Study of Corresponding Homologous States in ^{41}K and ^{42}Ca via $(\vec{p},\alpha)$ reactions

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Data Taking: Maier Leibnitz Laboratorium - Garching

Tandem Accelerator, Polarized Source, Q3D, Focal Plane Detector

The dependence of $\sigma(\theta)$ and $A_y(\theta)$ of the emitted particles on the transferred total angular momentum *J* is of the greatest importance for identifying the spin and parity of the levels excited in a nuclear reaction.
In particular for $(\vec{p},\alpha)$ reactions, as a general rule, the mean behavior is strictly J^{π} dependent ----->

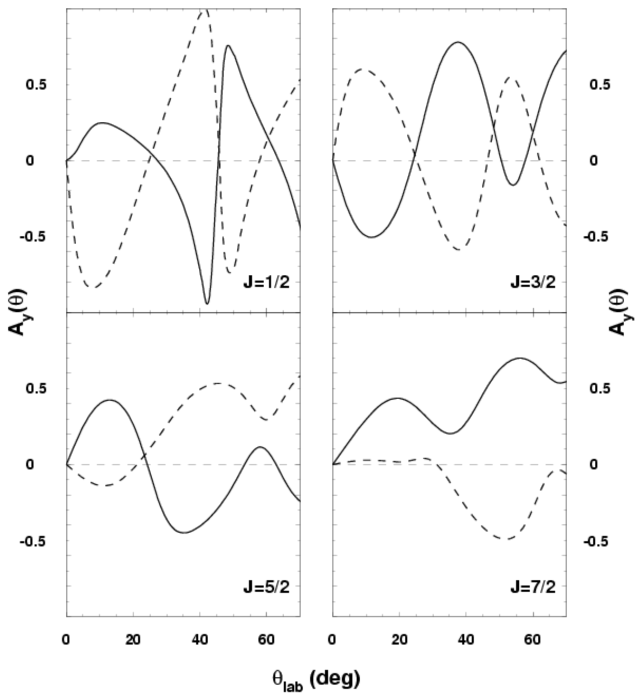
$^{44}Ca(\vec{p},\alpha)^{41}K$

Hypothetical level

at E_x=1500 keV

——— **positive parity states**

– – – – **negative parity states**



(p,α) and $(\vec{p},\alpha)$ reactions

studied for even-even

target nuclei

Only one transferred orbital
and total angular momentum

(p,α) and $(\vec{p},\alpha)$ reactions

on odd mass target nuclei;

several *l* and *j* transferred;

necessity of incoherent sum

of different contributions

Great advantage if only one *l* and *j*

dominate a given

transition amplitude

Good spectroscopic information from the analysis of the experimental data

When only one *l* and *j* dominate a given transition amplitude for (p,α) reactions on odd mass target nuclei?

This behavior can be systematically observed for a number of transitions induced on near magic target nuclei having one unpaired nucleon outside a completely filled magic shell

The dominant contribution to the α–spectrum results from a process in which the incident proton picks up a proton and a pair of neutrons from the nuclear core, while the valence nucleon outside the core acts as *spectator*

two parts in the α–spectrum :

higher excitation energies

multiplets of states are found, whose configuration results from a process in which the unpaired nucleon is not involved

lower excitation energies

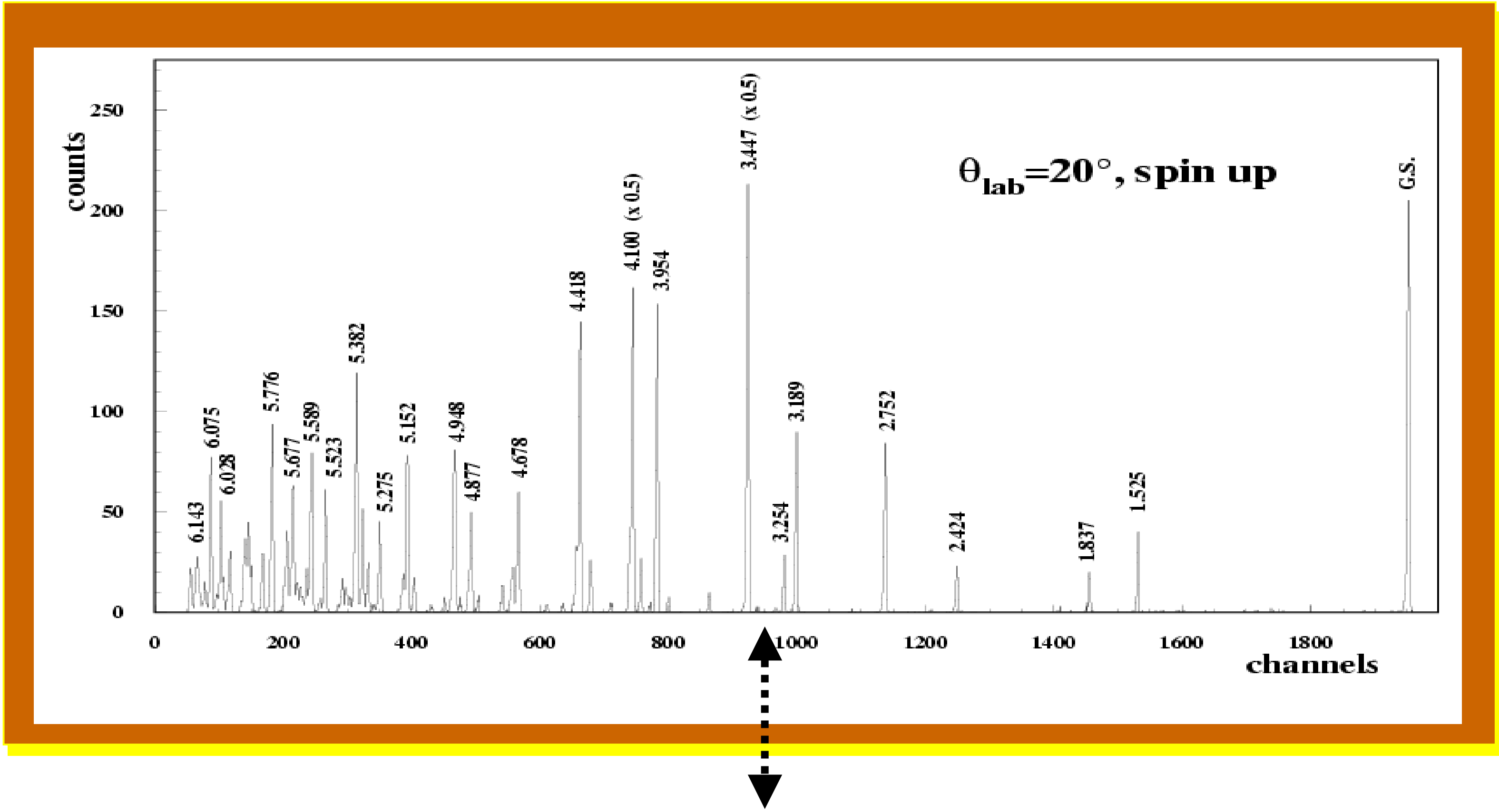
weakly excited states are found, populated by a process involving the unpaired nucleon

$^{45}Sc(\vec{p}, \alpha)^{42}Ca$

$^{45}Sc(p,\alpha)\,^{42}Ca$	Q_{val} = 2.3415 MeV
$^{44}Ca(p,\alpha)\,^{41}K$	Q_{val} = -1.0462 MeV

ΔQ_{val} = 3.3877 MeV

higher excitation energies **lower excitation energies**



~ 3.4 MeV

P.Guazzoni - spin2004, October 10_16 2004

HOMOLOGOUS STATES

The one-proton-hole-two-neutron-hole states excited in (p,α) reactions on magic target nuclei, with a magic neutron and/or proton shell- we denote as *parent states*.

In near magic target nuclei, with one more nucleon outside the magic shell *-the spectator nucleon-* the weak coupling of a parent state with the spectator nucleon originates a multiplet of states, *daughter states*, with spin J $|J_p-J_c| \leq J \leq (J_p+J_c)$

J_p= spin of the spectator

J_c = spin of the core.

We denote

the daughter states and the corresponding parent state as

HOMOLOGOUS STATES

states with a close structural relationship

Methodology

In case of *weak coupling* between the *parent state* and the *spectator nucleon*, it is expected for the *excited multiplets* of daughter states THAT:

1

Angular distributions of $\sigma(\theta)$ and $A_y(\theta)$ *very similar in shape* for all the multiplet and parent states

scaled by $(2J_i+1)/\Sigma_i\,(2J_i+1)$

2

Parent state $\sigma(\theta)$ magnitude same as $\sigma(\theta)$ SUM of all the corresponding daughter states

cumulative cross section

3

ratio between daughter (J) $\sigma(\theta)$ and parent state $\sigma(\theta)$ PROPORTIONAL to (2J+1)

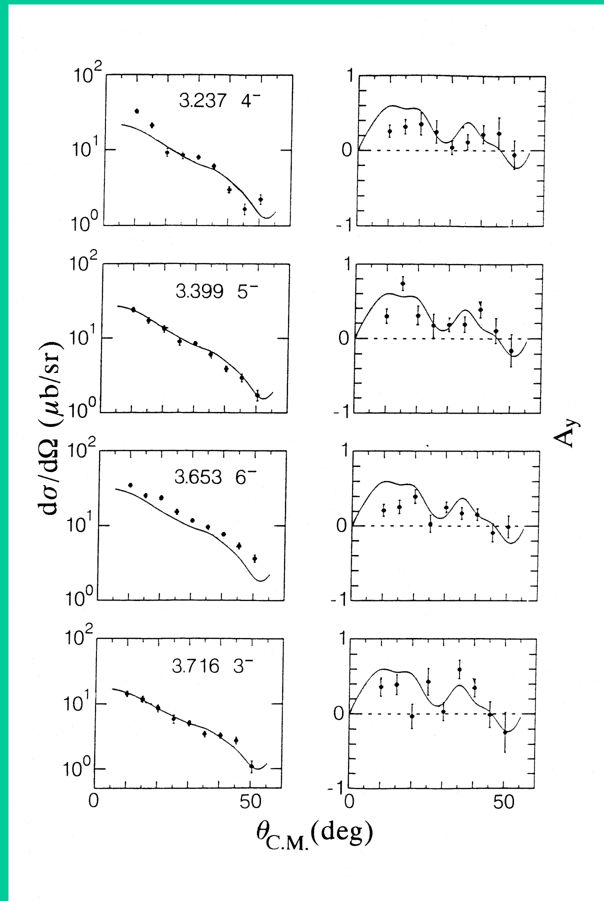
1

Angular distributions of $\sigma(\theta)$ and $A_y(\theta)$ very similar in shape for all the multiplet states and the parent state

scaled by $(2J_i+1)/\Sigma_i (2J_i+1)$

$^{208}Pb(\vec{p},\alpha)^{205}Tl$

$^{209}Bi(\vec{p},\alpha)^{206}Pb$



Parent	^{205}Tl 0.204 MeV $3/2^+$
Daughters	^{206}Pb Quartet $3^- \; 4^- \; 5^- \; 6^-$

2

σ(θ) for the parent state is the same as the SUM of the σ(θ)'s of all the corresponding daughter states of the multiplet

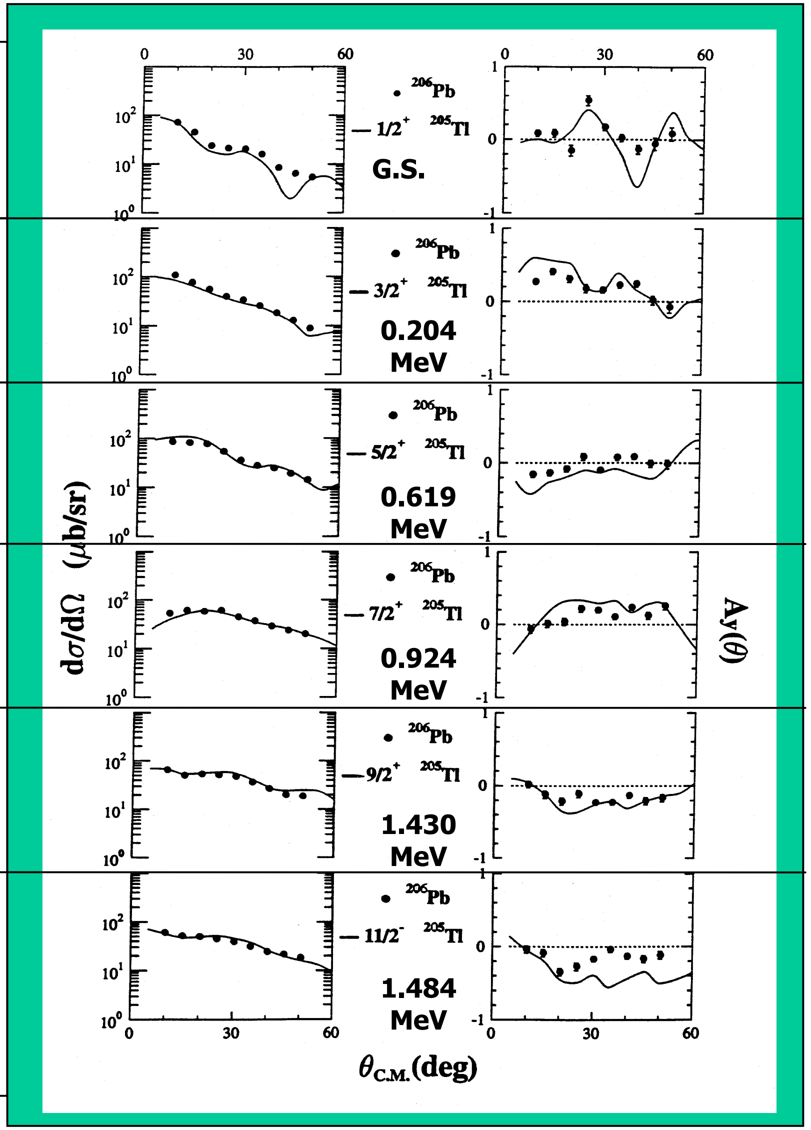
$^{208}Pb(\vec{p},\alpha)^{205}Tl$

$^{209}Bi(\vec{p},\alpha)^{206}Pb$

cumulative angular distributions

DAUGHTER STATES

found	missed
4-,5-	==
3-,4-, 5-,6-	==
2-,3-,4-, 5-,6-,7-	==
2-,3-,4-, 5-, 6-,7-,8-	1-
2-,3-,5-, 6-, 7-,8-, 9-	0-,1-, 4-
1^+,2^+ 3^+,4^+, 5^+, 6^+,7^+,8^+, 9^+,10^+	



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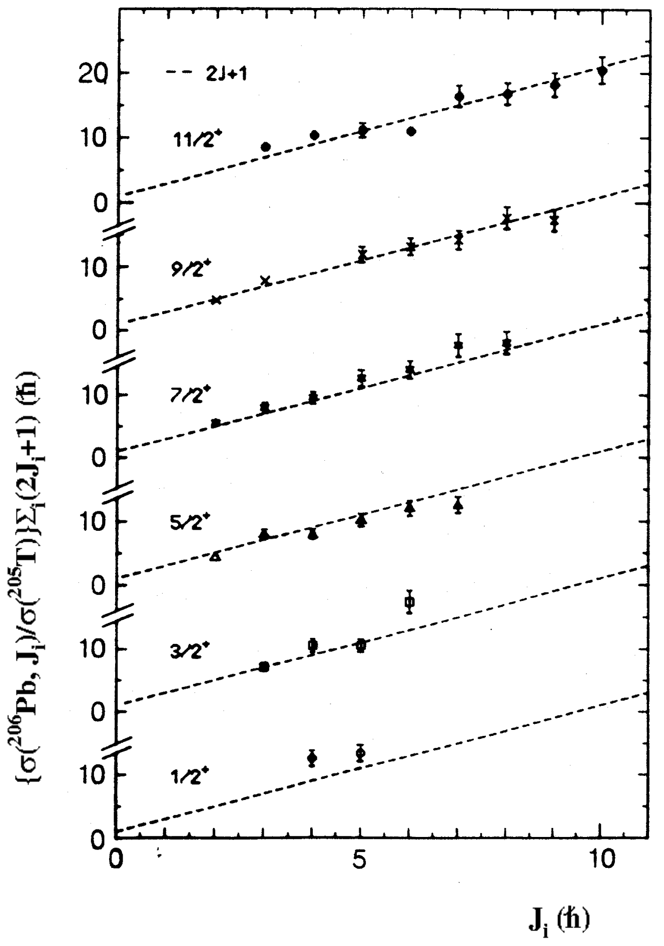
3

The ratio between the daughter (J_i) $\sigma(\theta)$ and parent state $\sigma(\theta)$ is PROPORTIONAL to ($2 J_i +1$).



$^{208}Pb(\vec{p},\alpha)^{205}Tl$

$^{209}Bi(\vec{p},\alpha)^{206}Pb$

$\sigma_{daughter}(^{206}Pb,J_i) = \sigma_{parent}(^{205}Tl) * (2 J_i+1)/\Sigma(2 J_i+1)$

Experiments

The concept of homologous states has been investigated in high resolution experiments

Maier Leibnitz Beschleuniger Laboratorium - Garching
Tandem Accelerator, Polarized Source, Q3D, Focal Plane Detector

Studied nuclei (already published):

the pair ^{209}Bi, ^{208}Pb
----> closed shells Z=82, N=126
$^{209}Bi(\vec{p},\alpha)^{206}Pb$
$^{208}Pb(\vec{p},\alpha)^{205}Tl$
spectator nucleon:
proton $1h_{9/2}$

the pair ^{91,90}Zr
----> closed shells Z=82, N=126
$^{91}Zr(\vec{p},\alpha)^{88}Y$
$^{90}Zr(\vec{p},\alpha)^{87}Y$
spectator nucleon:
neutron $2d_{5/2}$

Studied nuclei (to be published):

the pair ^{123}Sb, ^{122}Sn ----> closed shell Z=50

$$^{122}Sn(\vec{p},\alpha)^{119}In$$

$$^{123}Sb(\vec{p},\alpha)^{122}Sn$$

spectator nucleon: proton $1g_{7/2}$

Measured Reactions:

Z=38 Subshell → *spectator nucleon: proton $2p_{1/2}$*

$^{89}Y(\vec{p},\alpha)^{86}Sr$ & $^{88}Sr(\vec{p},\alpha)^{85}Rb$

N=82 closed shell → *spectator nucleon: neutron $2f_{7/2}$*

$^{143}Nd(\vec{p},\alpha)^{140}Pr$ & $^{142}Nd(\vec{p},\alpha)^{139}Pr$

Recent Results

$^{45}Sc(\vec{p},\alpha)^{42}Ca$ ***daughter reaction***

$^{44}Ca(\vec{p},\alpha)^{41}K$ ***parent reaction***

spectator nucleon: proton $1f_{7/2}$

Multiplet corresponding to ^{41}K G.S. $3/2^+$ Parent State

Expected $2^-, 3^-, 4^-, 5^-$

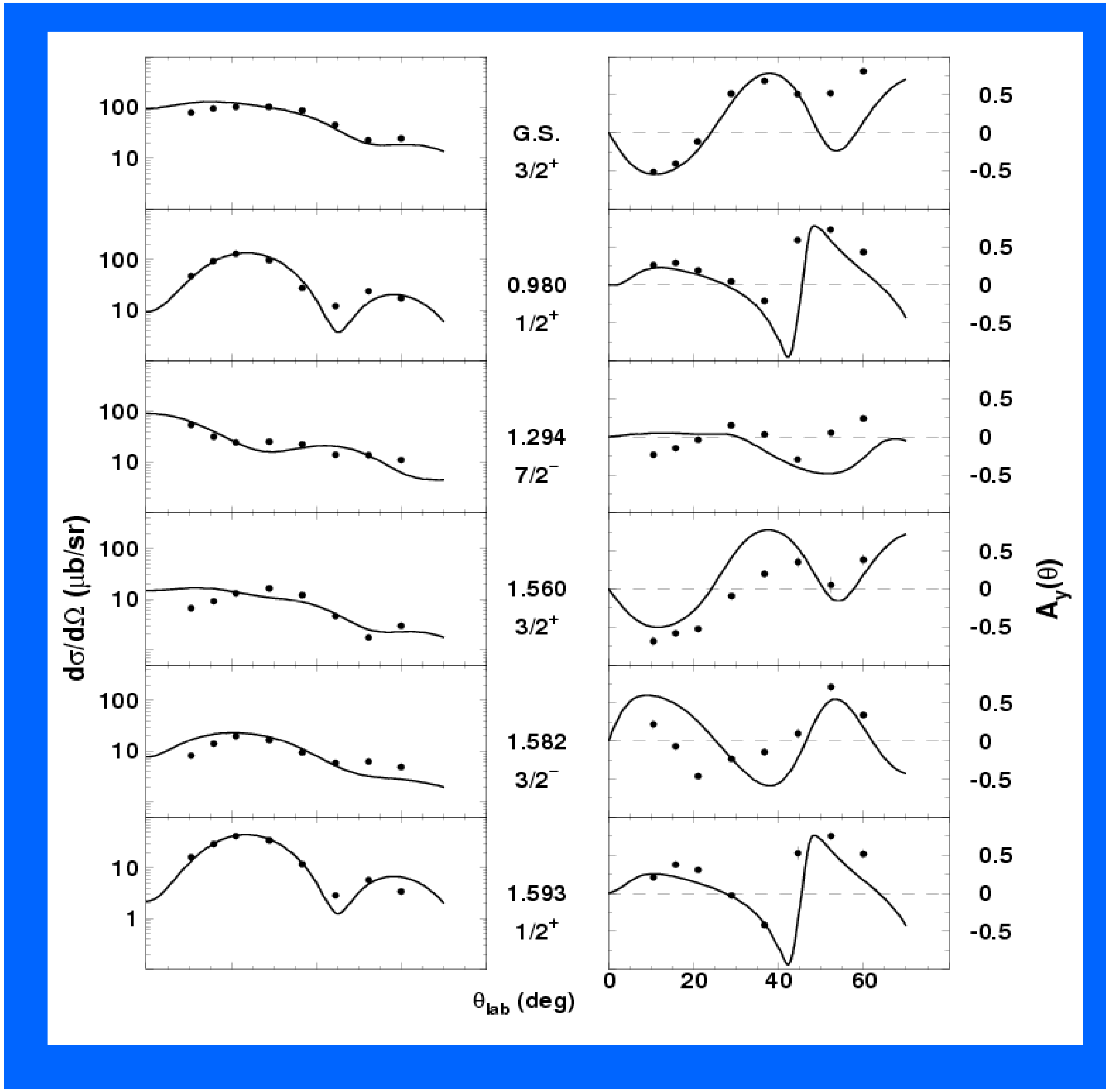
$|J_p - J_c| \leq J \leq (J_p + J_c)$ → $J^\pi = 2^-, 3^-, 4^-, 5^-$

$\sigma(\theta)$ values for all the daughter states

$J^\pi=2^-$	$\sigma(\theta)$ *parent*	scaled by 0.1562
$J^\pi=3^-$	$\sigma(\theta)$ *parent*	scaled by 0.2187
$J^\pi=4^-$	$\sigma(\theta)$ *parent*	scaled by 0.2812
$J^\pi=5^-$	$\sigma(\theta)$ *parent*	scaled by 0.3437

$^{44}Ca(\vec{p},\alpha)^{41}K$ parent reaction

Solid line: DWBA
Dots: exp



σ_{int}=159.11 μb (10°-65°)

σ_{int}=140.48 μb (10°-65°)

σ_{int}= 64.92 μb (10°-65°)

σ_{int}= 22.93 μb (10°-65°)

σ_{int}= 32.78 μb (10°-65°)

σ_{int}= 47.82 μb (10°-65°)

$^{45}Sc(\vec{p},\alpha)^{42}Ca$ daughter reaction

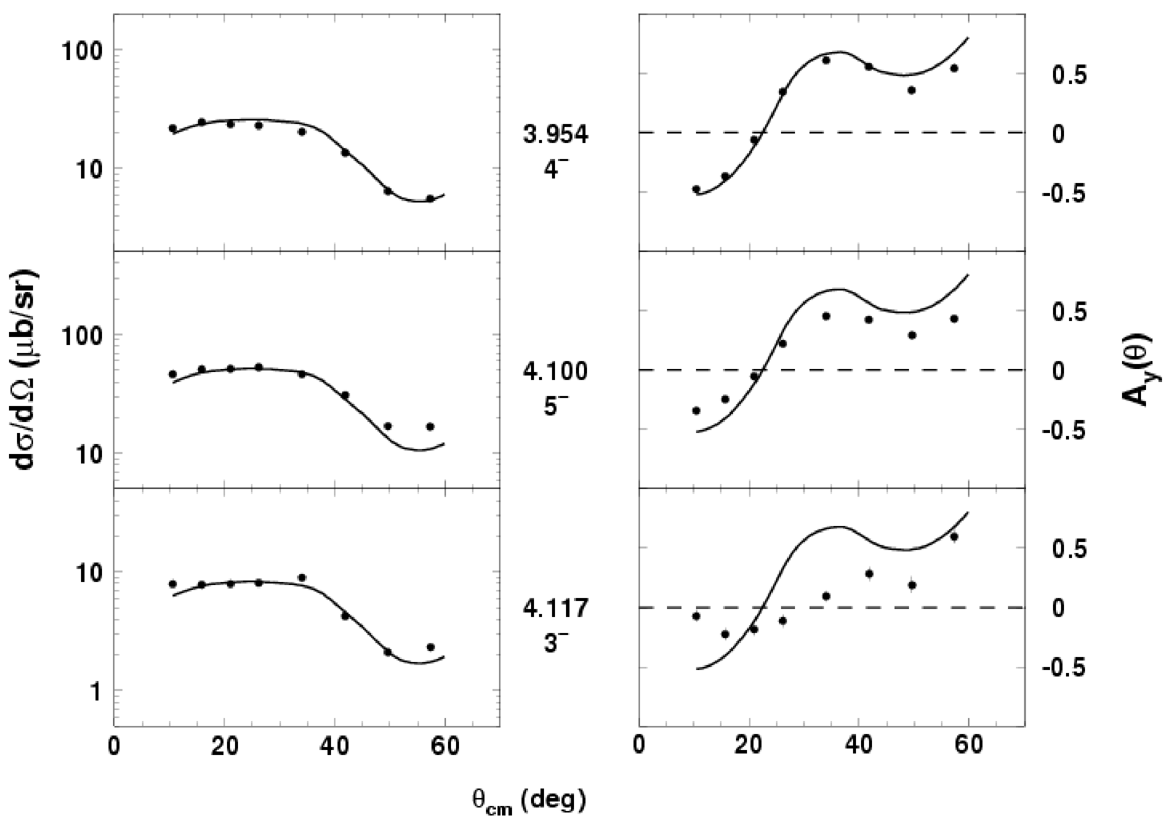
Expected $J^{\pi}=2^-,3^-,4^-,5^-$

Multiplet corresponding to

^{41}K G.S. 3/2$^+$ σ_{int}=159.11 μb (10°-65°)

Solid line: parent state, exp

Dots: daughter states, exp



σ_{int}= 47.82 μb (10°-65°)

σ_{int}=113.55 μb (10°-65°)

σ_{int}= 17.17 μb (10°-65°)

2^-: NOT SEEN

WHY?

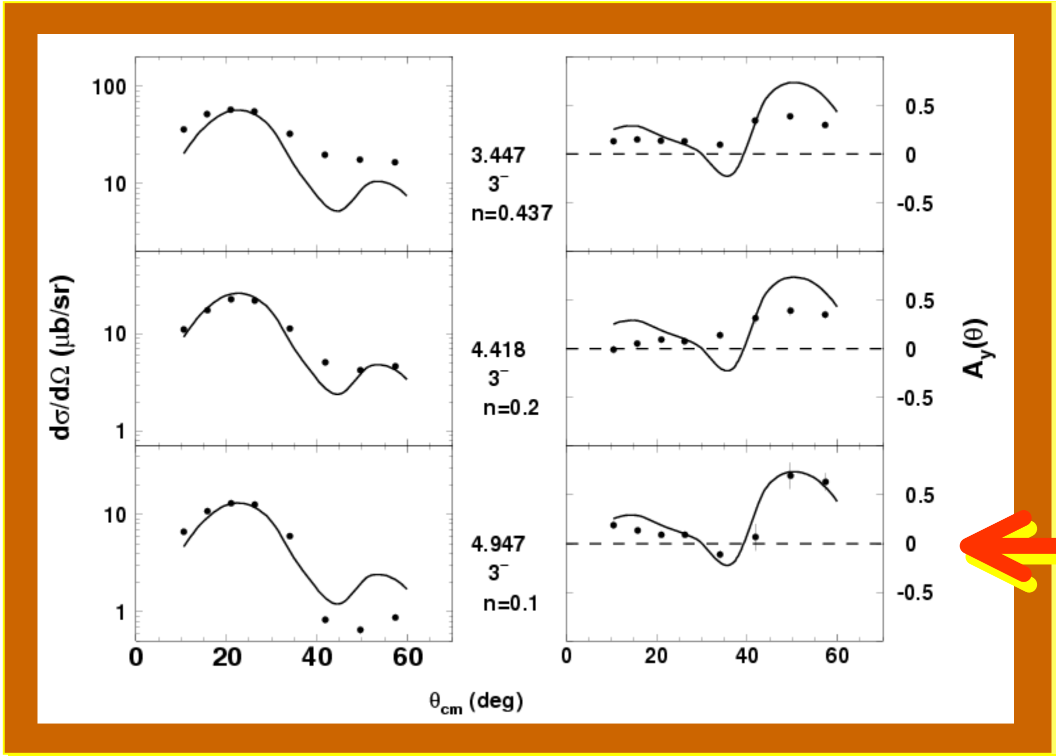
^{45}Sc($\vec{p}$,α)^{42}Ca daughter reaction

Expected $J^{\pi}=3^-,4^-$

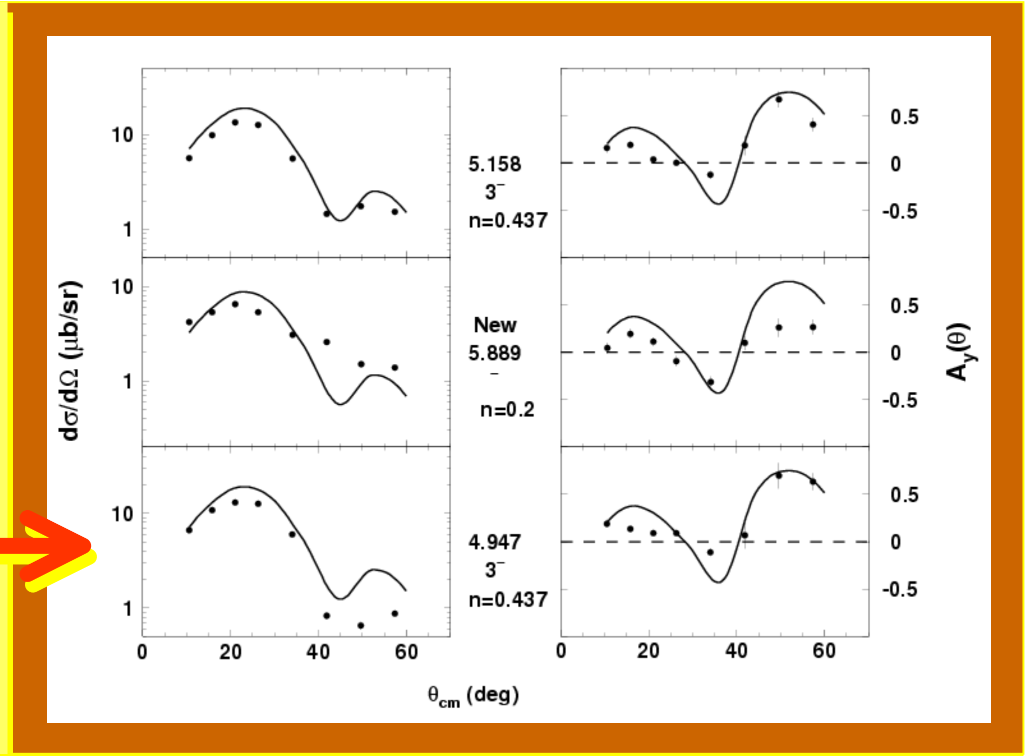
some levels of multiplets corresponding to

Solid line:	**parent state,**	**exp**
Dots:	**daughter states,**	**exp**

Parent level: 41K ½+ 0.980 MeV



Parent level: 41K ½+ 1.593 MeV



3^- n_{th}=0.437 4^- n_{th}=0.563

CLUSTER DWBA CALCULATIONS

A generally accepted rule for (p,α) reactions
is that α's feeding states with the same
J^{π} have nearly the same shape for
angular distributions
of cross sections and asymmetries.

True → Not Homologous States

False → Homologous States

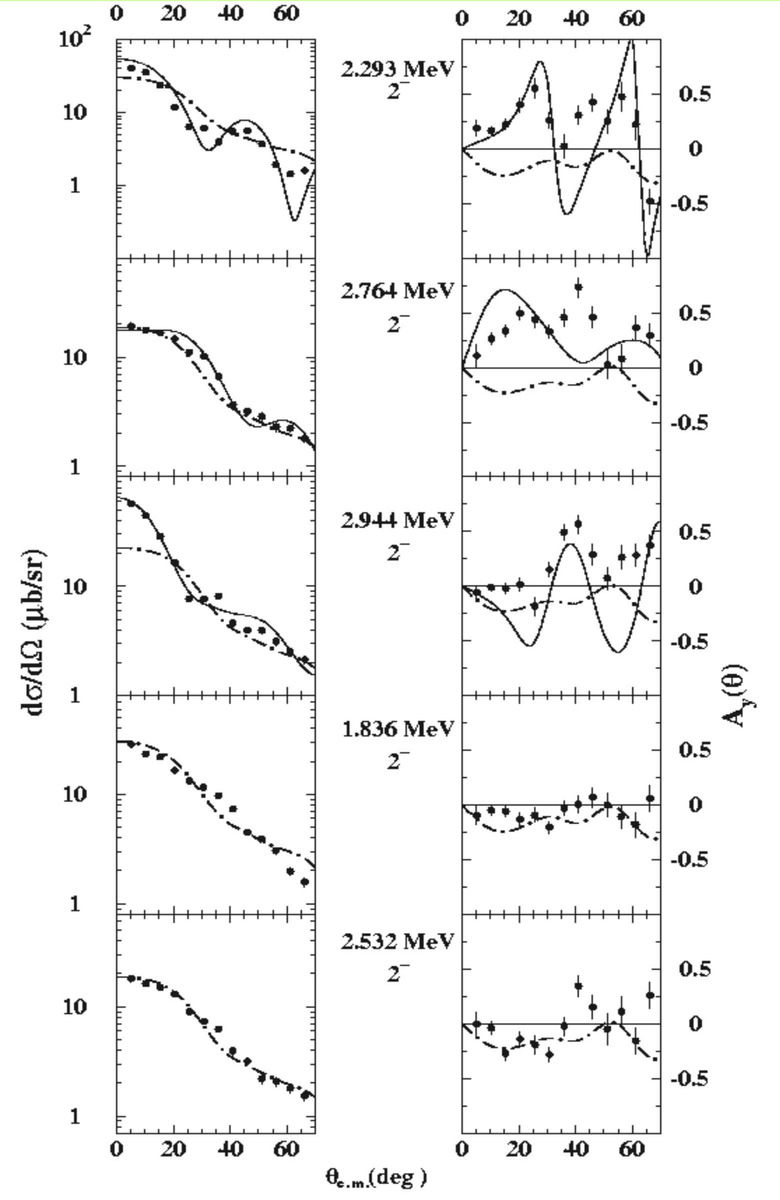
$^{91}Zr(\vec{p},\alpha)^{88}Y$ *daughters*

$^{90}Zr(\vec{p},\alpha)^{87}Y$ *parent*

DWBA - configuration of the parent state

DWBA - incoherent sum of different l,j ang. distr.

^{88}Y - experimental values



Homologous
^{87}Y G.S. $1/2^-$

Homologous
^{87}Y 0.794 $5/2^-$

Homologous
^{87}Y 0.982 $3/2^-$

Not Homologous

Not Homologous

SHELL MODEL CALCULATIONS FOR THE HOMOLOGOUS STATES

$A \approx 208$
$A \approx 90$
} **Done**

$A \approx 40$ } **Work in progress**

The achieved results clearly indicate:

COMMON CONFIGURATIONS

for

HOMOLOGOUS STATES

This similarity is more evident in case of purest states as, for example, the ^{206}Pb multiplet of daughter states, homologous to the 1.484 MeV, 11/2^{-}, ^{205}Tl parent state.

$^{208}Pb(\vec{p},\alpha)^{205}Tl$

$^{209}Bi(\vec{p},\alpha)^{206}Pb$

The parent state $11/2^-$ of ^{205}Tl
at 1.501 MeV (Calc.) (1.484 MeV - Exp.)

SHELL MODEL CALCULATIONS

[NO]	p(%)	D5	D3	S1	H11	F5	P3	P1	I13
[1]	7.97	6	4	2	11	6	4	2	12
[3]	1.48	6	3	2	12	5	4	2	13
[3]	1.00	6	4	2	11	5	3	2	14
[3]	1.13	6	3	2	12	6	3	2	13
[l]	17.28	6	4	2	11	4	4	2	14
[3]	0.66	5	4	2	12	6	4	1	13
[3]	8.61	6	4	2	11	5	4	1	14
[3]	1.28	6	4	1	12	6	3	2	13
[3]	9.52	6	3	2	12	6	4	1	13
[3]	3.68	6	4	2	11	6	3	1	14
[l]	5.60	6	4	2	11	6	2	2	14
[l]	40.90	6	4	2	11	6	4	0	14

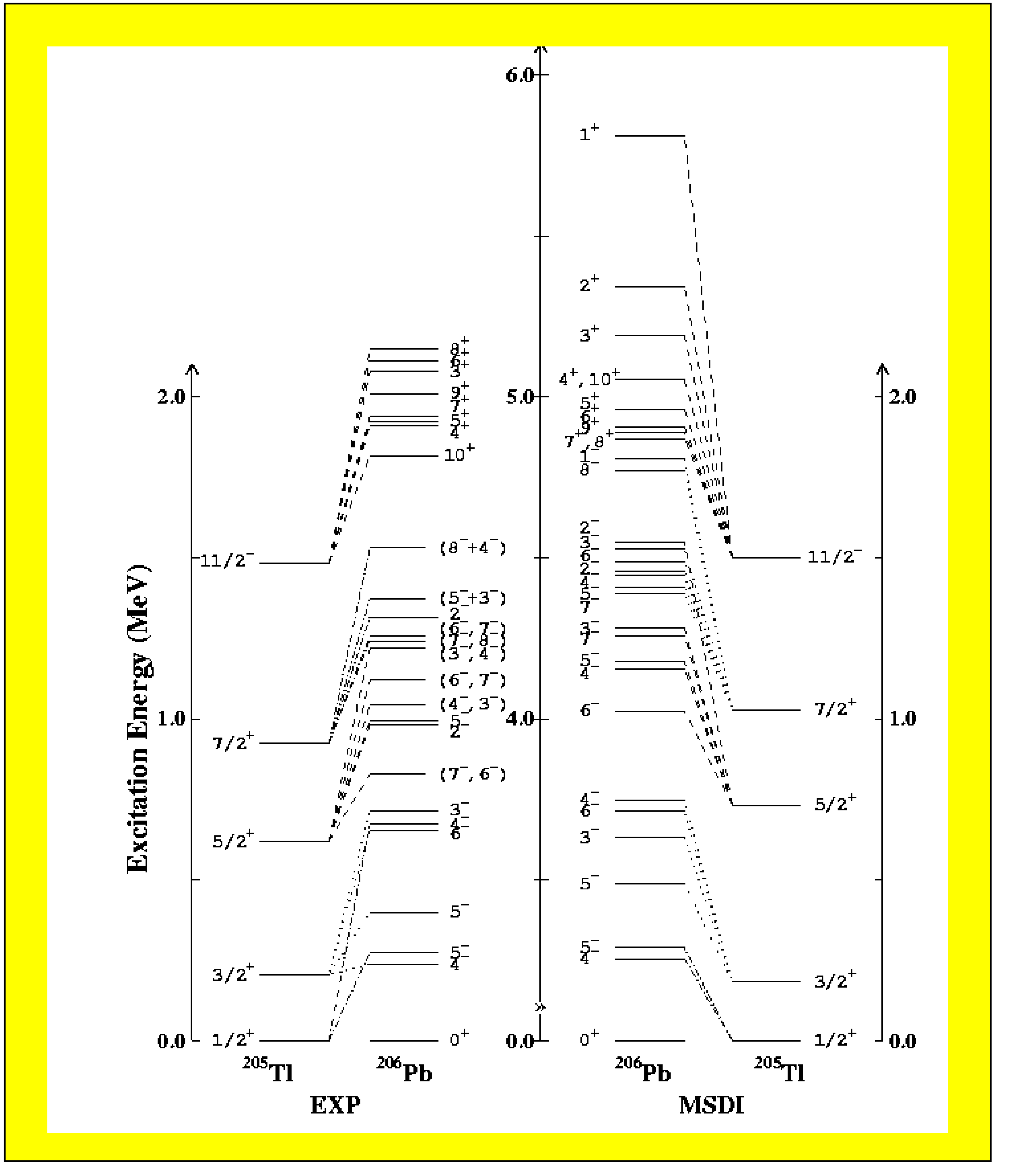
Homologous states: ^{206}Pb, ^{205}Tl

Parent	Son States									
$11/2^-$	10+	9+	8+	7+	6+	5+	4+	3+	2+	l+
1.501	5.068	4.909	4.886	4.887	4.923	4.977	5.068	5.202	5.356	5.833
1.484	4.818	5.011	5.149	4.941	5.112	4.925	4.912	5.078		
7.97	6.79	6.86	6.47	6.54	6.49	6.75	7.03	7.44	8.14	5.76
1.48	3.32	2.36	2.13	1.97	2.04	2.00	1.90	1.69	1.30	2.77
1.00	1.87	1.80	1.69	1.53	1.67	1.89	1.98	1.76	1.20	1.36
1.13		1.25	1.10	1.23	1.23	1.33	1.32	1.23	1.01	
17.28	17.75	16.33	16.40	15.88	16.33	16.76	17.68	18.24	19.34	16.01
0.66										
8.61	12.53	13.17	14.41	14.52	14.70	14.31	13.12	11.47	7.61	17.54
1.28	1.11	1.43	1.12	1.26	1.12	1.20	1.09	1.13		
9.52	6.54	9.61	8.02	8.82	8.12	8.37	7.89	8.18	7.88	10.84
3.68	4.80	5.31	5.71	5.76	5.86	5.74	5.19	4.38	2.68	4.23
5.60	5.27	5.17	5.12	5.02	5.10	5.25	5.47	5.61	5.88	4.42
40.90	35.66	34.60	35.37	35.28	35.07	34.41	35.46	37.23	42.43	32.41

$^{208}Pb(\vec{p},\alpha)^{205}Tl$

$^{209}Bi(\vec{p},\alpha)^{206}Pb$

EXPERIMENTAL AND SHELL MODEL ENERGY SPECTRUM



SHELL MODEL CALCULATIONS

$^{45}Sc(\vec{p},\alpha)^{42}Ca$

$^{44}Ca(\vec{p},\alpha)^{41}K$

Code Antoine by E. Caurier

Interaction used: sdfp.sm for both ^{41}K and ^{42}Ca {Nummela et al. Phys Rev C63 (2001) 044316}

^{41}K	GS $3/2^+$	Dominant configuration: $\pi(d_{3/2}^{-1})\ \ \nu(f_{7/2}^{\ 2})$
^{42}Ca	$3^-, 4^-, 5^-$	Dominant configuration: $\pi(f_{7/2}^{\ 1}\, d_{3/2}^{-1})\ \ \nu(f_{7/2}^{\ 2})$
		Homologous structure

^{42}Ca	2^-	Different structure: several configurations contribute to the state wave function

Multiplet of Daughter States corresponding to ^{41}K G.S. $3/2^+$ Parent State

ν							π							
$p_{1/2}$	$f_{5/2}$	$p_{3/2}$	$f_{7/2}$	$d_{3/2}$	$s_{1/2}$	$d_{5/2}$	$p_{1/2}$	$f_{5/2}$	$p_{3/2}$	$f_{7/2}$	$d_{3/2}$	$s_{1/2}$	$d_{5/2}$	%
^{41}K G.S. 3/2+ Parent State														
0	0	0	2	4	2	6	0	0	0	0	3	2	6	**87.8**
0	0	1	1	4	2	6	0	0	0	0	3	2	6	**1.4**
0	0	2	0	4	2	6	0	0	0	0	3	2	6	**3.2**
0	2	0	0	4	2	6	0	0	0	0	3	2	6	**2.9**
^{42}Ca 3^-											**Total Homologous 77.6 %**			
0	0	0	2	4	2	6	0	0	0	1	3	2	6	**64.7**
0	0	1	1	4	2	6	0	0	0	1	3	2	6	**8.5**
0	0	2	0	4	2	6	0	0	0	1	3	2	6	**2.5**
0	2	0	0	4	2	6	0	0	0	1	3	2	6	**1.9**
^{42}Ca 4^-_1											**Total Homologous 82.4%**			
0	0	0	2	4	2	6	0	0	0	1	3	2	6	**74.1**
0	0	1	1	4	2	6	0	0	0	1	3	2	6	**3.8**
0	0	2	0	4	2	6	0	0	0	1	3	2	6	**2.3**
0	2	0	0	4	2	6	0	0	0	1	3	2	6	**2.2**
^{42}Ca 5^-_1											**Total Homologous 78.4%**			
0	0	0	2	4	2	6	0	0	0	1	3	2	6	**68.9**
0	0	1	1	4	2	6	0	0	0	1	3	2	6	**4.6**
0	0	2	0	4	2	6	0	0	0	1	3	2	6	**2.6**
0	2	0	0	4	2	6	0	0	0	1	3	2	6	**2.3**
^{42}Ca 2^-_1											**Not Homologous**			
0	0	0	2	4	2	6	0	0	0	1	3	2	6	**29.4**
0	0	1	1	4	2	6	0	0	0	1	3	2	6	**18.6**
0	0	2	0	4	2	6	0	0	0	1	3	2	6	**1.9**

$^{123}Sb(\vec{p},\alpha)^{122}Sn$

MICROSCOPIC DWBA CALCULATIONS

Fully microscopic calculations: the proton and two neutrons are picked up from individual shell-model states, and then their overlap with respect to the transferred three-particle cluster is calculated

^{123}Sb G.S. is taken to be a $1g_{7/2}$ proton outside filled proton shells.
22 valence neutrons move in the $1g_{7/2} - 2d_{5/2} - 2d_{3/2} - 3s_{1/2} - 1h_{11/2}$ shells interacting via a neutron-neutron pairing force which spreads the neutrons over the valence cells with a total neutron angular momentum of zero

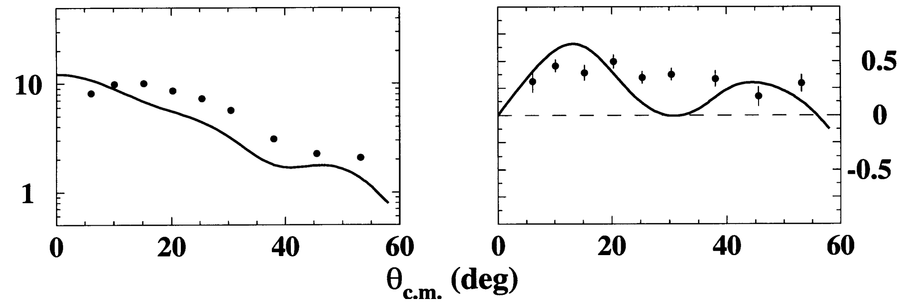
The pickup reaction to ^{120}Sn G.S. involves the transfer of a $1g_{7/2}$ proton and a neutron pair coupled to zero angular-momentum

The pickup reaction to ^{120}Sn multiplet homologous to ^{119}In G.S. removes a $1g_{9/2}$ proton and a neutron pair coupled to zero angular-momentum,
while the $1g_{7/2}$ proton remains spectator

$^{123}Sb(\vec{p},\alpha)^{120}Sn$

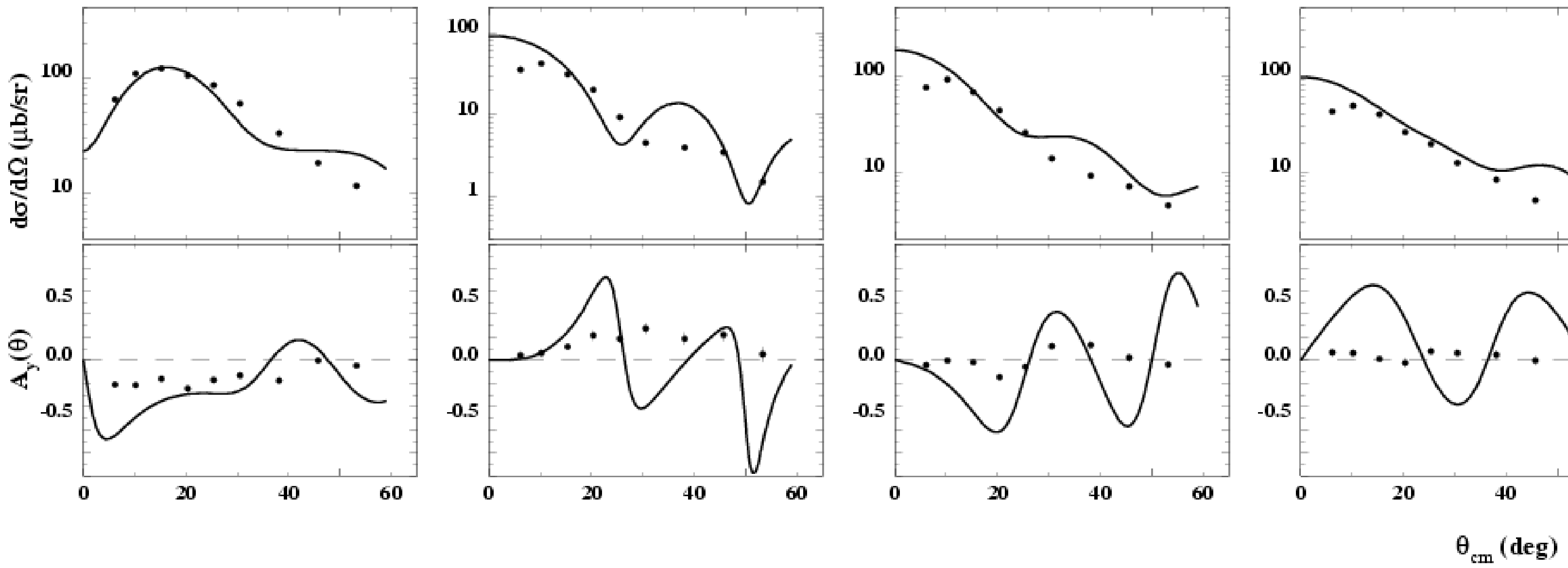
MICROSCOPIC DWBA CALCULATIONS

^{120}Sn G.S.



Cumulative angular distributions of Multiplet homologous to

^{119}In G.S. $9/2^+$ ^{119}In 0.311 $1/2^-$ ^{119}In 0.604 $3/2^-$ ^{119}In 1.044 $5/2^-$



Dots : experimental values Solid : Microscopic DWBA calculations

CONCLUSIONS

- **Shell Model calculations strongly support the Homologous state experimental results**
- **Shell Model calculations seem to indicate the correctness of the approach also for closed subshells, to be verified experimentally**
- **Applicability limits for the theory are the shell model limitations**

CONCLUSIONS

- **DWBA microscopic calculations also support the validity of the spectator role of the unpaired proton weakly coupled to the parent core-state.**

- **Homology concept useful spectroscopic tool for regions nearby closed shells**

- **The use of the concept of the spectator nucleon allows a *unambiguous* attribution of spin and parity to several states at relatively high excitation energies.**