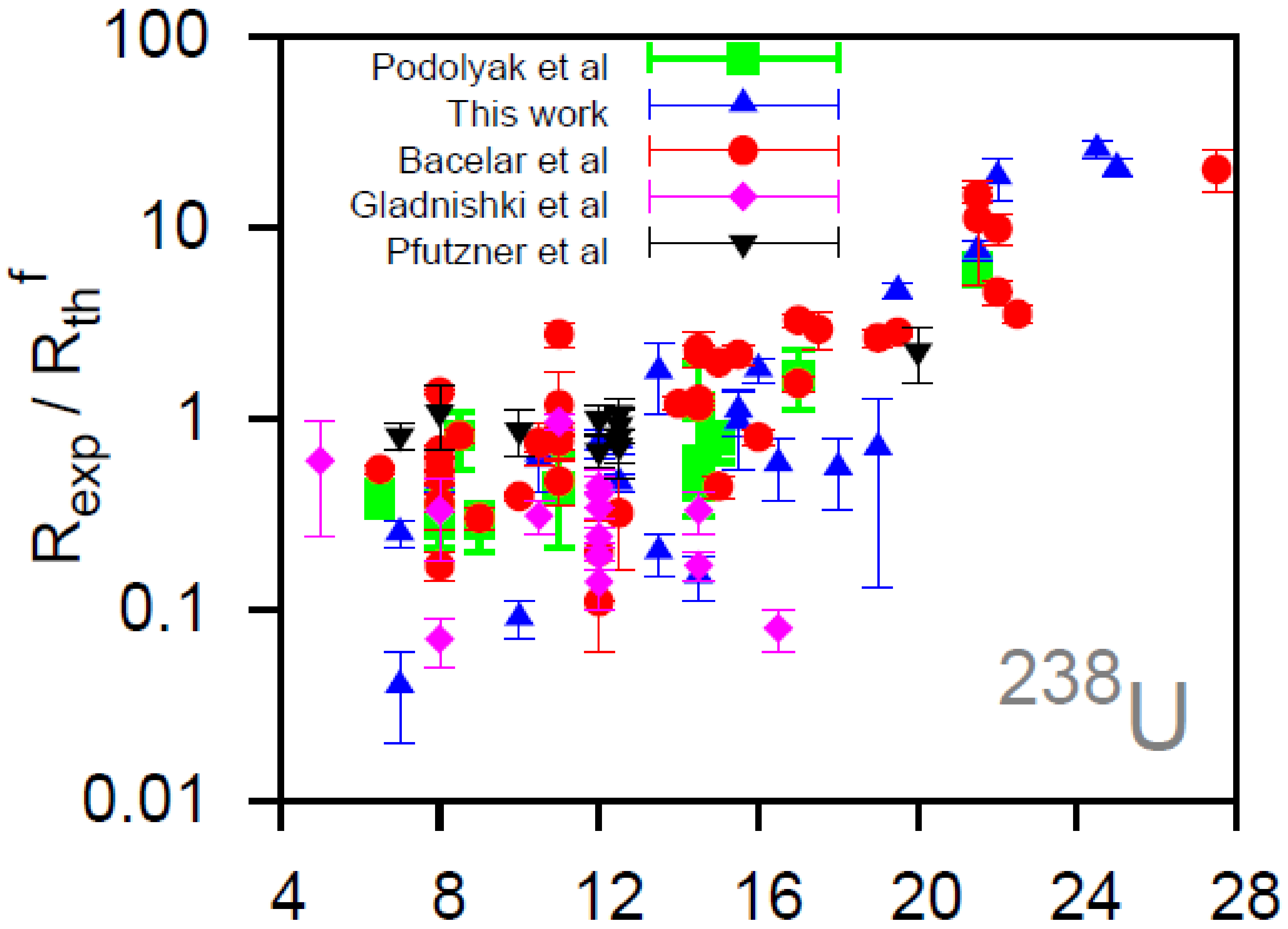


EPAX ABRABLA/COFRA

H. Alvarez-Pol et al., Phys. Rev. C 82, 041602(R) (2110)

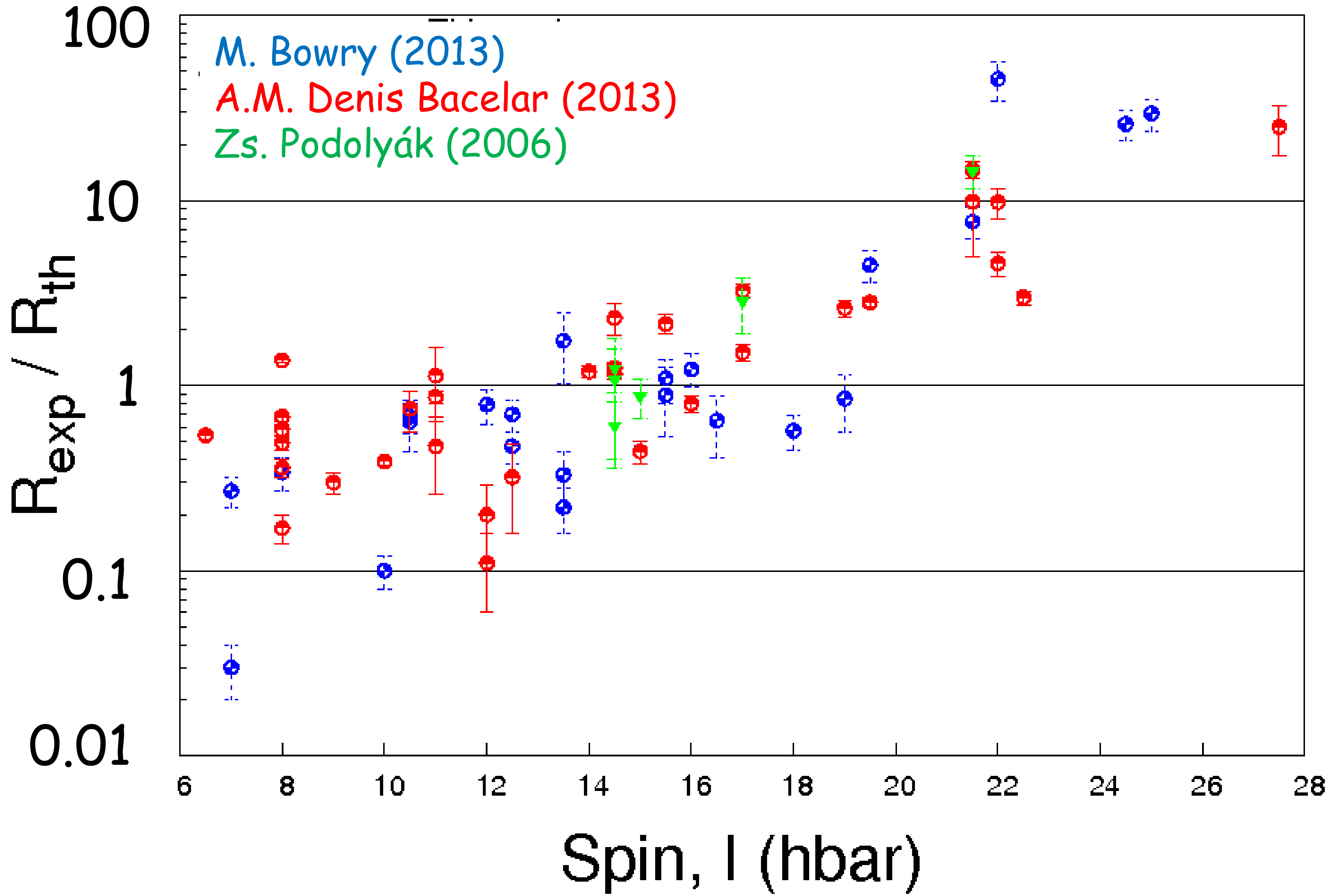
238U fragmentation (A~200-210)

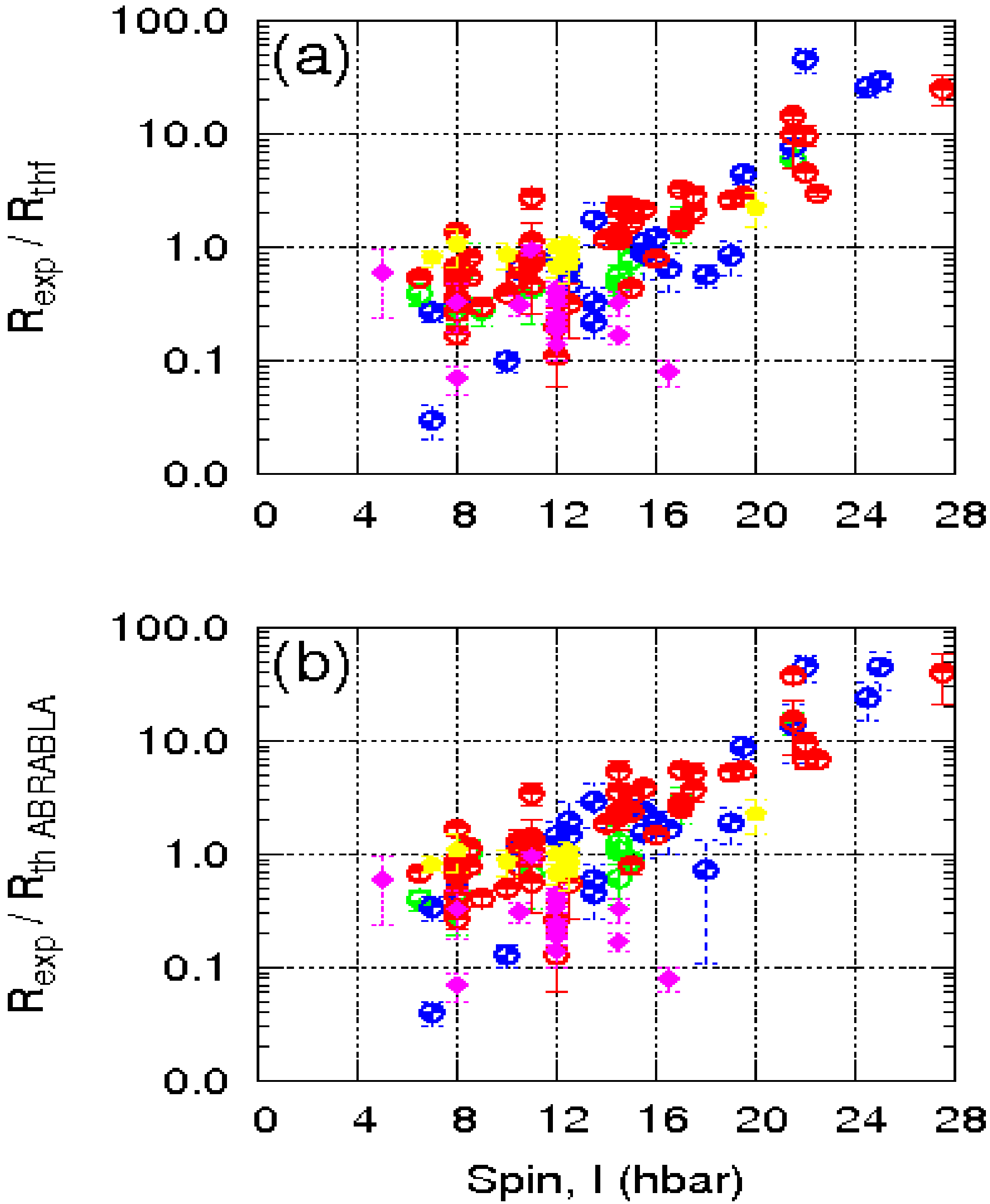




100
10
1
0.1
0.01
R_{exp} / R_{th}^{f}
4
8
12
16
20
24
28
Podolyak et al
This work
Bacelar et al
Gladnishki et al
Pfutzner et al
^{238}U

Comparison with theory (sharp cut-off approx.)



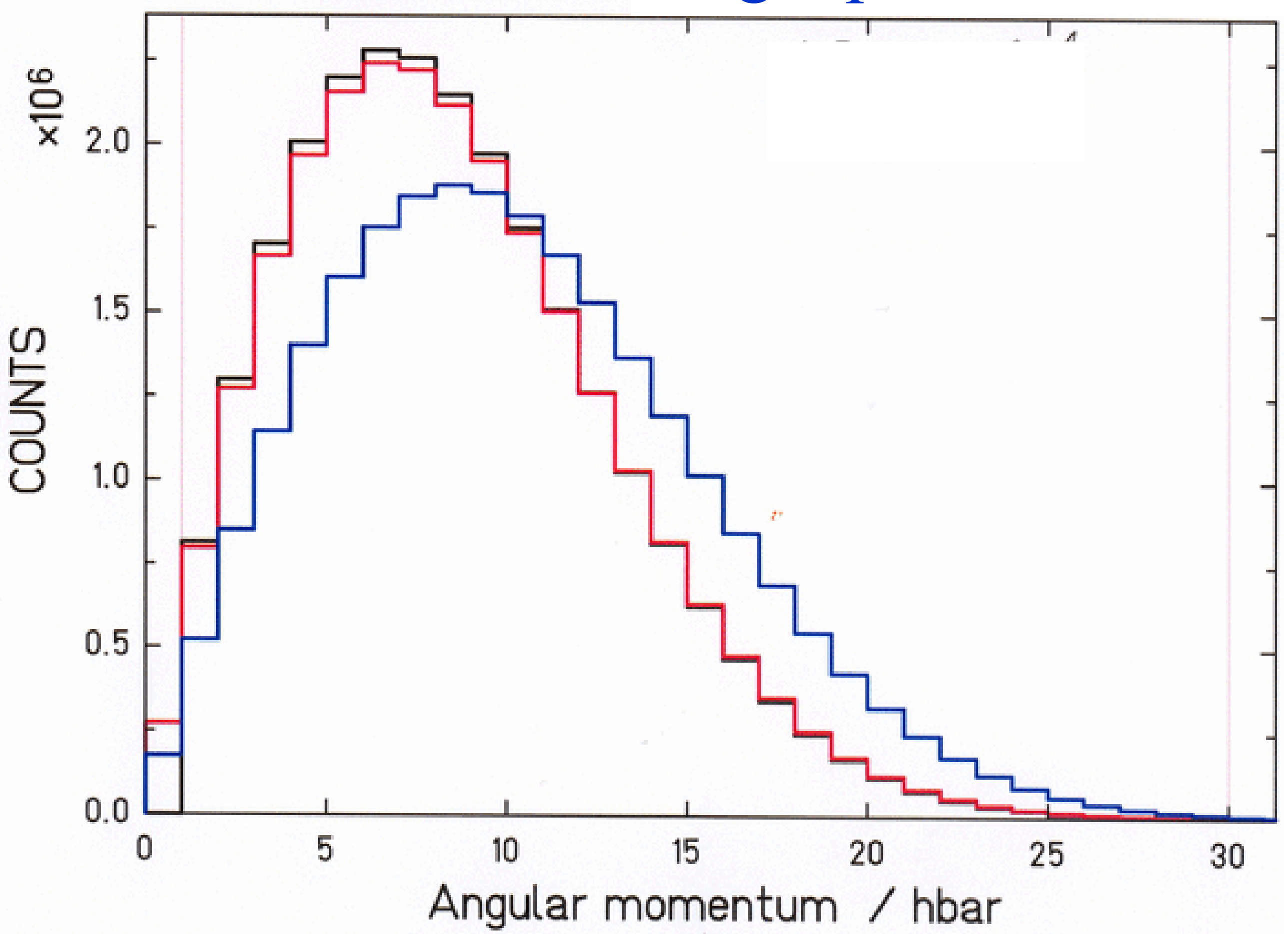


(a)
100.0
10.0
1.0
0.1
0.0
R_{exp} / R_{thf}
0
4
8
12
16
20
24
28
(b)
100.0
10.0
1.0
0.1
0.0
R_{exp} / $R_{th\ ABRABLA}$
0
4
8
12
16
20
24
28
Spin, I (hbar)

We need to couple: single particle holes *I* (any direction in 3D) collective *I* (2D)

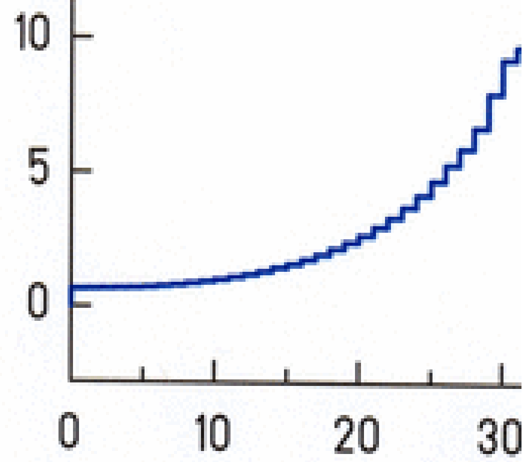
single particle only (Analytical)

single particle + collective

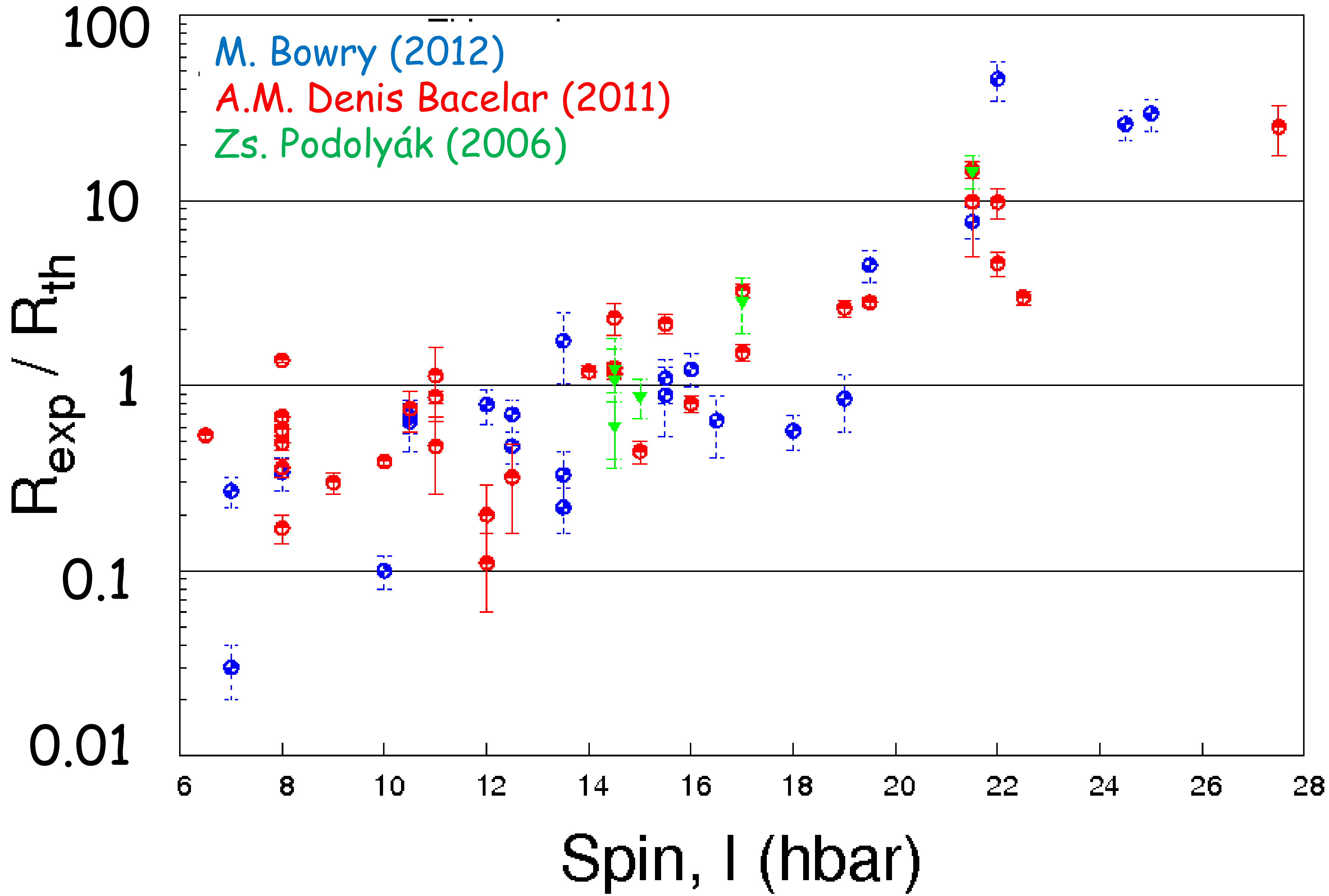


increased high-spin population due

to **collective *I***

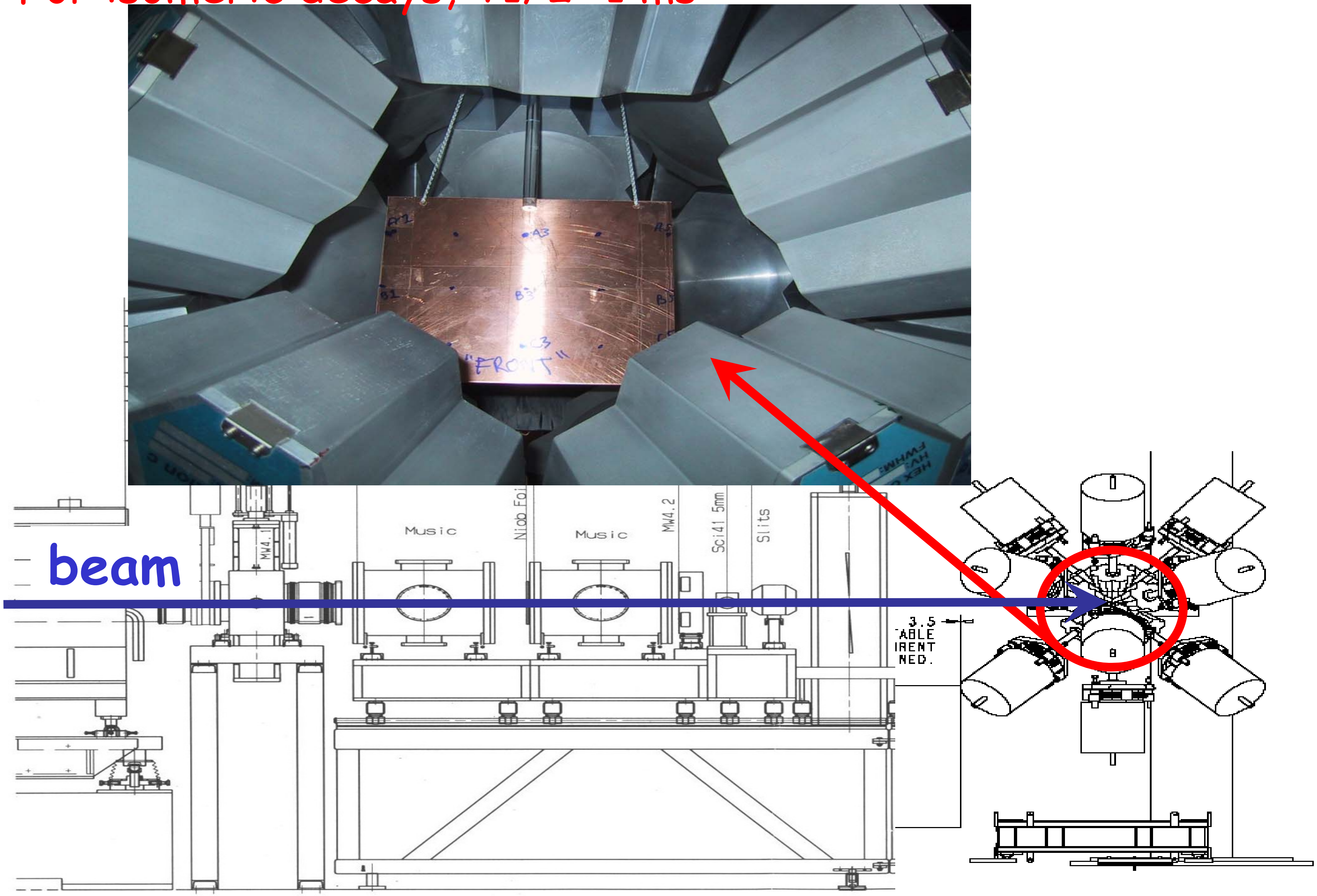


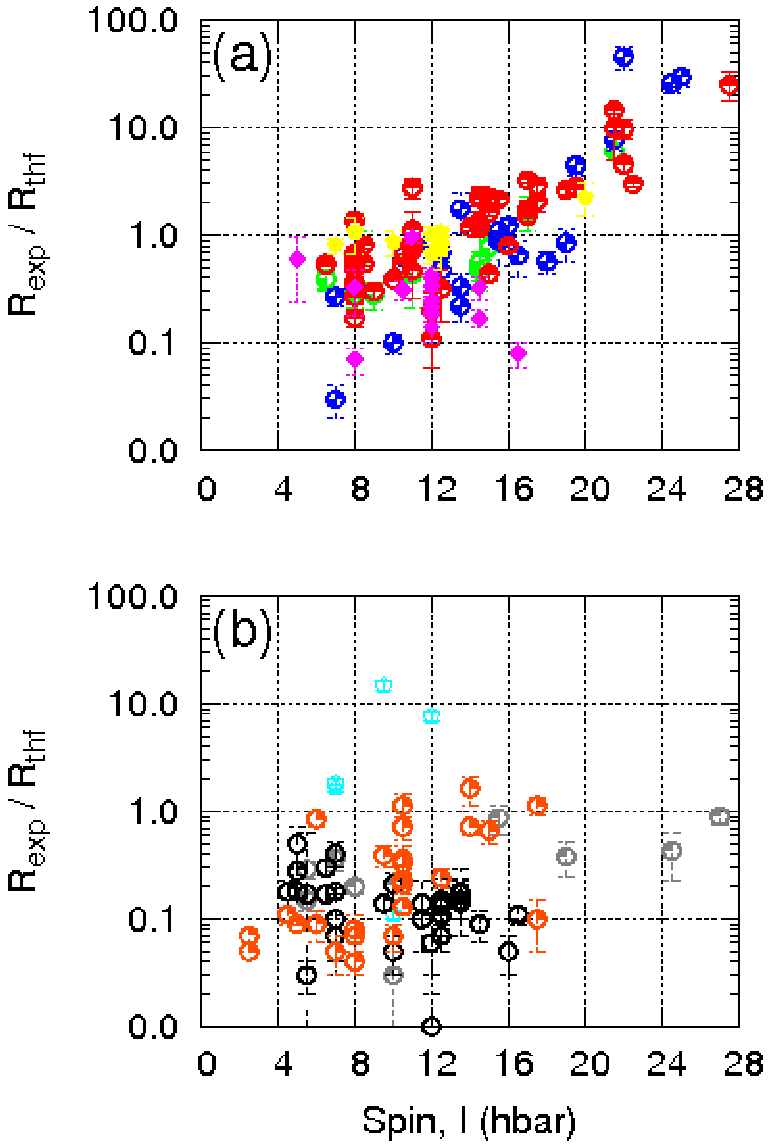
Comparison with theory (sharp cut-off approx.)



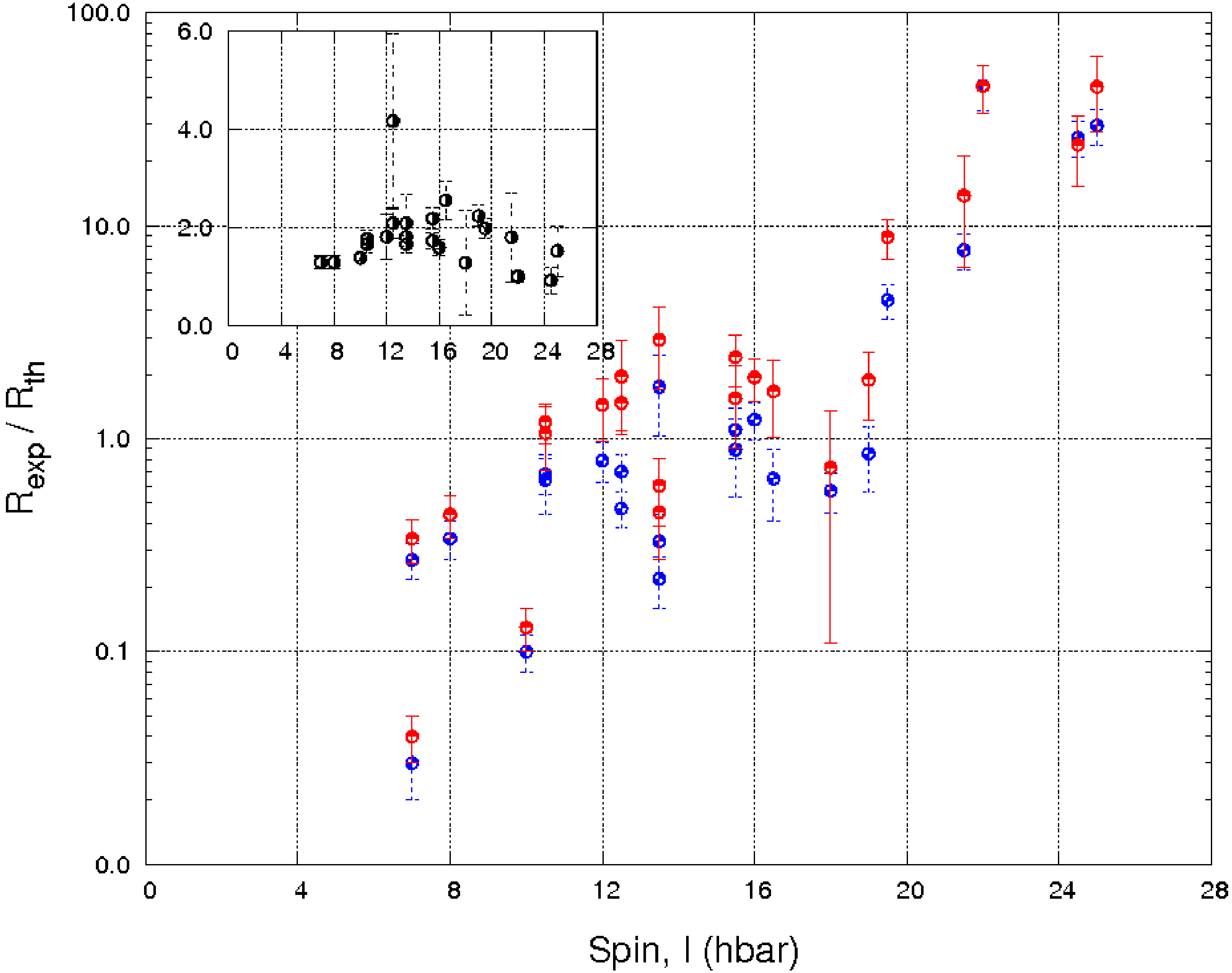
Passive stopper:

For isomeric decays, T1/2< 1 ms

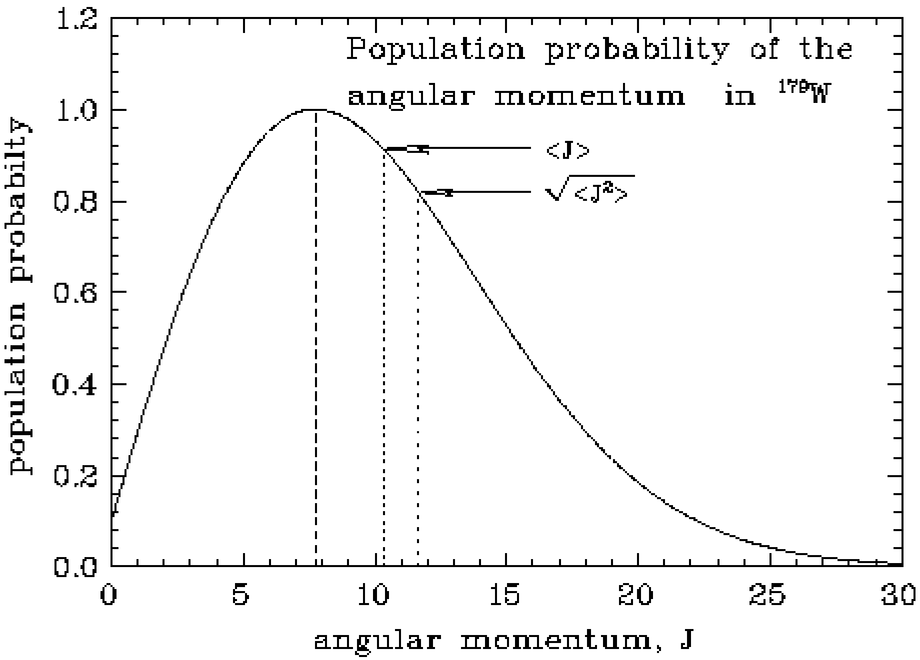




(a)
(b)
100.0
10.0
1.0
0.1
0.0
R_{exp} / R_{thf}
0
4
8
12
16
20
24
28
Spin, I (hbar)



100.0
10.0
1.0
0.1
0.0
0
4
8
12
16
20
24
28
R_{exp} / R_{th}
Spin, I (hbar)
6.0
4.0
2.0
0.0



Population probability of the
angular momentum in ^{179}W
<J>
$\sqrt{<J^2>}$
population probabilty
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30
angular momentum, J

Abrasion-ablation model

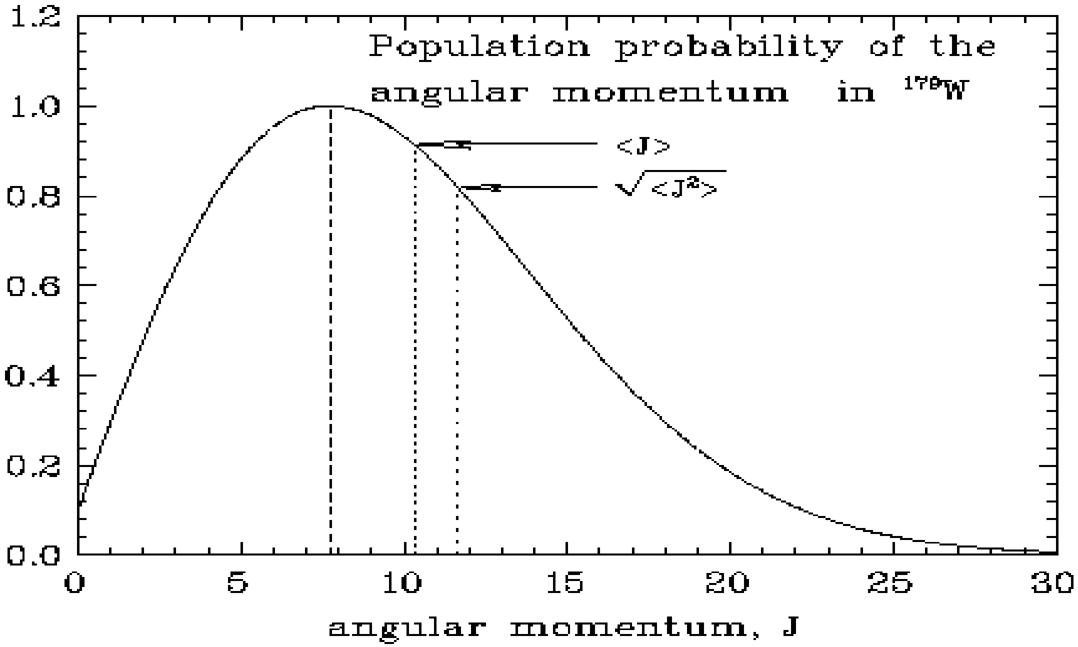
Distribution of the angular momentum in a fragmentation process

$$P(J) = \frac{2J+1}{2\sigma_f^2} exp\left(-\frac{J(J+1)}{2\sigma_f^2}\right)$$

$$\sigma_f^2 = 0.16 A_p^{2/3} \frac{(A_p - A_f)(\bar{k}A_p + A_f)}{(\bar{k}+1)^2(A_p - 1)}$$ (1-2β/3)

k = 2 $\Delta A > 10$

De Jong, Ignatyuk, Schmidt, NP A613 (1997) 435



"sharp cut-off" approximation: $R_{th} = \int_{J_m}^{\infty} P(J)dJ = \exp[\frac{J_m(J_m+1)}{2\sigma_f^2}]$

Theory

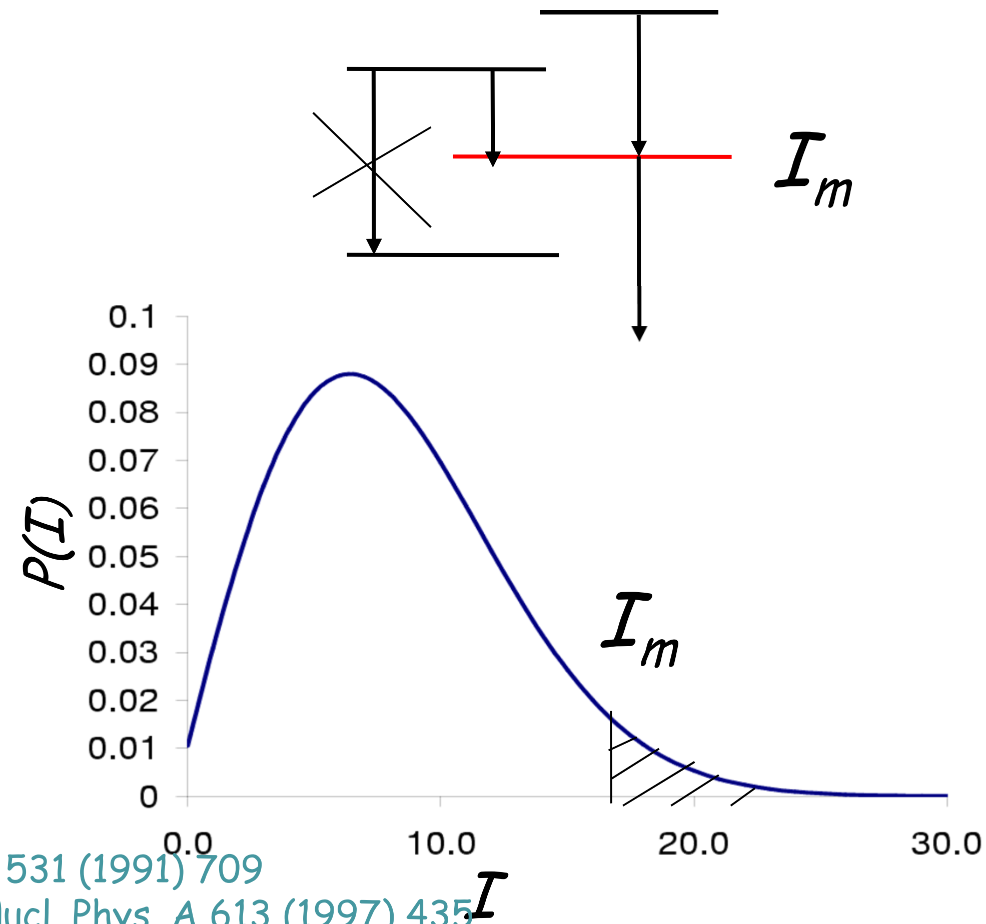
Abrasion-ablation model

Angular momentum distribution: **ABRABLA** code (abrasion stage).

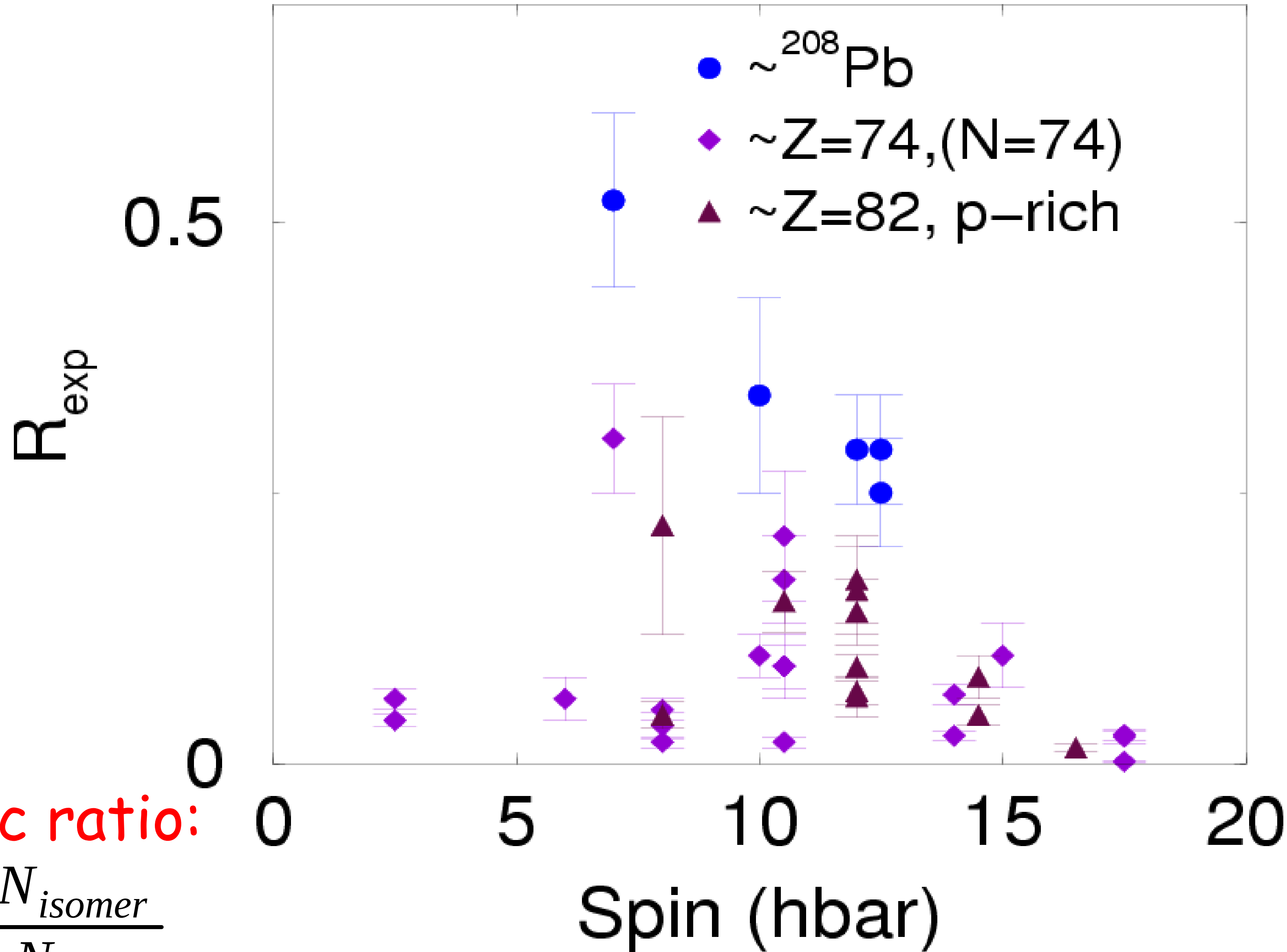
$$P(I)=\frac{2I+1}{2\sigma_f^2}\exp\left(-\frac{I(I+1)}{2\sigma_f^2}\right)$$

$$\sigma_f^2=0.16A_p^{2/3}\frac{(A_p-A_f)(\nu A_p+A_f)}{(\nu+1)^2(A_p-1)}$$

$$\rho_{theo}=\int_{I_m}^{\infty}P(I)dI$$



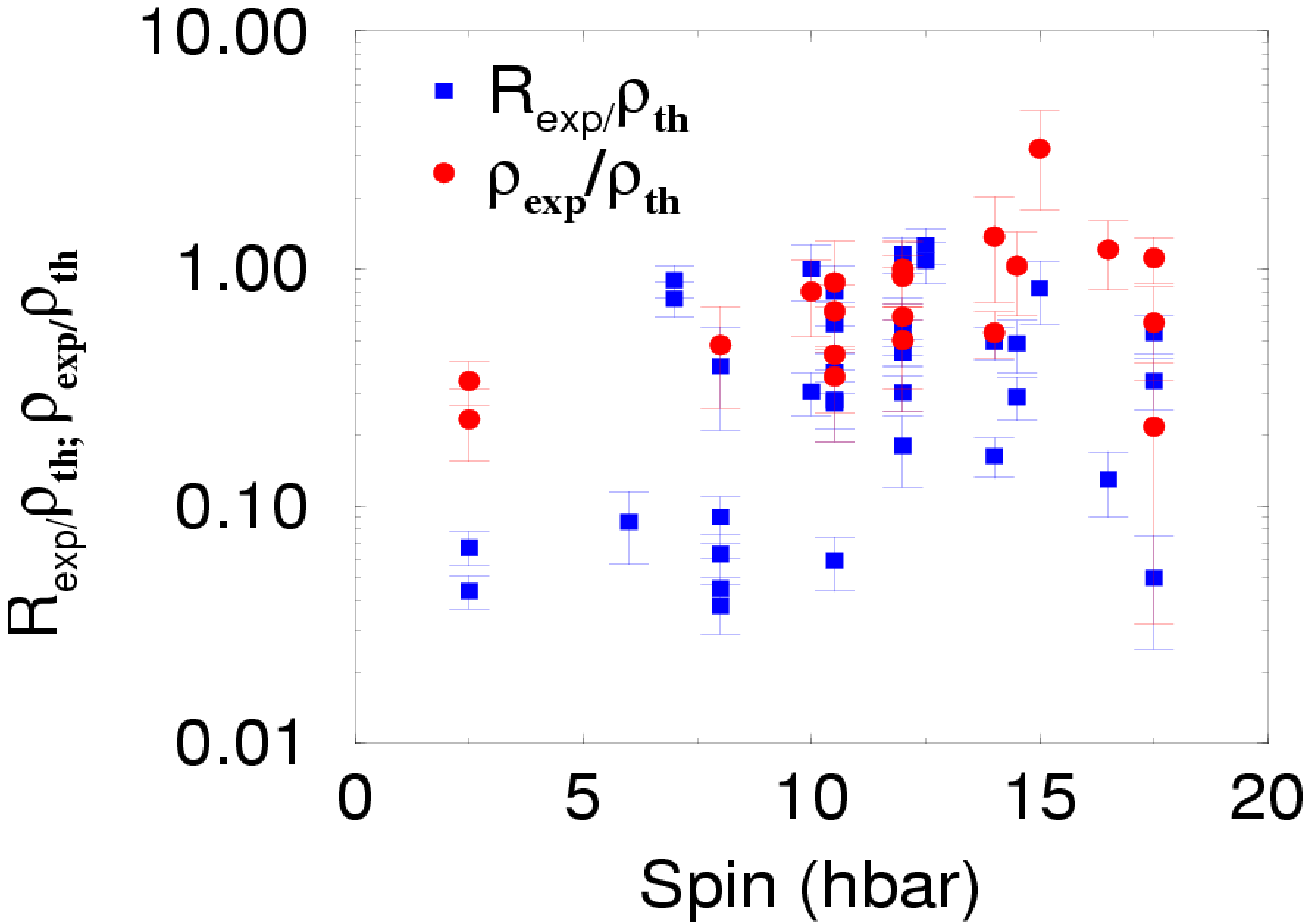
J.-J. Gaimard and K.-H. Schmidt, Nucl. Phys. A 531 (1991) 709
M. De Jong, A.V. Ignatyuk and K.-H. Schmidt, Nucl. Phys. A 613 (1997) 435



isomeric ratio:

$$R_{\exp} = \frac{N_{isomer}}{N_{total}}$$

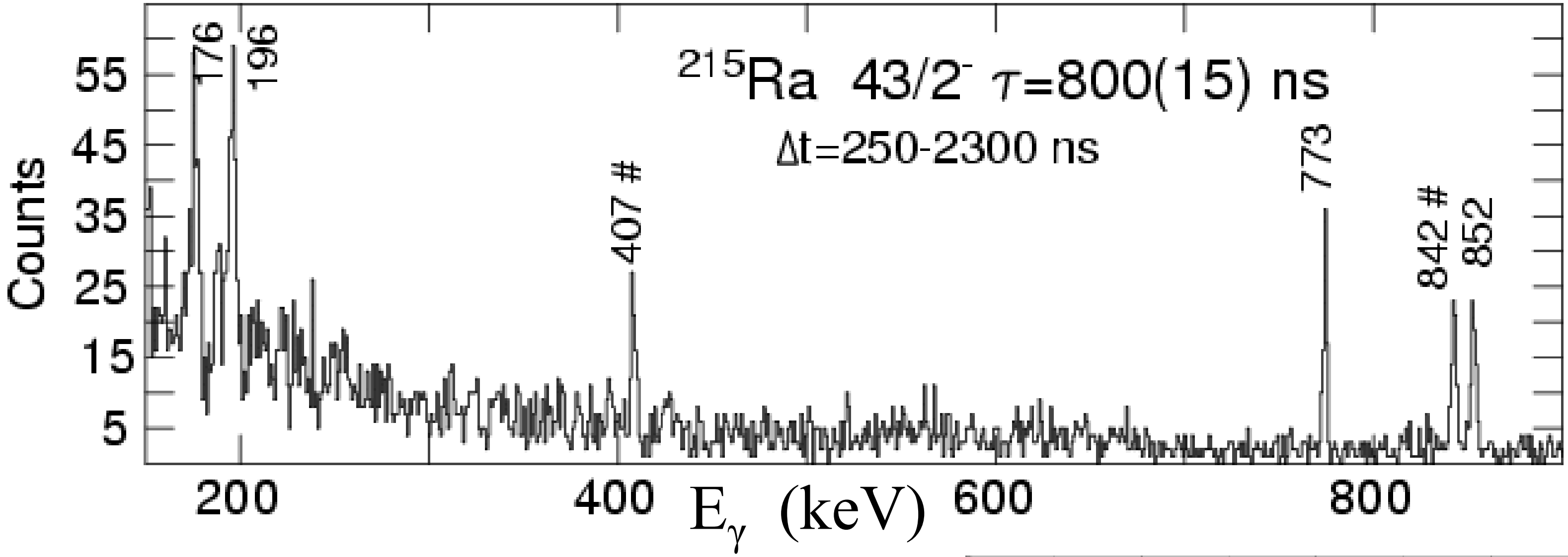
- M. Pfützner *et al.*, Phys. Lett. B444 (1998) 32.
- M. Pfützner *et al.*, Phys. Rev. C65 (2002) 064604.



R - isomeric ratio

ρ - probability of populating states

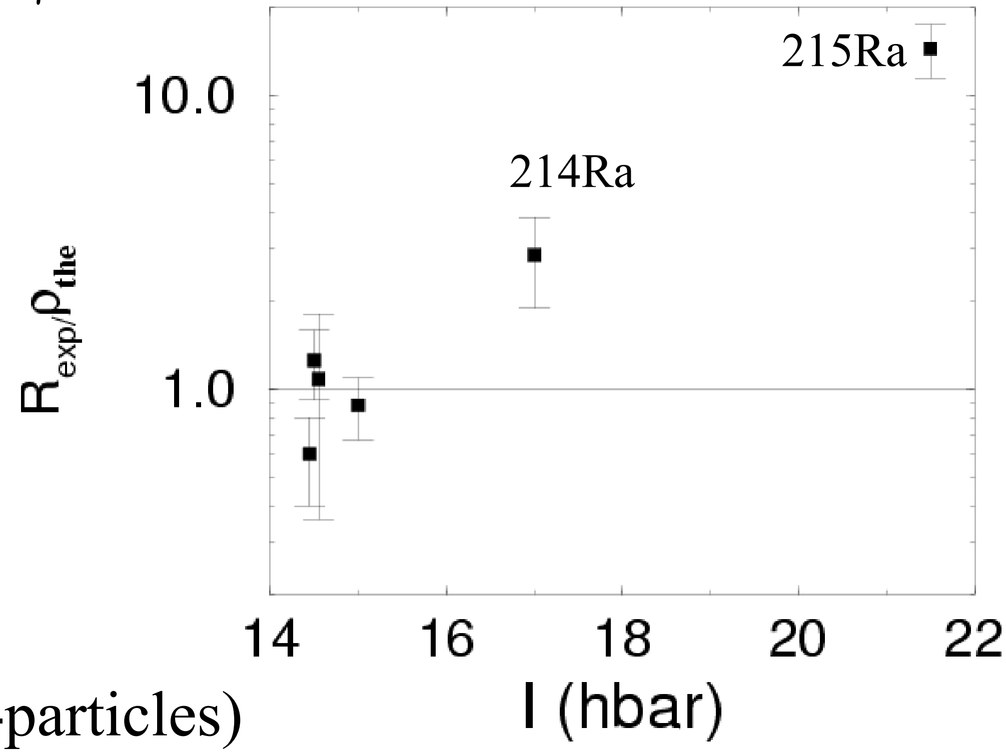
High-spin isomers from ^{238}U fragmentation:



enhanced production of high-spin states

⇩

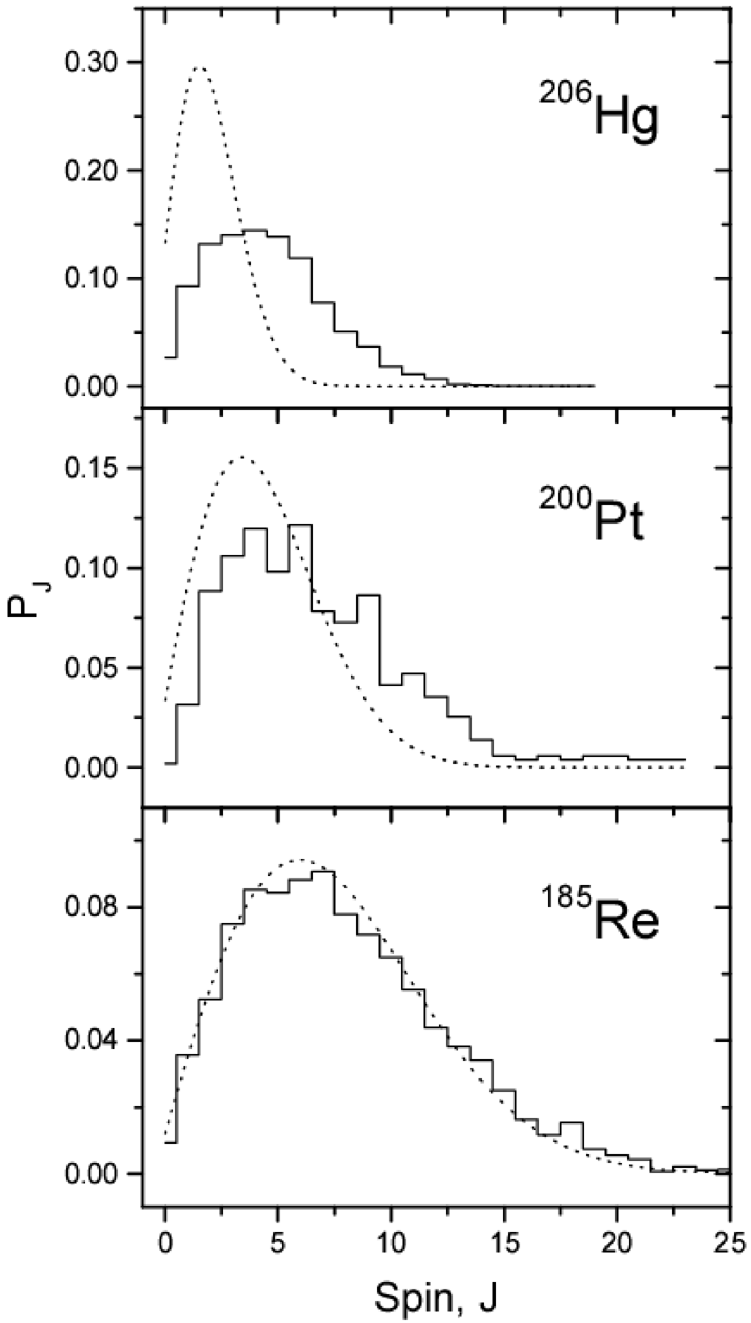
additional source of angular momentum?



(original theory: *I* from single-particles)

Zs. Podolyák *et al.*, Phys. Lett. B632 (2006) 203.

M. Pfützner *et al.*, Phys. Rev. C 65 (2002) 054604.

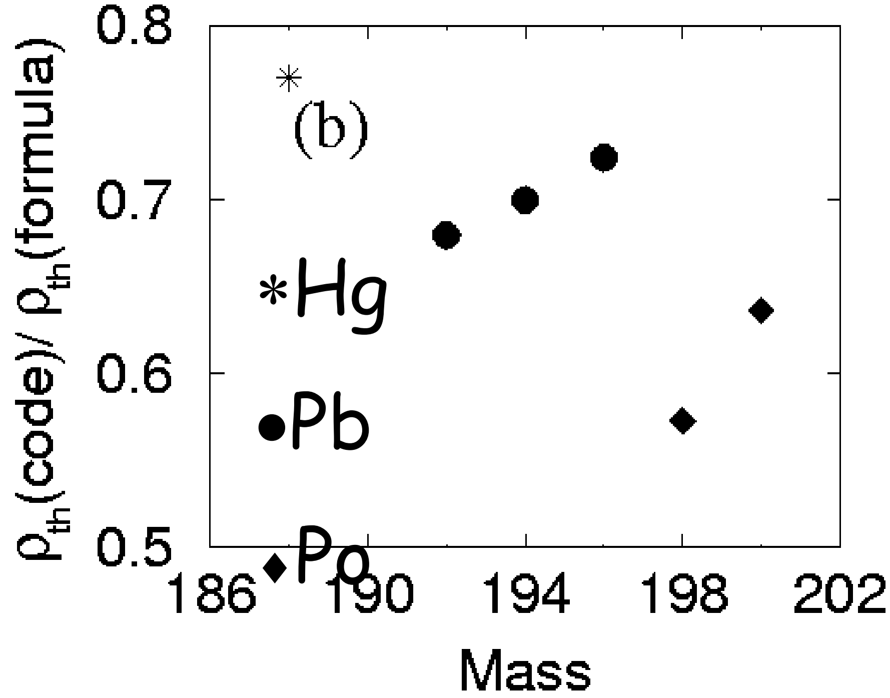


fragmentation of ^{208}Pb

- - - - - - - - - - Analytical formulc

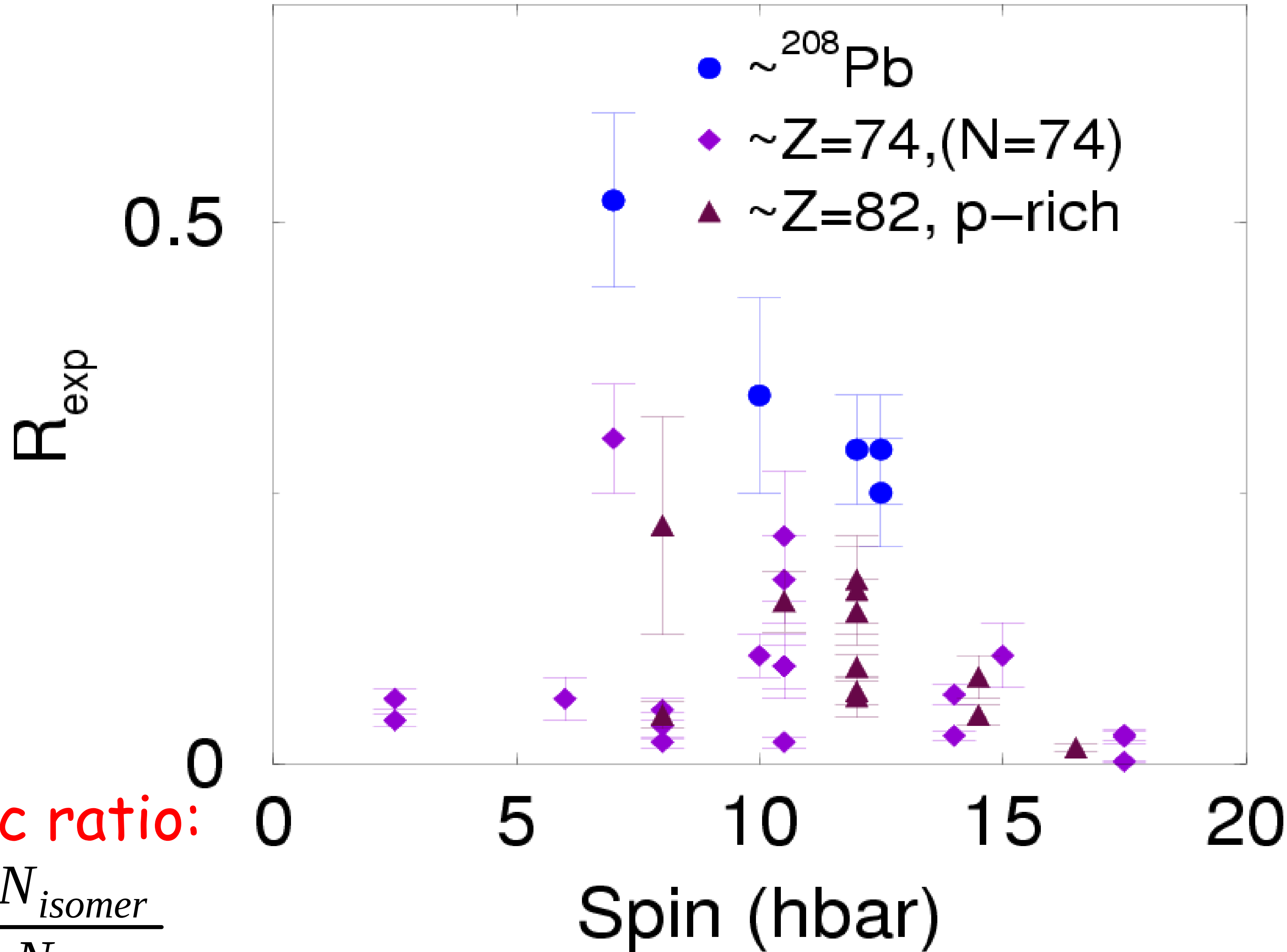
——— ABRABLA

more reliable, this is use



K. Gladnishki et al., Phys. Rev. C (20

fragmentation of ^{238}U



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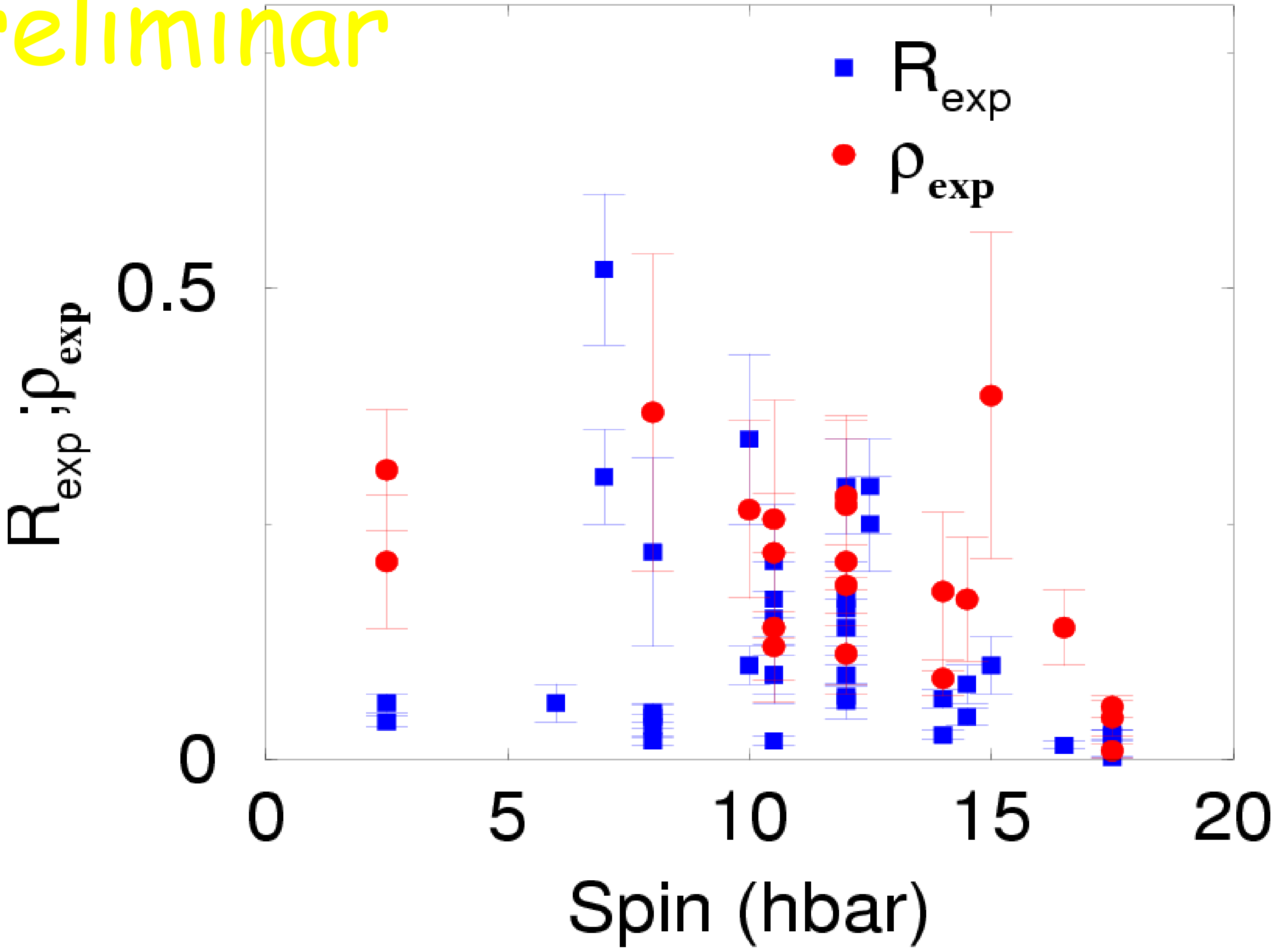
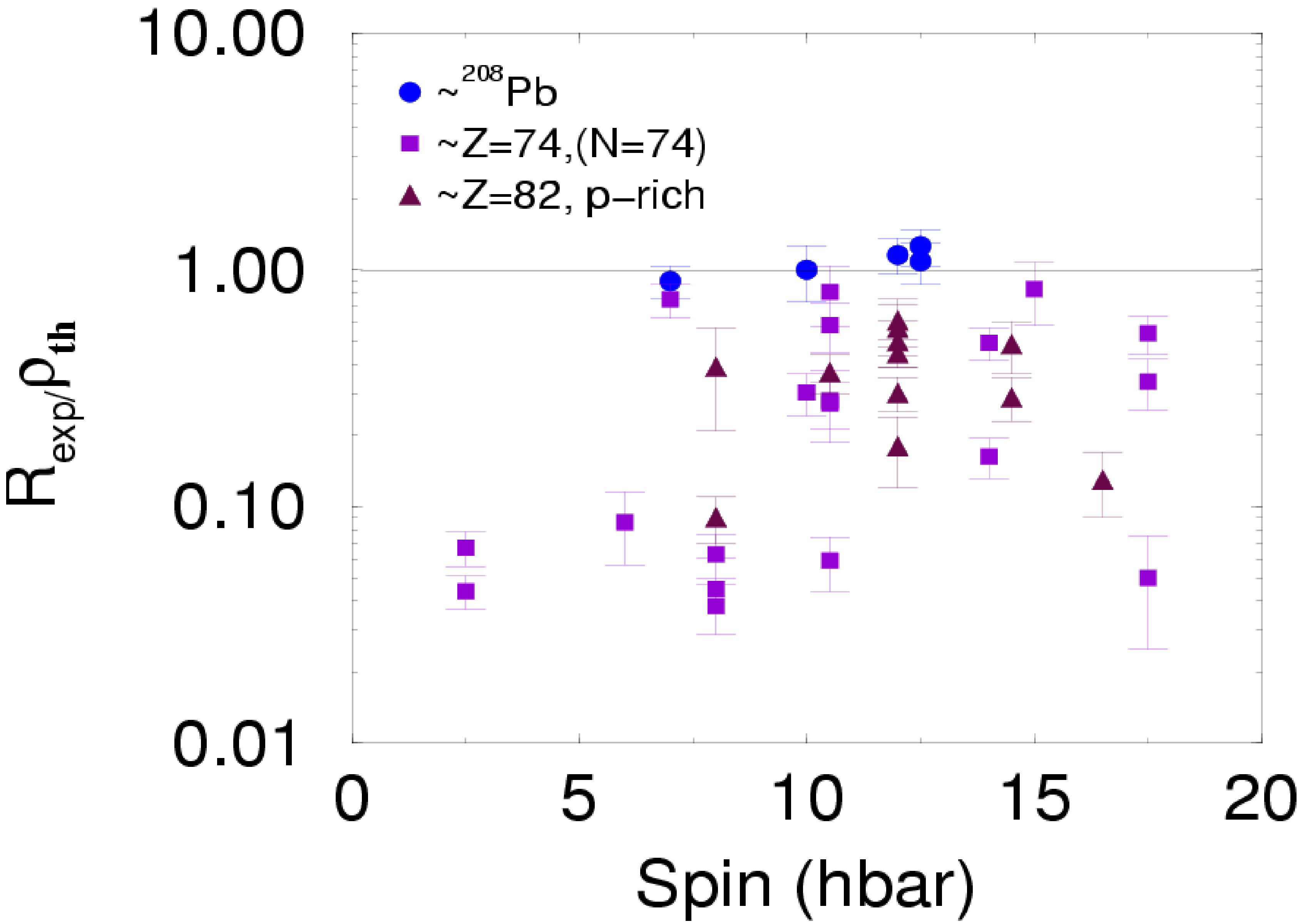
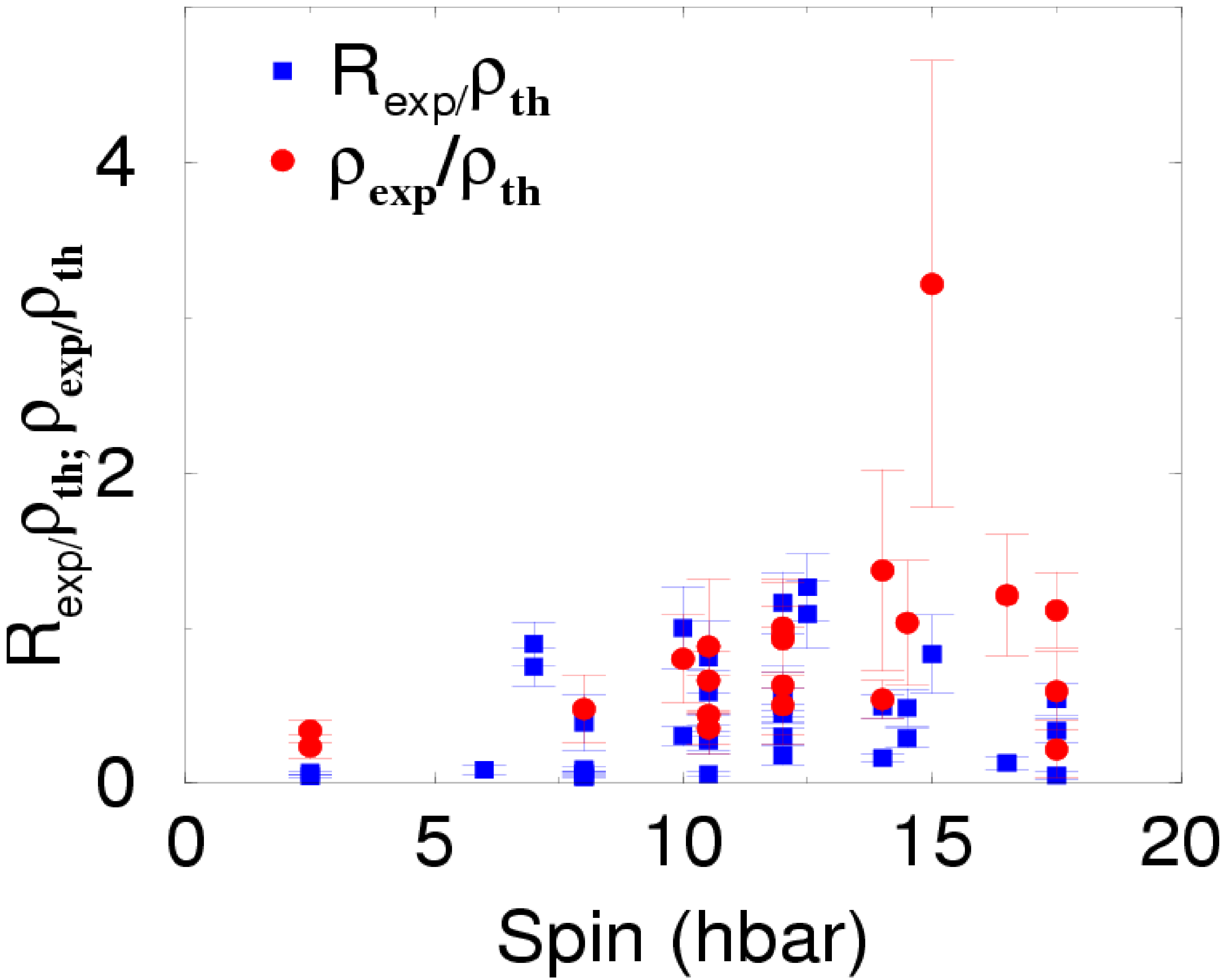
- M. Pfützner *et al.*, Phys. Lett. B444 (1998) 32.
- M. Pfützner *et al.*, Phys. Rev. C65 (2002) 064604.

preliminar
y

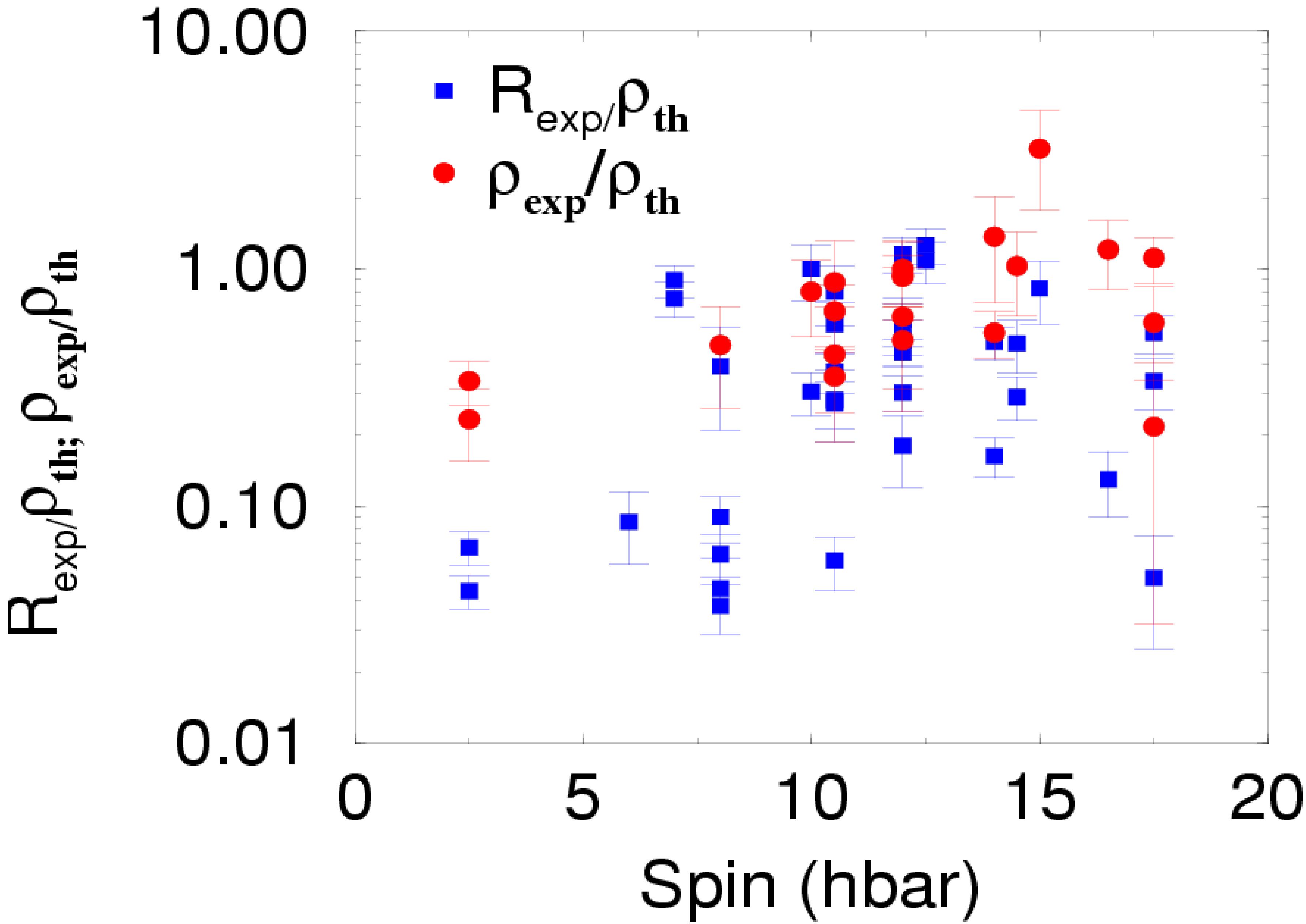




~^{208}Pb
~Z=74,(N=74)
~Z=82, p–rich
10.00
1.00
0.10
0.01
R_{exp}/ρ_{th}
0
5
10
15
20
Spin (hbar)

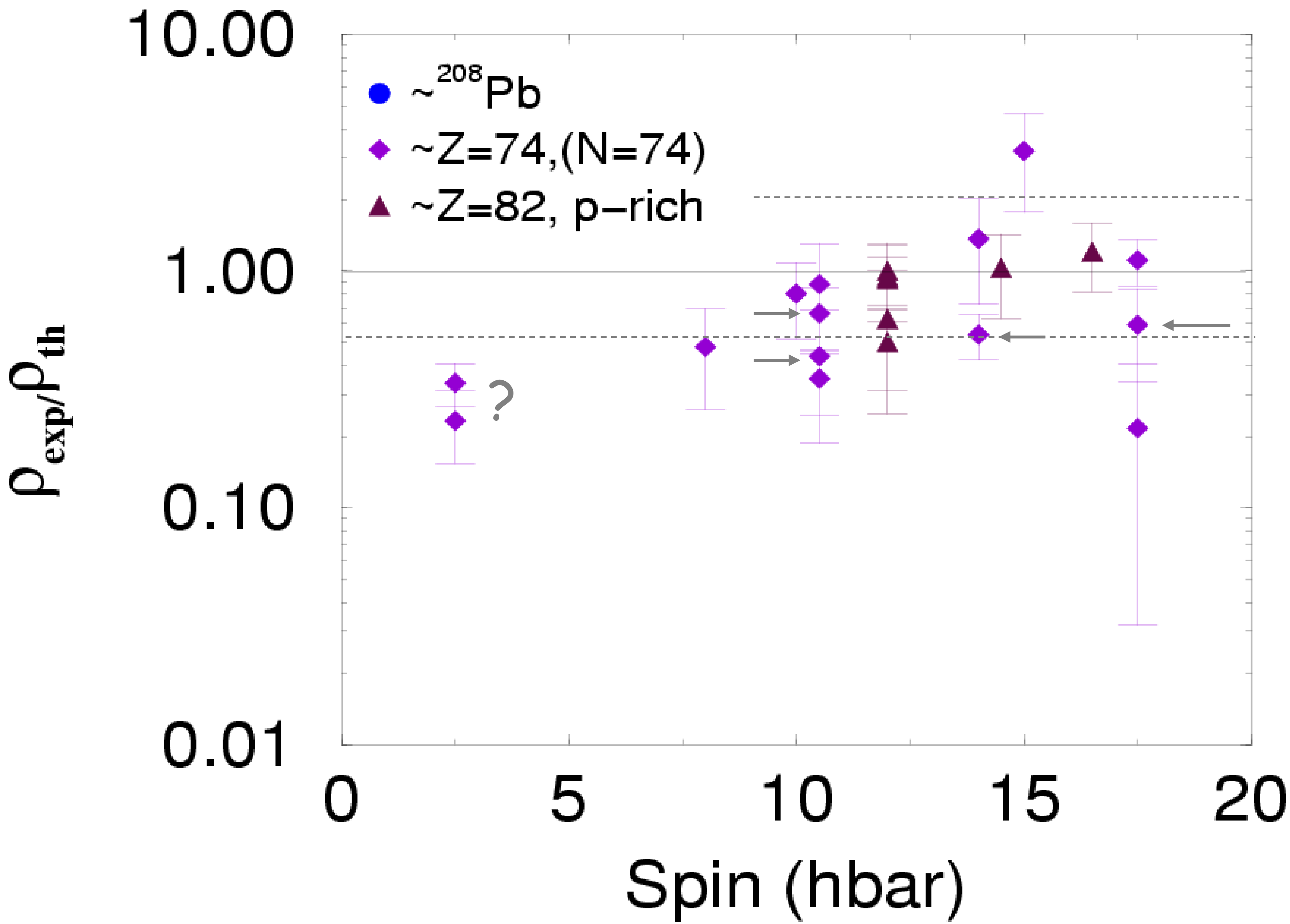


$R_{exp/}\rho_{th}$
ρ_{exp}/ρ_{th}
4
2
0
$R_{exp/}\rho_{th;}\ \rho_{exp/}\rho_{th}$
0
5
10
15
20
Spin (hbar)



R - isomeric ratio

ρ - probability of populating states



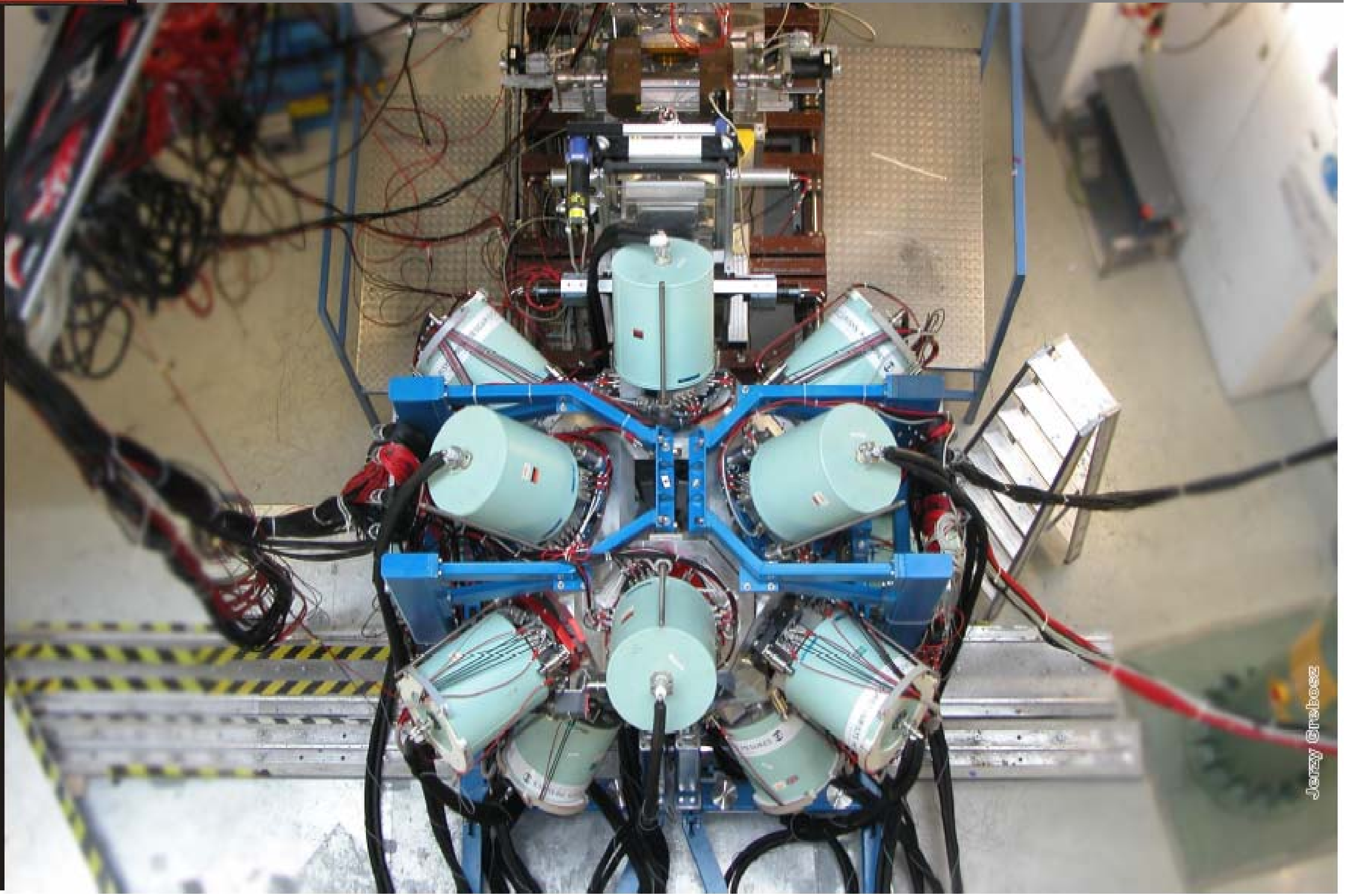
The highlighted points: higher lying isomers decay int stopped beam setup

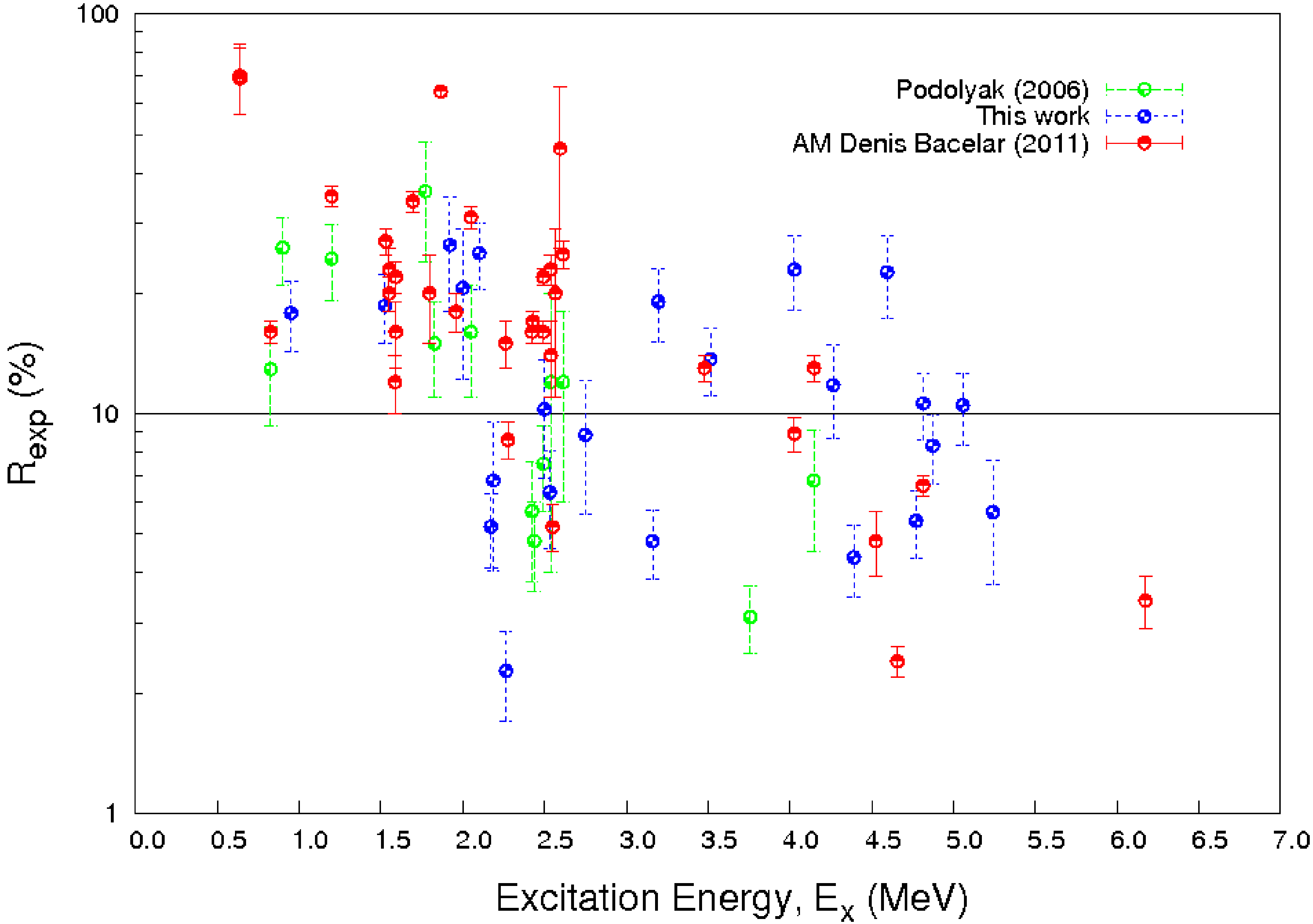
RISING

Stopped Rising Array @ GSI: 15 x 7 element CLUSTERs

ε_{γ} =11% at 1.3 MeV, 20% at 550 keV, 35% at 100 keV

flight time ~300ns



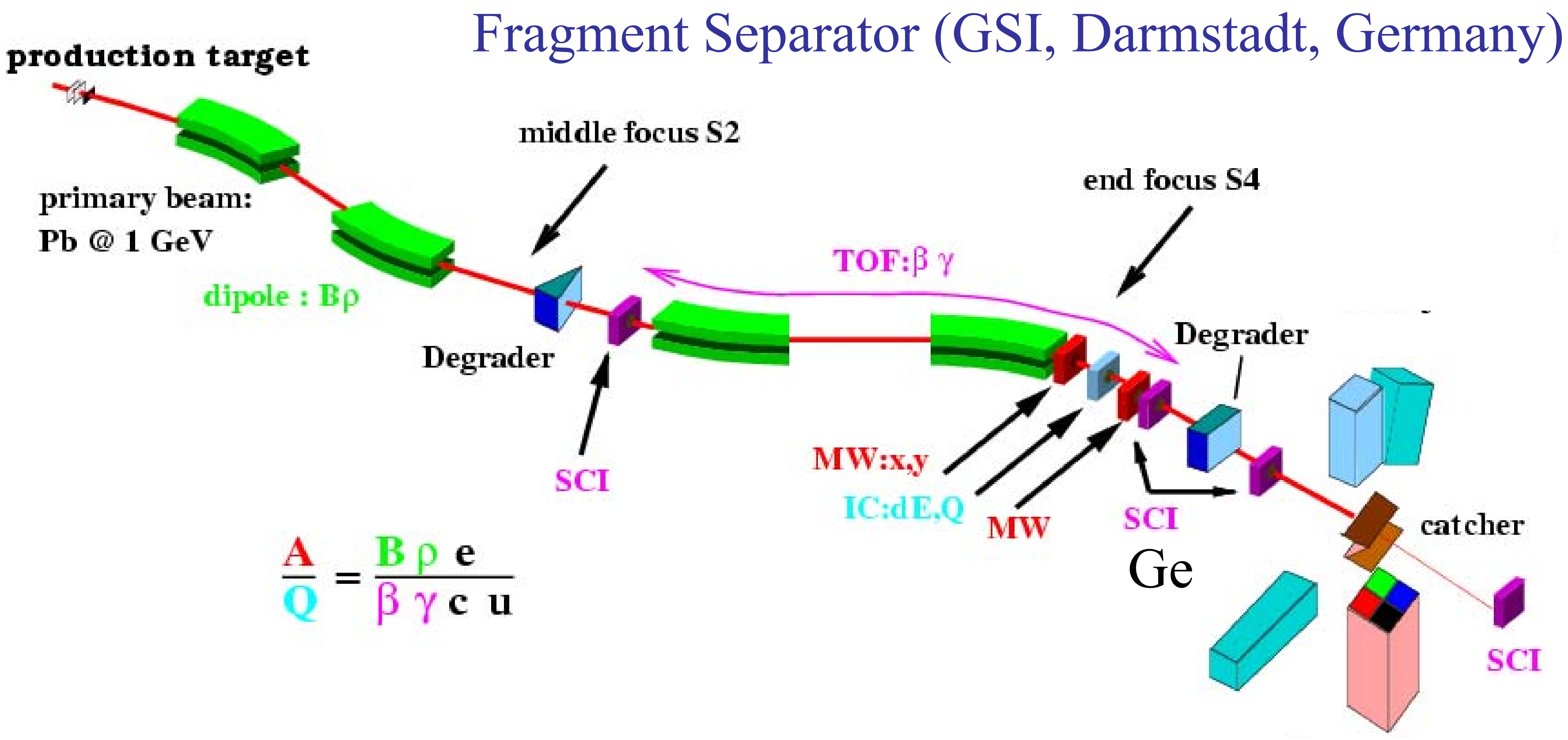


100
10
1
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
Podolyak (2006)
This work
AM Denis Bacelar (2011)
R$_{exp}$ (%)
Excitation Energy, E$_X$ (MeV)

Study [Ref]	Projectile / Energy	Target	Range, Z	Range, A	Range, I ($\hbar$)	No. Nuclei	No. IR
M. Pfützner *et al* [1]	^{238}U @ 1 GeV/A	1.0 g/cm^2 Be	81→83	203→212	7→20	10	10
M. Pfützner *et al* [2]	^{208}Pb @ 1 GeV/A	1.6 g/cm^2 Be	62→80	136→206	5/2→35/2	18	26
K.A. Gladnishki *et al* [3]	^{238}U @ 0.75 GeV/A	1.6 g/cm^2 Be	80→84	188→202	5→33/2	12	14
M. Caamaño *et al*, [4]	^{208}Pb @ 1 GeV/A	1.6 g/cm^2 Be	73→79	188→203	7→19/2	11	13
Zs. Podolyák *et al* [5, 6]	^{238}U @ 0.9 GeV/A	1.0 g/cm^2 Be	86→89	207→215	13/2→43/2	13	13
AM Denis Bacelar * [7]	^{238}U @ 1 GeV/A	2.5 g/cm^2 Be	84→89	198→215	13/2→55/2	24	50
S.J. Steer *et al* [8]	^{208}Pb @ 1 GeV/A	2.5 g/cm^2 Be	73→81	188→206	9/2→33/2	31	39
S. Myalski *et al* [9]	^{208}Pb @ 1 GeV/A	2.5 g/cm^2 Be	62→67	142→153	11/2→27	9	10
M.D. Bowry (2012) *	^{238}U @ 1 GeV/A	1.6 g/cm^2 Be	78→86	192→215	7→25	24	23
Total IR							198

[1] M. Pfützner *et al.*, Phys. Lett. B **444**, 32 (1998).
[2] M. Pfützner *et al.*, Phys. Rev. C **65**, 064604 (2002).
[3] K.A. Gladnishki *et al.*, Phys. Rev. C **69**, 024617 (2004).
[4] M. Caamaño *et al.*, Eur. Phys. J. A **23**, 201-215 (2005).
[5] Zs. Podolyák *et al.*, Phys. Lett. B **632**, 203-206 (2006).
[6] Zs. Podolyák, Private Communication.
[7] AM Denis Bacelar, PhD. Thesis (unpublished), (2011).
[8] S.J. Steer *et al.*, Phys. Rev. C **84**, 044313 (2011).
[9] S. Myalski *et al.*, Acta. Phys. Pol. B **43**, 253-259 (2012).

In flight fragmentation: separation and identification

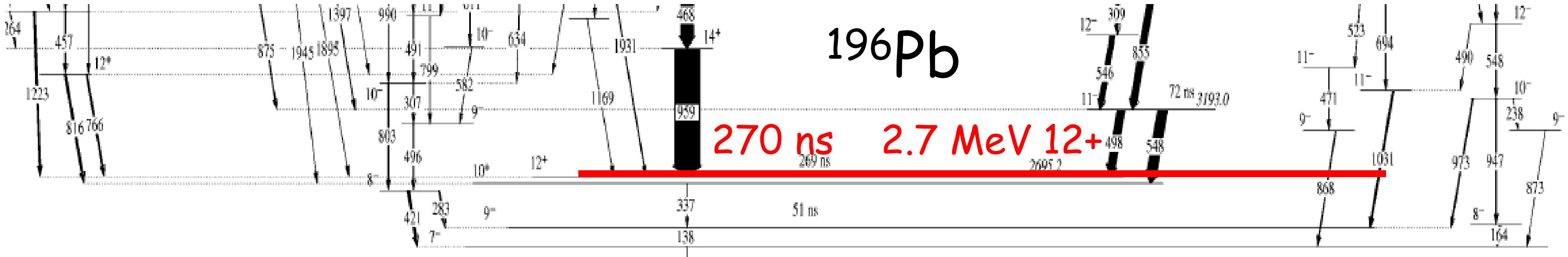


$$\frac{A}{Q} = \frac{B\rho\ e}{\beta\ \gamma\ c\ u}$$

Decay (internal and β, α) spectroscopy:

- decay out from the isomer is correlated with the fragment (100 ns – 1 ms)
- very sensitive (ion beams > 1 ion/hour)

Nuclear structure has to be considered



^{196}Pb: A.K.Singh *et al.*, Nucl. Phys. A707 (2002) 3

$^{186}W(^{16}O,6n)$ at 110 MeV; $^{170}Er(^{30}Si,4n)$ at 144 Me

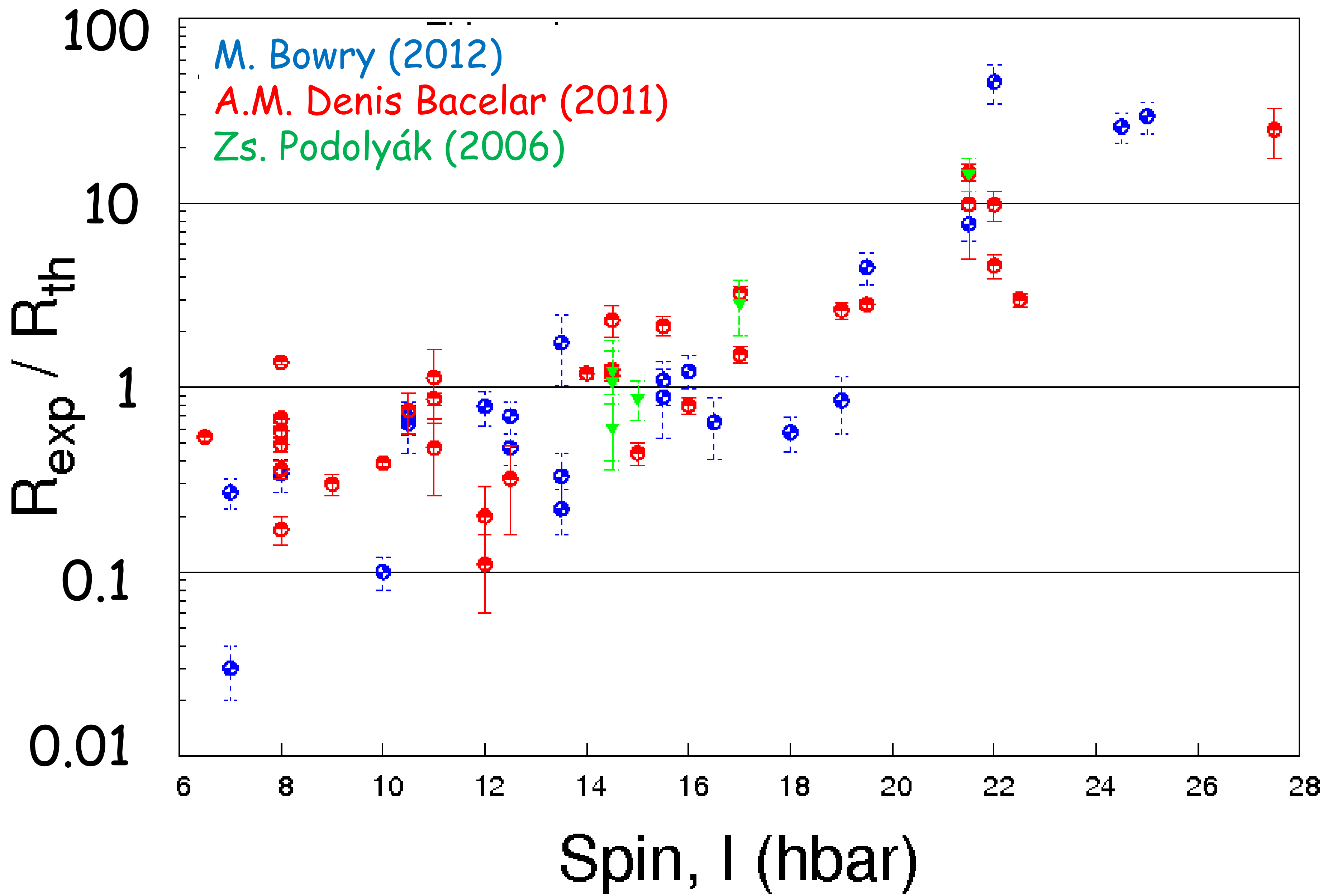
fusion-evaporation reaction!

$\varphi = I_{isomer}/(I_{parallel}+I_{isomer}) = I_{isomer}/I_{total}$

$\rho_{exp} = R_{exp}/\varphi$

ρ_{exp} - the probability of populating states with higher spin than the isomer - can be compared with t

Comparison with theory (sharp cut-off approx.)

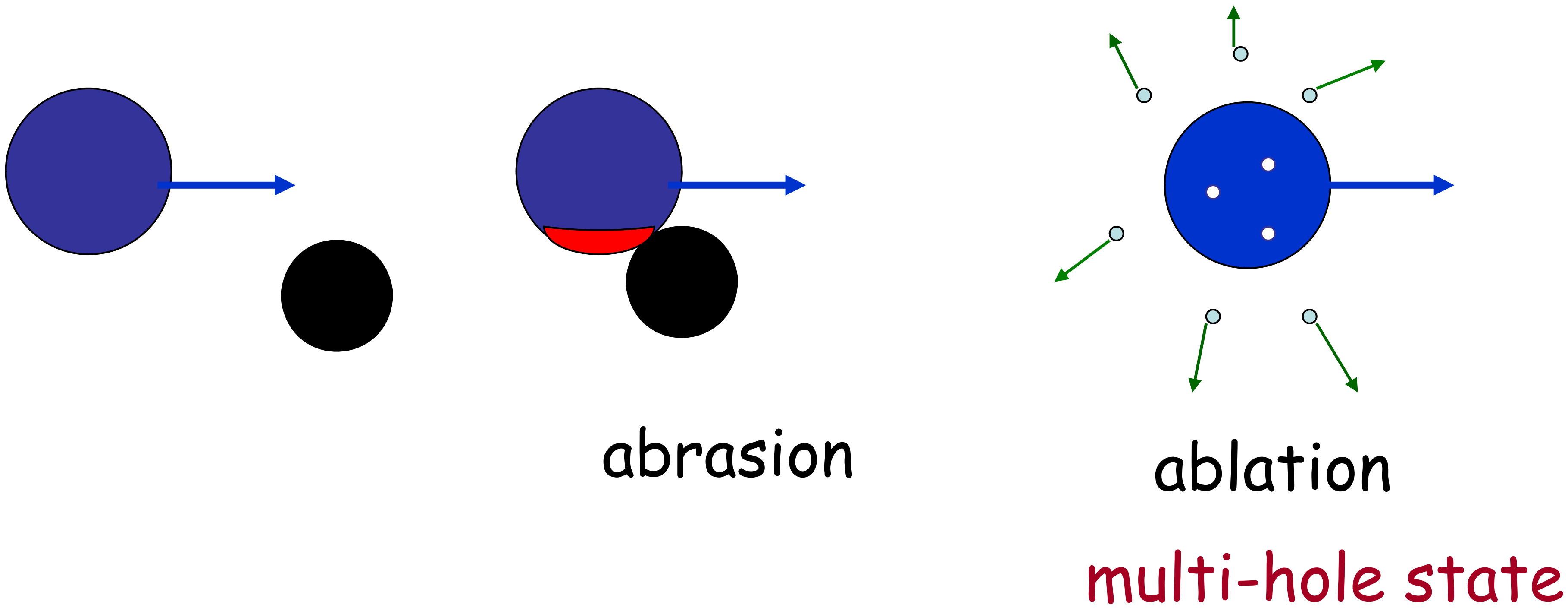


Isomeric beams: population of high-spin states in projectile fragmentation

Zsolt Podolyák

University of Surrey

Fragmentation/spallation is (one of the) main source(s) of radioactive beams/exotic nuclei



Fragmentation reaction at relativistic energies

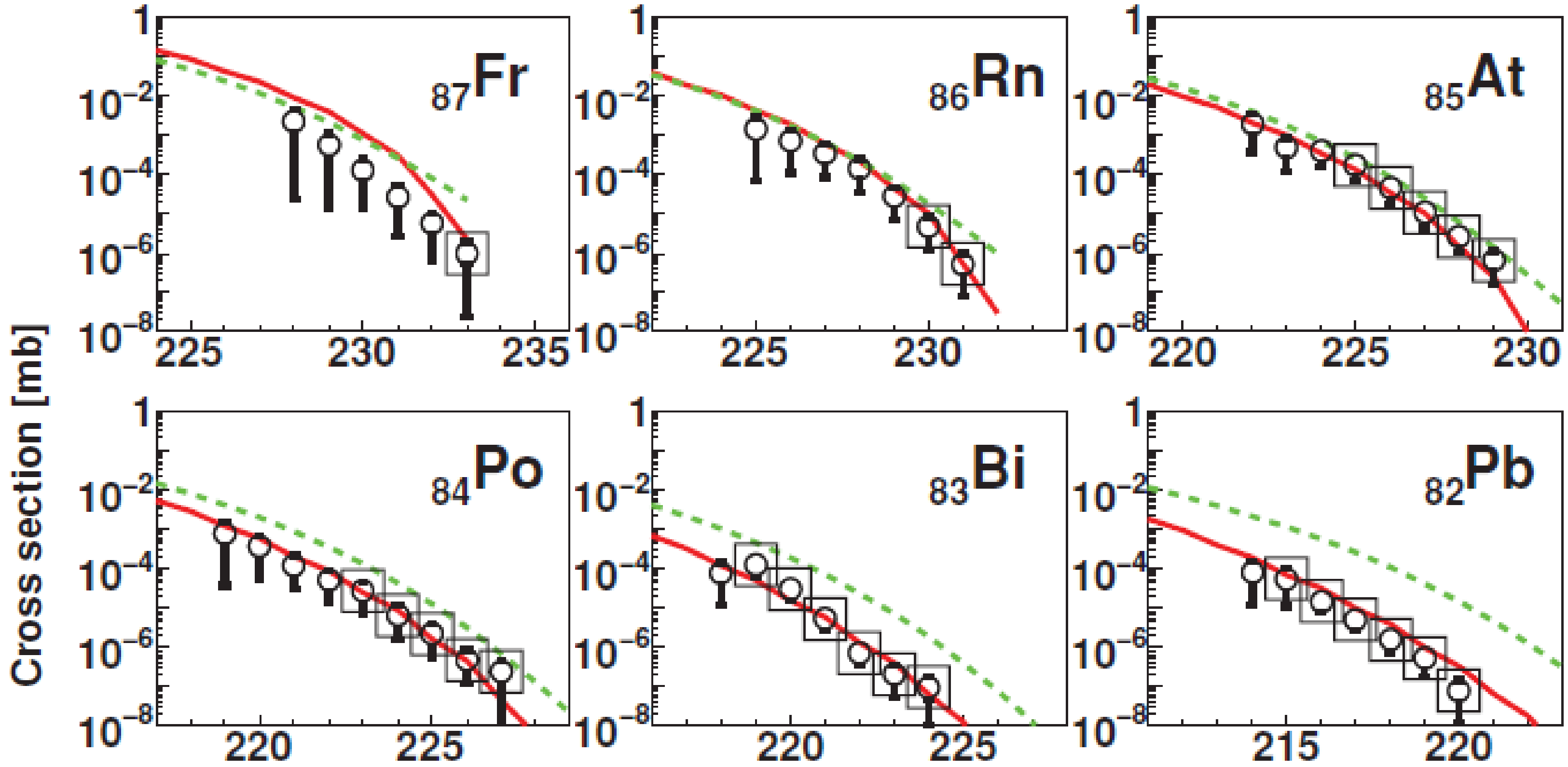
How to study fragmentation?

Cross section: measures the end product

What would give information about abrasion?

<u>Angular</u> (and linear) momentum

↘ from isomers

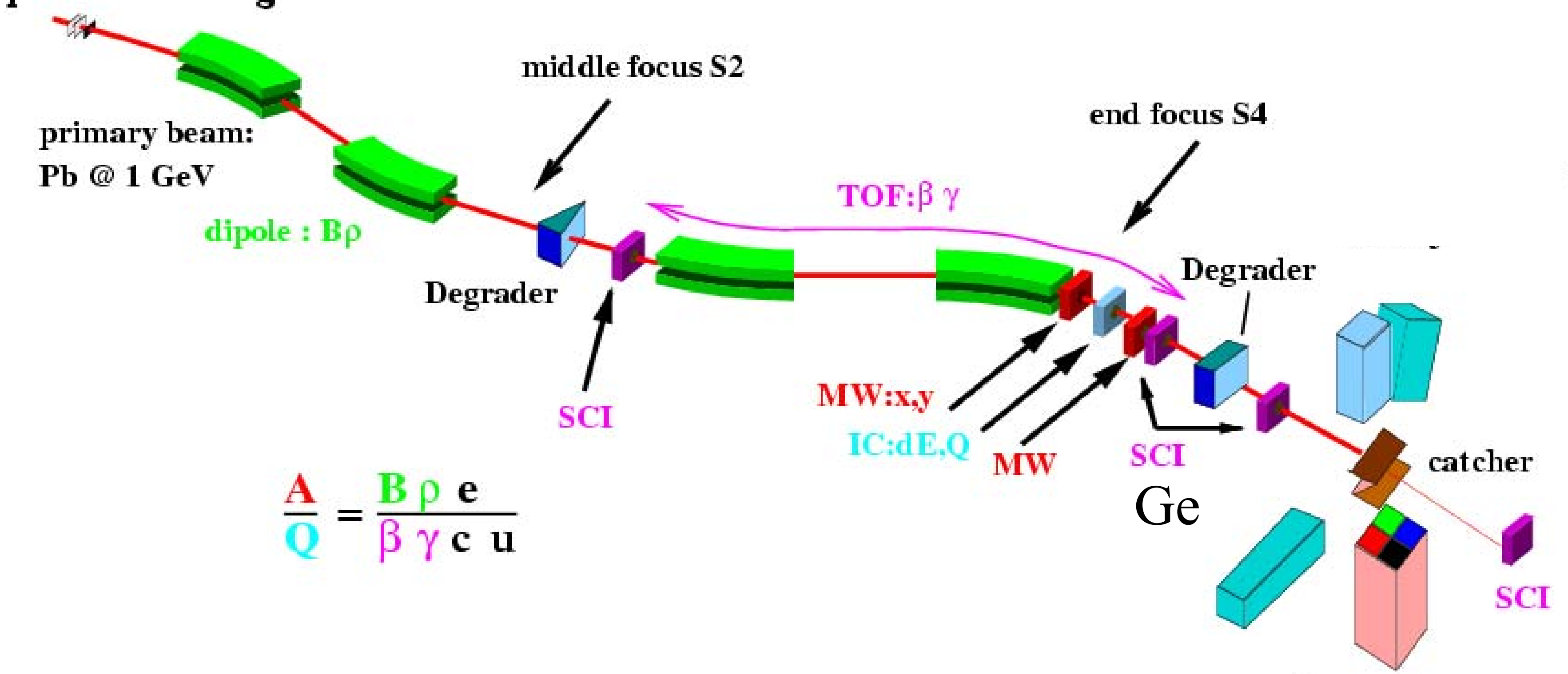


EPAX ABRABLA/COFRA

H. Alvarez-Pol et al., Phys. Rev. C 82, 041602(R) (2110)

In flight fragmentation: separation and identification

Fragment Separator (GSI, Darmstadt, Germany)

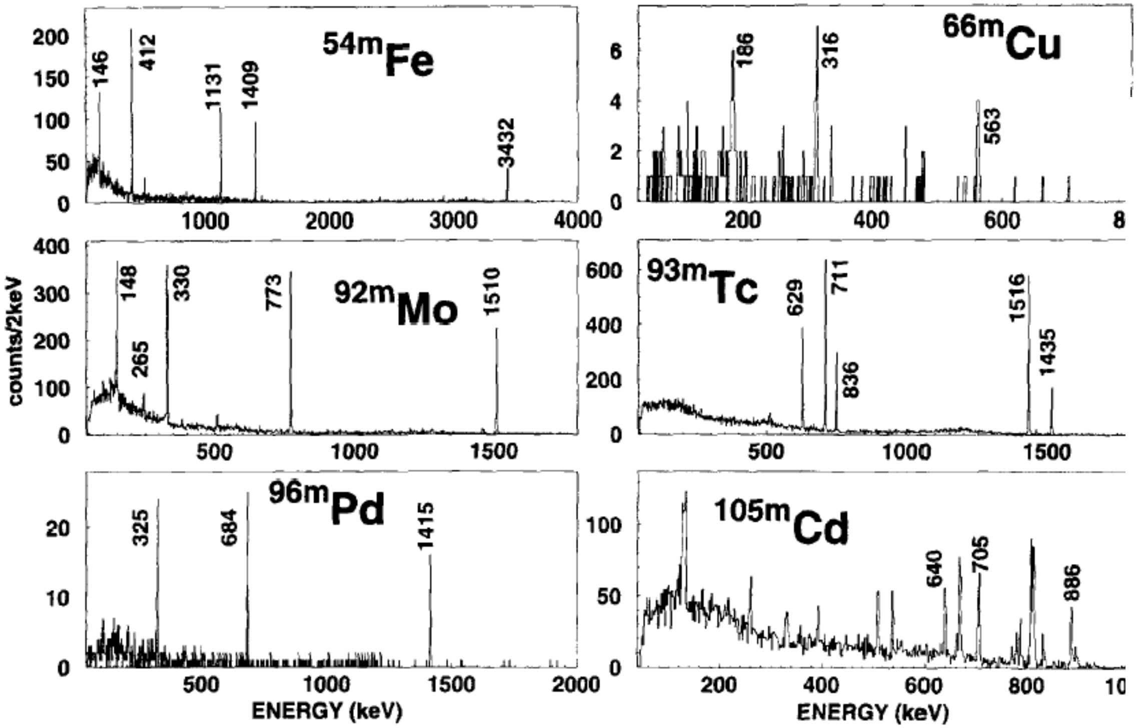


$$\frac{A}{Q} = \frac{B\rho\, e}{\beta\gamma c\, u}$$

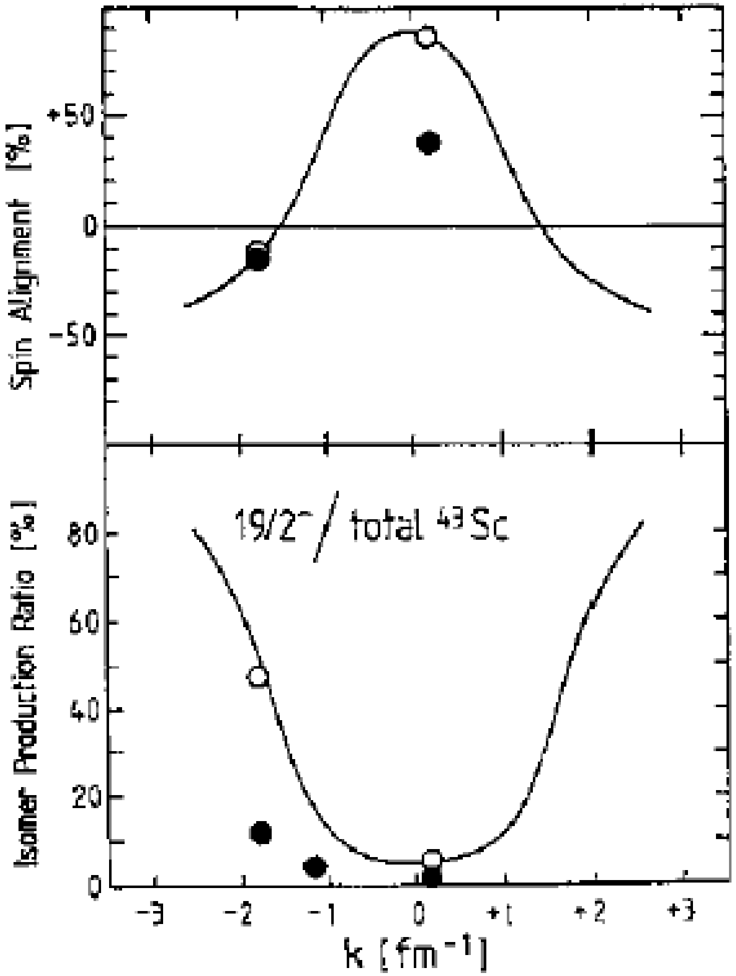
Decay (internal and β, α) spectroscopy:

- decay out from the isomer is correlated with the fragment (100 ns – 1 ms)
- very sensitive (ion beams > 1 ion/hour)

Isomers are special

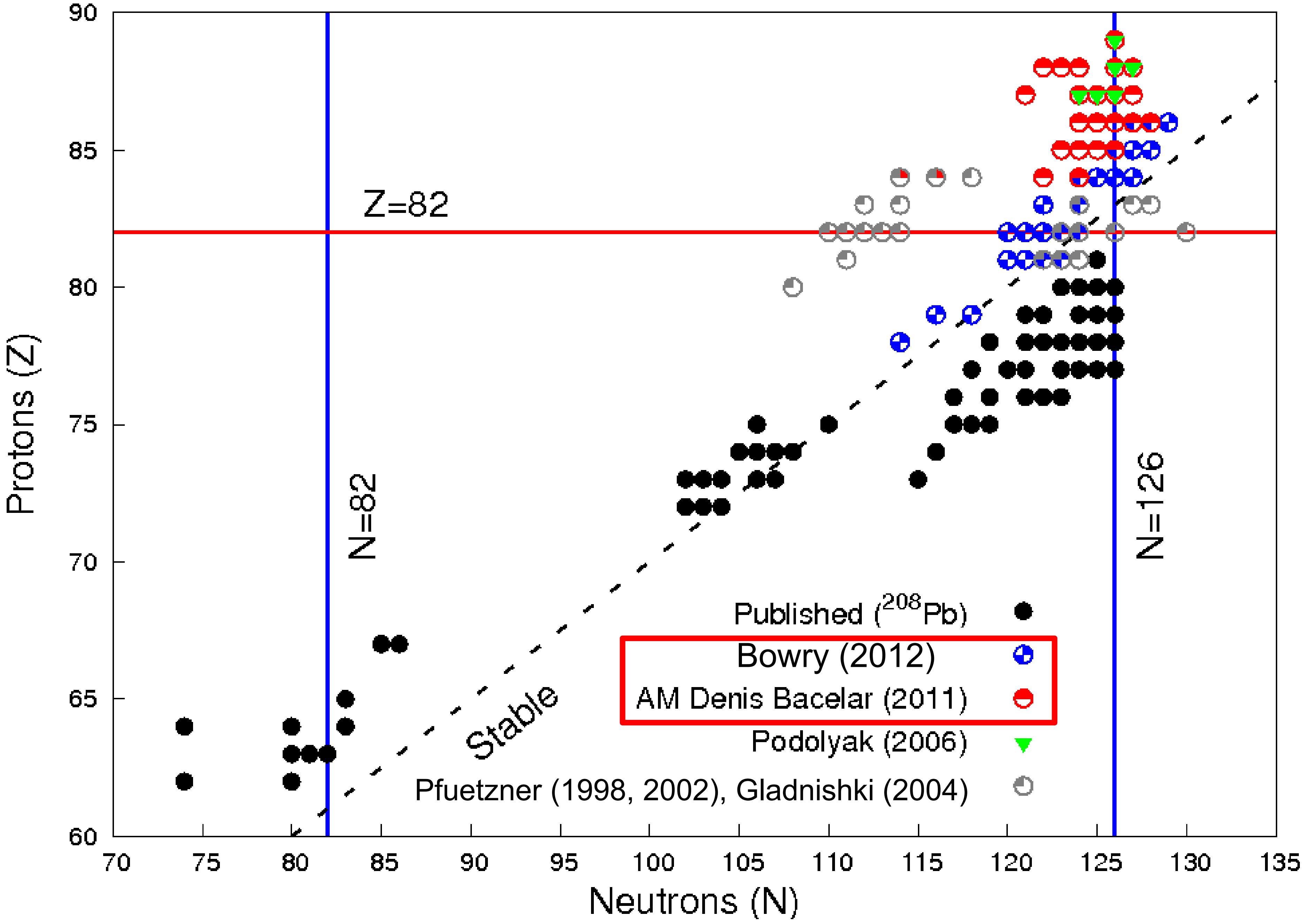


R. Grzywacz et al., Phys. Lett. B 355 (1995) 439.

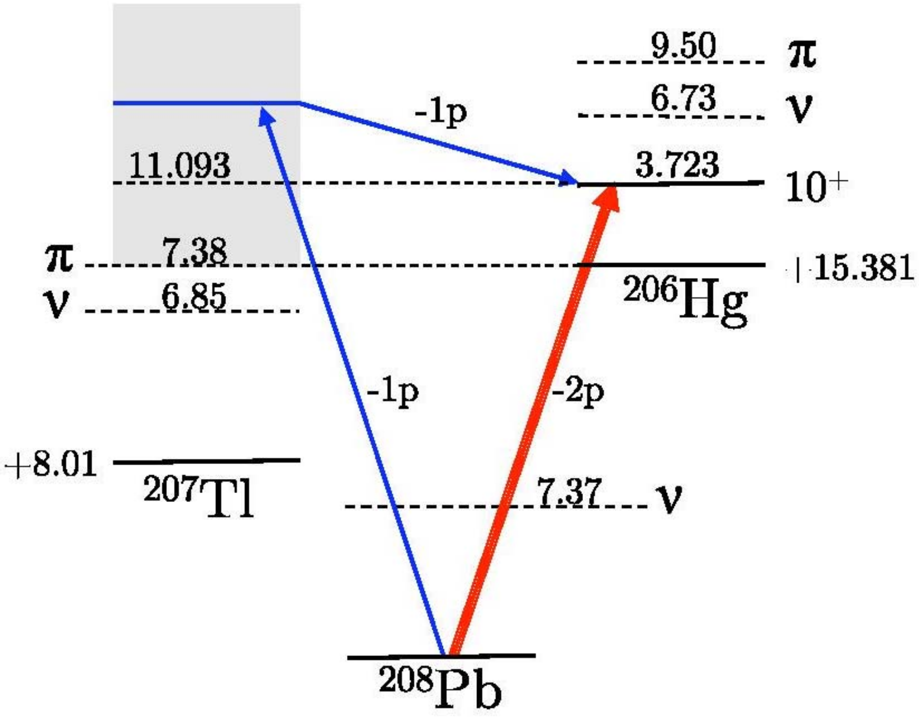


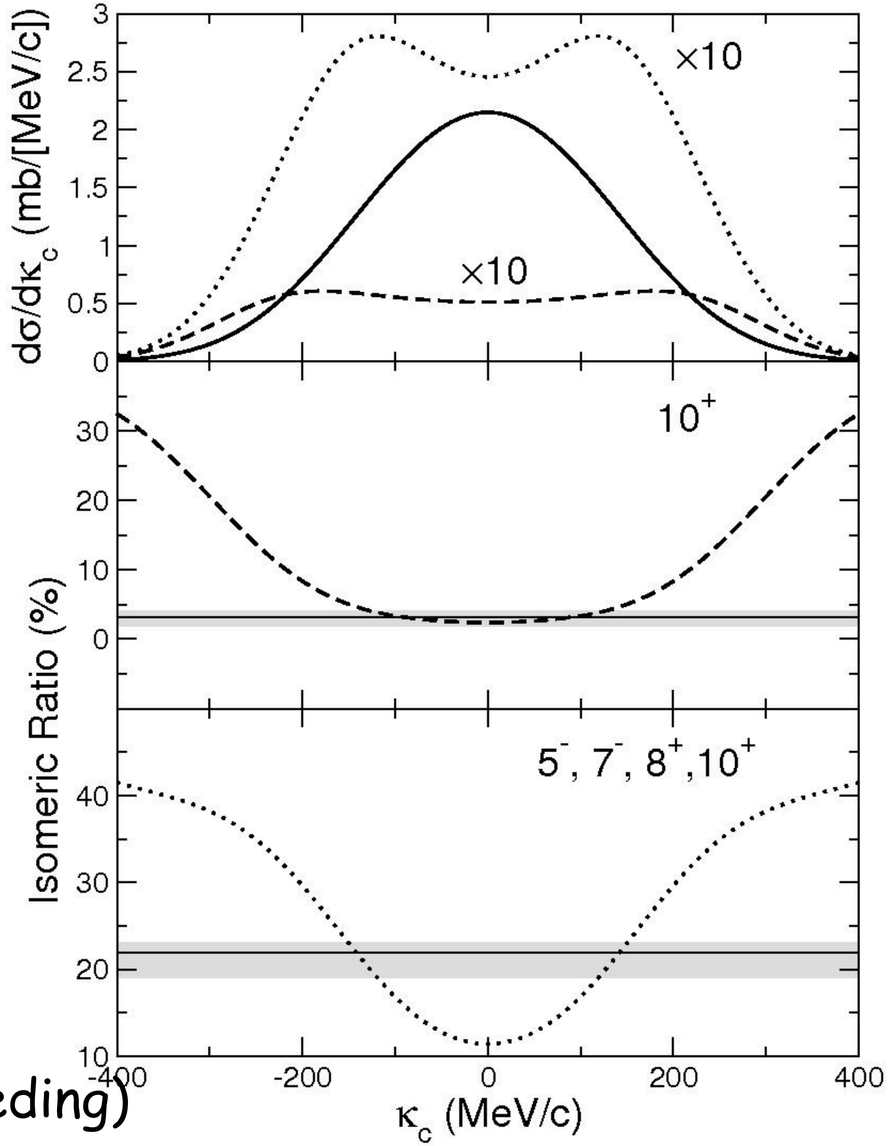
W.-D. Schmidt-Ott et al., Z. Phys. A 350 (1994) 215.

Isomeric ratios from ^{208}Pb and ^{238}U fragmentation



Population of isomers by two-proton knockout reaction in ^{206}Hg





Isomeric ratios		fig.
Exp.	Theory	——— Total
3(1)%	4.7	- - - - 10+
22(+1-2)%	18.8	········· 5- (with feeding)

E.Simpson *et al.*, Phys. Rev. C 80 (2009) 064608.

Abrasion-ablasion model
(ABRABLA code)

Excitation energy

~27 MeV/abrated nucleon=

=2 x single particle (holes) energy

Ablated nuclei/abraded nuclei ~2

Good cross sections

Angular momentum

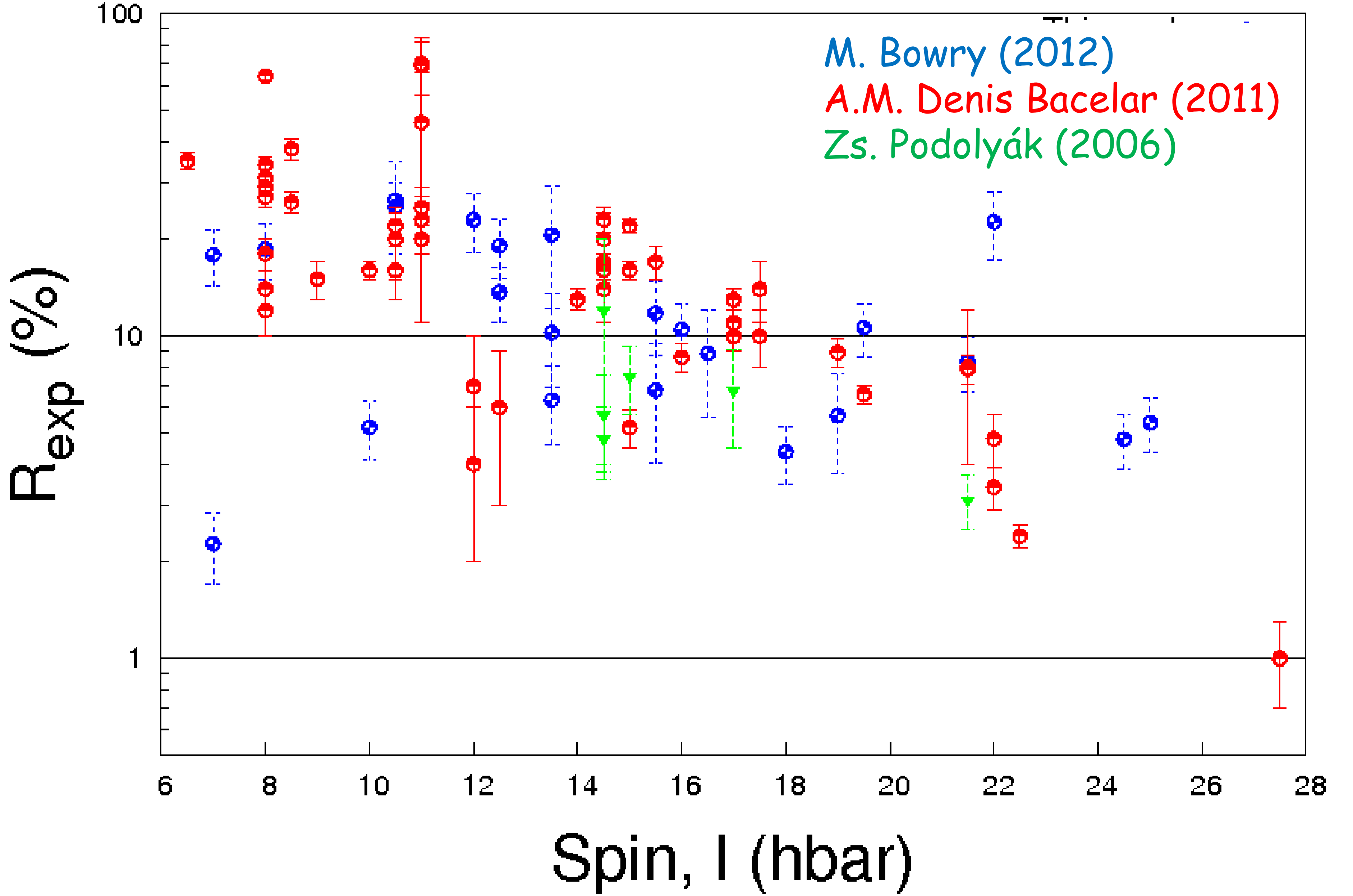
from single particle

states only

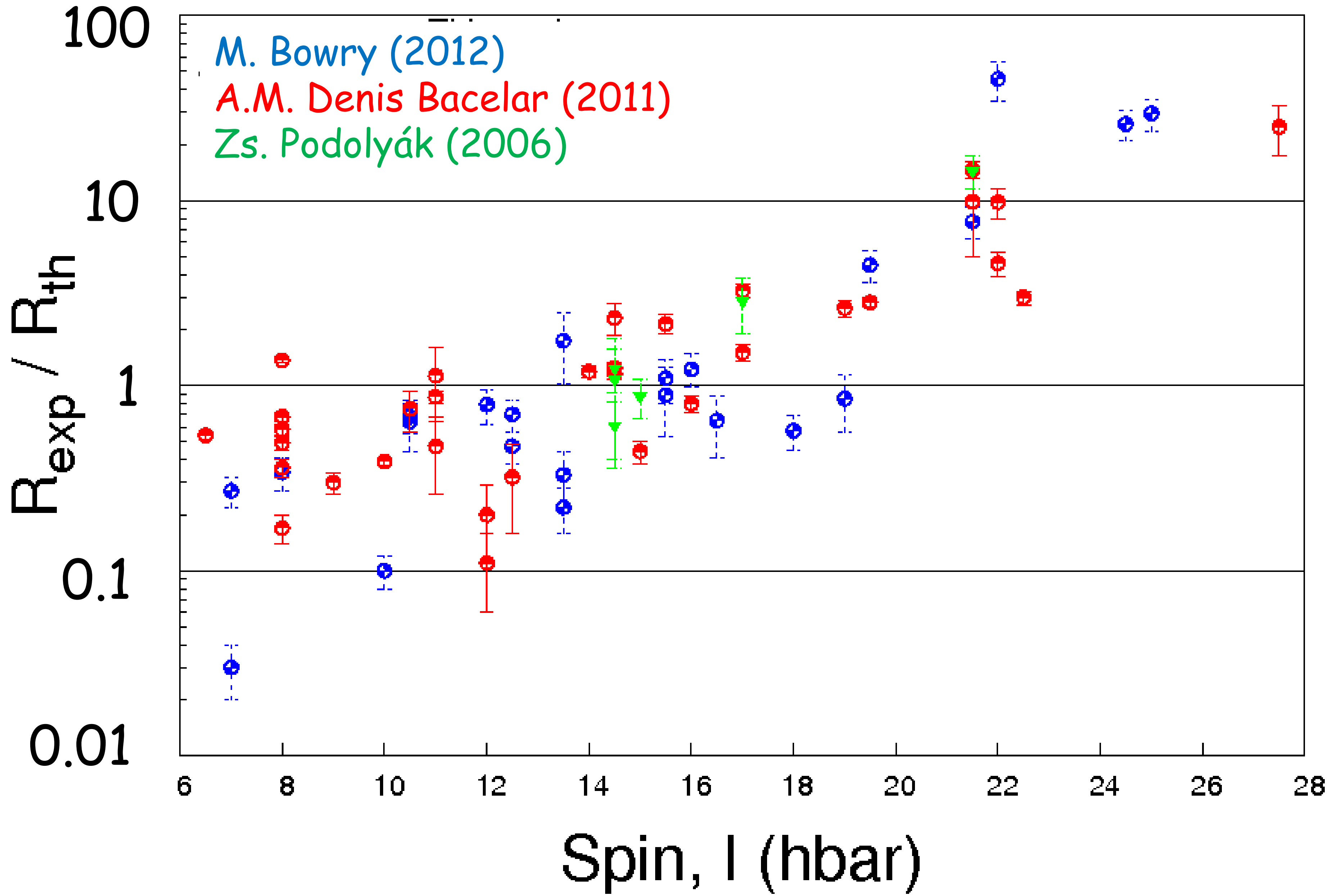
Is this good enough?

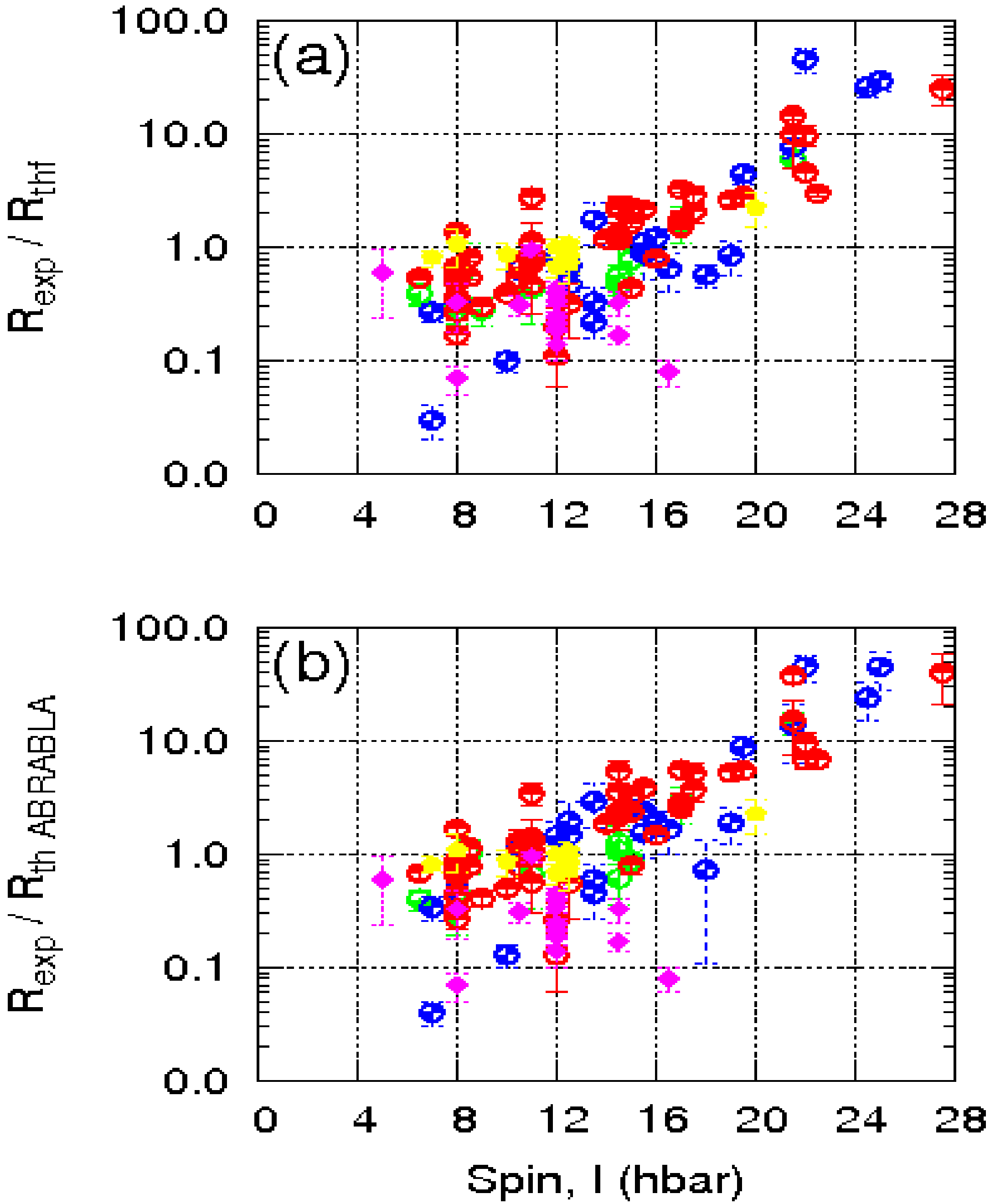
M. De Jong, A.V. Ignatyuk and K.-H. Schmidt, Nucl. Phys. A 613 (1997) 435

238U fragmentation (A~200-210)



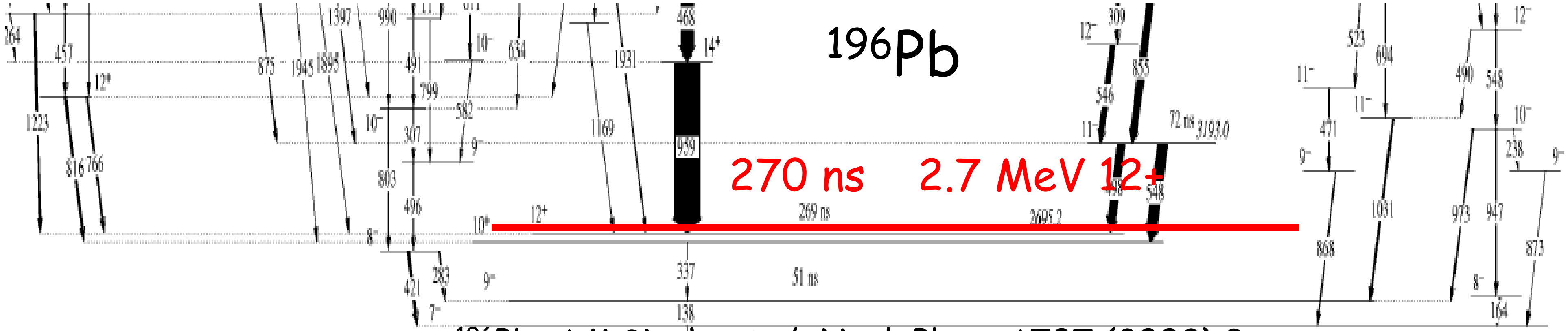
Comparison with theory (sharp cut-off approx.)





(a)
R_{exp} / R_{thf}
100.0
10.0
1.0
0.1
0.0
0
4
8
12
16
20
24
28
(b)
R_{exp} / $R_{th\ ABRABLA}$
100.0
10.0
1.0
0.1
0.0
0
4
8
12
16
20
24
28
Spin, I (hbar)

Nuclear structure has to be considered



^{196}Pb: A.K.Singh *et al.*, Nucl. Phys. A707 (2002) 3

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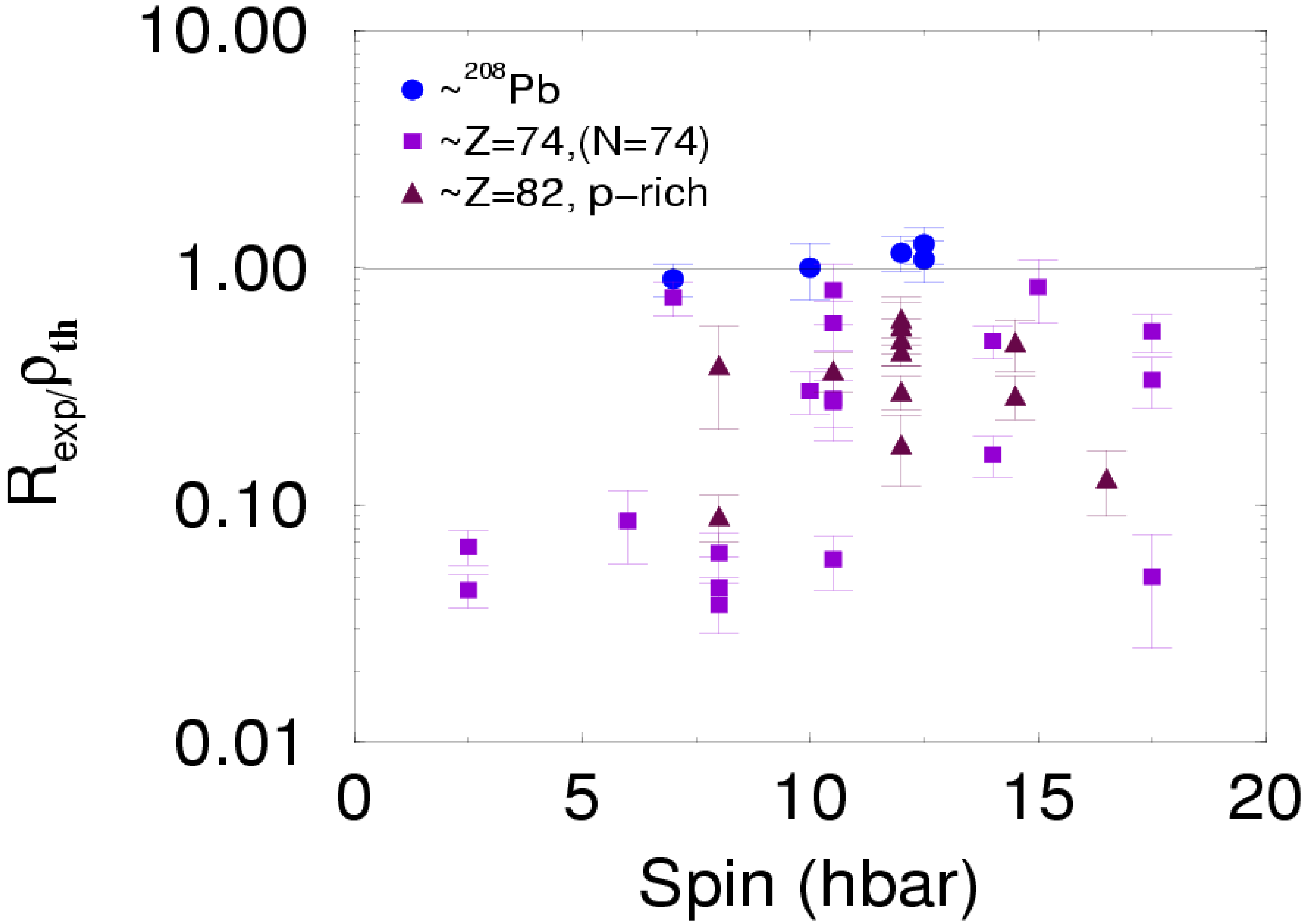
fusion-evaporation reaction!

$$\varphi = I_{isomer}/(I_{parallel}+I_{isomer}) = I_{isomer} / I_{total}$$

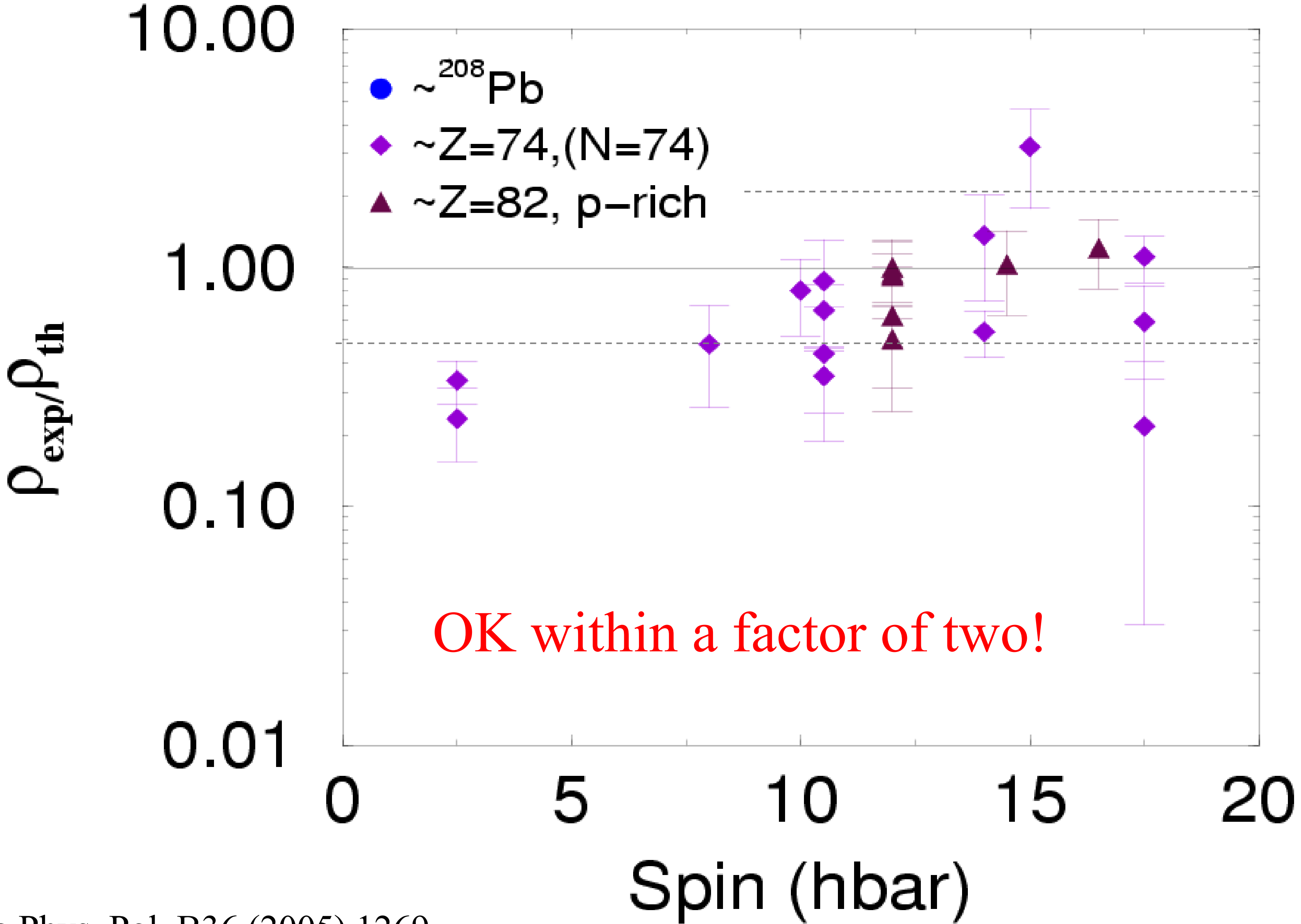
$$\rho_{exp}=R_{exp}/\varphi$$

ρ_{exp} - the probability of populating states with higher spin than the isomer – can be compared with theory!

Without structure considerations

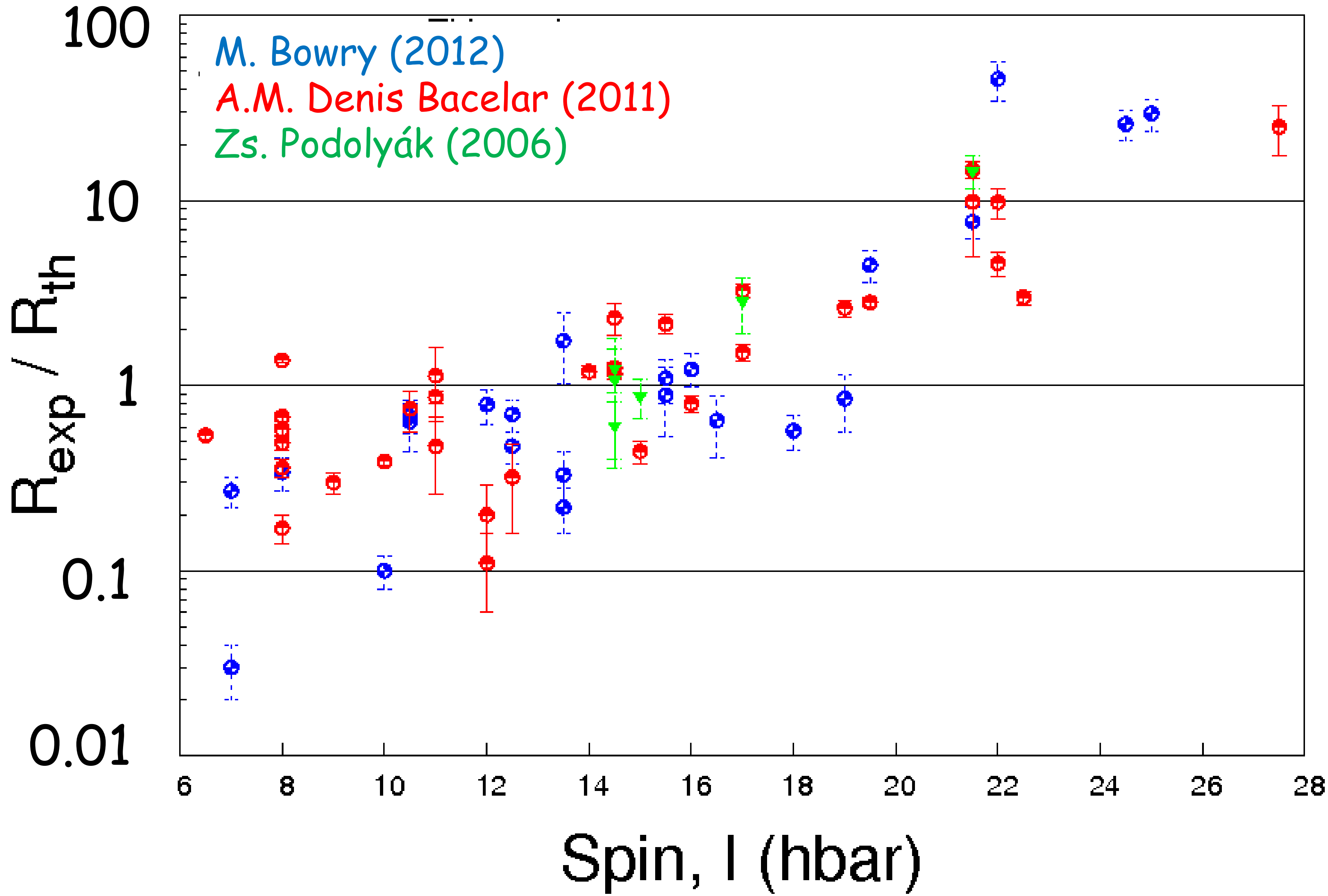


With structure considerations

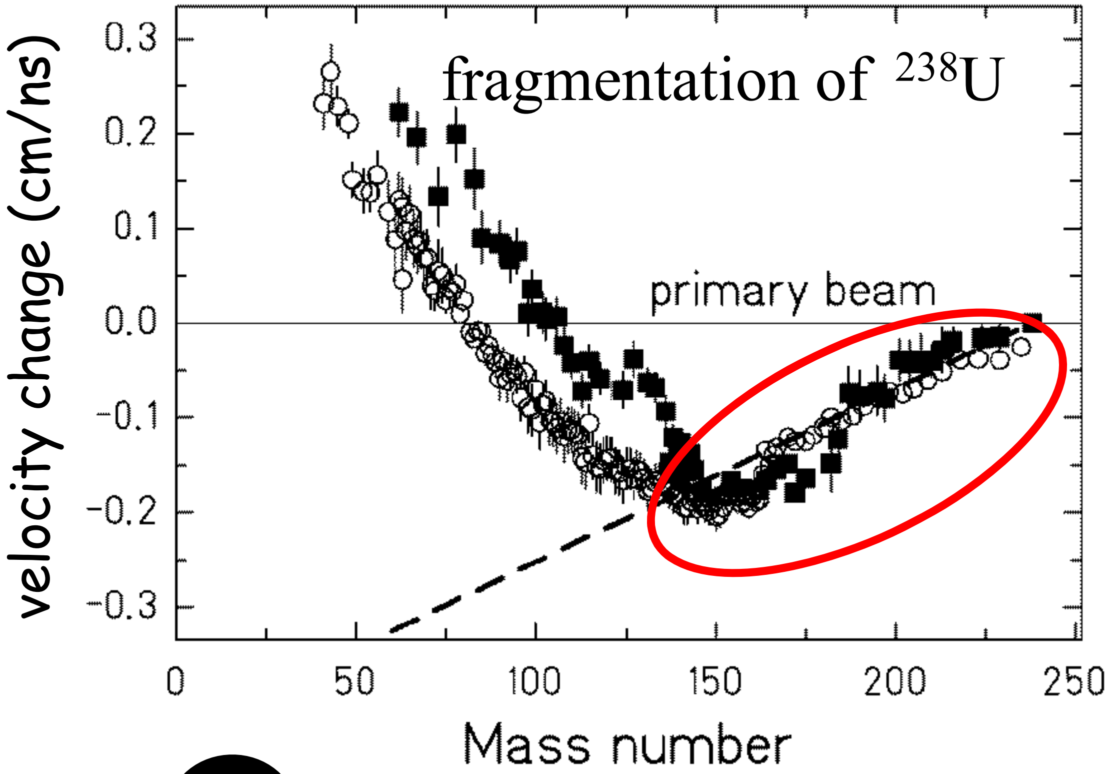


Zs. P. , Acta Phys. Pol. B36 (2005) 1269

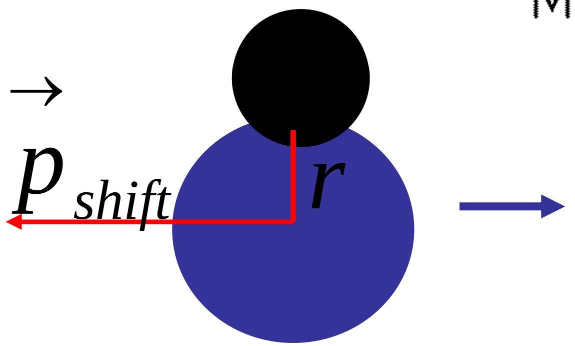
Comparison with theory (sharp cut-off approx.)



Fragments are slower than projectile: momentum shift (friction)



M.V. Ricciardi et al., PRL 90 (2003) 212302

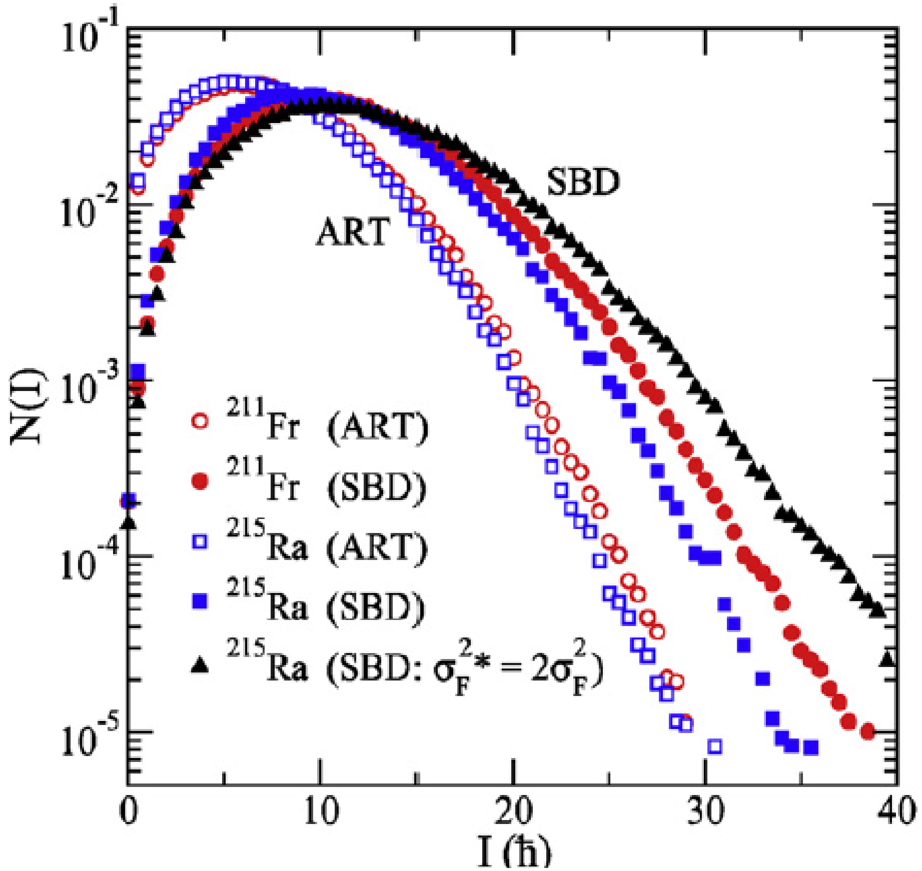


$$\vec{I} = \vec{r} \times \vec{p}_{shift}$$

⇨ angular momentum produced

(collective)

I perpendicular to the beam



Abrasion (incl. friction)

(relativistic transport model)

Abrasion+ablation

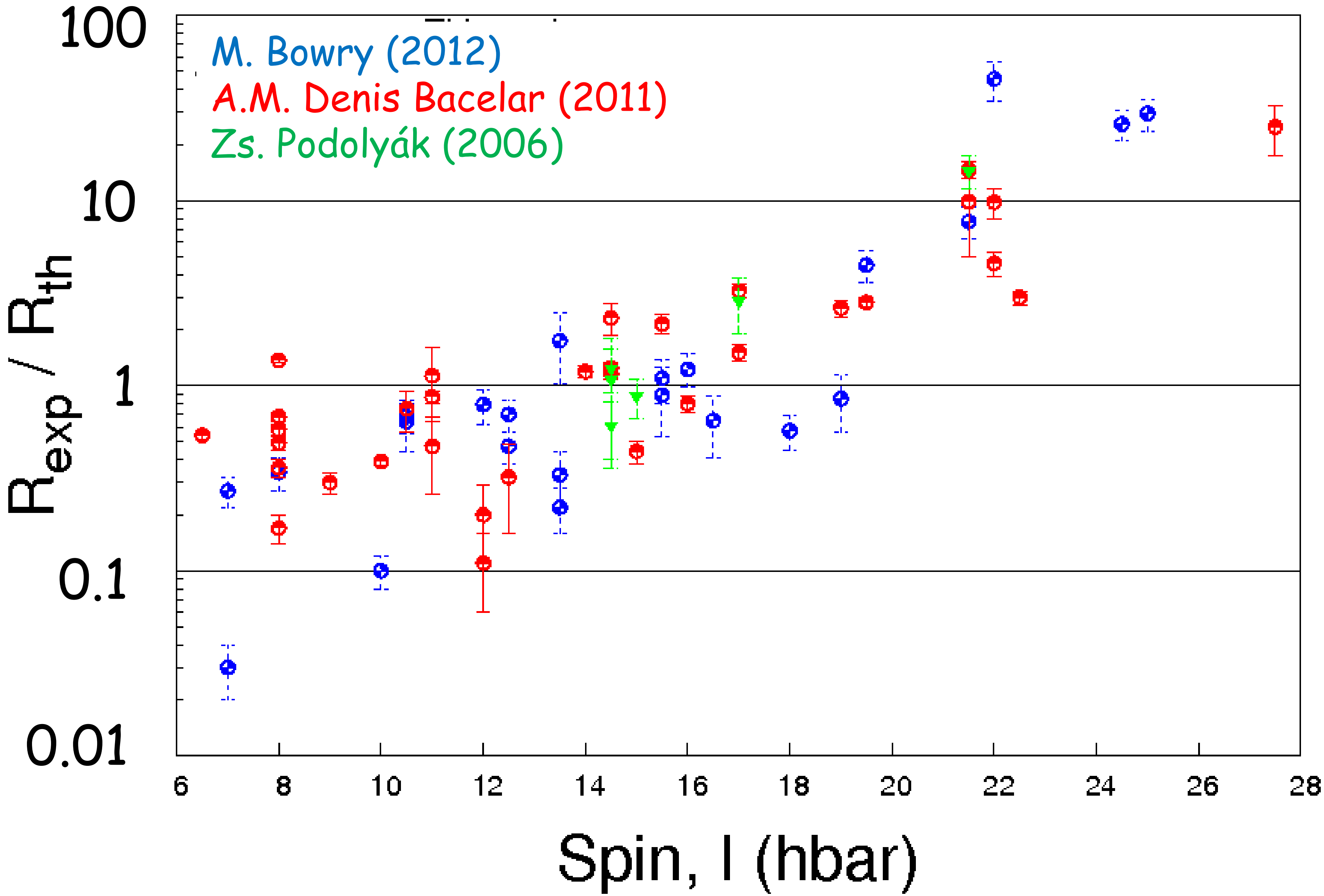
(+sequential binary decay)

Ion	I^π	E (keV)	R_{exp} [%]	R_{the}^{ART} [%]	R_{the}^{SBD} [%]
^{211}Fr	$29/2^+$	2423	5.7(19)	2.59	10.03
^{212}Fr	15^-	2492	7.5(18)	2.24	9.15
^{213}Fr	$29/2^+$	2538	12(8)	2.65	10.82
^{214}Ra	17^-	4147	6.8(23)	0.58	3.20
^{215}Ra	$43/2^-$	$3757 + \Delta$	3.1(6)	0.07	0.82

Better agreement

S. Pal and R. Palit, Phys. Lett. B 665 (2008) 164.

Comparison with theory (sharp cut-off approx.)



Abrasion-ablation model

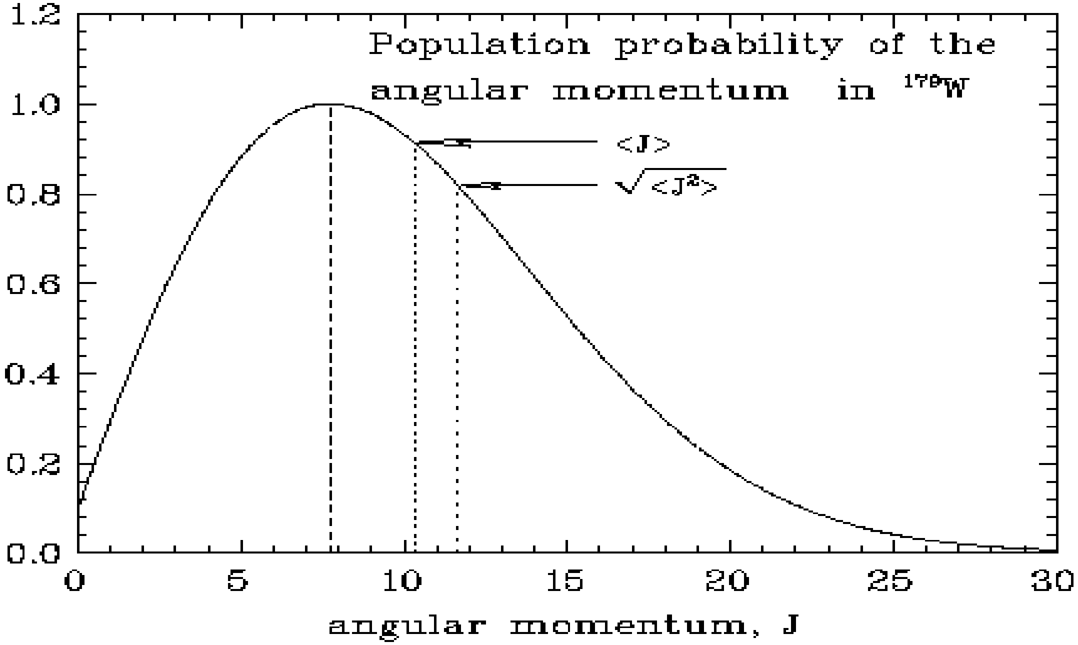
Distribution of the angular momentum in a fragmentation process

$$P(J) = \frac{2J+1}{2\sigma_f^2} exp\left(-\frac{J(J+1)}{2\sigma_f^2}\right)$$

$$\sigma_f^2 = 0.16 A_p^{2/3} \frac{(A_p - A_f)(\bar{k}A_p + A_f)}{(\bar{k}+1)^2(A_p-1)} \quad (1\text{-}2\beta/3)$$

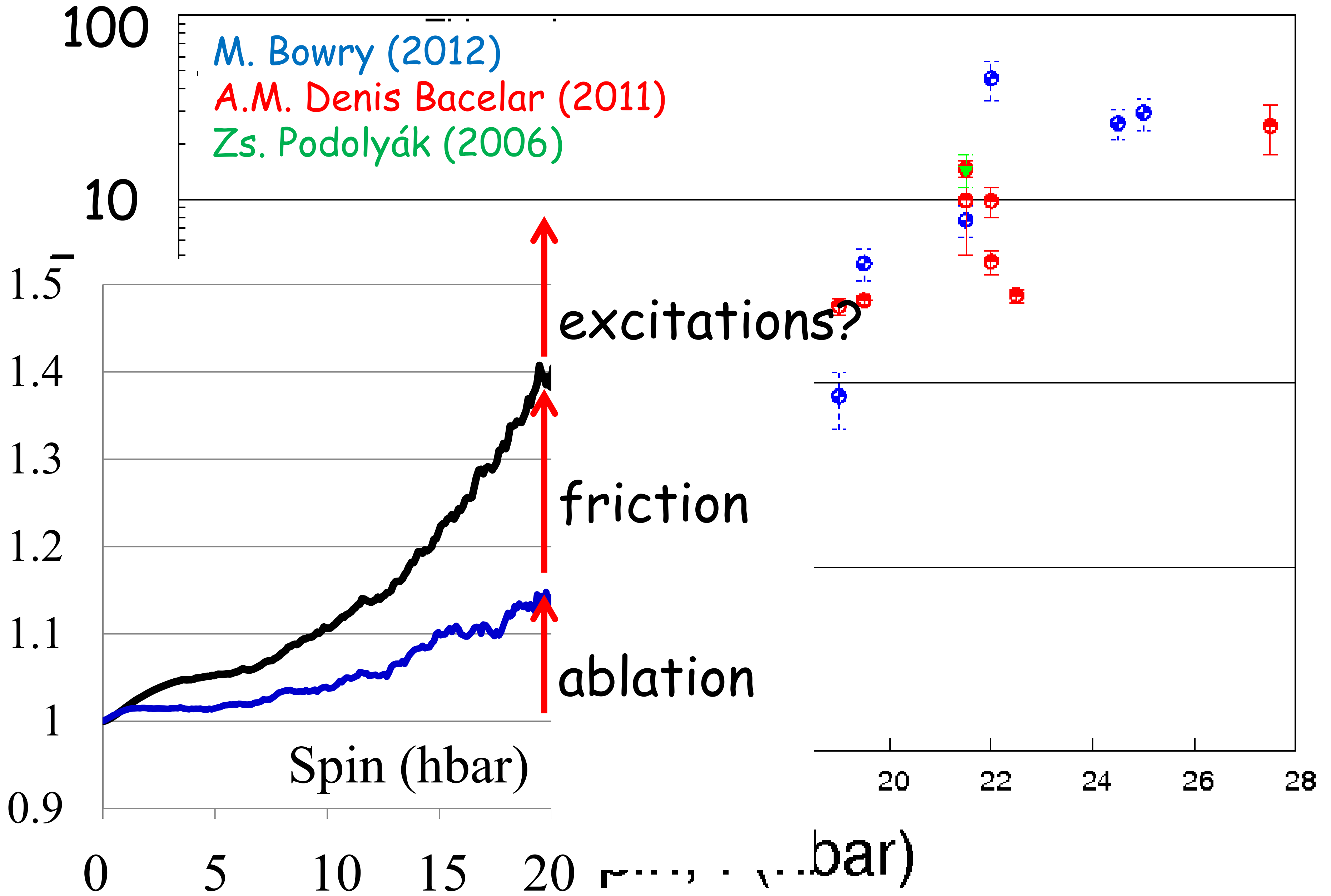
k = 2 ΔA>10

De Jong, Ignatyuk, Schmidt, NP A613 (1997) 435.



"sharp cut-off" approximation: $R_{th} = \int_{J_m}^{\infty} P(J)dJ = \exp[\frac{J_m(J_m+1)}{2\sigma_f^2}]$

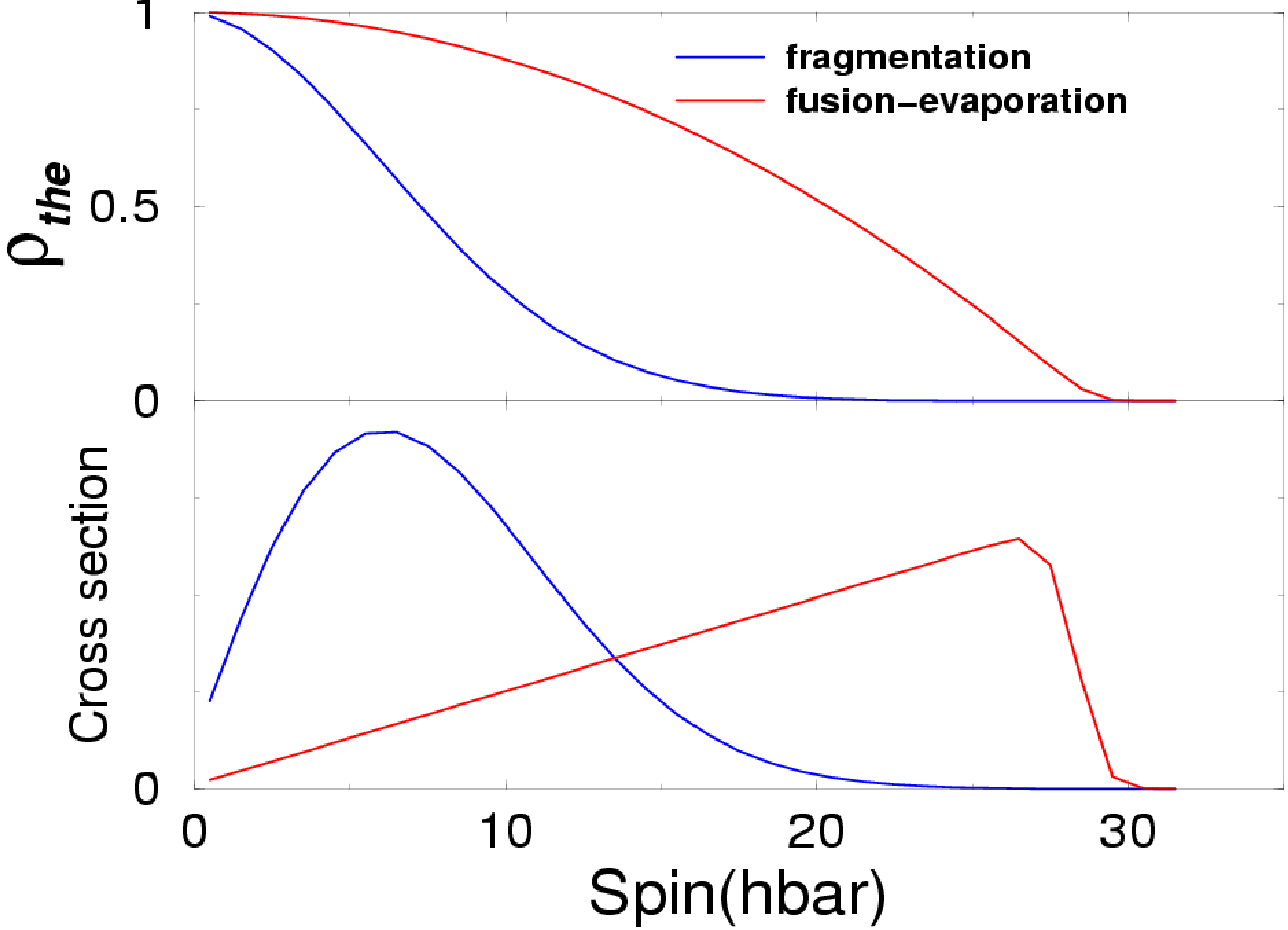
Comparison with theory (sharp cut-off approx.)



^{179}W populated in:

fragmentation of ^{208}Pb at 1 GeV/u

fusion evaporation: $^{170}Er(^{13}C,4n)$ at 67 MeV

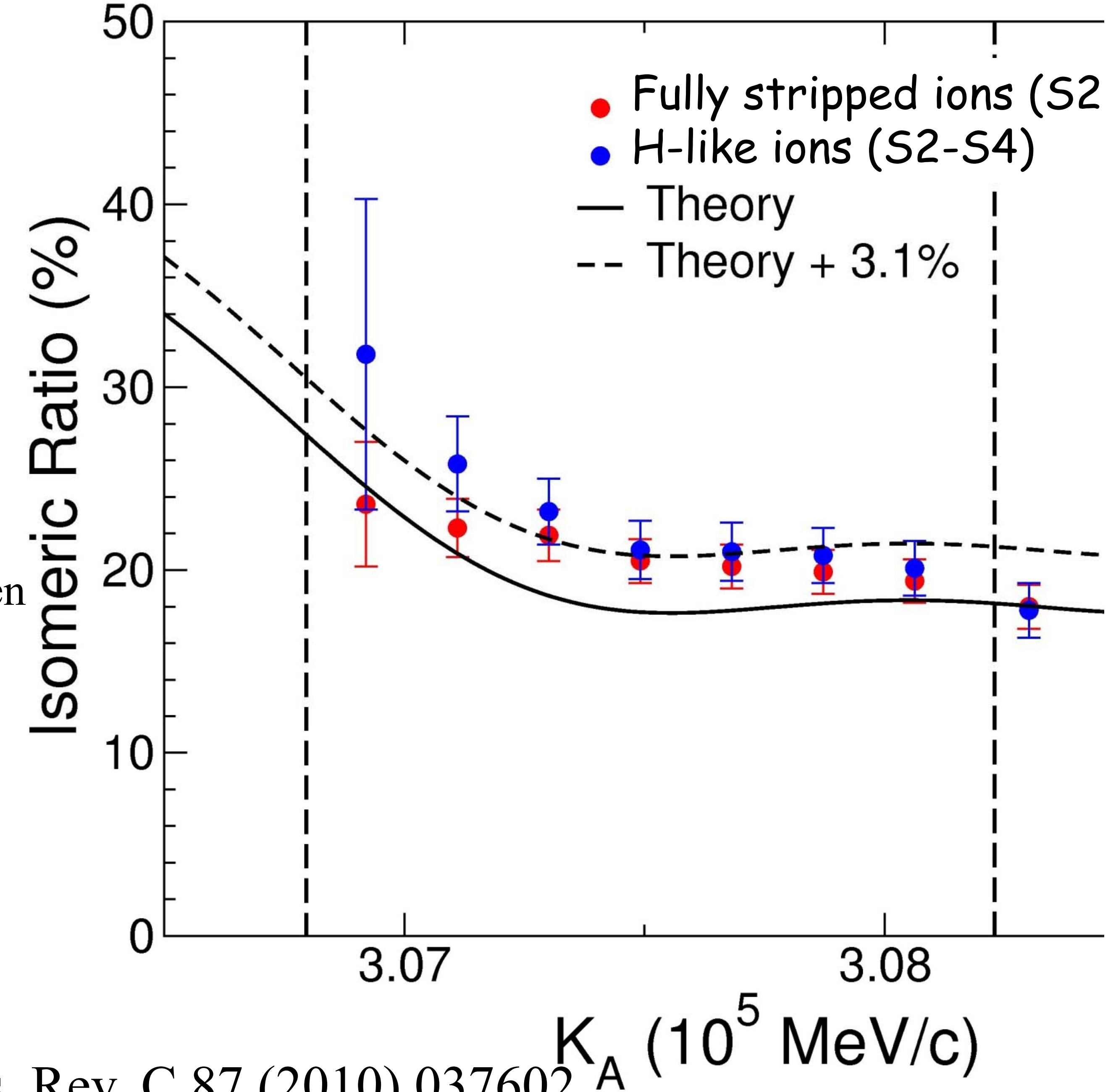


Isomeric ratio as function of longitudinal momentum

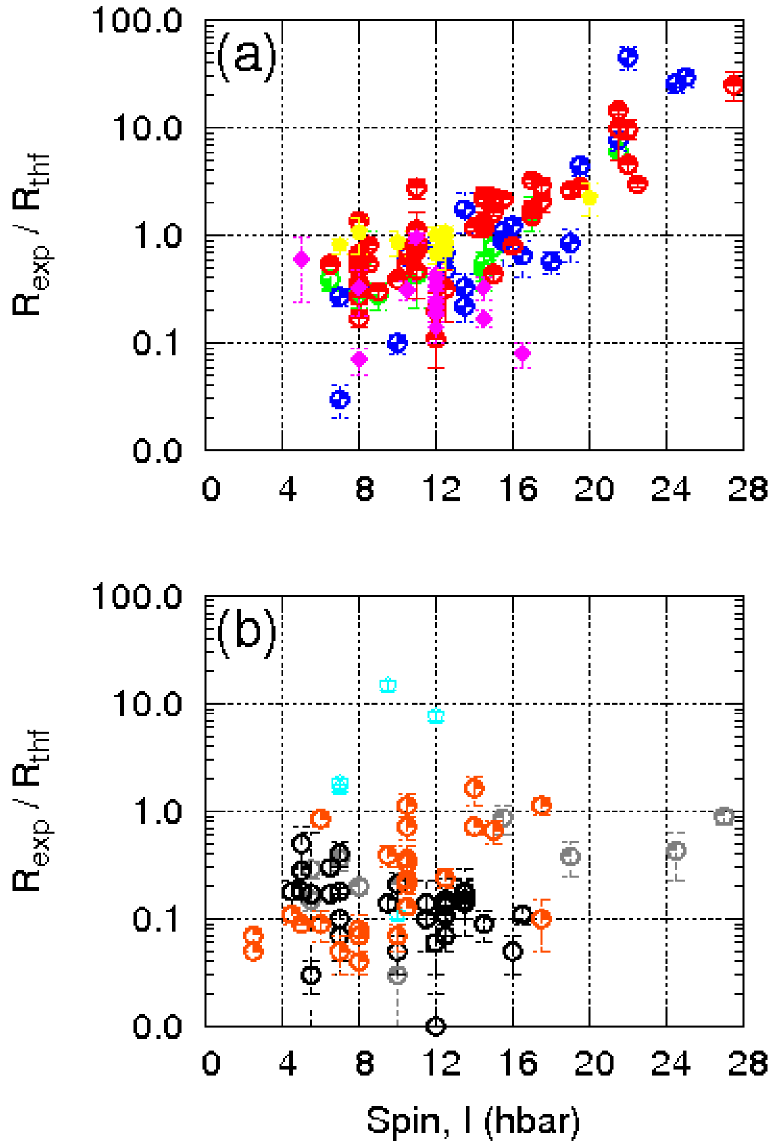
5- isomer

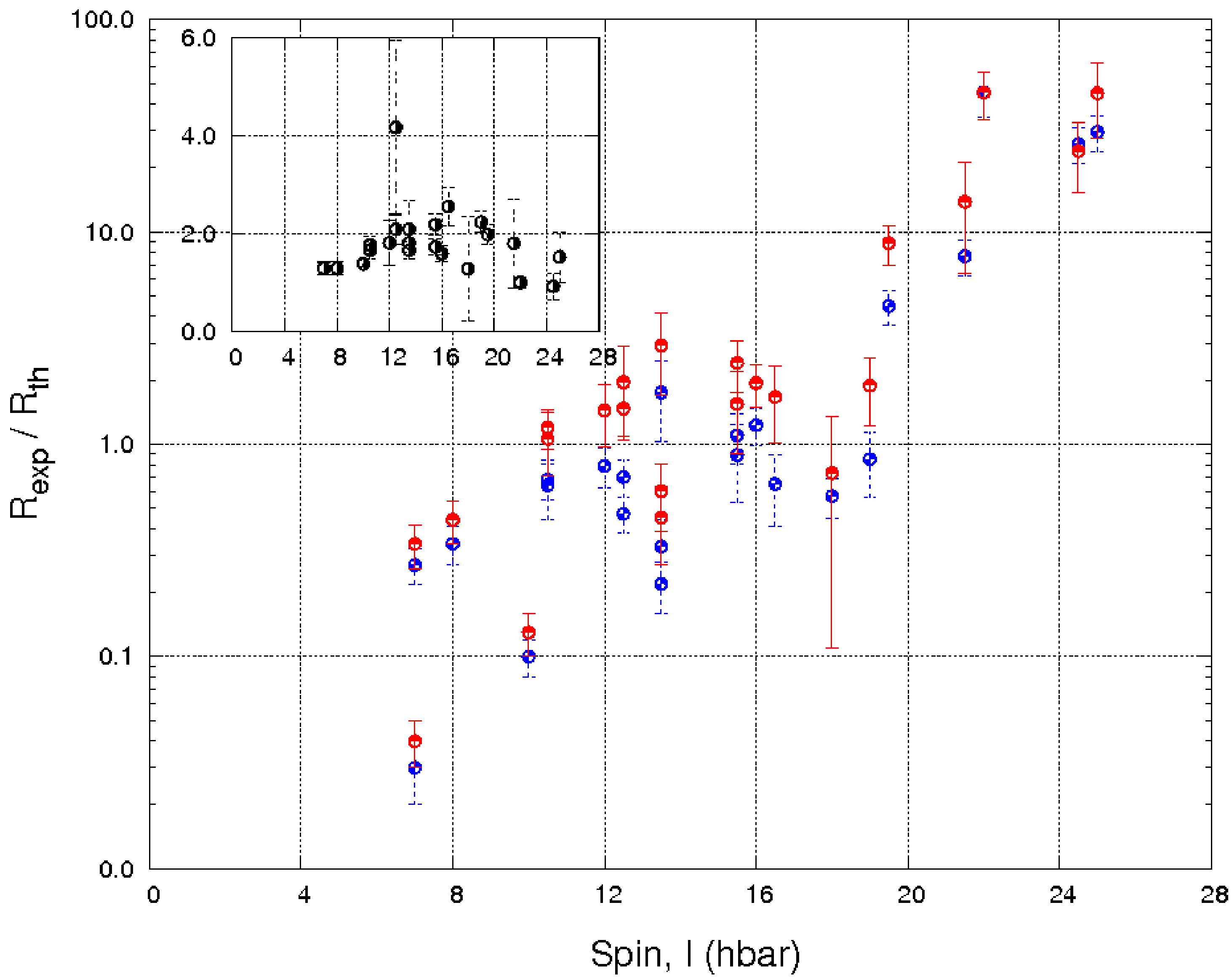
— Theory
-- Theory + 3.1%

(3.1%=difference between experiment and theory; additional feeding?)

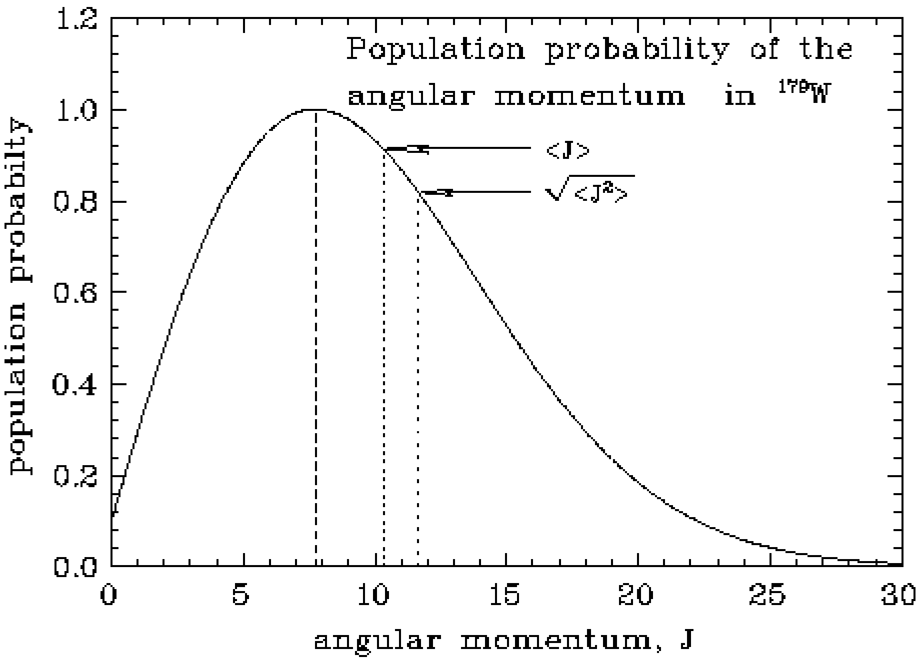


E. Simpson et al., Phys. Rev. C 87 (2010) 037602

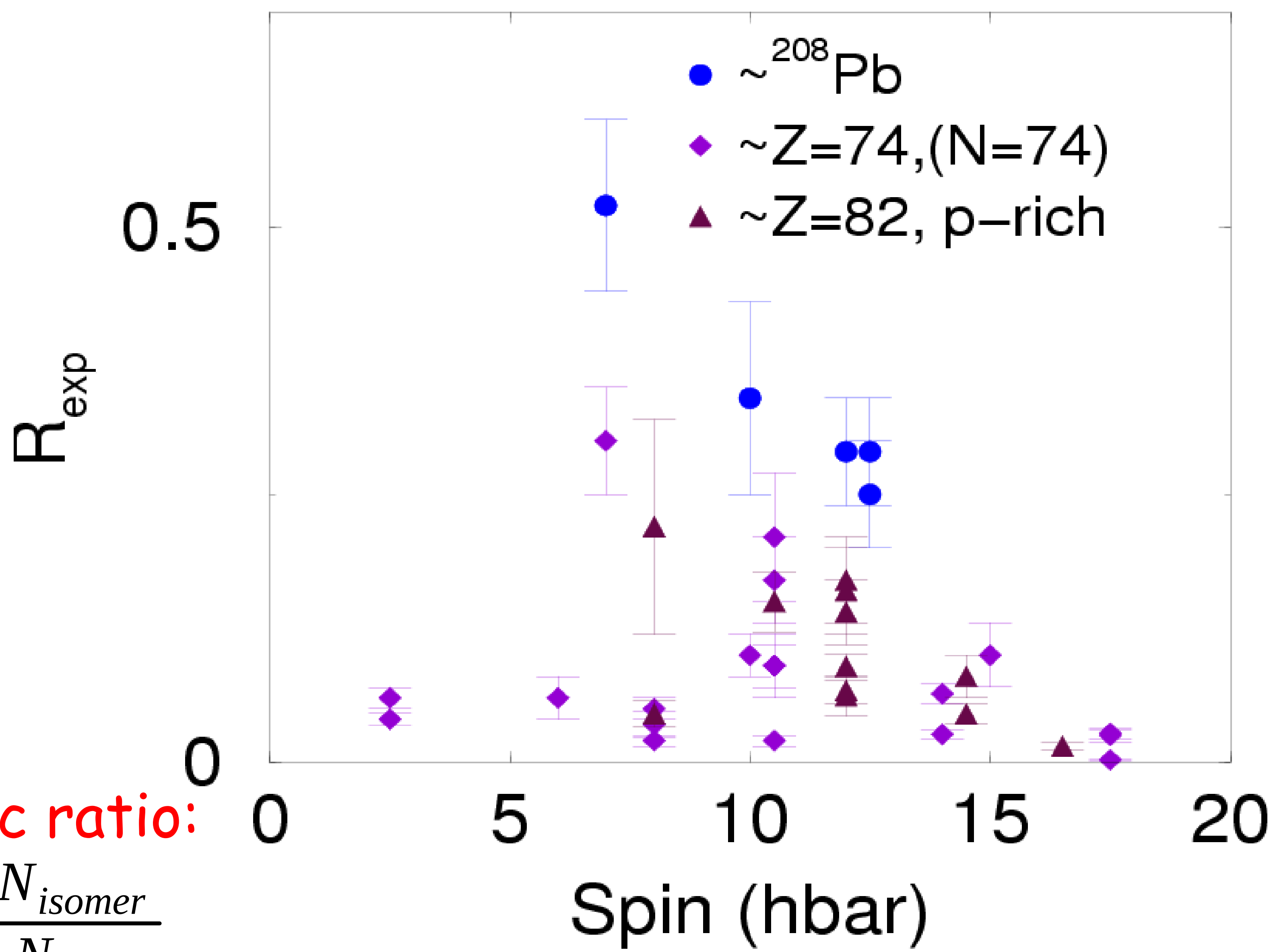

(a)
(b)
100.0
10.0
1.0
0.1
0.0
0
4
8
12
16
20
24
28
R_exp / R_thf
Spin, I (hbar)



100.0
10.0
1.0
0.1
0.0
0
4
8
12
16
20
24
28
R_{exp} / R_{th}
Spin, I (hbar)
6.0
4.0
2.0
0.0



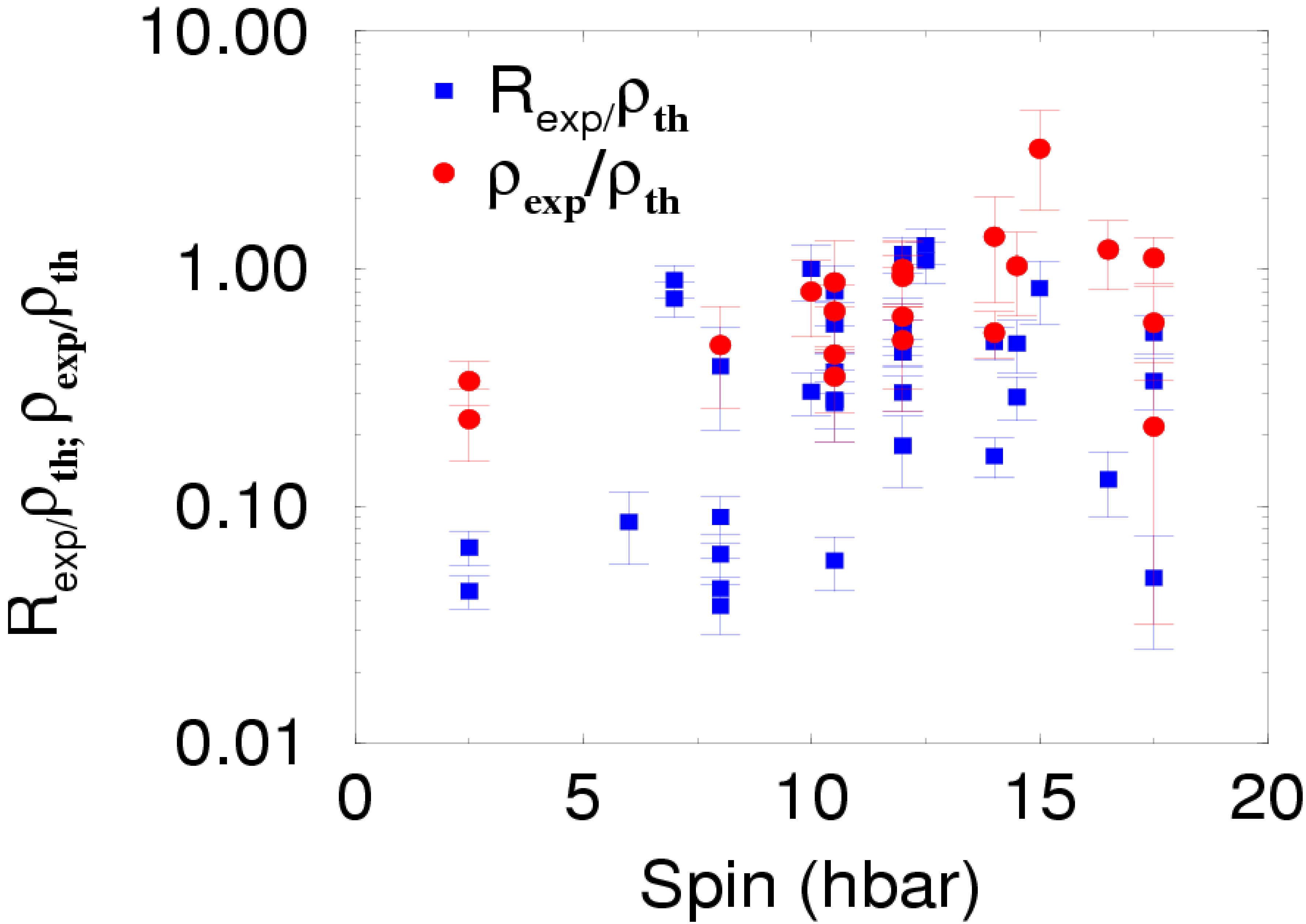
Population probability of the
angular momentum in 179W
<J>
√<J²>
population probabilty
angular momentum, J
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
5
10
15
20
25
30



isomeric ratio:

$$R_{\exp} = \frac{N_{isomer}}{N_{total}}$$

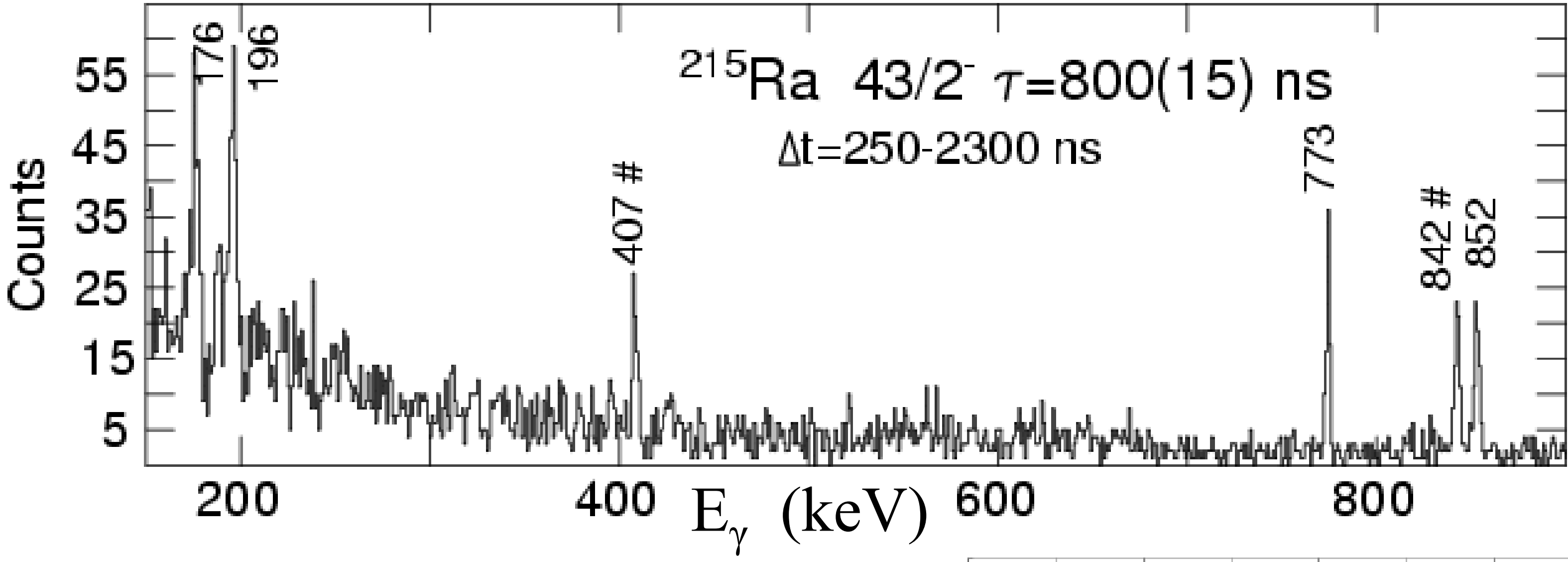
- M. Pfützner *et al.*, Phys. Lett. B444 (1998) 32.
- M. Pfützner *et al.*, Phys. Rev. C65 (2002) 064604.

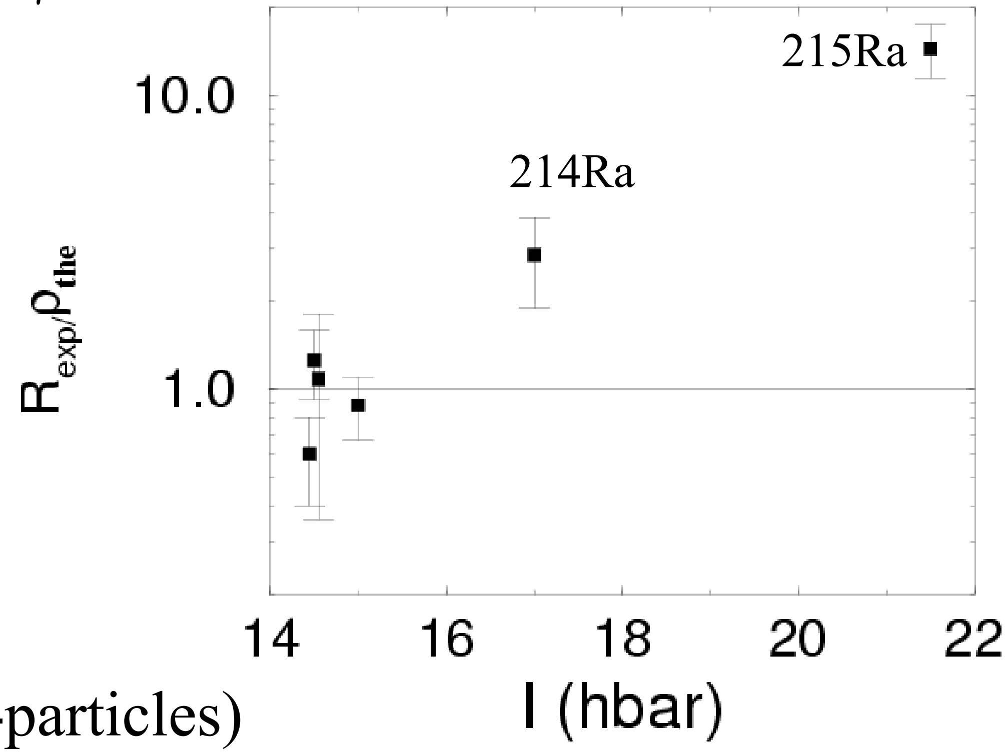


R - isomeric ratio

ρ - probability of populating states

High-spin isomers from ^{238}U fragmentation:





enhanced production
of high-spin states

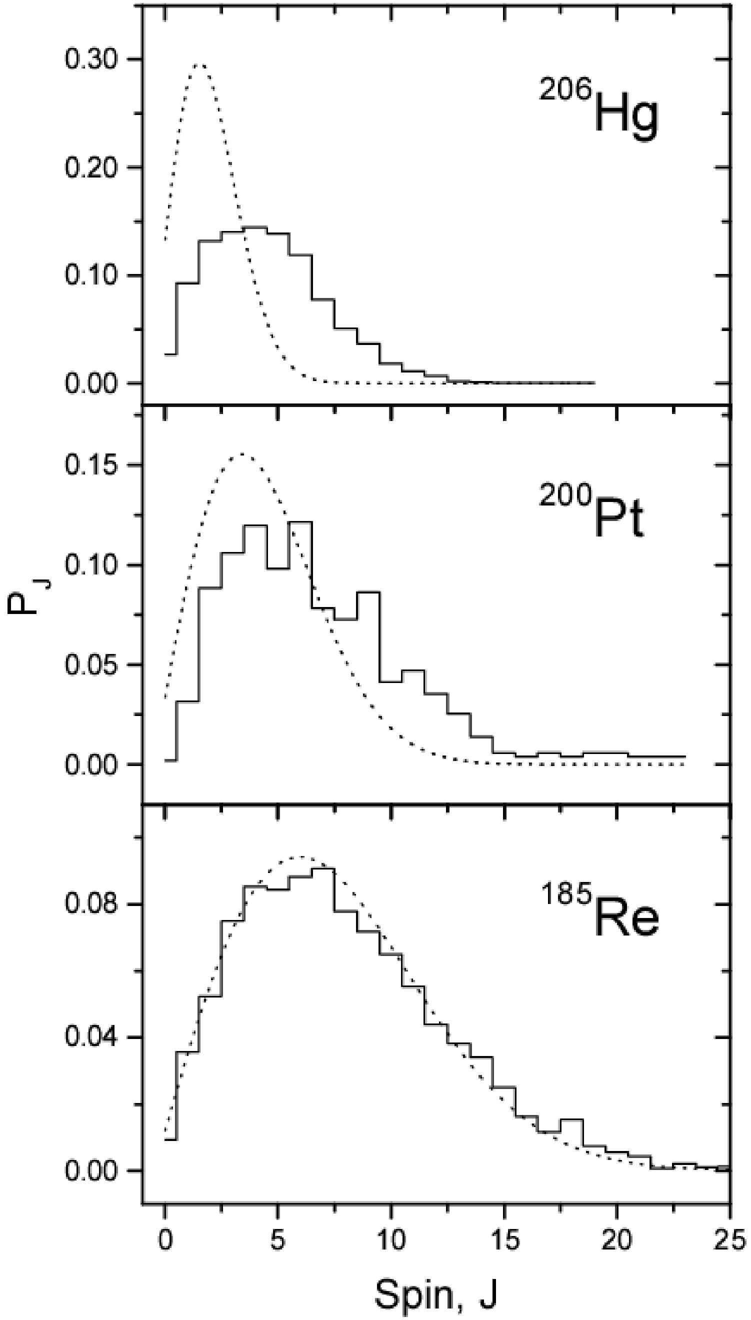
⇩

additional source of
angular momentum?

(original theory: *I* from single-particles)

Zs. Podolyák *et al.*, Phys. Lett. B632 (2006) 203.

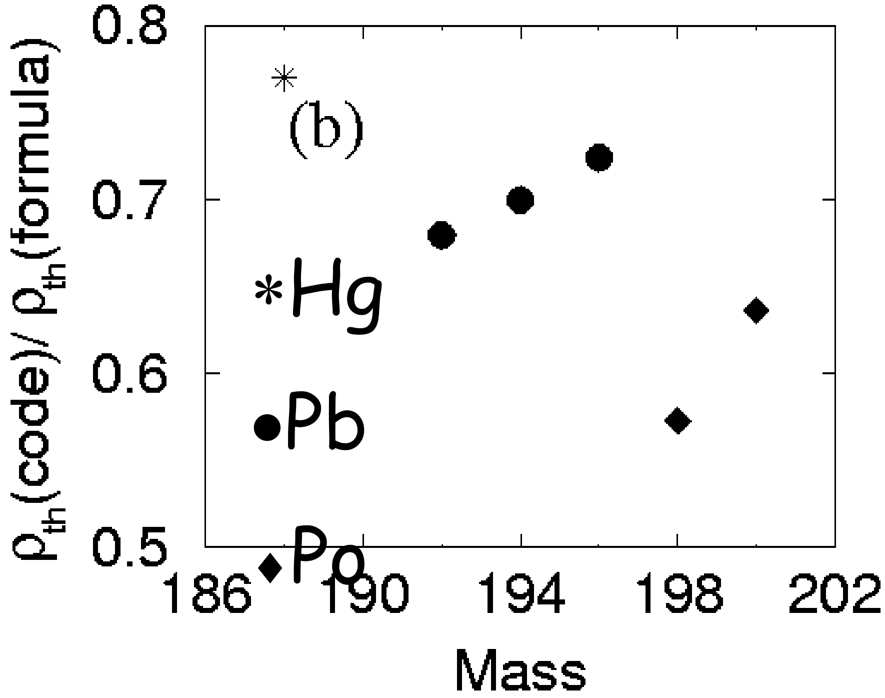
M. Pfützner *et al.*, Phys. Rev. C 65 (2002) 054604.



------------ Analytical formulc

———— ABRABLA

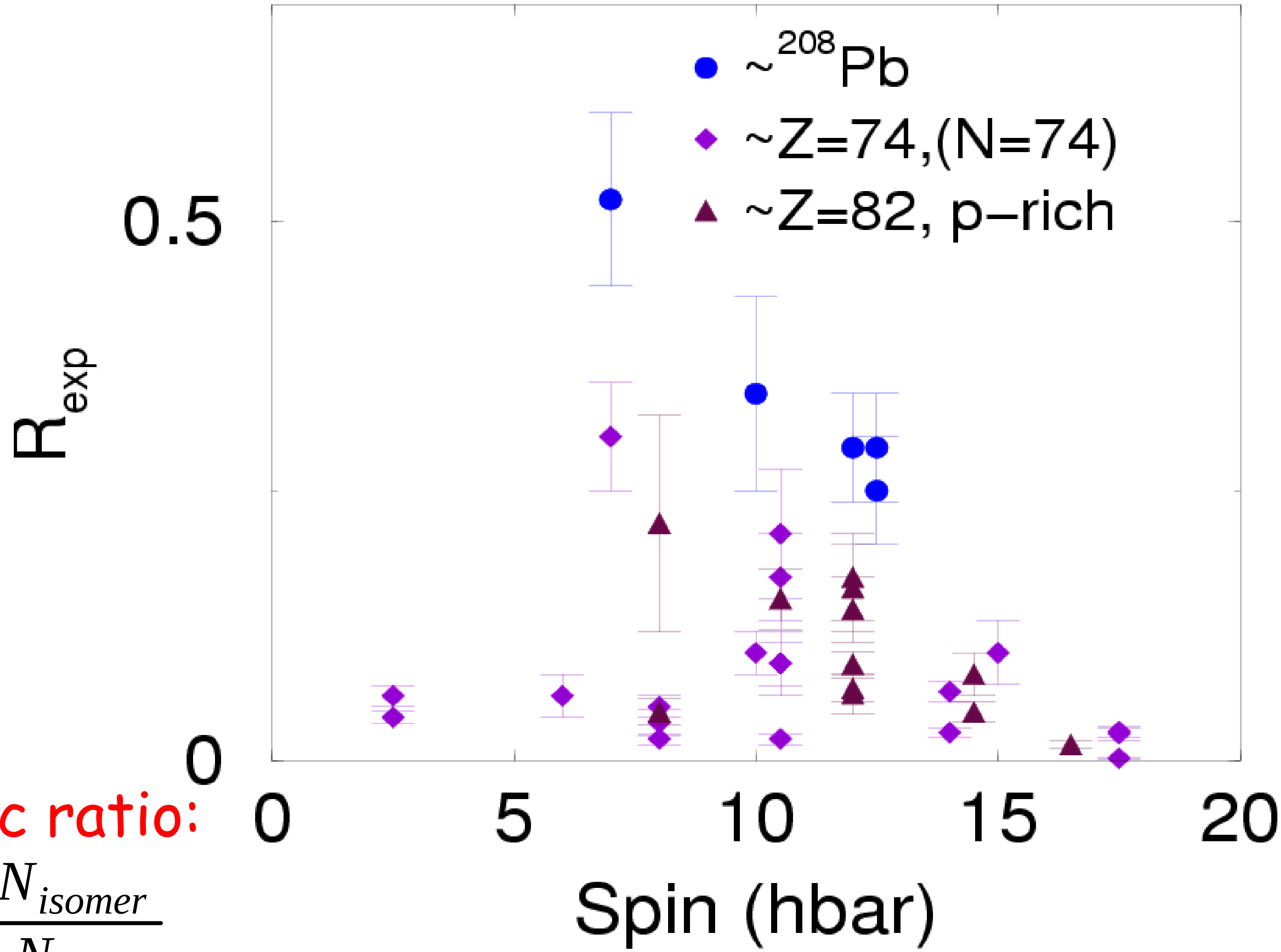
more reliable, this is use



K. Gladnishki et al., Phys. Rev. C (20

fragmentation of ^{208}Pb

fragmentation of ^{238}U

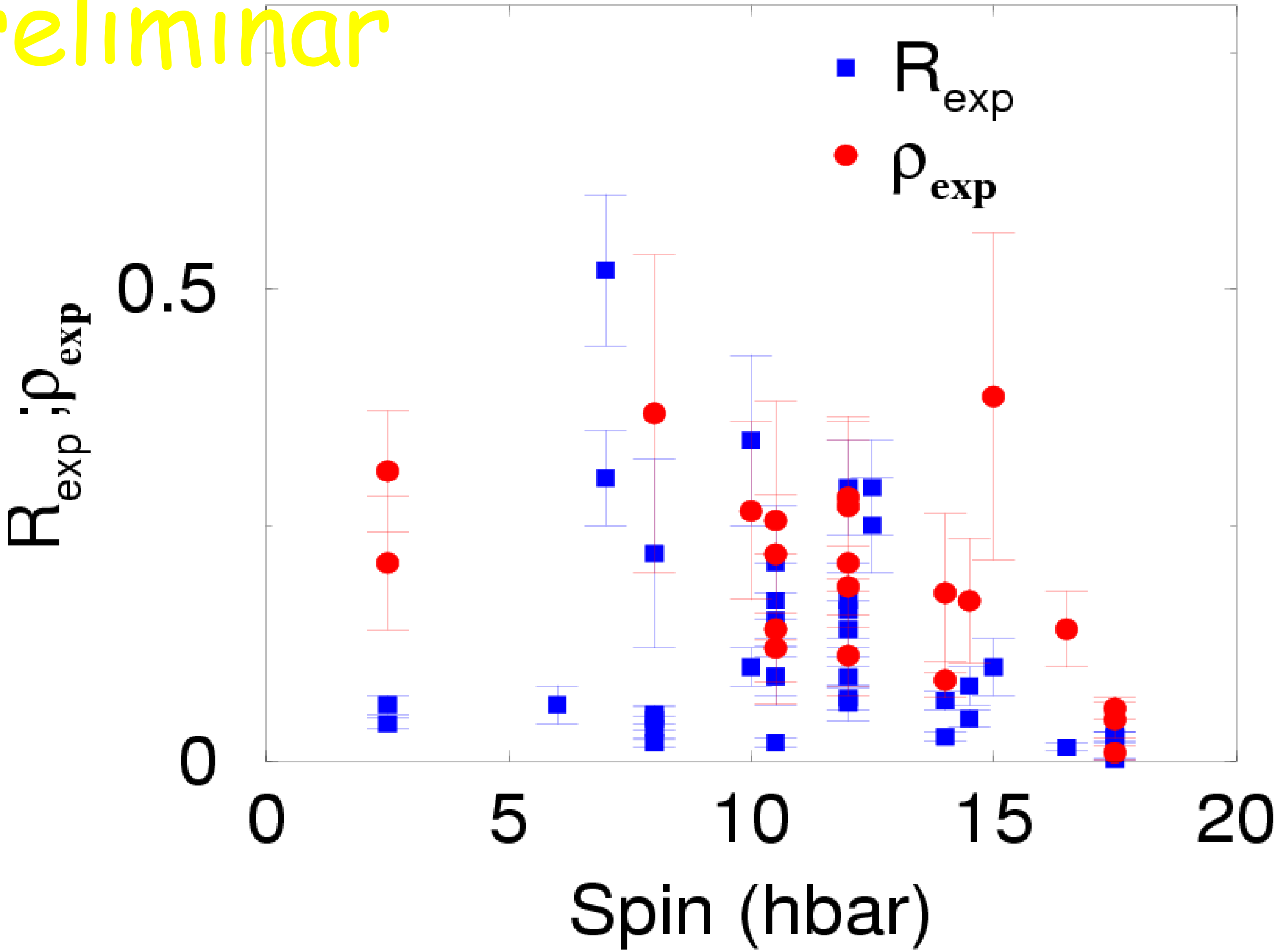


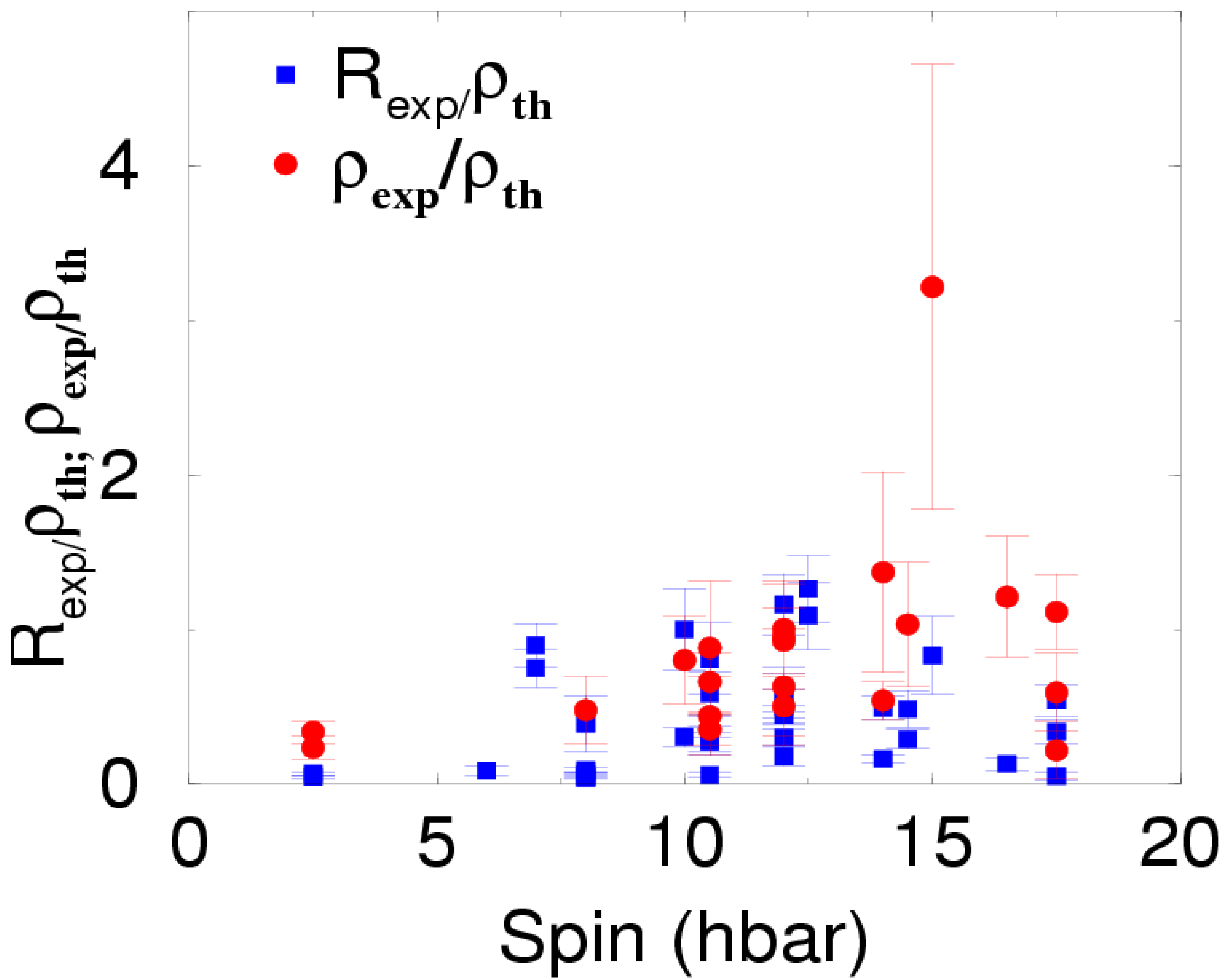
isomeric ratio:

$$R_{\exp} = \frac{N_{isomer}}{N_{total}}$$

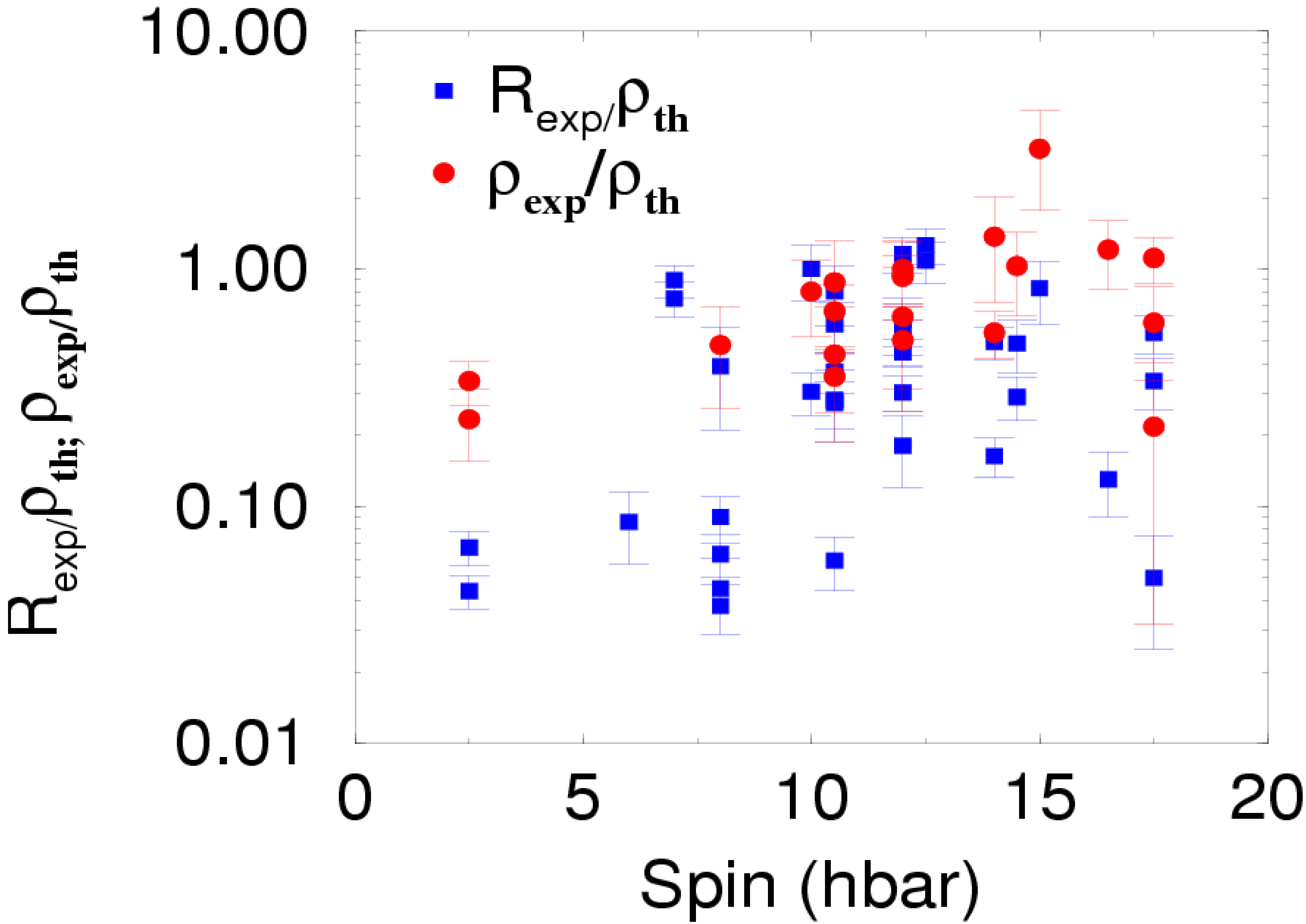
- M. Pfützner *et al.*, Phys. Lett. B444 (1998) 32.
- M. Pfützner *et al.*, Phys. Rev. C65 (2002) 064604.

preliminar
y



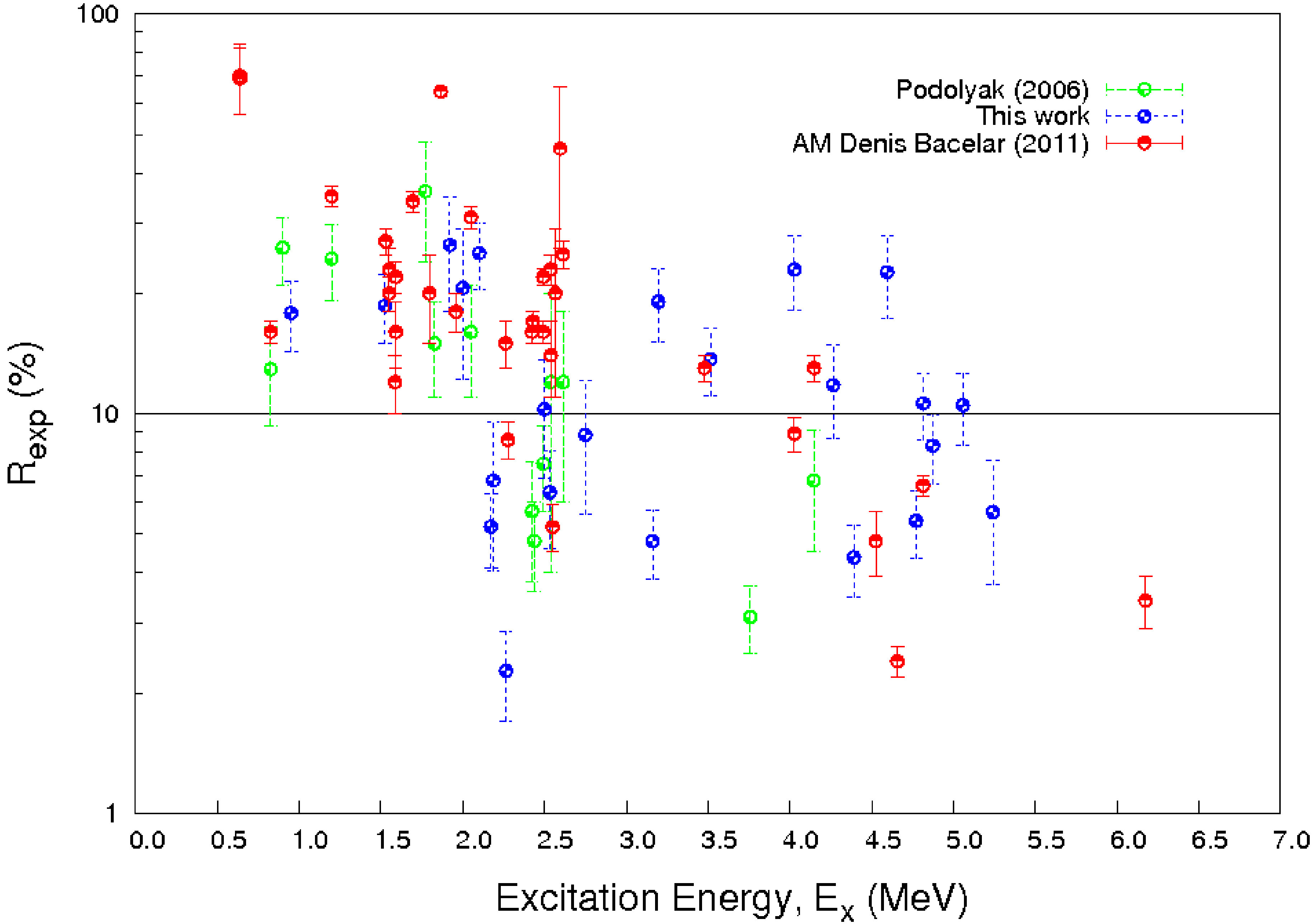


R_exp/ρ_th
ρ_exp/ρ_th
R_exp/ρ_th; ρ_exp/ρ_th
Spin (hbar)
0
2
4
0
5
10
15
20



R - isomeric ratio

ρ - probability of populating states

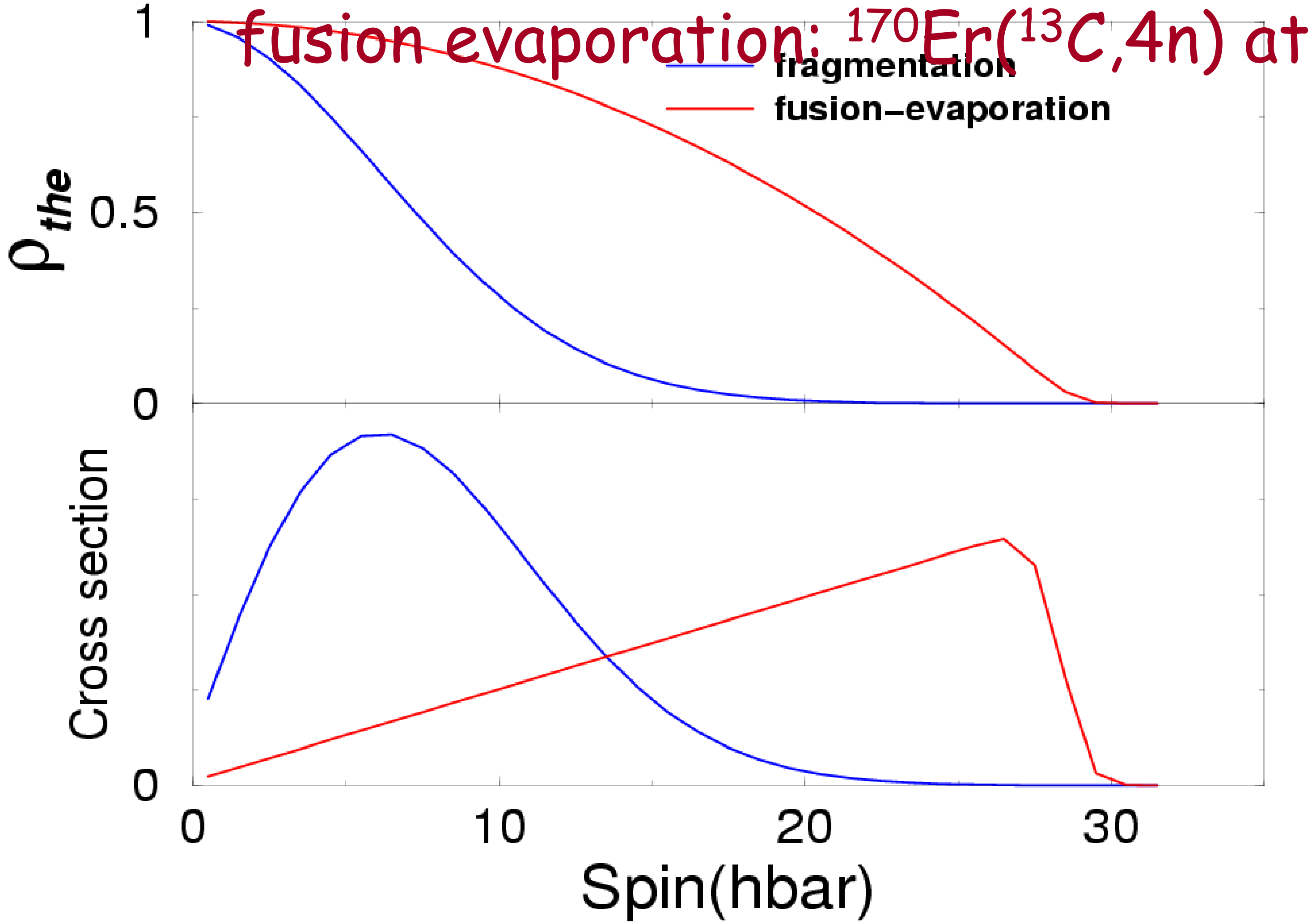


Podolyak (2006)
This work
AM Denis Bacelar (2011)
100
10
1
R_{exp} (%)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
Excitation Energy, E_x (MeV)

^{179}W populated in:

fragmentation of ^{208}Pb at 1 GeV/u

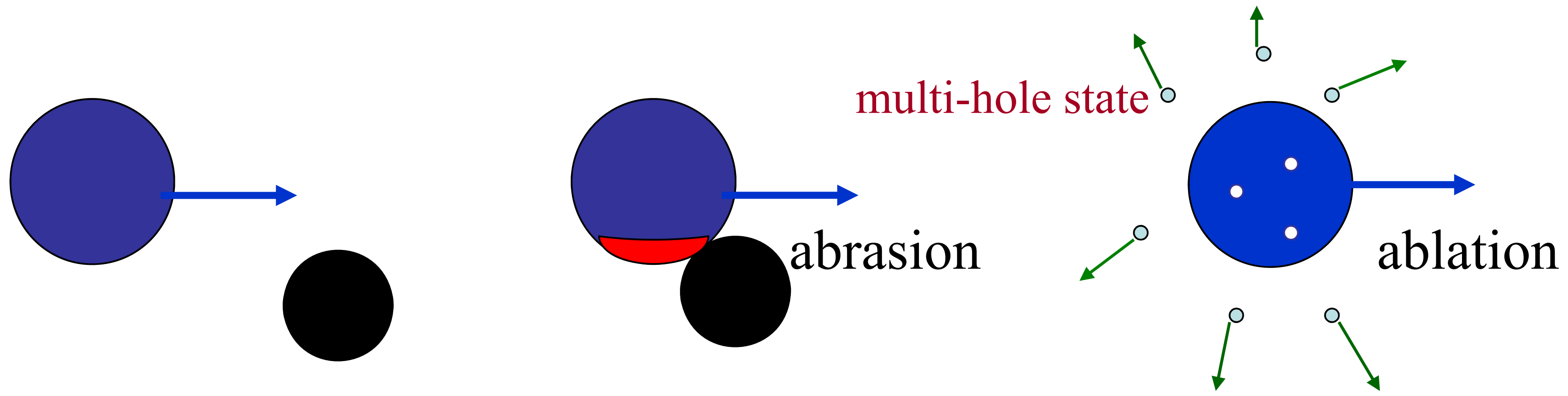
fusion evaporation: $^{170}Er(^{13}C,4n)$ at 67 M

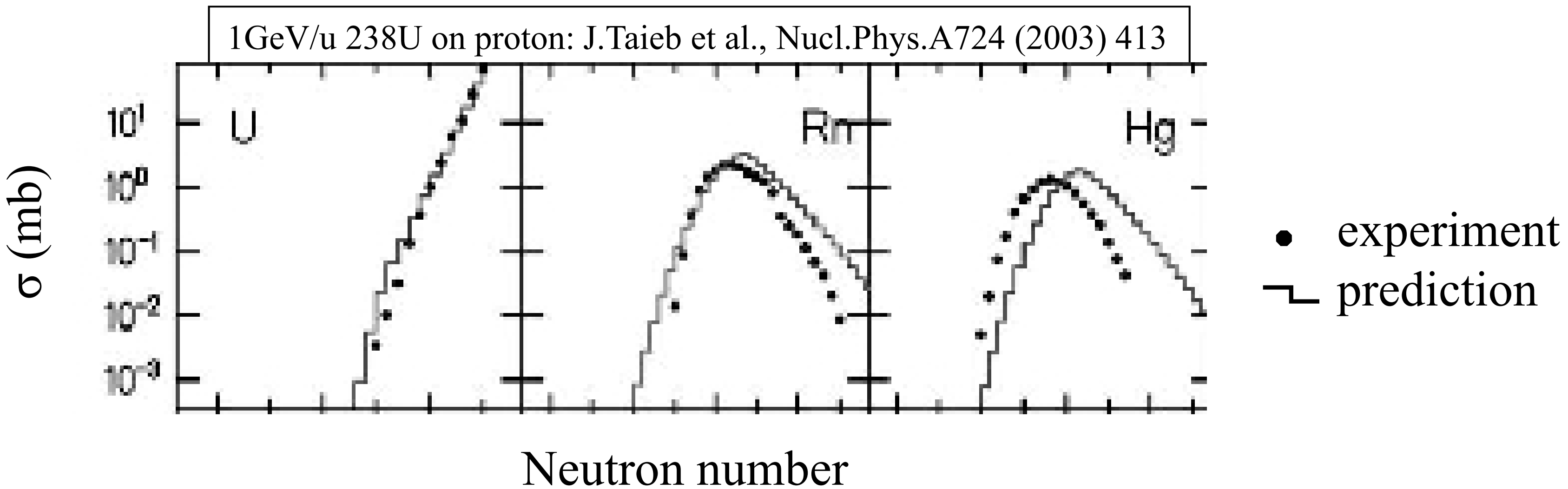


Study [Ref]	Projectile / Energy	Target	Range, Z	Range, A	Range, I ($\hbar$)	No. Nuclei	No. IR
M. Pfützner *et al* [1]	^{238}U @ 1 GeV/A	1.0 g/cm^2 Be	81→83	203→212	7→20	10	10
M. Pfützner *et al* [2]	^{208}Pb @ 1 GeV/A	1.6 g/cm^2 Be	62→80	136→206	5/2→35/2	18	26
K.A. Gladnishki *et al* [3]	^{238}U @ 0.75 GeV/A	1.6 g/cm^2 Be	80→84	188→202	5→33/2	12	14
M. Caamaño *et al*, [4]	^{208}Pb @ 1 GeV/A	1.6 g/cm^2 Be	73→79	188→203	7→19/2	11	13
Zs. Podolyák *et al* [5, 6]	^{238}U @ 0.9 GeV/A	1.0 g/cm^2 Be	86→89	207→215	13/2→43/2	13	13
AM Denis Bacelar * [7]	^{238}U @ 1 GeV/A	2.5 g/cm^2 Be	84→89	198→215	13/2→55/2	24	50
S.J. Steer *et al* [8]	^{208}Pb @ 1 GeV/A	2.5 g/cm^2 Be	73→81	188→206	9/2→33/2	31	39
S. Myalski *et al* [9]	^{208}Pb @ 1 GeV/A	2.5 g/cm^2 Be	62→67	142→153	11/2→27	9	10
M.D. Bowry (2012) *	^{238}U @ 1 GeV/A	1.6 g/cm^2 Be	78→86	192→215	7→25	24	23
Total IR							198

[1] M. Pfützner *et al.*, Phys. Lett. B **444**, 32 (1998).
[2] M. Pfützner *et al.*, Phys. Rev. C **65**, 064604 (2002).
[3] K.A. Gladnishki *et al.*, Phys. Rev. C **69**, 024617 (2004).
[4] M. Caamaño *et al.*, Eur. Phys. J. A **23**, 201-215 (2005).
[5] Zs. Podolyák *et al.*, Phys. Lett. B **632**, 203-206 (2006).
[6] Zs. Podolyák, Private Communication.
[7] AM Denis Bacelar, PhD. Thesis (unpublished), (2011).
[8] S.J. Steer *et al.*, Phys. Rev. C **84**, 044313 (2011).
[9] S. Myalski *et al.*, Acta. Phys. Pol. B **43**, 253-259 (2012).

Fragmentation (spallation) reactions at relativistic energies:





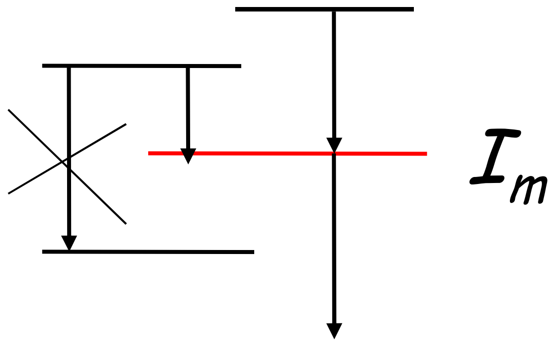
Cross section: measures the end product

What would give information about abrasion?

***Angular** (and linear) momentum*

Isomeric ratio

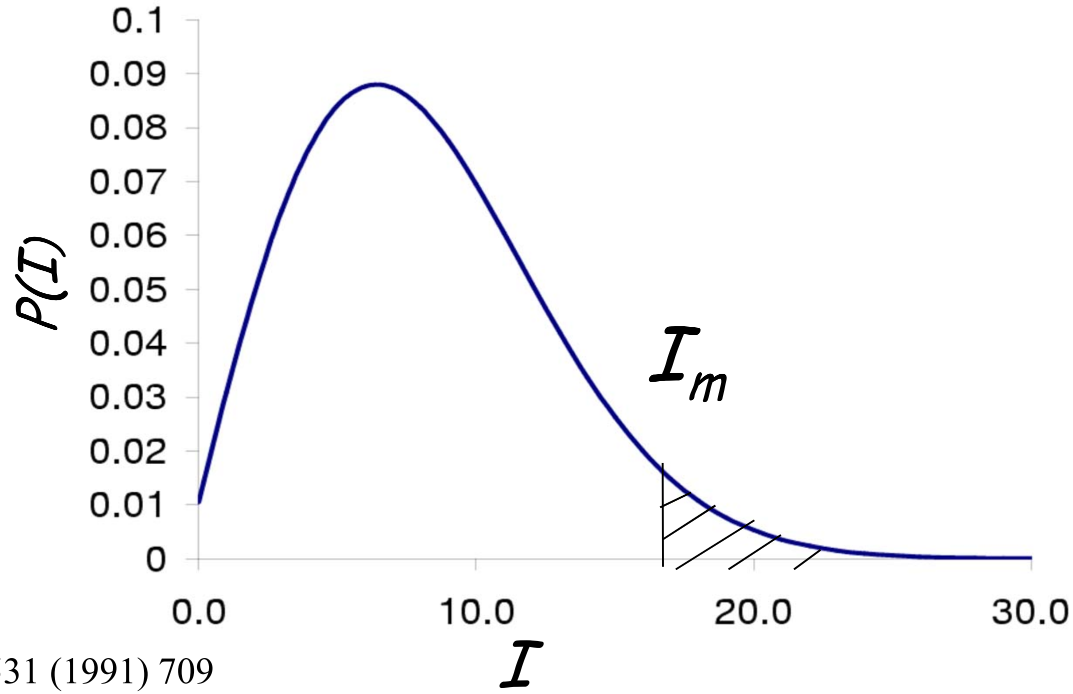
$$R_{\exp} = \frac{N_{isomer}}{N_{total}}$$



$$P(I) = \frac{2I+1}{2\sigma_f^2}\exp\left(-\frac{I(I+1)}{2\sigma_f^2}\right)$$

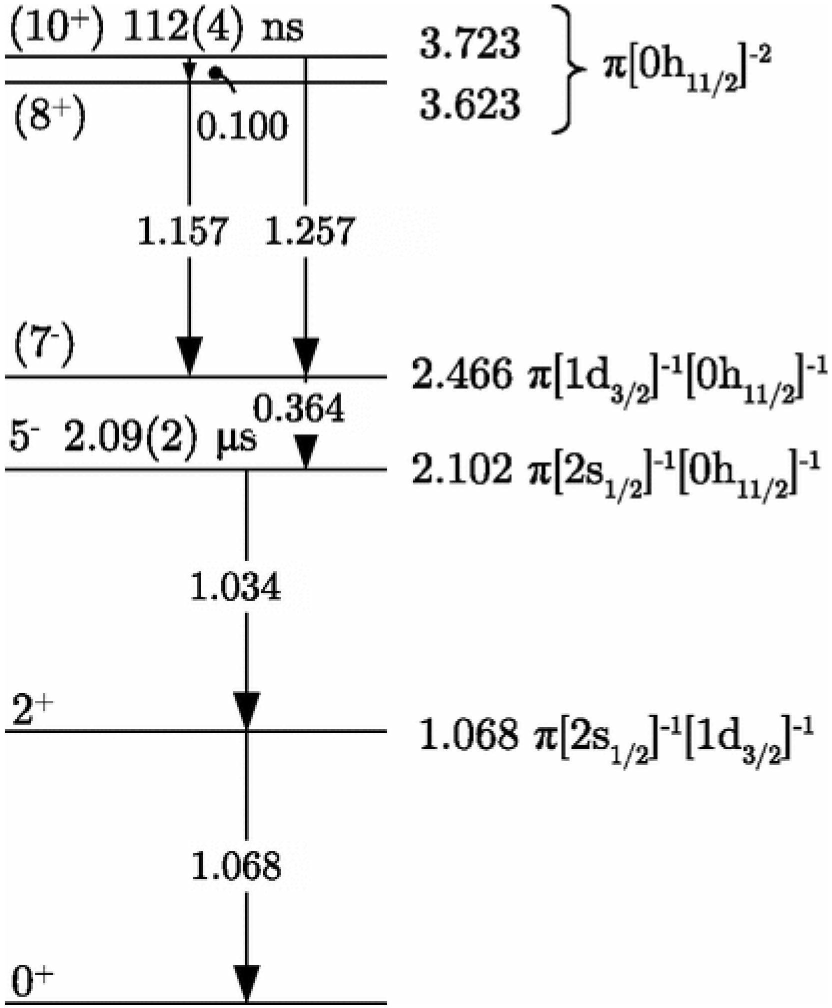
$$\rho_{theo} = \int_{I_m}^{\infty} P(I)\,dI$$

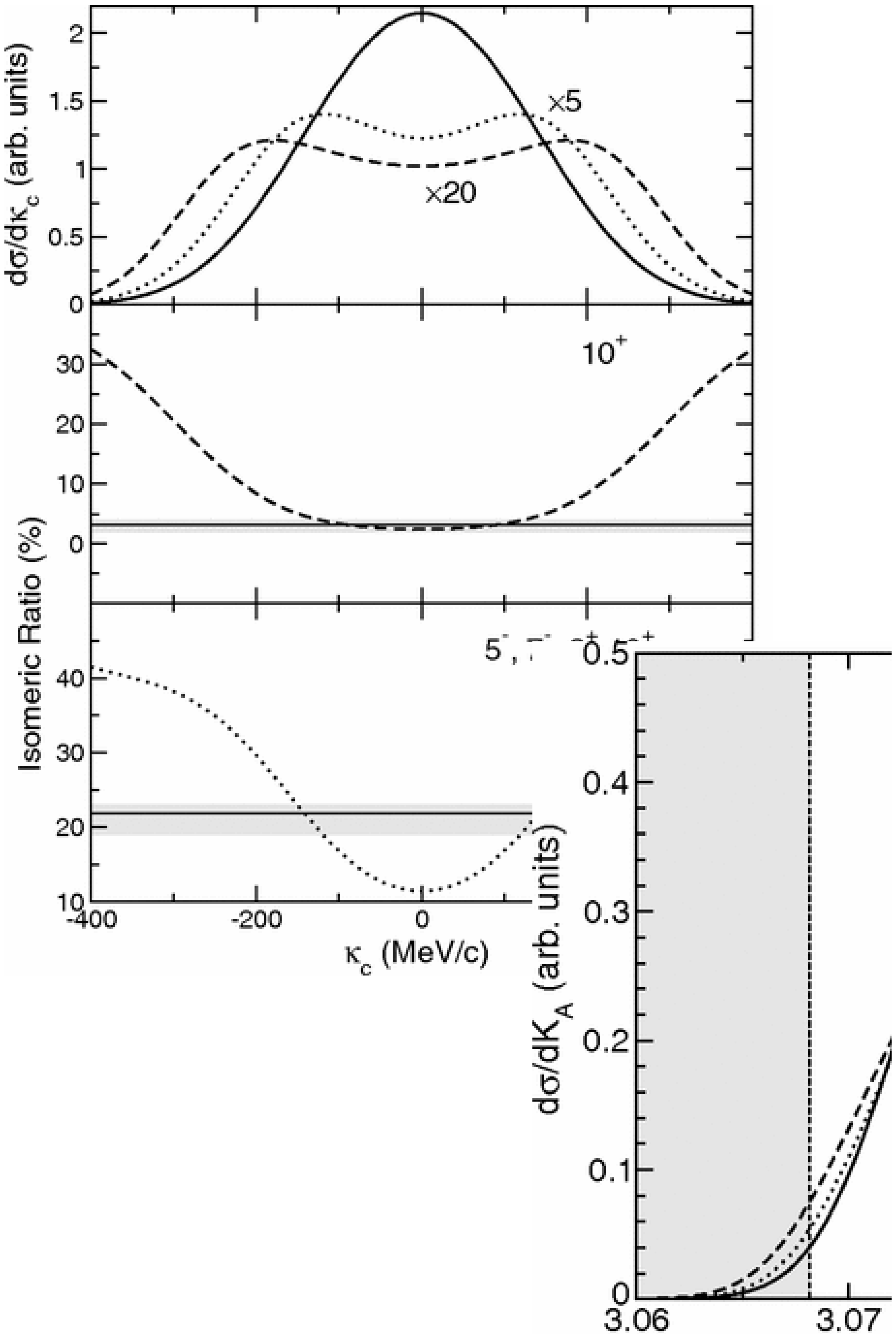
(sharp cut-off approx.)

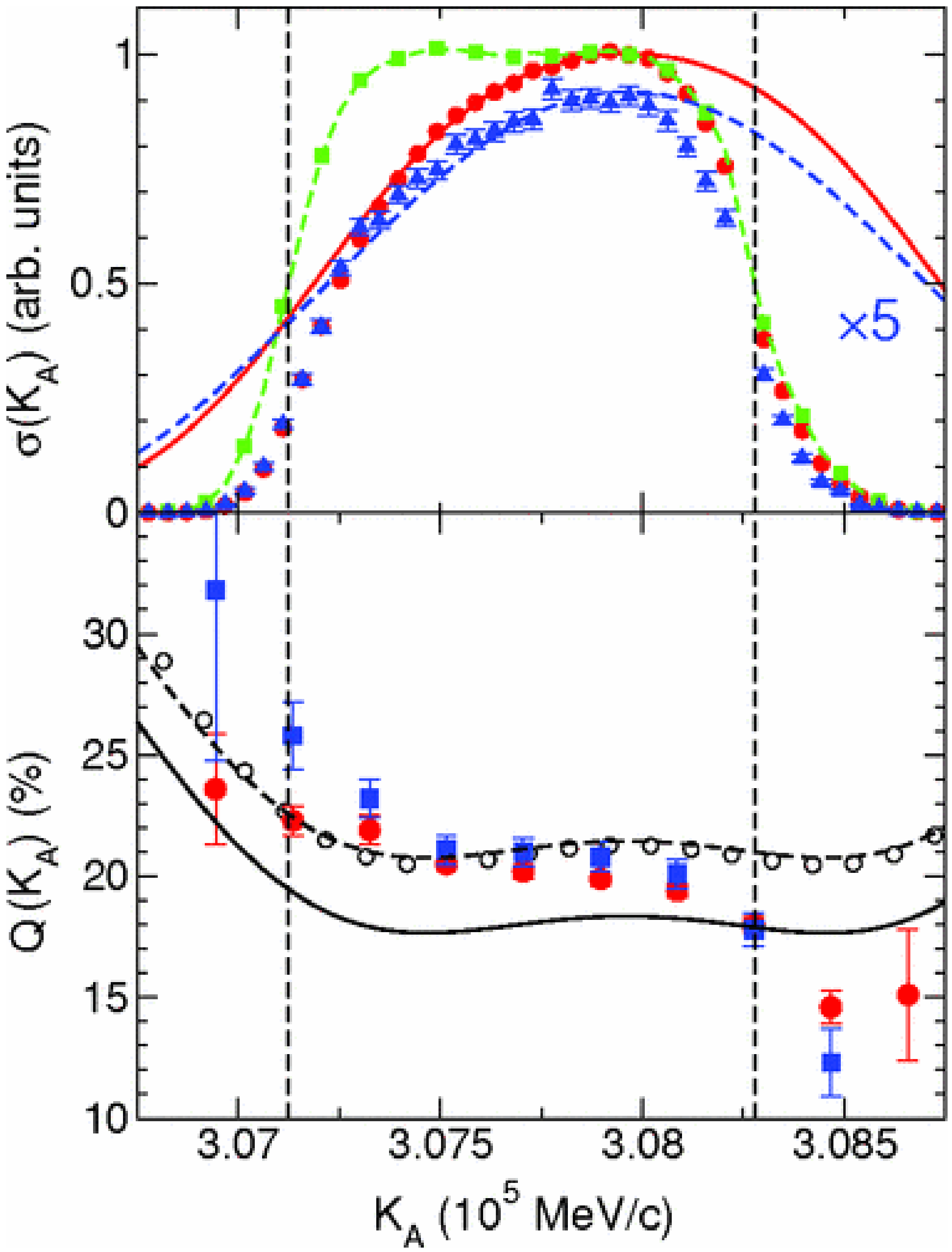


J.-J. Gaimard and K.-H. Schmidt, Nucl. Phys. A 531 (1991) 709

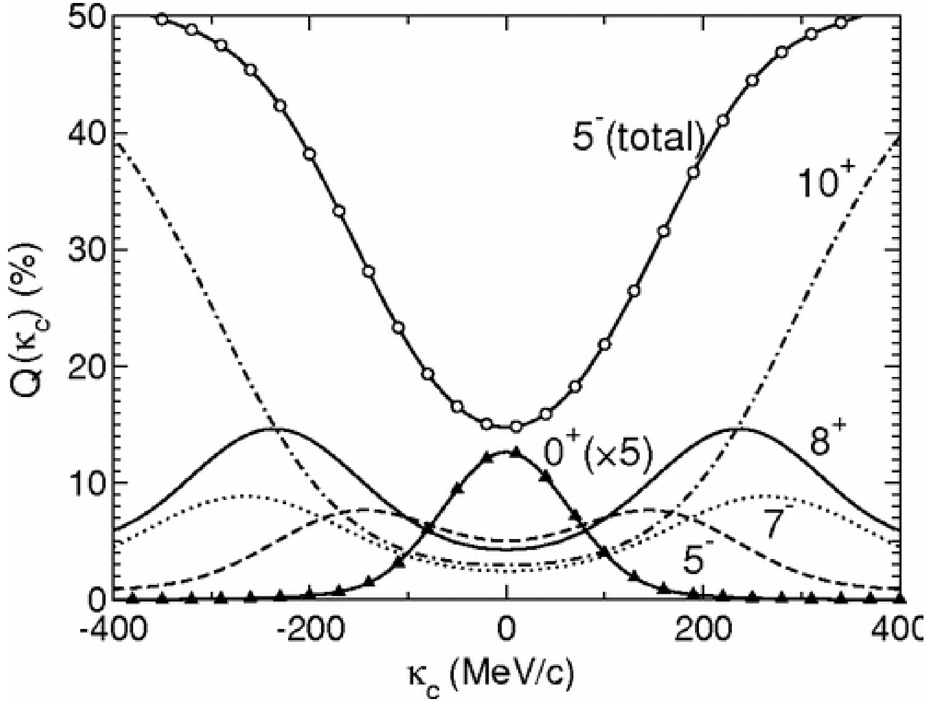
M. De Jong, A.V. Ignatyuk and K.-H. Schmidt, Nucl. Phys. A 613 (1997) 435


(10+) 112(4) ns
3.723
3.623
π[0h11/2]-2
(8+)
0.100
1.157
1.257
(7-)
2.466 π[1d3/2]-1[0h11/2]-1
0.364
5- 2.09(2) μs
2.102 π[2s1/2]-1[0h11/2]-1
1.034
2+
1.068 π[2s1/2]-1[1d3/2]-1
1.068
0+


dσ/dκc (arb. units)
×5
×20
10+
Isomeric Ratio (%)
κc (MeV/c)
dσ/dKA (arb. units)
3.06
3.07



Using a thick target



E. C. Simpson, J. A. Tostevin, Zs. Podolyák, P. H. Regan, and S. J. Steer, Phys. Rev. C 82, 037602 (2010)

Highest spin from fragmentation: I=(55/2)

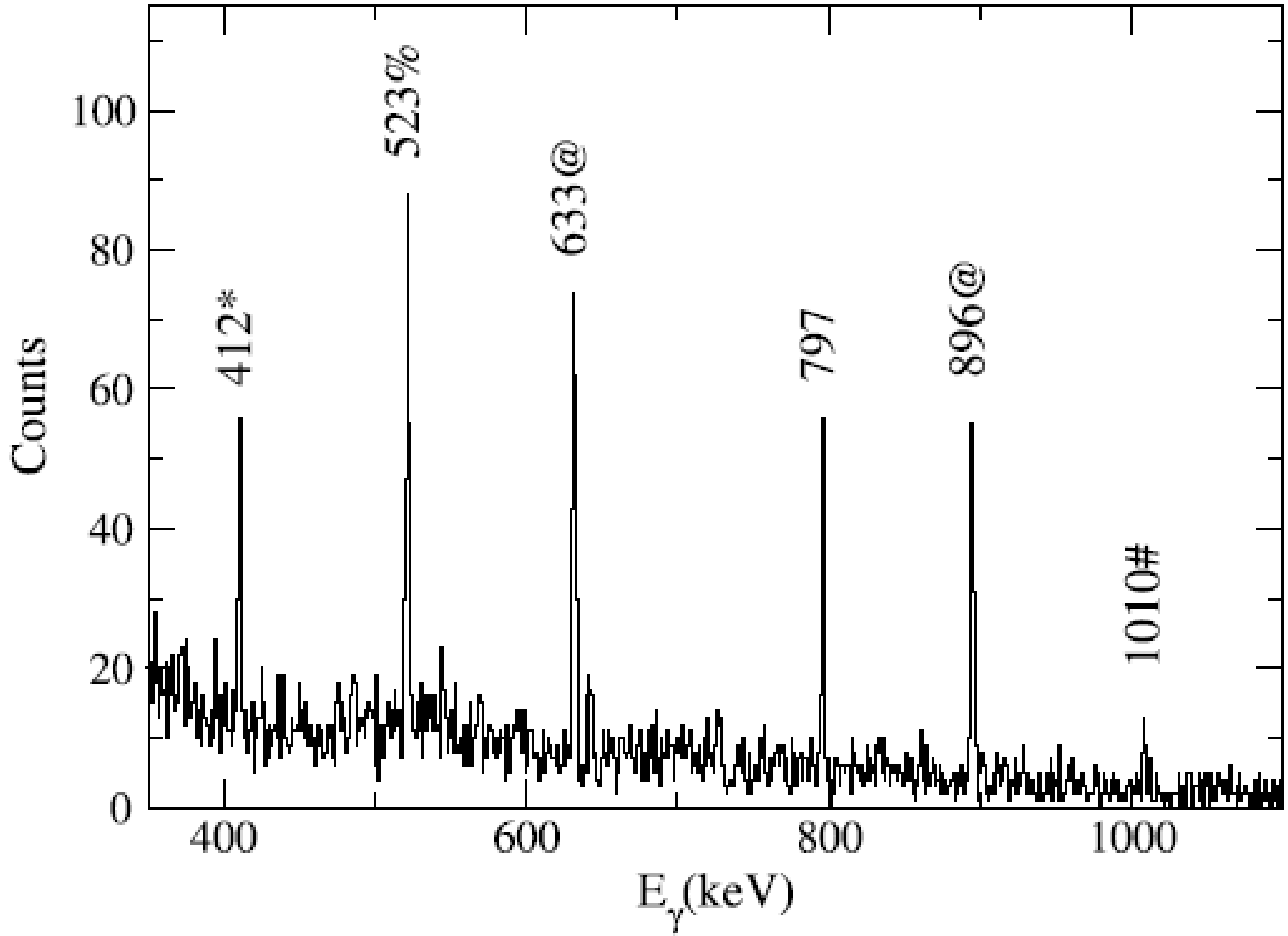
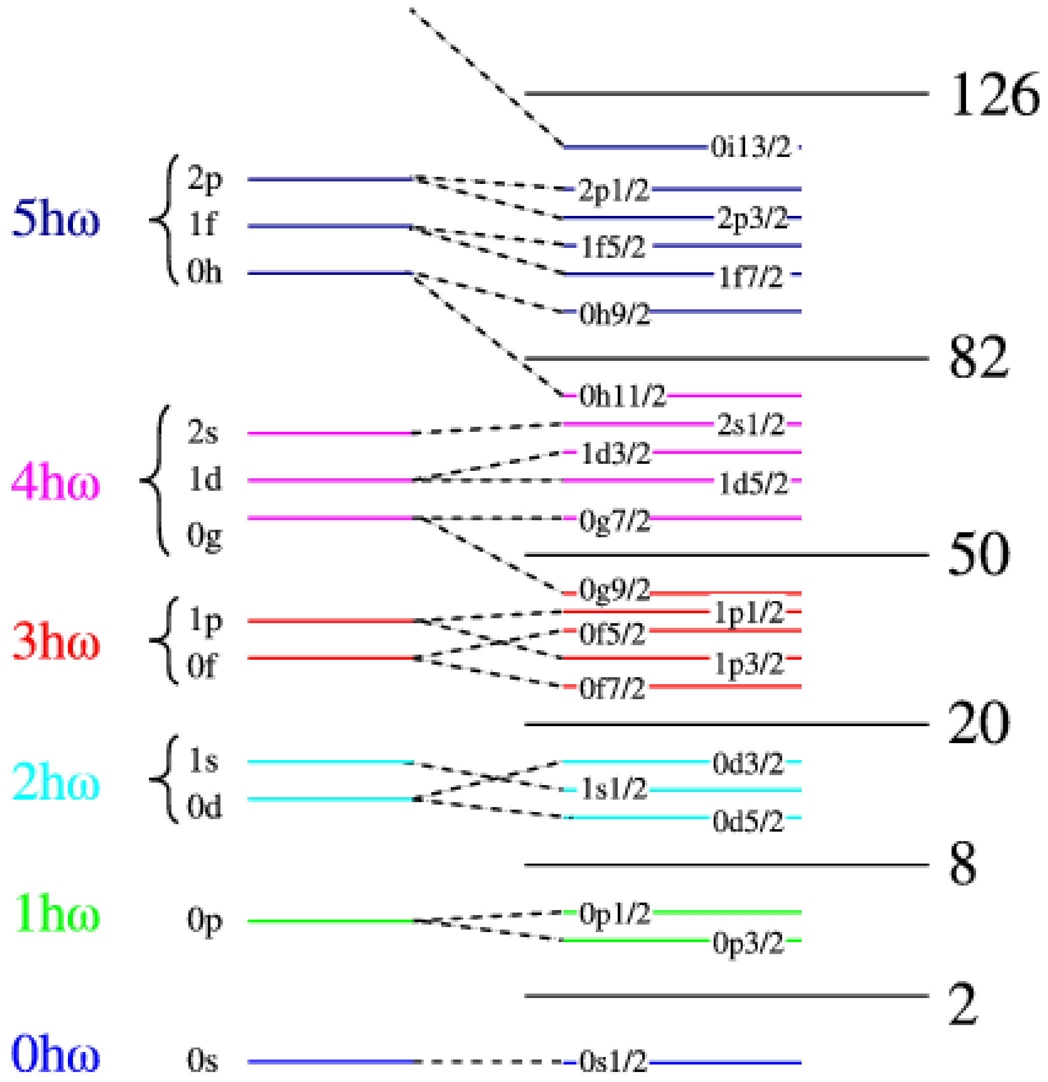


Fig. 1. Gamma-ray energy spectrum obtained in coincidence with ^{213}Rn ions using a time gate of width 1.4 μs starting ~50 ns after the prompt flash. The transitions used to obtain the isomeric ratios for the $(55/2)^+$, $43/2^-$, $31/2^-$ and $25/2^+$ levels are denoted #, *, % and @ respectively. 213Rn:A.E. Stuchbery et al., NPA 482 (1988) 692

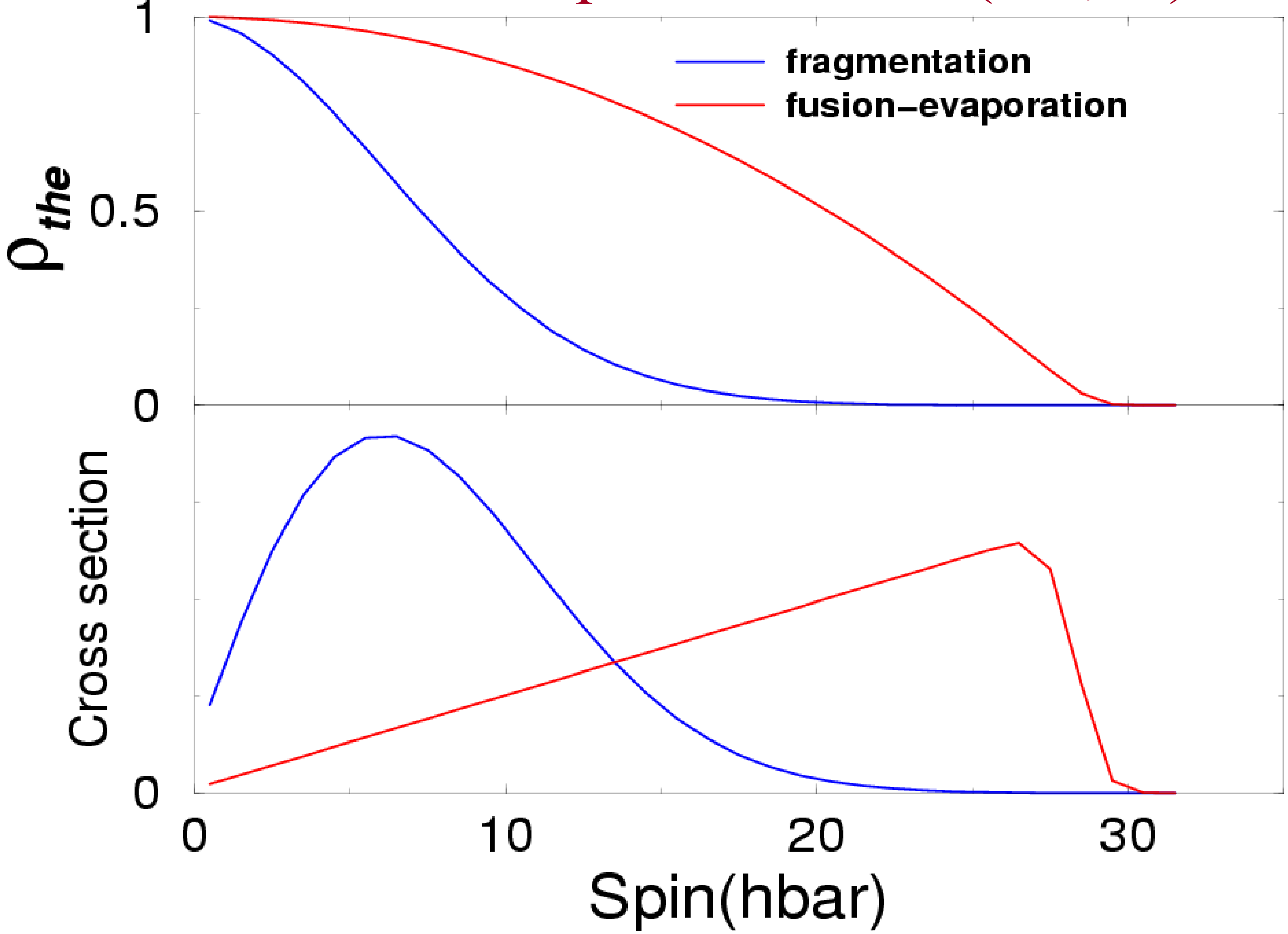
A.M. Denis Bacelar et al., Phys. Lett. B 723, 302 (2012)


126
0i13/2
5hω
2p
1f
0h
2p1/2
2p3/2
1f5/2
1f7/2
0h9/2
82
0h11/2
4hω
2s
1d
0g
2s1/2
1d3/2
1d5/2
0g7/2
50
3hω
1p
0f
0g9/2
1p1/2
0f5/2
1p3/2
0f7/2
20
2hω
1s
0d
0d3/2
1s1/2
0d5/2
8
1hω
0p
0p1/2
0p3/2
2
0hω
0s
0s1/2

^{179}W populated in:

fragmentation of ^{208}Pb at 1 GeV/u

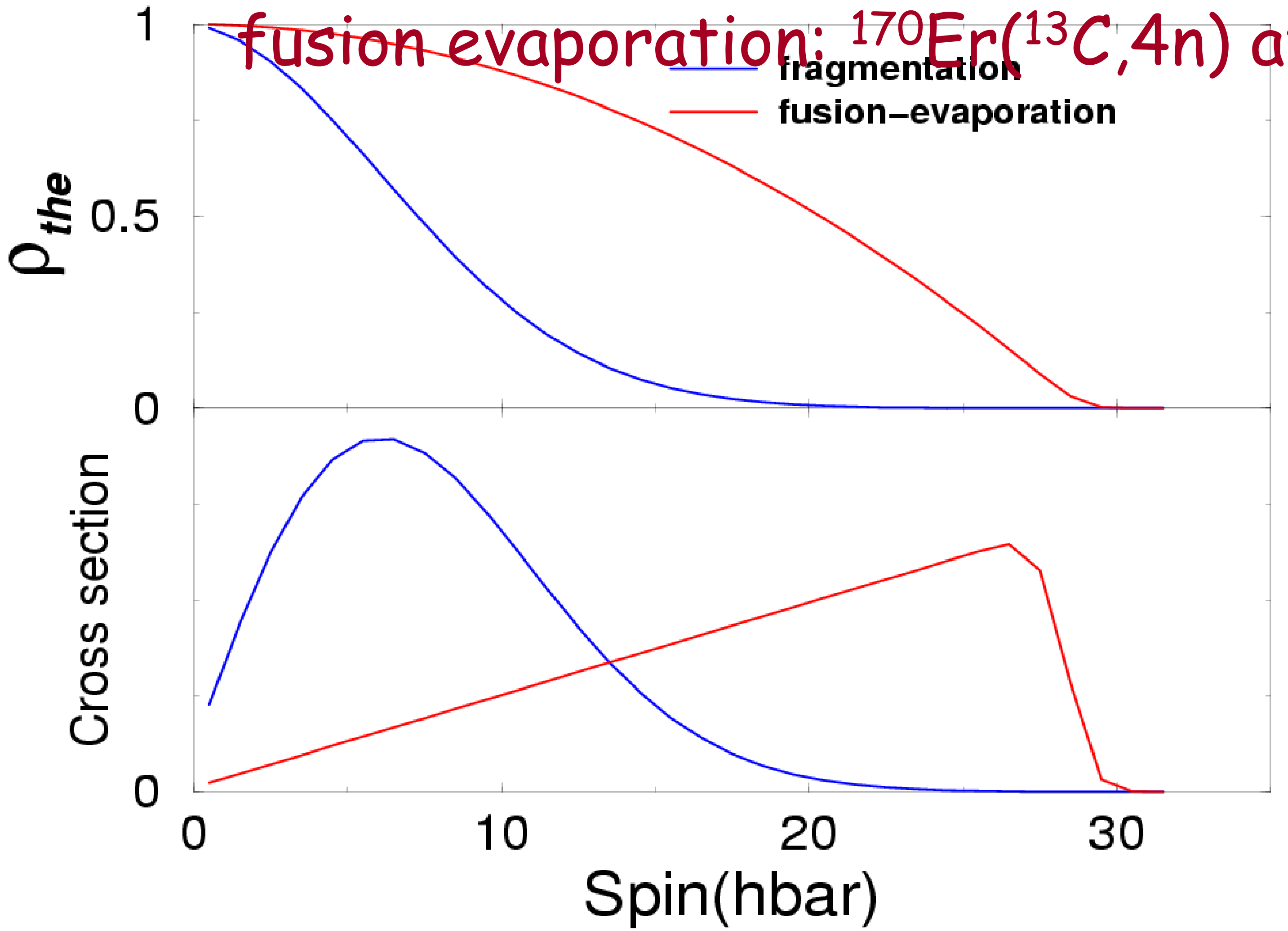
fusion evaporation: $^{170}Er(^{13}C,4n)$ at 67 MeV

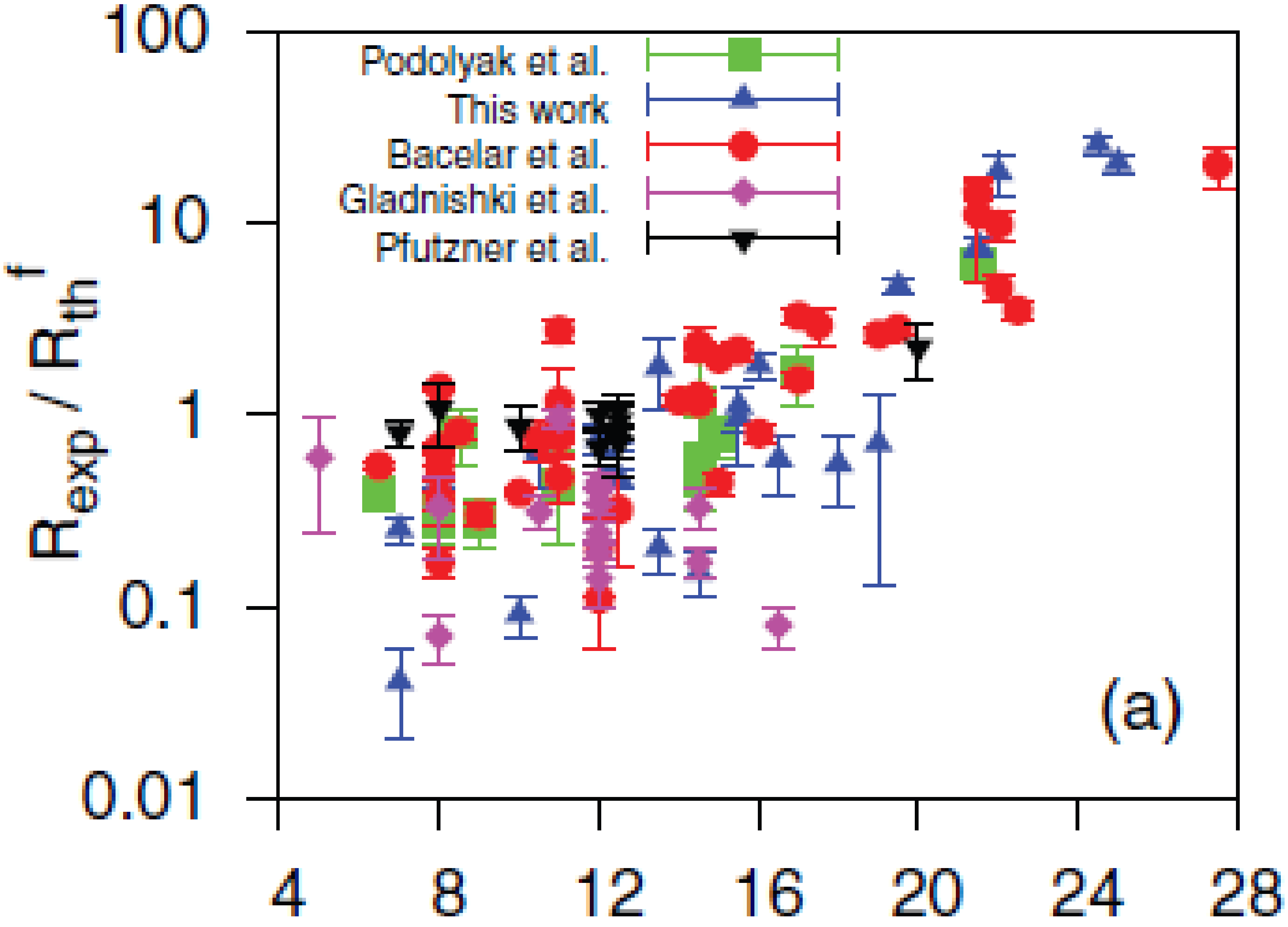


^{179}W populated in:

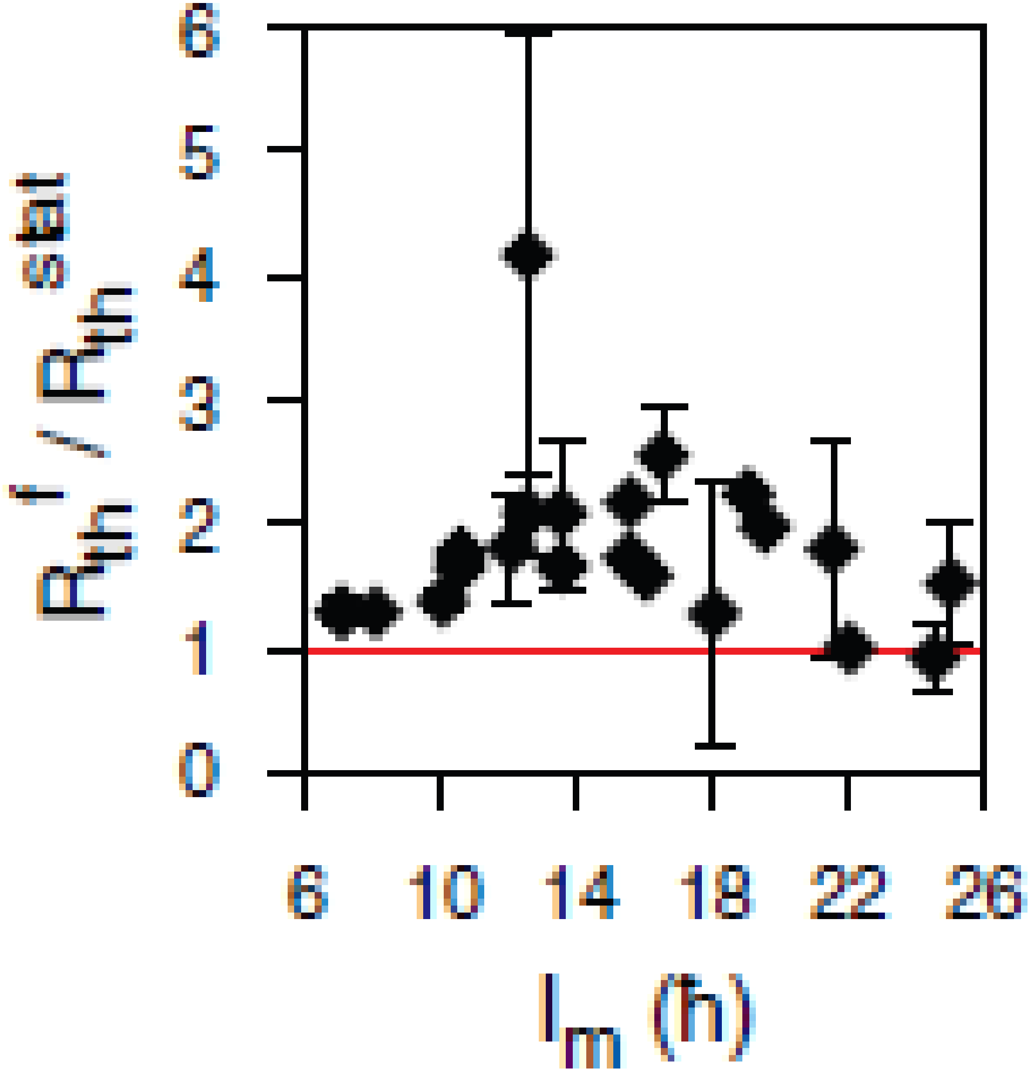
fragmentation of ^{208}Pb at 1 GeV/u

fusion evaporation: $^{170}Er(^{13}C,4n)$ at 67 Me





M. Bowry et al., Phys. Rev. C 88, 024611 (2013)



$R_{th}^{f} / R_{th}^{stat}$
0
1
2
3
4
5
6
6
10
14
18
22
26
l_m (h)