Proton knockout and transfer reactions on light and medium-mass nuclei

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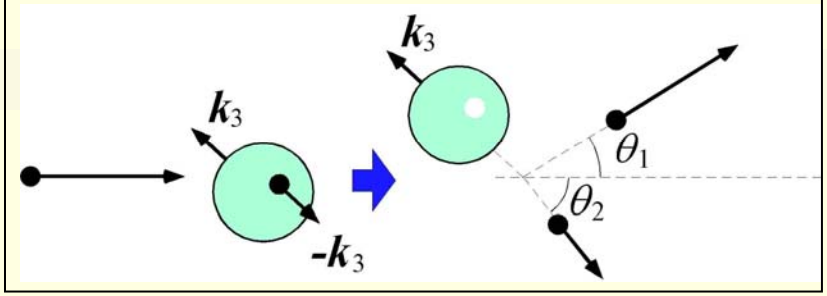
Contents

- (*p*,2*p*) reaction as a tool to study nuclear structure and radii of 1s proton distributions deduced from (p,2p) reactions for light nuclei

- Measurement of shell energies in Ca isotopes by using (^{3}He,*t*) and (*p*,2*p*) reactions

Introduction: Exclusive nucleon knockout

Kinematics



provides a direct means to study
single-particle properties of target nuclei.

(*e*,*e*'*p*): ・Distortion effect is less serious.
・Interaction is well known.

(*p*,2*p*):
・Large cross section is suited for systematic studies.
・Spin degree of freedom provides additional information.
・Inverse-kinematics experiment is feasible.

Is the reaction mechanism simple enough?
Does the impulse approximation work reasonably well?

(p,2p) reactions as a tool to study nuclear structure

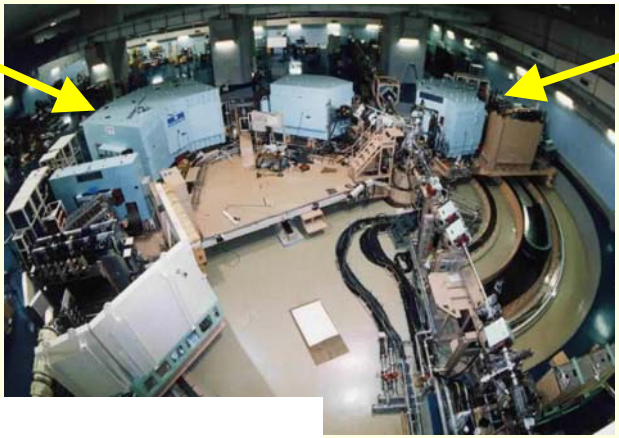
-- Comparison with DWIA calculations

-- Comparison with (*e*,*e*'*p*) data

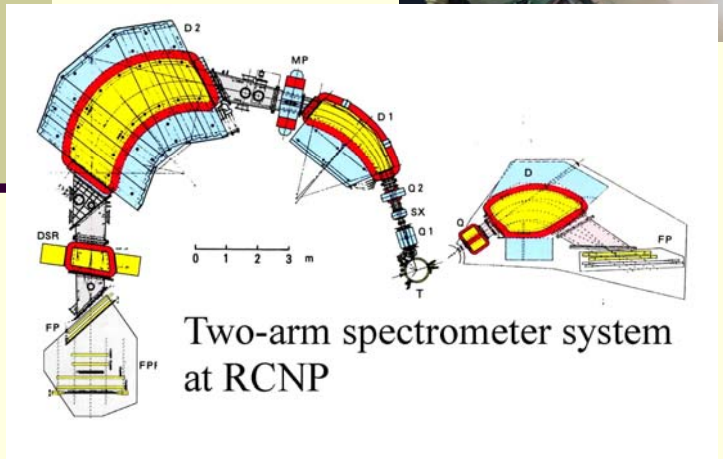
Experiment

Experimental Apparatus

High resolution spectrometer 'Grand Raiden'

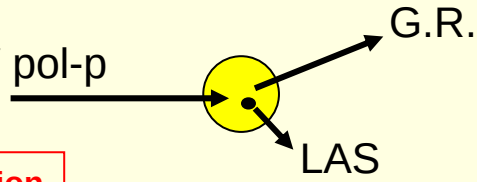


Large Acceptance Spectrometer 'LAS'

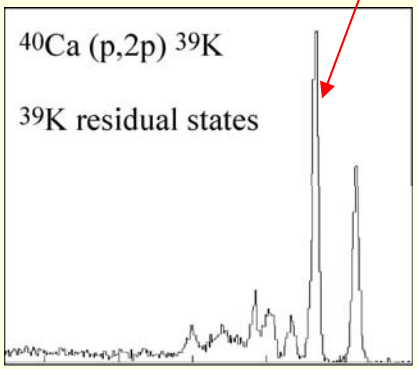


Two-arm spectrometer system at RCNP

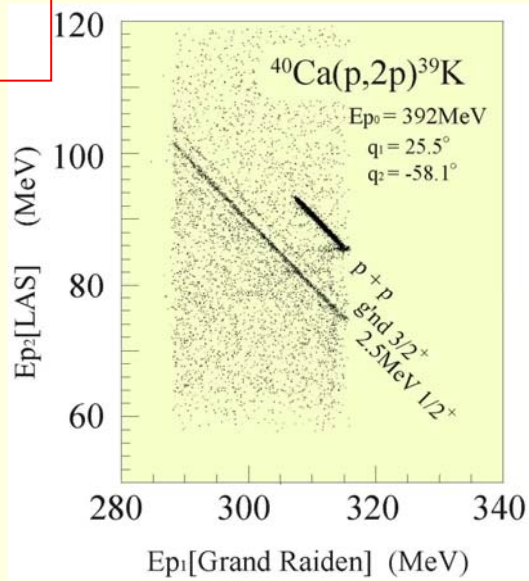
392 MeV pol-p



250keV resolution In recent measurements



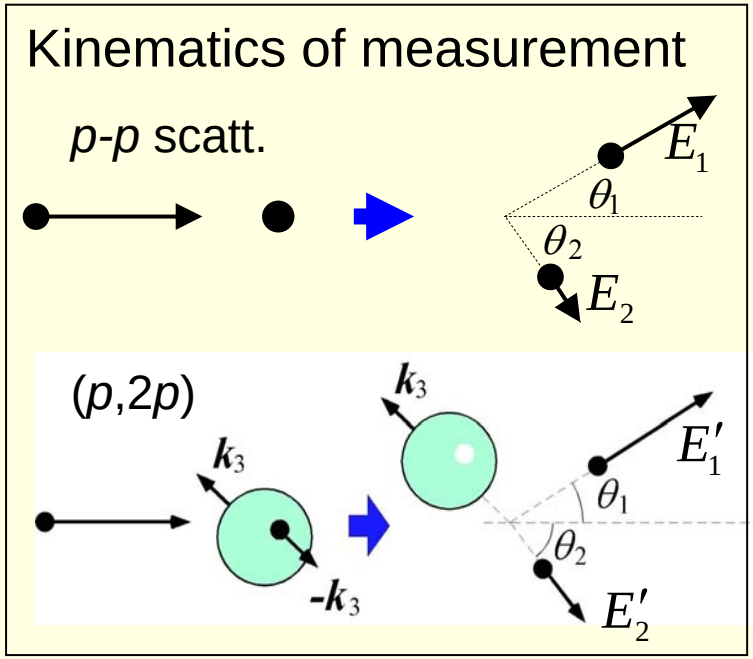
Projected spectrum

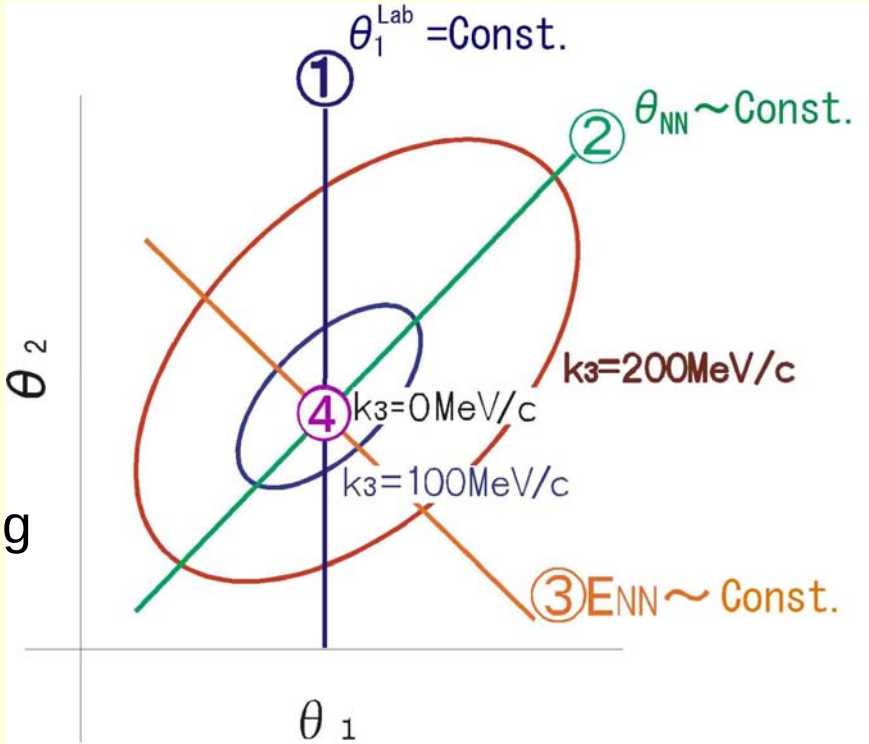


Summed energy (E_1+E_2)

[← *Ex* or *Es*]

(*p*,2*p*) reactions to discrete states in various kinematical conditions





Observation of $\boldsymbol{k_3}$ dependence along

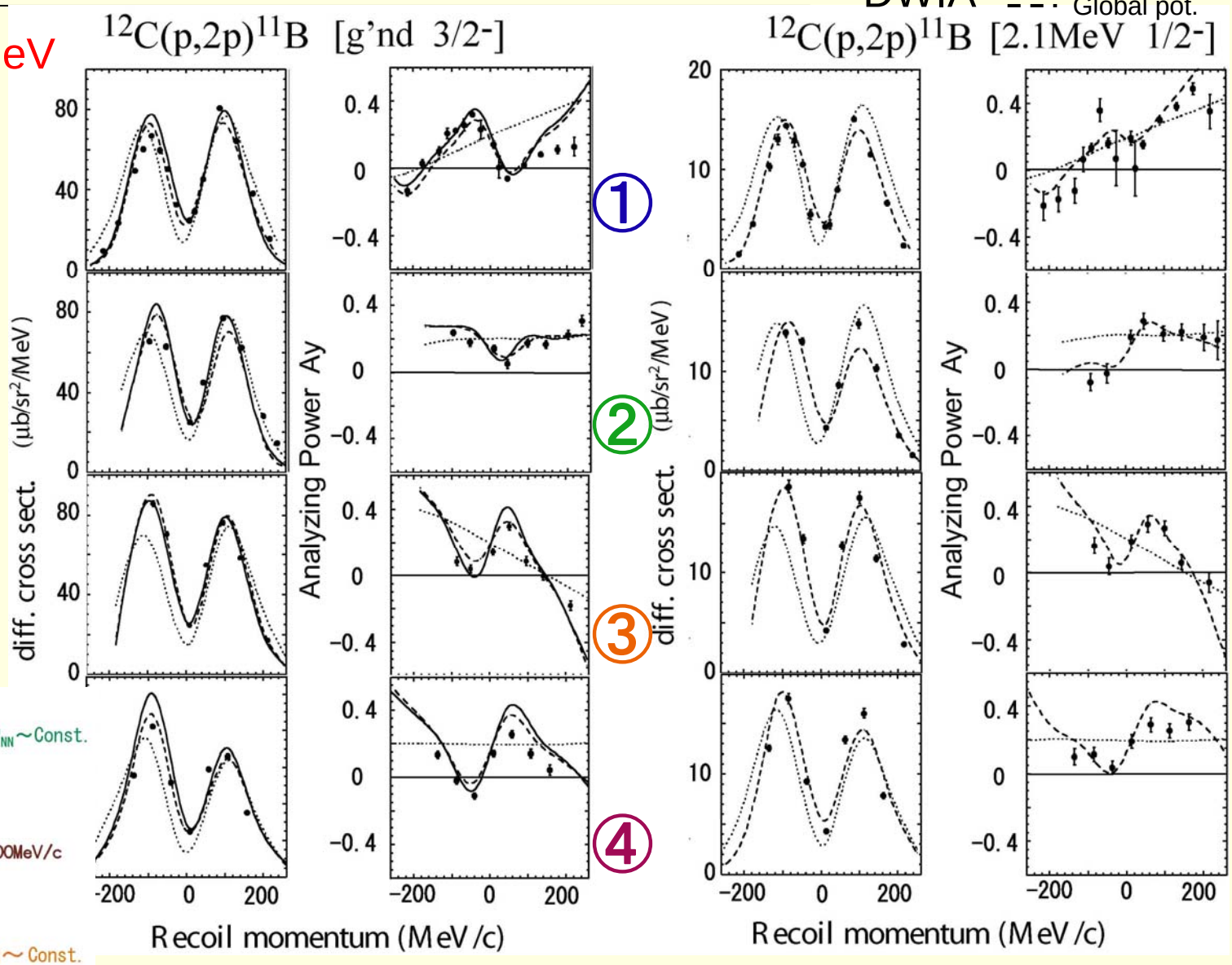
①②③ : (E_1=250MeV, E_2~130MeV) fixed

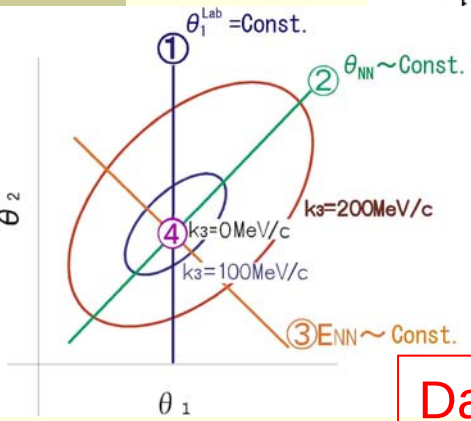
④ : (θ_1=32.5° , θ_2~60°) fixed

Experimental data for various kinematics

PWIA .....
DWIA —— RIA w.f. & pot.
- - - Global pot.

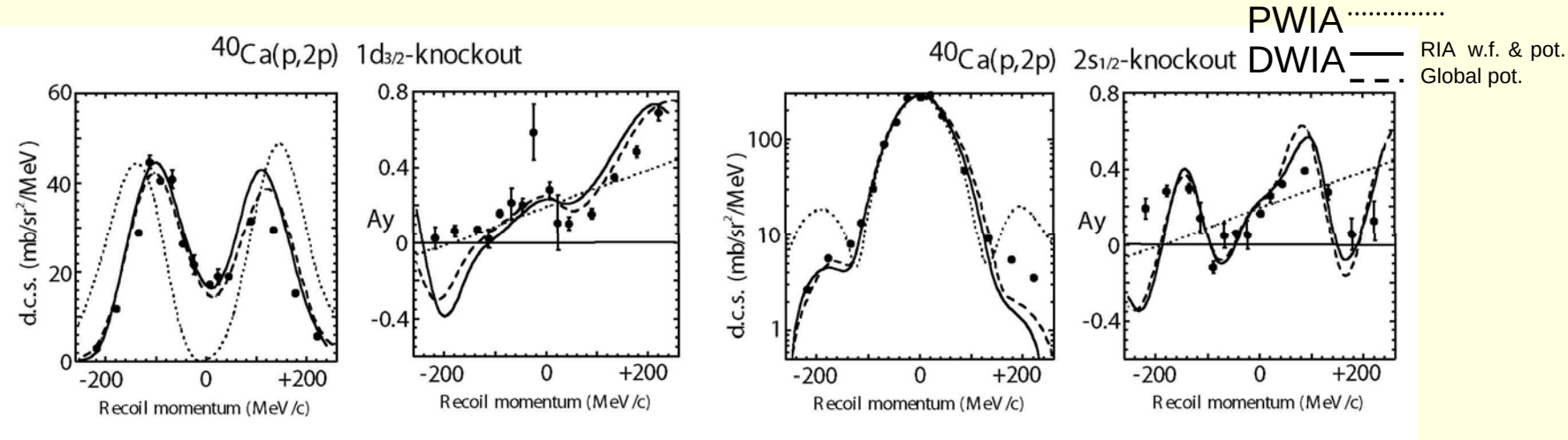
Ep=392MeV





Data are reasonably well reproduced, including *Ay*, by DWIA

Typical data and spectroscopic factors



Spectroscopic factors (preliminary analysis)

(ZR, NL analysis)

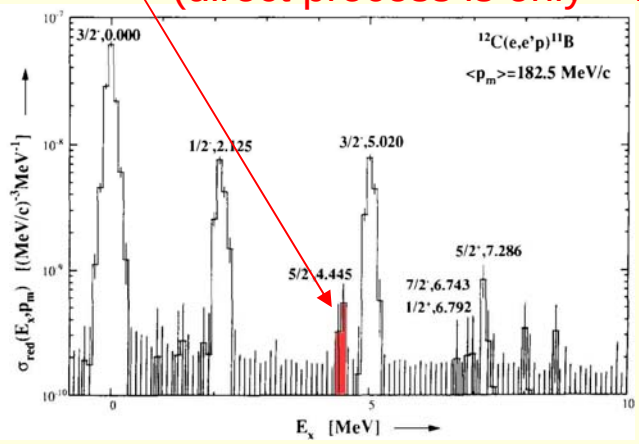
Target	State	RIA w.f. & pot.	Global pot.	(PWIA)	(d,^{3}He) E_d=52MeV	(e,e'p) E_e=280-500MeV
^{12}C	$1p_{3/2}$	1.4	1.3	(0.35)	2.98	1.72
^{12}C	$1p_{1/2}$	-	0.35	(0.09)	0.69	0.26
^{40}Ca	$1d_{3/2}$	1.8	2.1	(0.3)	3.76	2.58
^{40}Ca	$2s_{1/2}$	0.71	0.91	(0.2)	1.65	1.02

Agree with (*e*,*e*'*p*) results within ~20%.
From Ay, *j*-values can be determined.

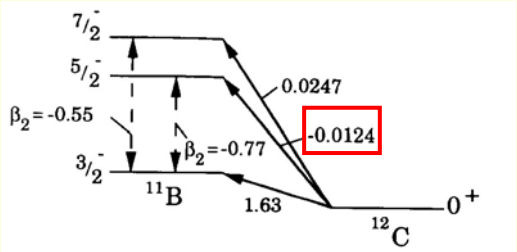
Mixture of multi-step processes

Excitation of 5/2⁻(4.45MeV) state
by $^{12}C(e,e'p)^{11}B$

5/2⁻: multistep dominant
(direct process is only ~1%)

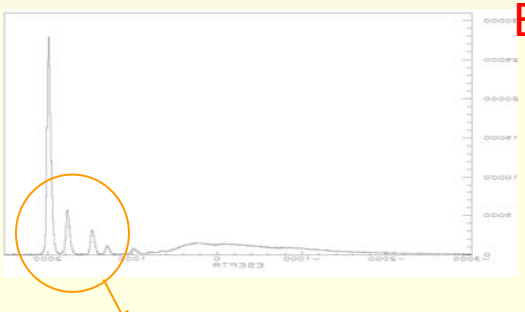


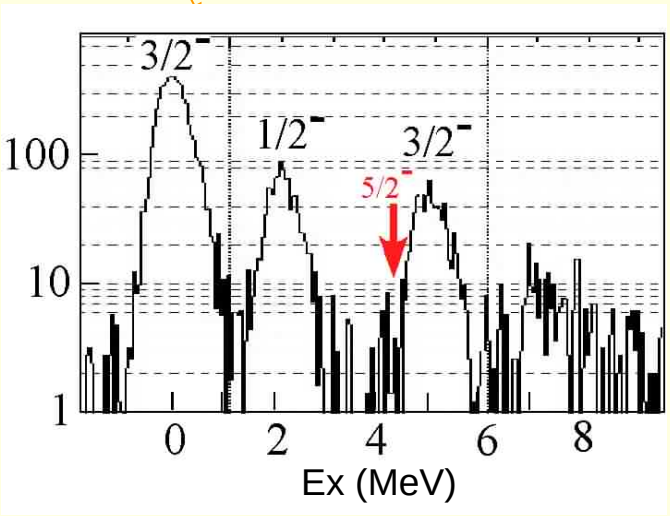
Reaction mechanism



In the case of $^{12}C(p,2p)$

Ep=392MeV





Similar result with (*e*,*e'p*) spectrum

Deduced momentum dependence for ^{6}Li target

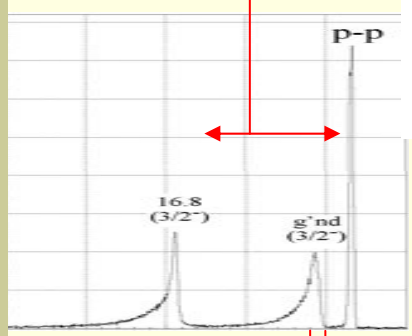
Comparison of ^{6}Li(*e*,*e'p*) and ^{6}Li(*p*,2*p*)

Ep=392MeV

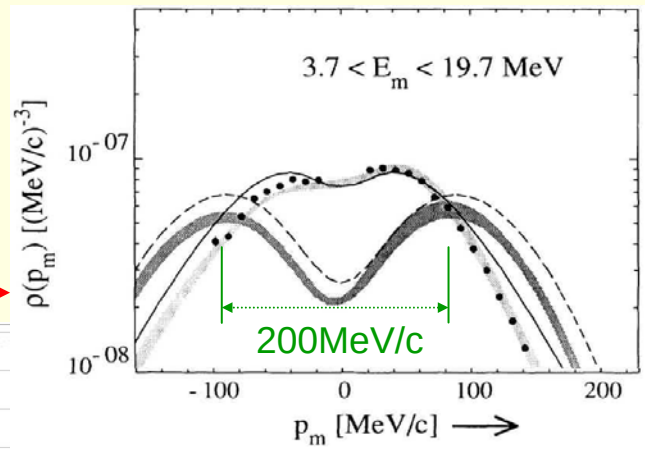
(*e*,*e'p*)

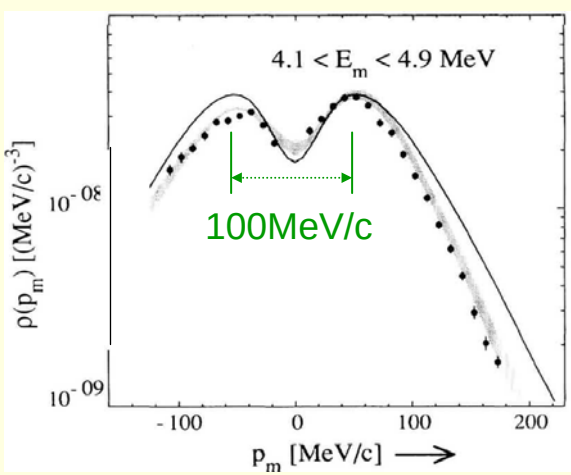
(*p*,2*p*) Narrow solid-angle measurement

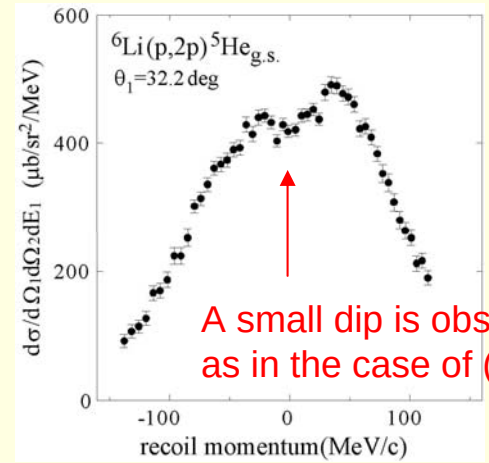
Fully integrated



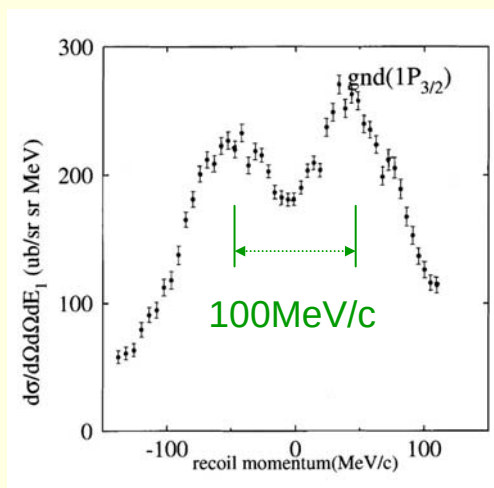
Peak region only





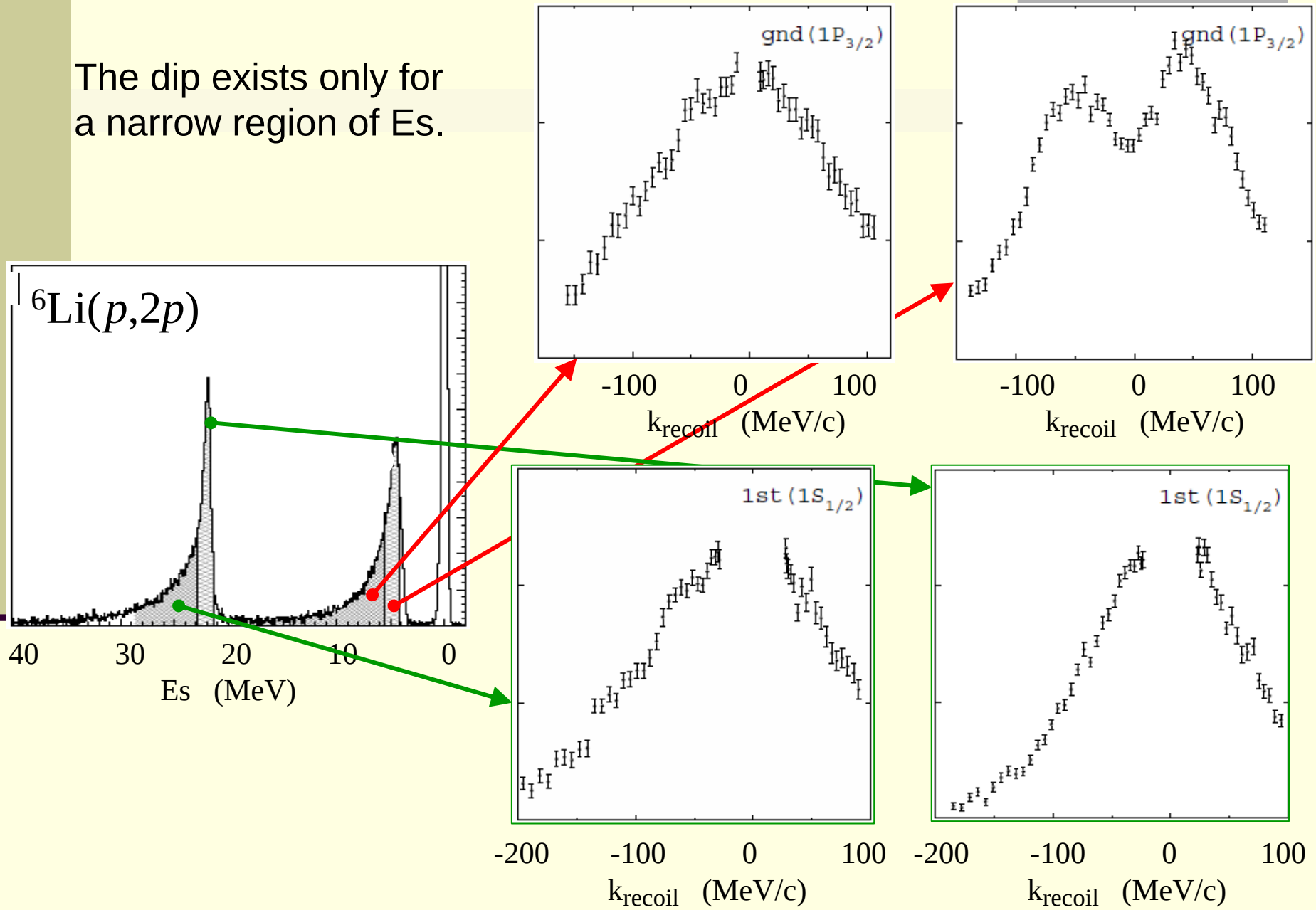


A small dip is observed as in the case of (*e*,*e'p*)

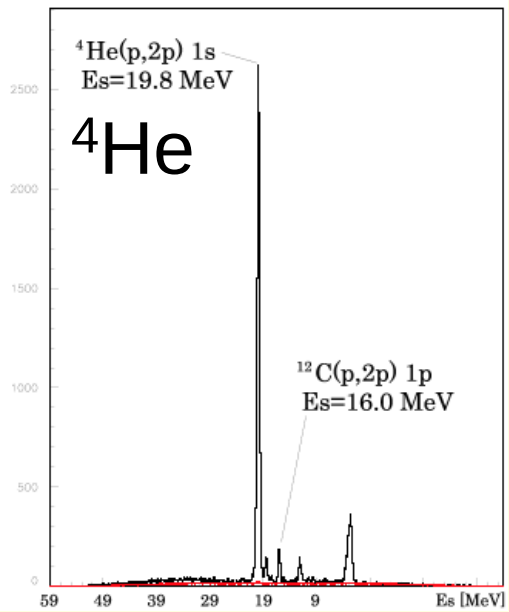


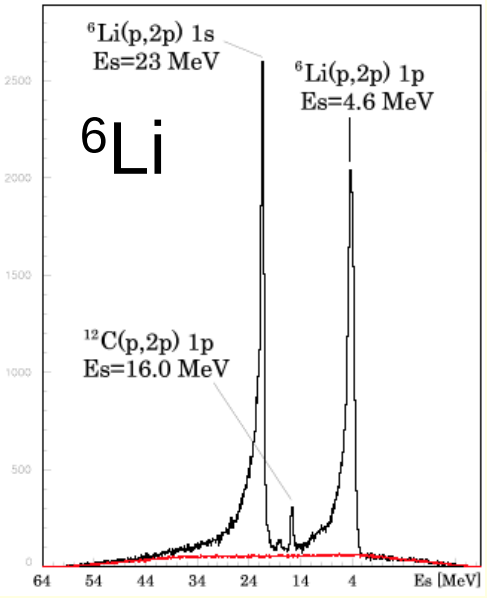
Deduced momentum dependence for ^{6}Li target

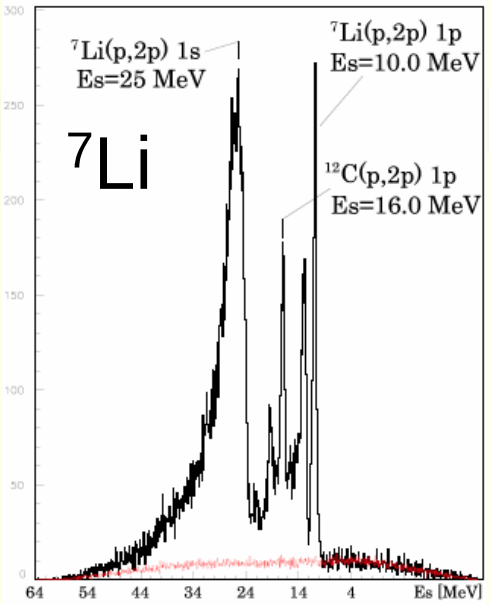
The dip exists only for a narrow region of Es.

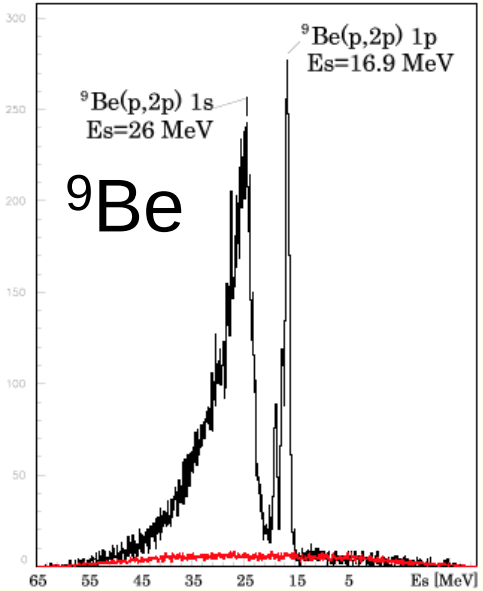


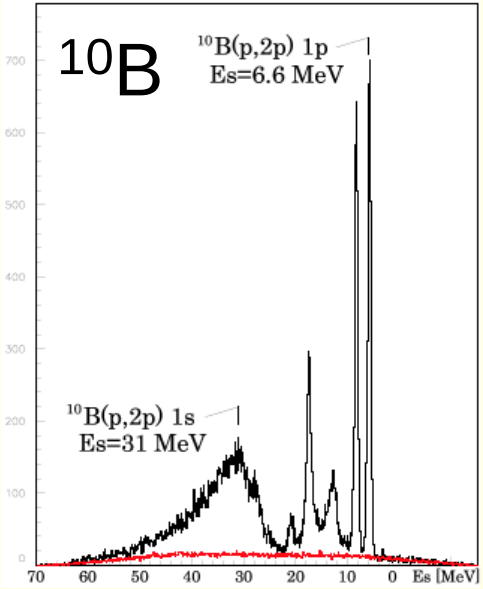
Radii of 1s-proton distribution for light target nuclei

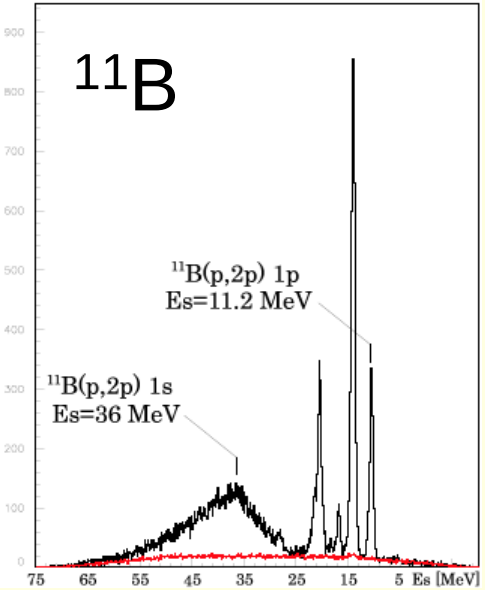






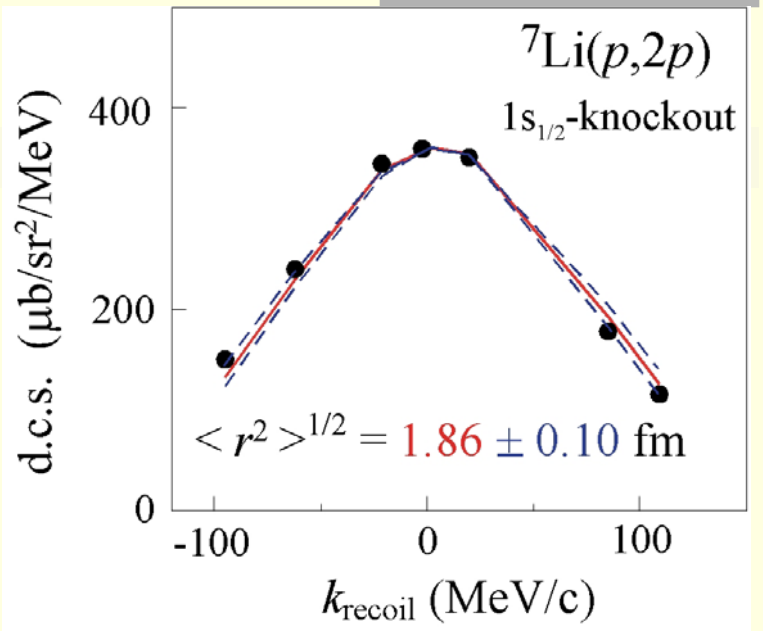


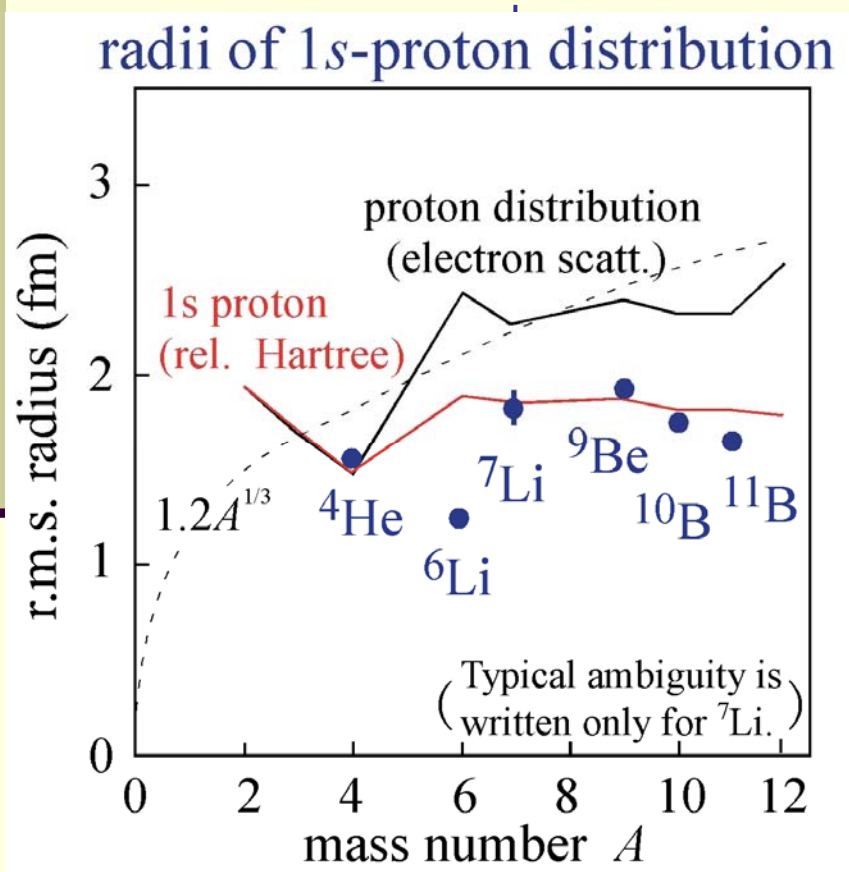




Radii of 1s-proton distribution for light target nuclei

From recoil momentum Distribution of 1s knockout, r.m.s. radii are deduced.





Result:

- Almost constant for ^{4}He -^{11}B. (consistent with Hartree calc.)
- Significantly small for ^{6}Li.
- Gradually reduced from ^{9}Be to 11B ?

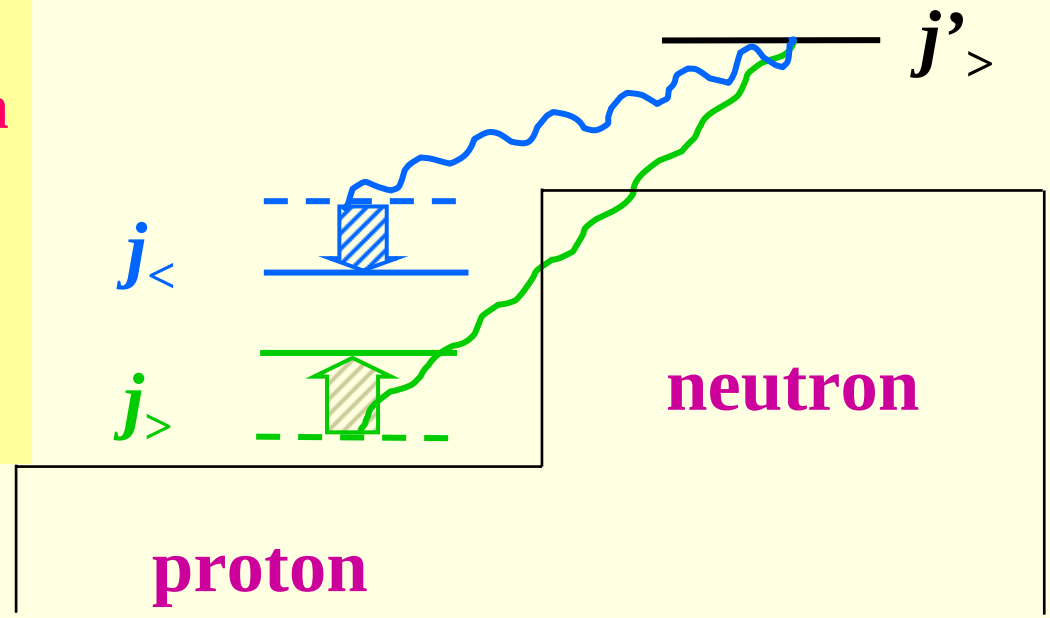
Measurement of shell energies in Ca isotopes by using (d,^{3}He) and (p,2p) Reactions

Motivation : Looking for shifts of effective single-particle energies caused by tensor interaction

Monopole Interaction due to Tensor Interaction

$$V_{ab}^{T} = \frac{\sum_J (2J+1) V_{abab}^{JT}}{\sum_J (2J+1)}$$

➡ **Angular averaged Interaction V_M**



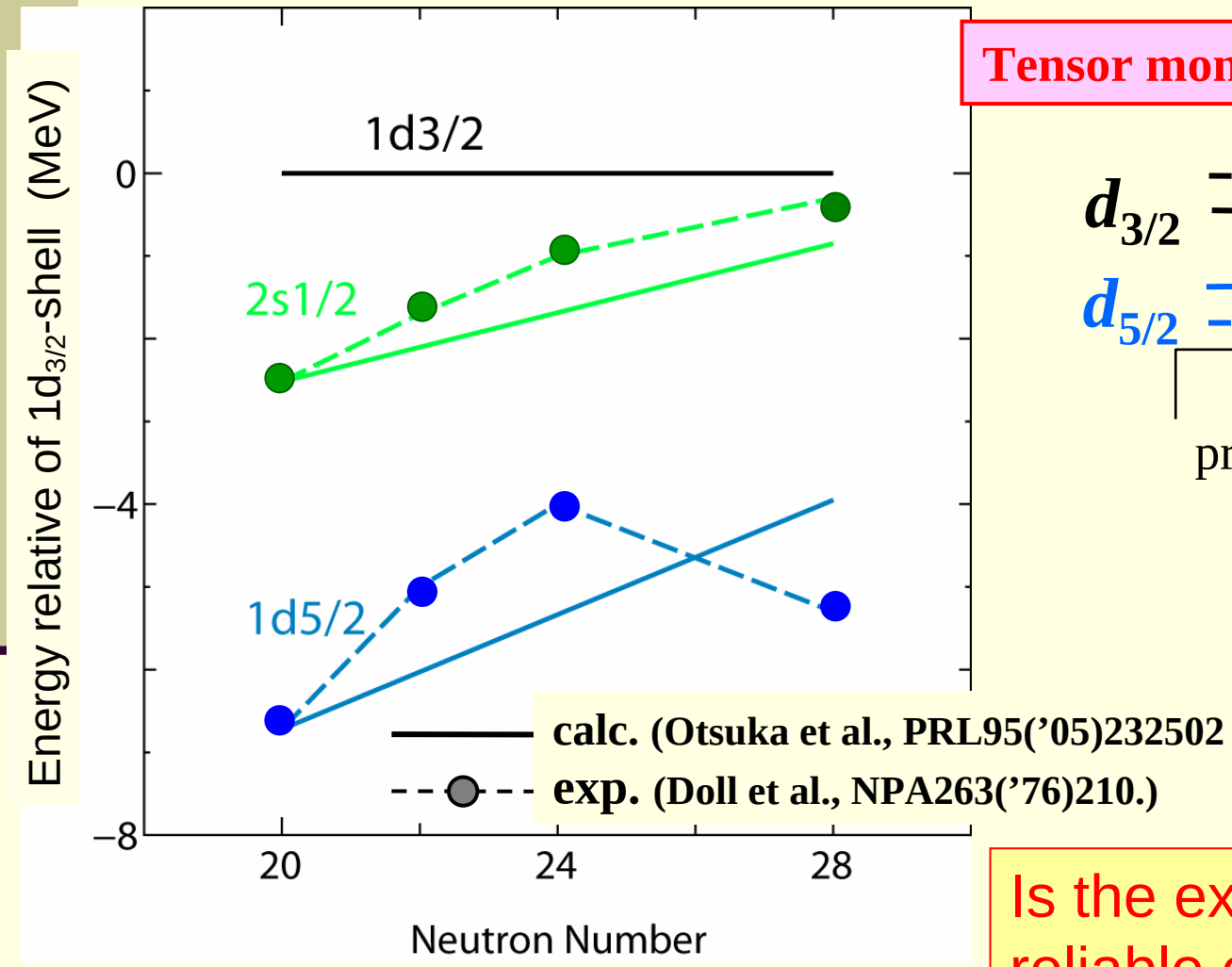
Identity

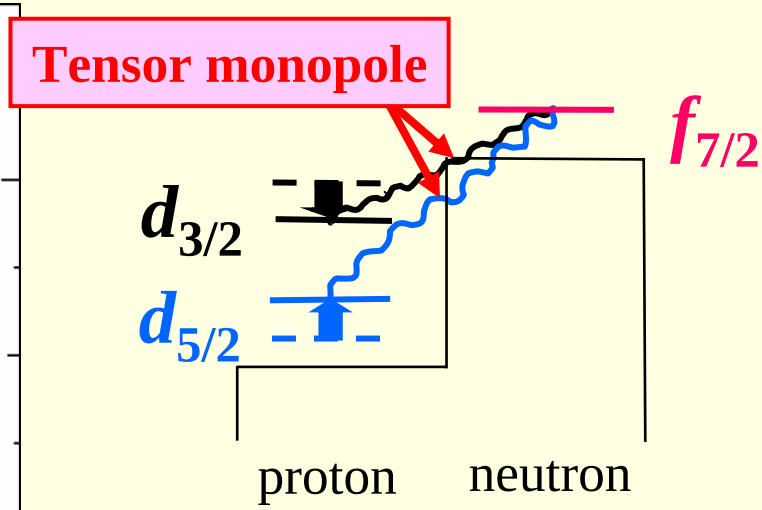
$$(2j_{>}+1)\, V_{M,T}^{(j' j_{>})} + (2j_{<}+1)\, V_{M,T}^{(j' j_{<})} = 0$$

$V_{M,T}$: monopole strength for isospin T

➡ **e.g. $s_{1/2}$ - $d_{5/2}$ inversion between C and O**

Shifts of effective single-particle energies in Ca isotopes





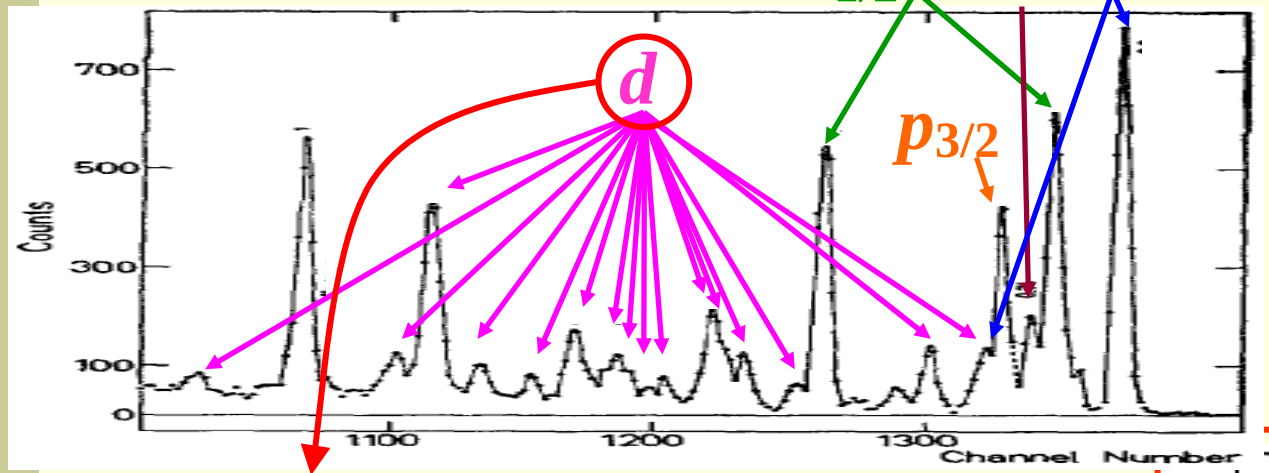
Is the experimental result reliable enough?

Existing experimental result (1)

(d,^{3}He) data with unpolarized d-beam : for ^{40,42,44,48}Ca

^{40}Ca(d,^{3}He)^{39}K

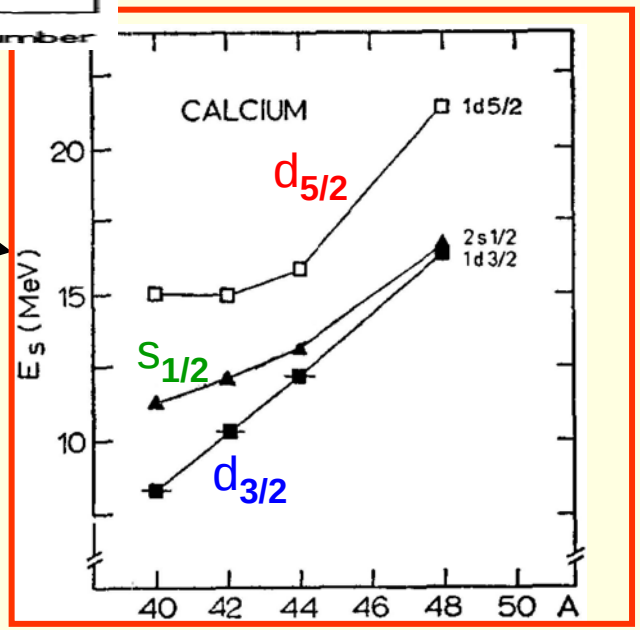
P. Doll *et al*, NPA263 ('76) 210



j is not determined experimentally

$$\text{ESPE} : E_s \equiv \sum_i S_i E_i$$

Shell energies are estimated with an assumption that all of high-Ex d states are $d_{5/2}$.



Existing experimental result (2)

Polarization data exist only for ^{48}Ca (IUCF data)

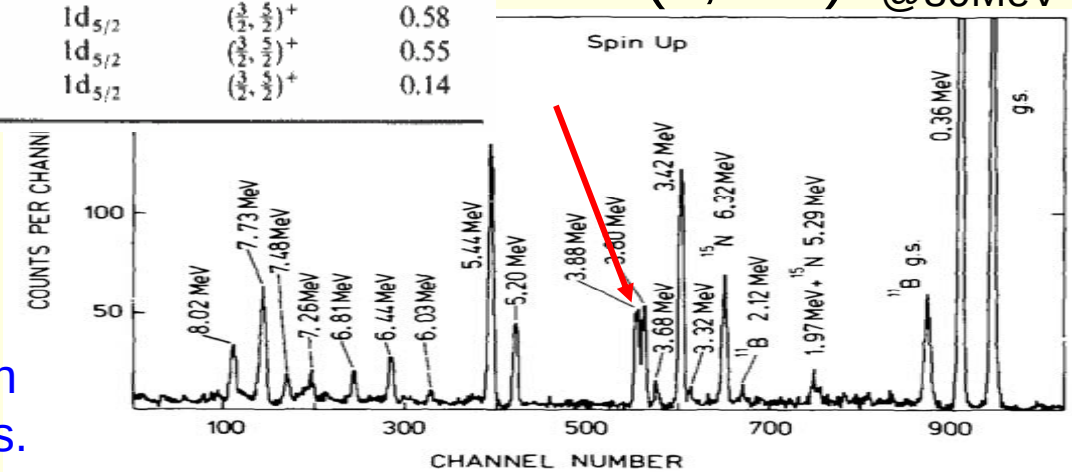
	This experiment (E_d = 80 MeV)			Previous experiment [6] (E_d = 52 MeV)		
E_x (MeV)	nlj	J^π	C^2S	nlj	J^π	C^2S
0.00	$2s_{1/2}$	$\frac{1}{2}^+$	1.55	$2s_{1/2}$	$\frac{1}{2}^+$	1.49
0.36	$1d_{3/2}$	$\frac{3}{2}^+$	4.16	$1d_{3/2}$	$(\frac{3}{2},\frac{5}{2})^+$	3.88
1.97	$1f_{7/2}$	$\frac{7}{2}^-$	0.08			
3.32	$1d_{5/2}$	$(\frac{3}{2},\frac{5}{2})^+$	0.05 [a]			
3.42	$1d_{5/2}$	$\frac{5}{2}^+$	0.97	$1d_{5/2}$	$(\frac{3}{2},\frac{5}{2})^+$	0.95
3.68 [b]						
3.80 [c]	$2s_{1/2}$	$\frac{1}{2}^+$	0.28	$2s_{1/2}$	$\frac{1}{2}^+$	0.3
3.88 [c]	$1d_{3/2}$	$\frac{3}{2}^+$	0.70	$1d_{5/2}$	$(\frac{3}{2},\frac{5}{2})^+$	(0.6, 0.4)
5.20	$1d_{5/2}$	$\frac{5}{2}^+$	0.32	$1d_{5/2}$	$(\frac{3}{2},\frac{5}{2})^+$	0.33
5.44	$1d_{5/2}$	$\frac{5}{2}^+$	0.94	$1d_{5/2}$	$(\frac{3}{2},\frac{5}{2})^+$	1.01
6.03	$1d_{5/2}$	$(\frac{3}{2},\frac{5}{2})^+$	0.04 [a]			
6.44	$1d_{5/2}$	$\frac{5}{2}^+$	0.22	$1d_{5/2}$	$(\frac{3}{2},\frac{5}{2})^+$	0.38
6.81	$1d_{5/2}$	$\frac{5}{2}^+$	0.14			
	—	—	—			
7.48	$1d_{5/2}$	$\frac{5}{2}^+$	0.14			
7.73	$1d_{5/2}$	$\frac{5}{2}^+$	0.71	$1d_{5/2}$	$(\frac{3}{2},\frac{5}{2})^+$	0.58
8.02	$1d_{5/2}$	$\frac{5}{2}^+$	0.33	$1d_{5/2}$	$(\frac{3}{2},\frac{5}{2})^+$	0.55
8.53 [e]				$1d_{5/2}$	$(\frac{3}{2},\frac{5}{2})^+$	0.14

One peak, with significant S-factor, was assigned to be $d_{3/2}$.

$\Delta E_{d_{3/2}}$ = -0.51 MeV

$\Delta E_{d_{5/2}}$ = -0.09 MeV

^{48}Ca(d,^{3}He) @80MeV

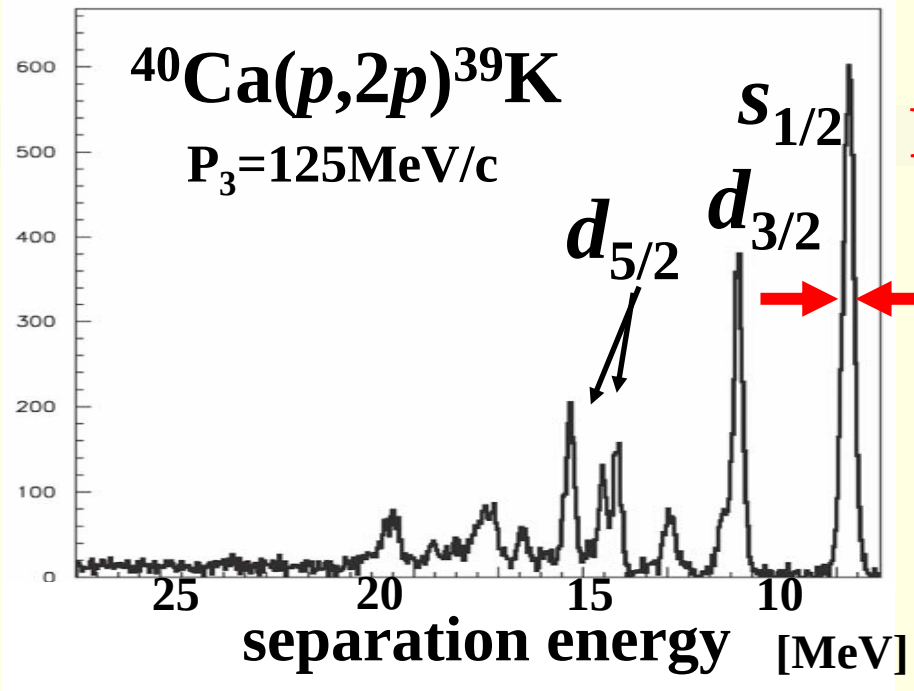


→ Experimental j-determination is required for other isotopes.

RCNP data under analysis

- ^{40}Ca : $(\vec{p},2p)$ at Ep=200 MeV
  250keV resolution
- ^{44}Ca: $(\vec{d},{}^{3}\mathrm{He})$ at Ed=80 MeV
  60-80keV resolution
- ^{48}Ca: limited $(\vec{d},{}^{3}\mathrm{He})$ data at Ed=80 MeV
  for consistency check with the IUCF data
- quite limited $(\vec{p},2p)$ and $(\vec{d},{}^{3}\mathrm{He})$ data
  for all of ^{40,42,44,48}Ca

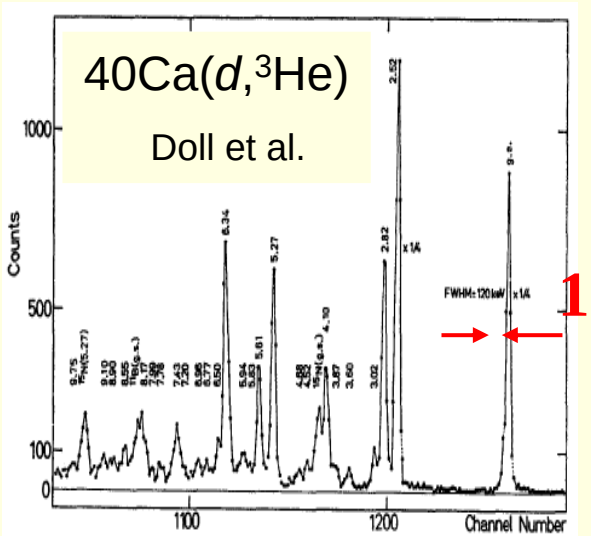
^{40}Ca(p,2p): Spectrum



FWHM 240keV

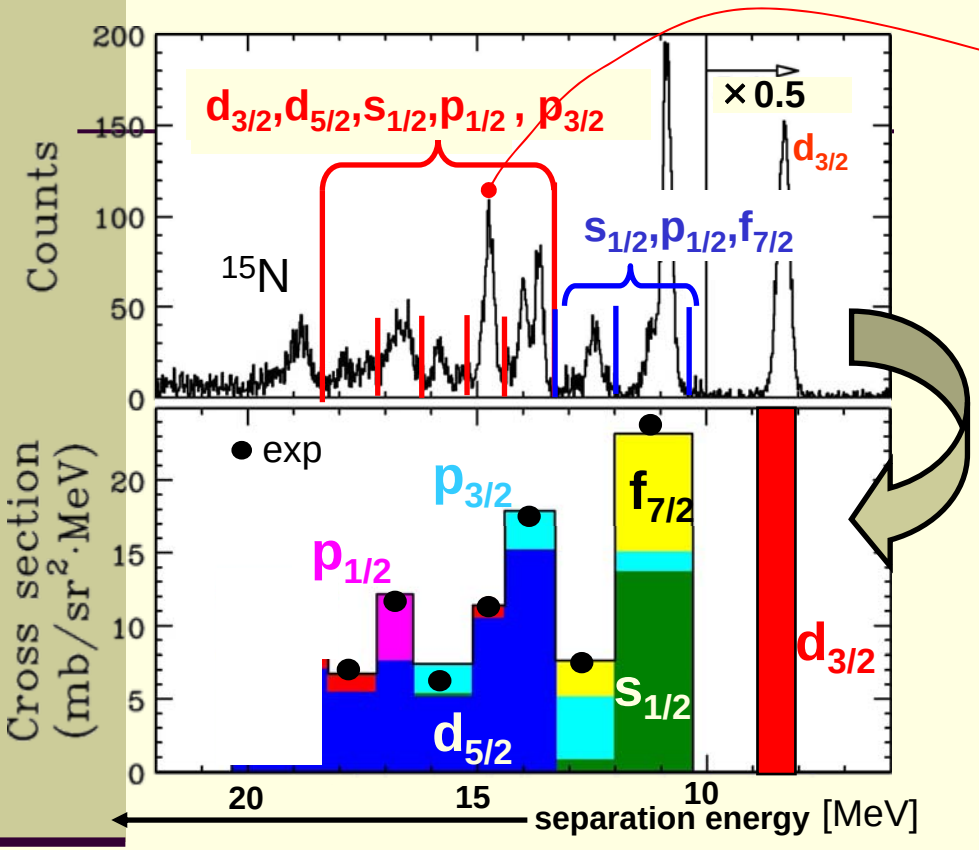
The best resolution in the world but not enough to separate peaks.

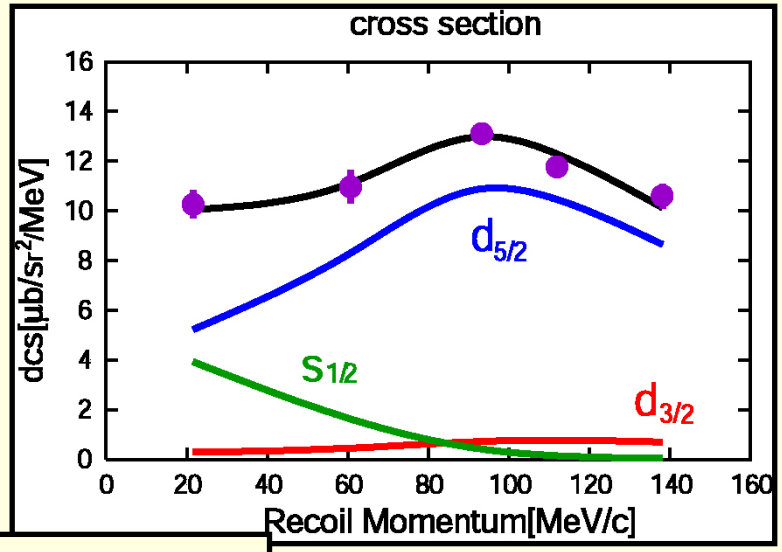
Multi-pole decomposition analysis (MDA) is performed.



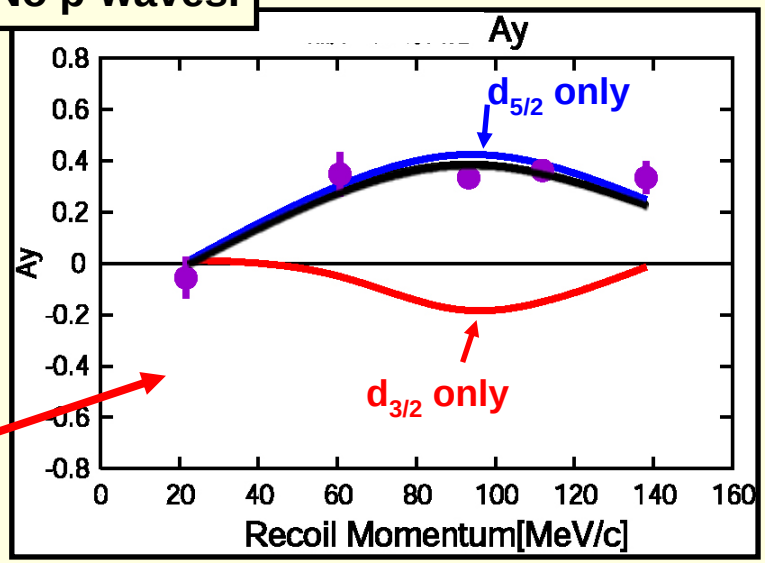
120keV

^{40}Ca: Multipole decomposition



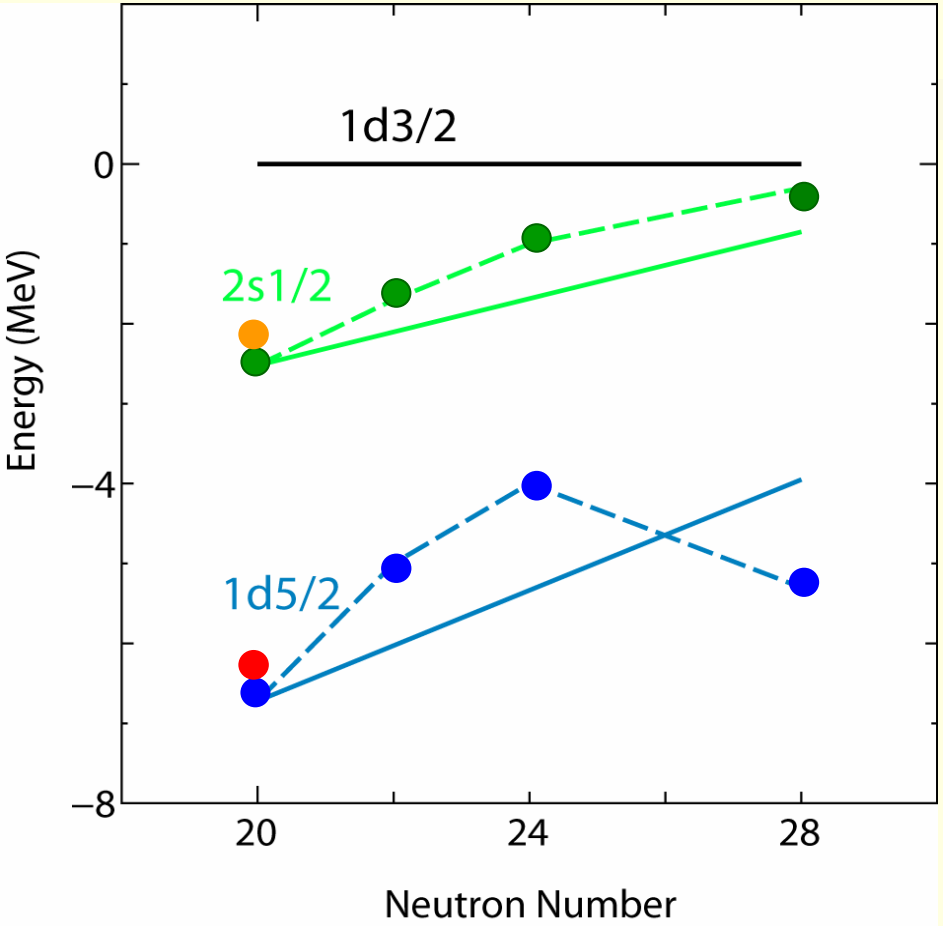


No p-waves.

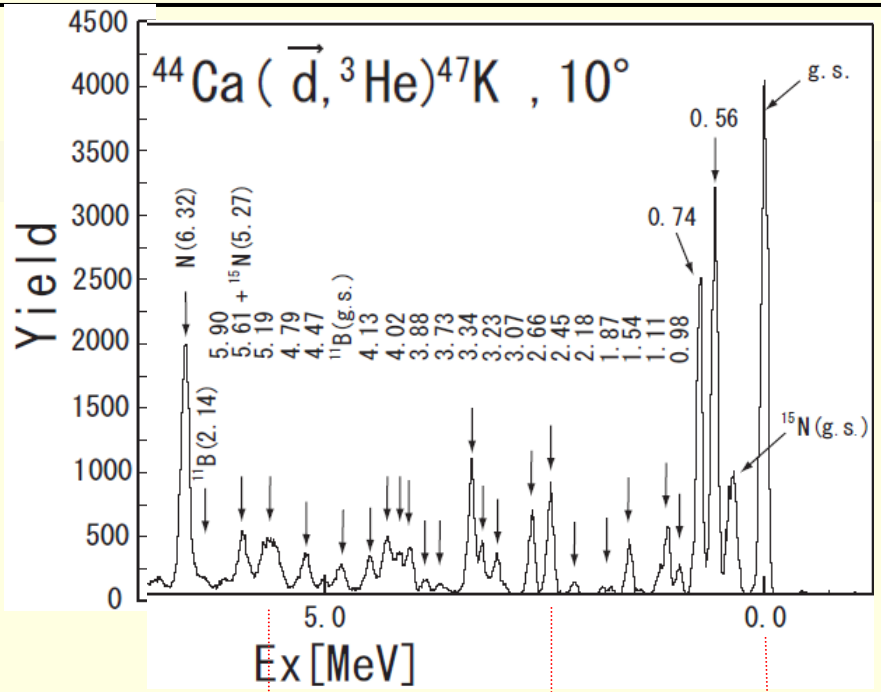


Clear j-dependence exists.

Result

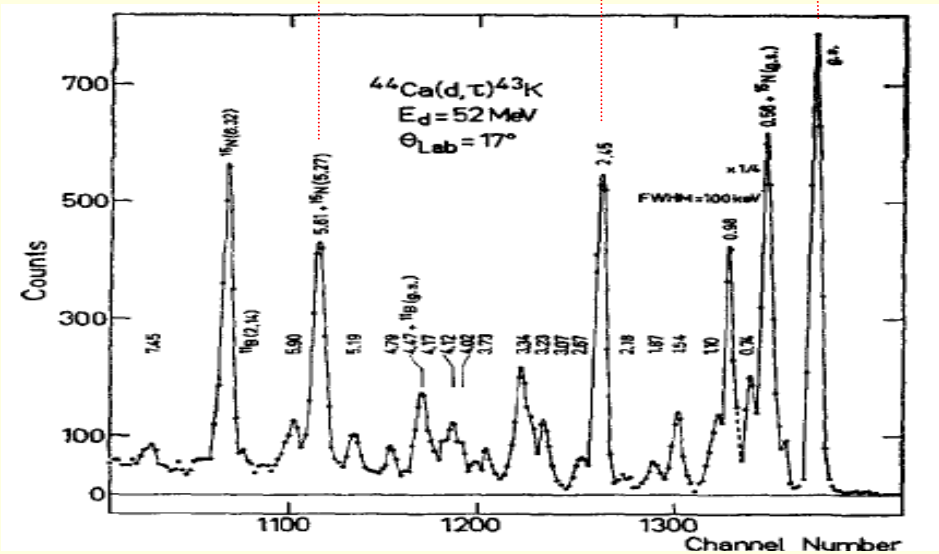


$^{44}Ca(d,^{3}He)$: Obtained spectrum



Present data

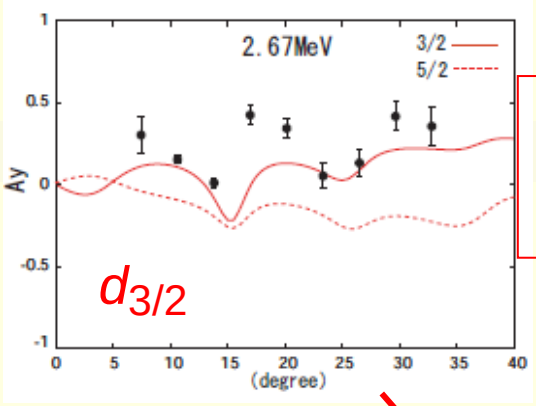
ΔE = 60-85 keV



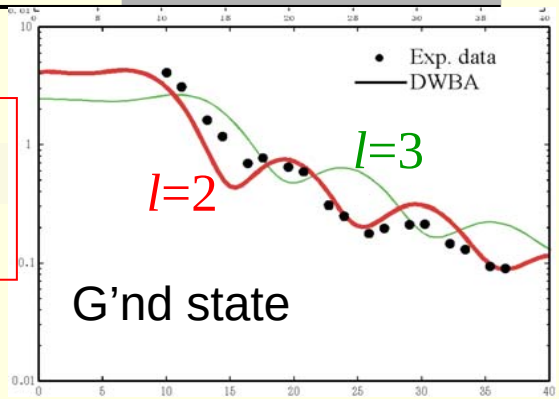
Doll et al.

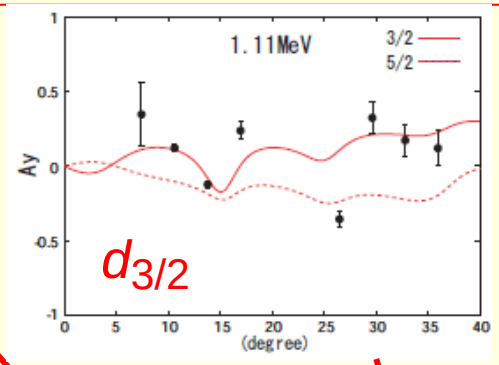
ΔE = 120 keV

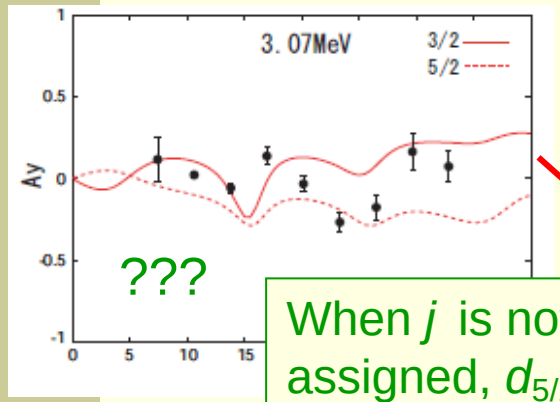
^{44}Ca: j^{π} assignment (preliminary)



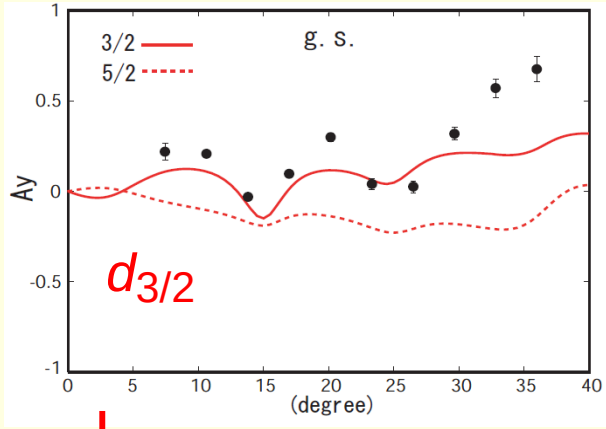
Several levels with significant S-factors are assigned to be $d_{3/2}$.

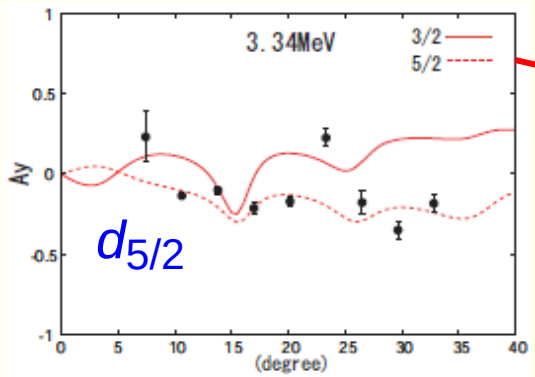


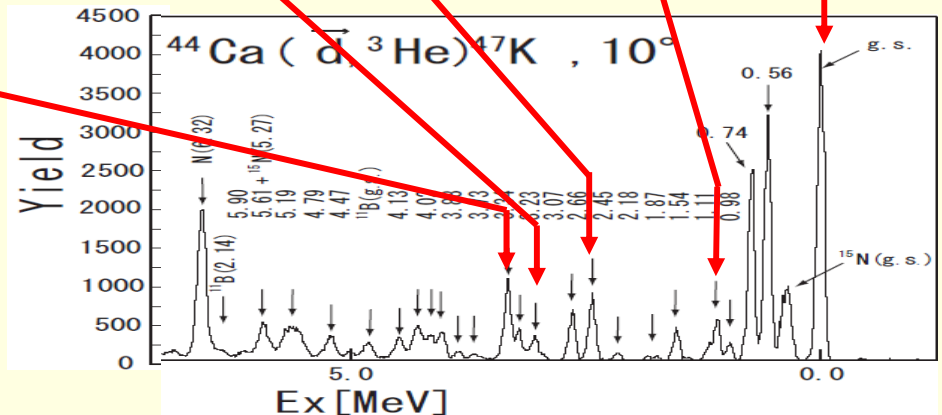




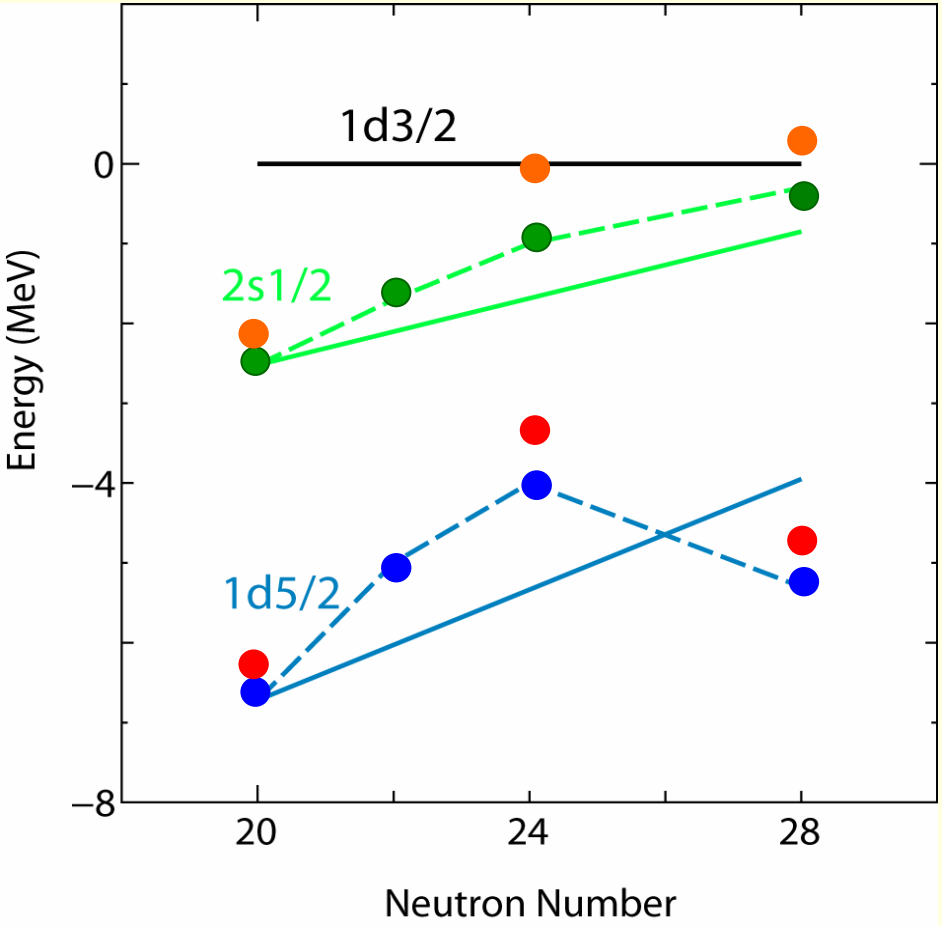
When j is not clearly assigned, $d_{5/2}$ is assumed.







Result



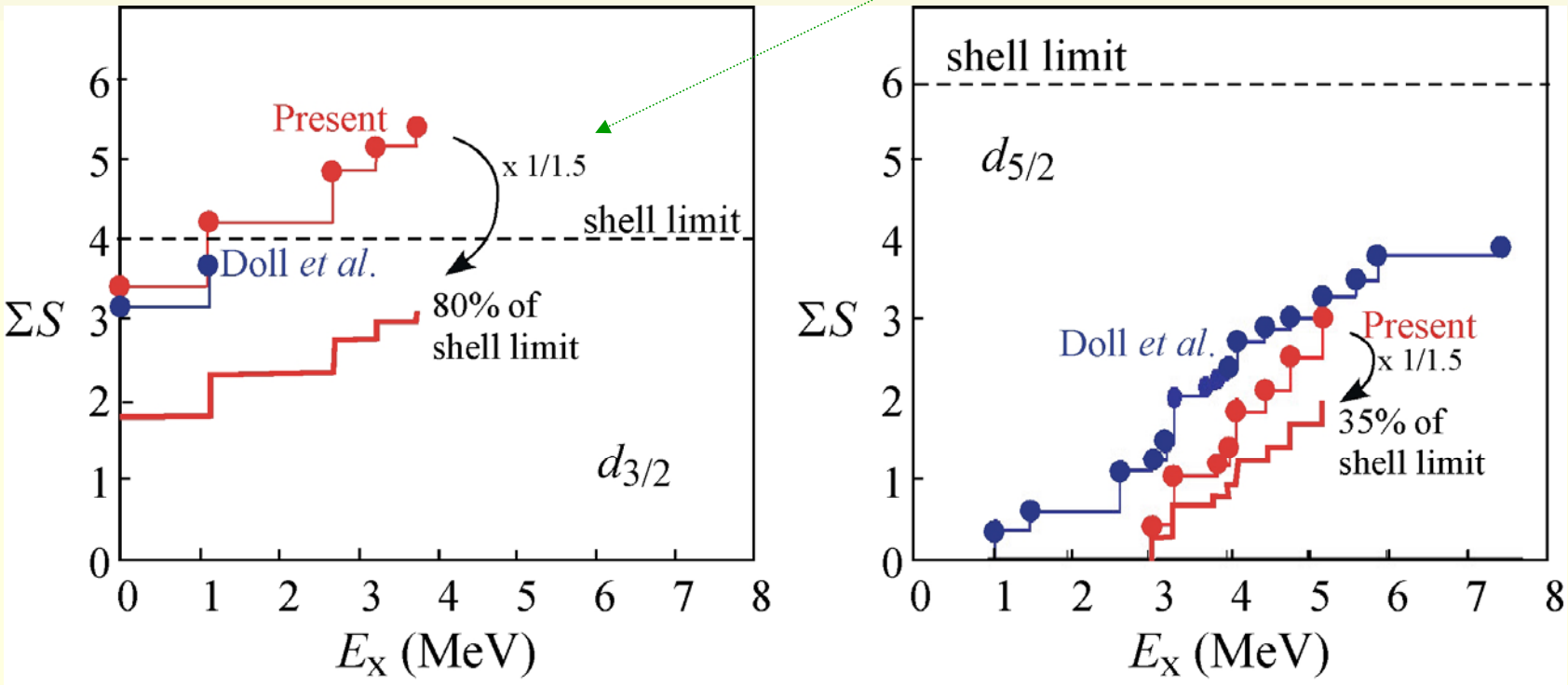
- Effective shell energy of $d_{3/2}$ states are shifted to some extent for all of three isotopes.

- N dependence of the $d_{5/2}$-$d_{3/2}$ difference shows no essential changes, but …

Sum of S-factors

Finite range and
Non-local effect

$^{44}Ca(p,2p)^{43}K$



- Only 35% of S-factors are found for $d_{5/2}$.
- In the case of ^{48}Ca case,
  81%($d_{3/2}$) and 54%($d_{5/2}$) are found.

Summary

- (p,2p) at Ep=200-400MeV as a spectroscopic tool
  - Reaction mechanism is simple enough and DWIA works reasonably well.
  - S-factors were obtained with 20% accuracy and r.m.s. radii were deduced with 0.1fm accuracy.
  - Polarization information is quite useful.
- Effective shell energy in Ca isotopes (Preliminary)
  - $d_{3/2}$ states with significant S-factors are found.
  - Total S-factors observed for $d_{5/2}$ states are less than 50%. Effective shell energies for these states has not been reliably determined.