École Internationale Joliot-Curie

RÉACTIONS DE DISSOCIATION:

-Aspects théoriques par D. Baye
-Aspects expérimentaux

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MAUBUISSON (France) 17-22 September 2007

ECOLE JOLIOT CURIE 1994

GOAL

How can we obtain spectroscopic information using dissociation reactions?

→ Daniel lectures

What do we mean by dissociation?

breakup or knockout, coulomb breakup.

my lecture will concentrate on the nuclear dissociation

How are the dissociation reactions experiments done?

→ This is my task

Layout

On the lecture's title

- ❖Introduction: reactions with fast radioactive beams
- ❖Experimental aspects associated: shopping list
- ❖ Experimental determination of the measured observables:
- ❖ Overview on the studied cases
- ❖ The case of halo states: ^{8}B and ^{11}Be
- ❖ Other selected cases
- ❖ Experimental determination of the spectroscopic information. Comparison with Coulomb dissociation experiments
- ❖ Perspectives: Two-nucleon removal
- ❖ Summary and conclusions
- ❖ Bibliography

A propos du titre du cours

Pour éviter la confusion/imprécision des termes **breakup** et **knockout** nous avons utilisé le terme generique de **dissociation**

http://en.wikipedia.org/wiki

A **knockout** (also referred to as a K.O.) is a winning criterion in several full-contact combat sports, such as boxing, kickboxing, Muay Thai, mixed martial arts and others sports involving striking

A **breakup** refers to the ending of a relationship, typically a romantic one. A breakup can vary between emotionally traumatic to consensual for those involved, especially if romantic love is involved.

Nuclear physics

It's a knockout

David Warner

In collisions between nuclei, a proton or neutron might be knocked out of one nucleus. Now, two-proton knockout has been demonstrated, opening a new route to the creation of neutron-rich systems for study.

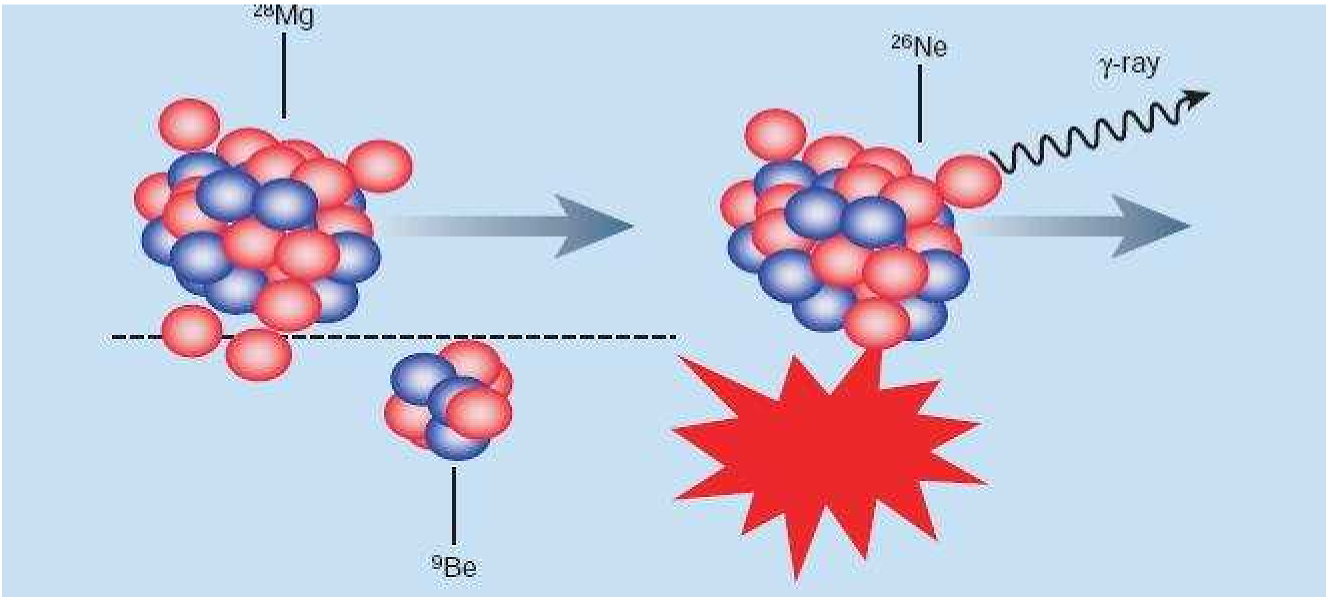
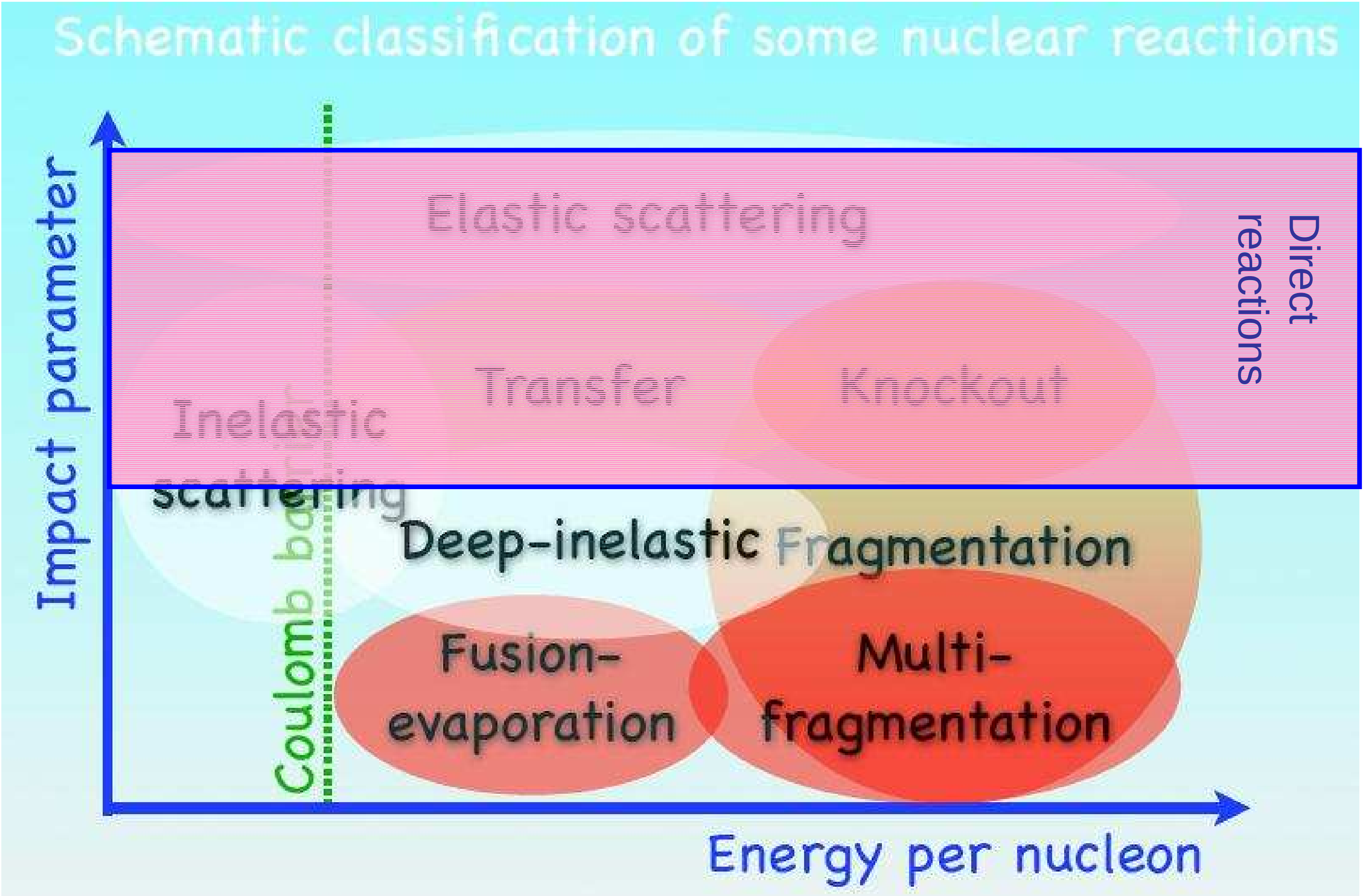


Figure 1 Two-proton knockout. Bazin *et al.*[1] have demonstrated that the incidence of a beam of unstable magnesium nuclei (^{28}Mg) on a target of stable beryllium nuclei (^{9}Be) produces a residue of neon (^{26}Ne) nuclei. During the reaction, two of the four loosely bound, outermost protons in the beam nucleus are removed, leaving the ^{26}Ne nucleus, which then emits γ-radiation. The velocity of the residue is the same as that of the beam particles.

 NATURE | VOL 425 | 9 OCTOBER 2003 | www.nature.com/nature

Nuclear reactions

D. Bazin RIA school 2006



Single-particle experimental information with exotic nuclei

We want to determine our exotic nuclei wave function

- identify single-particle states (J^{Π})
- identify if they are pure or mixed states and determine this degree of purity

❖Transfer reactions

Energy regime : 10-20 MeV/nucleon

Required intensity > 10^4 pps

Typical cross-section : 1 mb

❖Knockout reaction

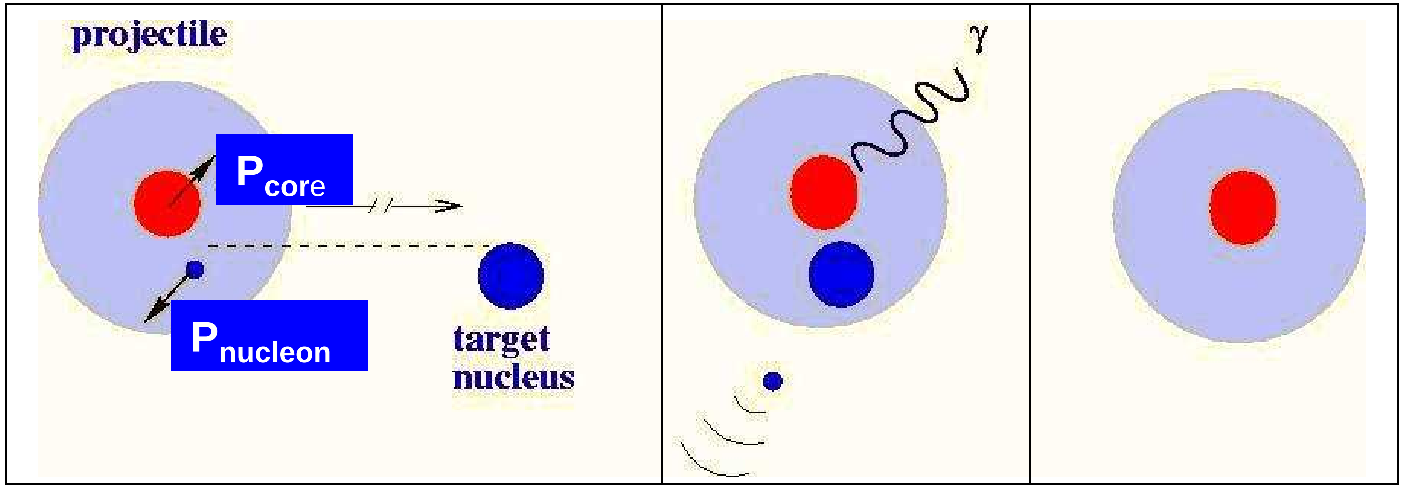
Energy regime : > 50-70 MeV/nucleon

Required intensity: from 1 pps for dripline nucleus

Typical cross-section : 100 mb for dripline, 1 mb for stable

Ideal for exploratory studies

Knockout reactions: "clean" peripheral reactions



1) We measure the core fragment momentum distribution. In the CM system $|P_{core}| = |P_{neutron}|$ ➔ we get information about wave function of the valence neutron

2) If we tag with γ rays we can know the spin of the core fragment produced in the reaction.

3) We can couple the it spectroscopic information from core and neutron valence to determine the ground state of the exotic projectile

4) The ground state of the exotic projectile can be made of a superposition of core and valence neutron couplings

Knockout reactions

Exotic projectile wave function

$$|P\rangle = \sum C^2S\,(\,|C\rangle \otimes |n\rangle\,)$$

Ground state of the exotic projectile

Spectroscopic factor

core fragment

valence neutron

Exclusive Cross-sections

Analysis in an eikonal reaction theory

Gamma ray tagging

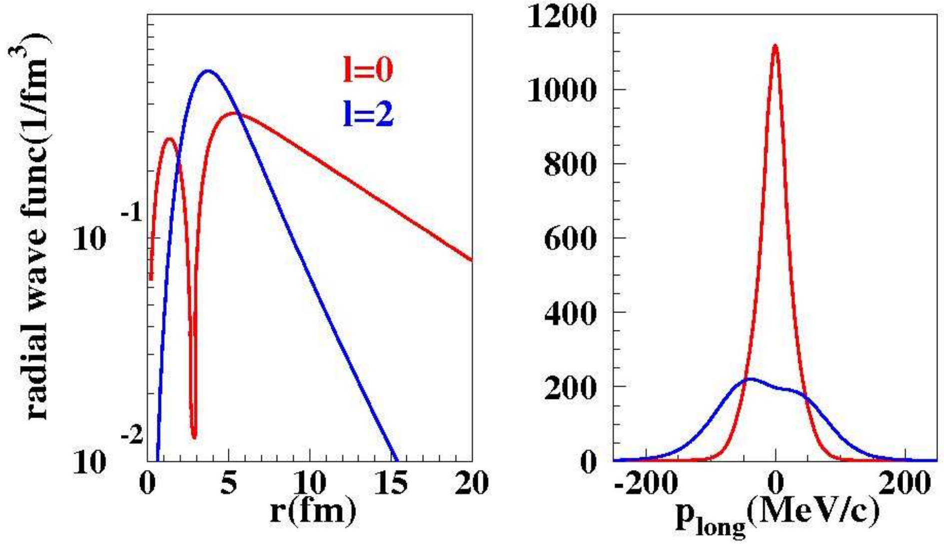
Identification of the bound final states of the residues

Exclusive core fragment momentum distributions

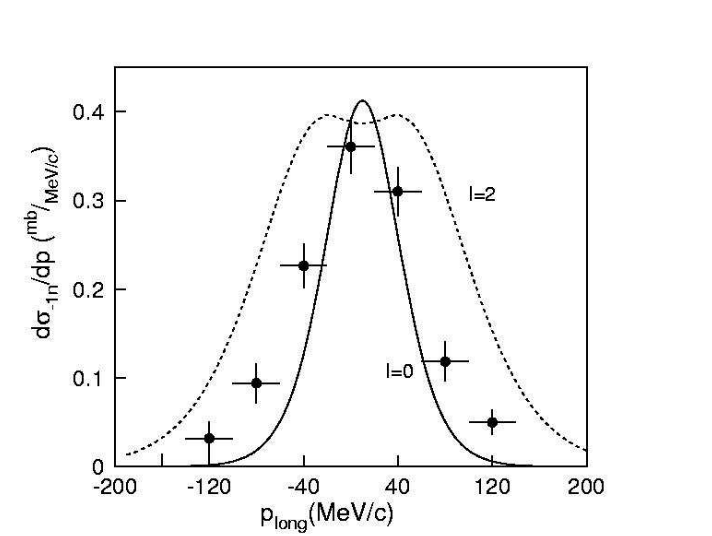
The shape of the measured distribution determines the l of the removed neutron

How to extract the information

Momentum distributions inform about the orbital angular momentum of the removed nucleon → comparison with black-disk model



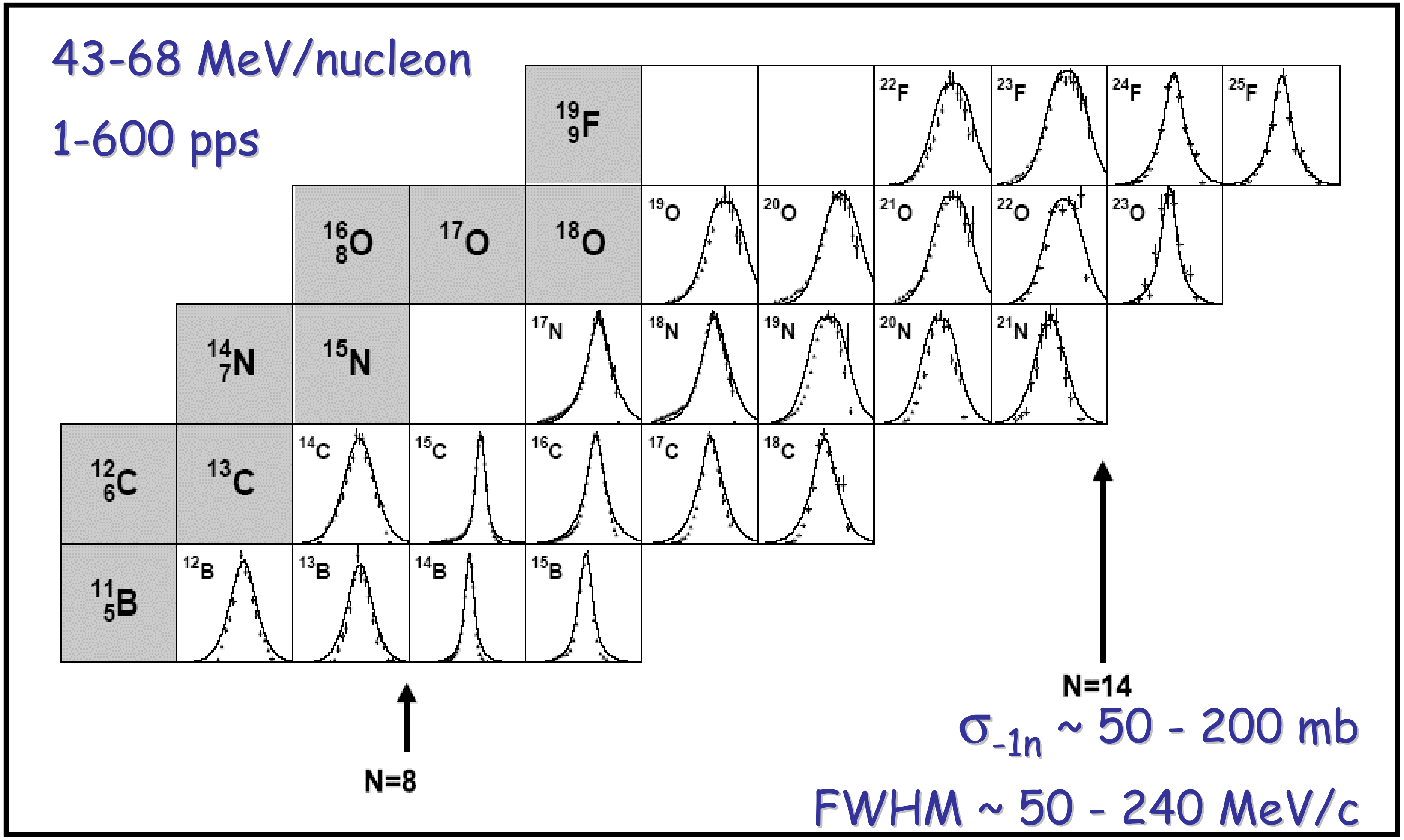
^{23}O → ^{22}O



D. Cortina et al., PRL 93(2003)

How to extract the information

Momentum distributions inform about the orbital angular momentum of the removed nucleon



E Sauvan, et al., PRC (2004)

Comparison between experimental and theoretical cross-sections inform about the spectroscopic factor associated to each configuration

P.G. Hansen and J.A.Tostevin Ann. Rev. Nucl. Part. Sci. 53 (2003) 219

For the case of single nucleon knockout the cross-section for a given j channel factorises into

- a part describing the contribution from many-body nuclear structure (spectroscopic factors)
- and a part describing the reaction dynamics (single particle cross-section)

$$\sigma_{theo} = \Sigma_j \, S_j \, \sigma_{sp}(nlj)$$

The projectile energy allows to use semiclassical theoretical description of the reaction

$$\sigma_{sp} = \sigma\sigma_{str} + \sigma_{dif} + \sigma_C$$

coulomb

stripping = inelastic

diffraction = elastic

Knockout reactions: shopping list

- ➢ Fast radioactive beams → produced by nuclear fragmentation
- ➢ Impinging on a light target → Inverse kinematics
- ➢ Determination and tracking of projectiles and fragmets → Complete kinematical measurement
- ➢ High precision momentum measurements of projectile like fragment
- ➢ Appropriate ancillary detectors to determine final states

Show the power of the thecnique as spectroscopic tool

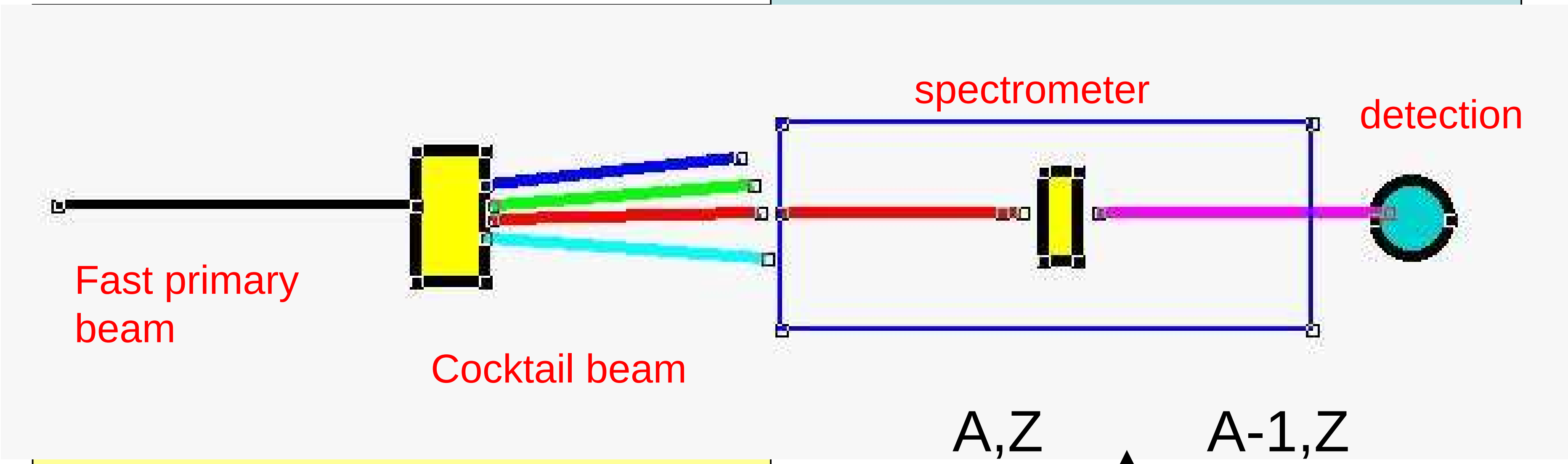
Show the experimental limitatitions

Compare with other techniques (i.e: transfer)

* compare with exotic nuclei coulomb dissociation

Knockout reactions: shopping list

In-flight projectile and
fragment identification

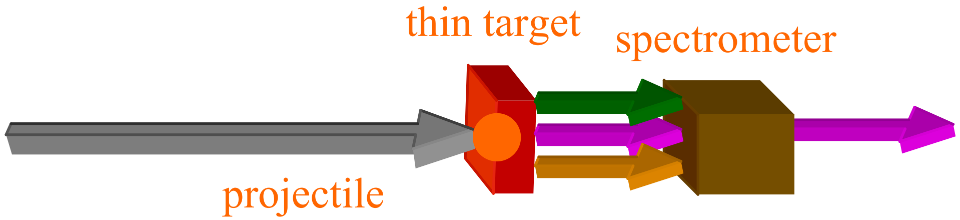


In-flight projectile
fragmentation

Nucleon knockout

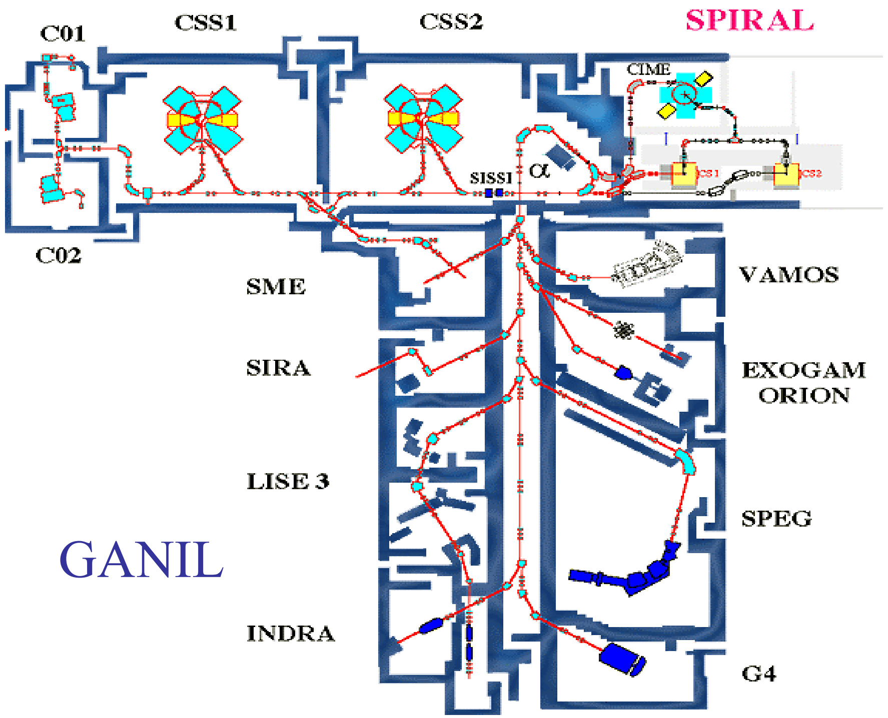
Fast radioactive ion beams

In-flight projectile fragmentation



Accelerator :

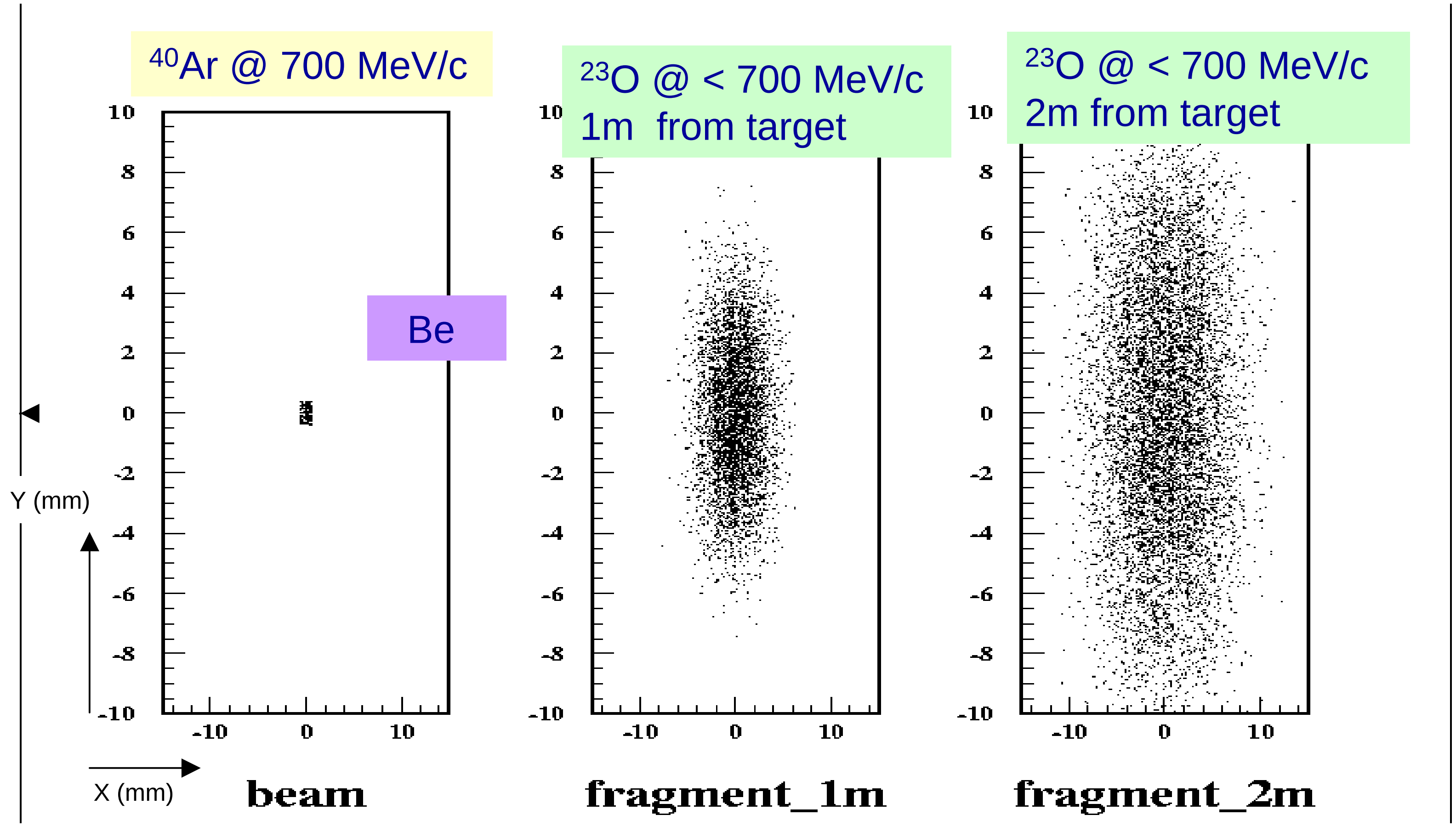
- Cyclotron
- Synchrotron



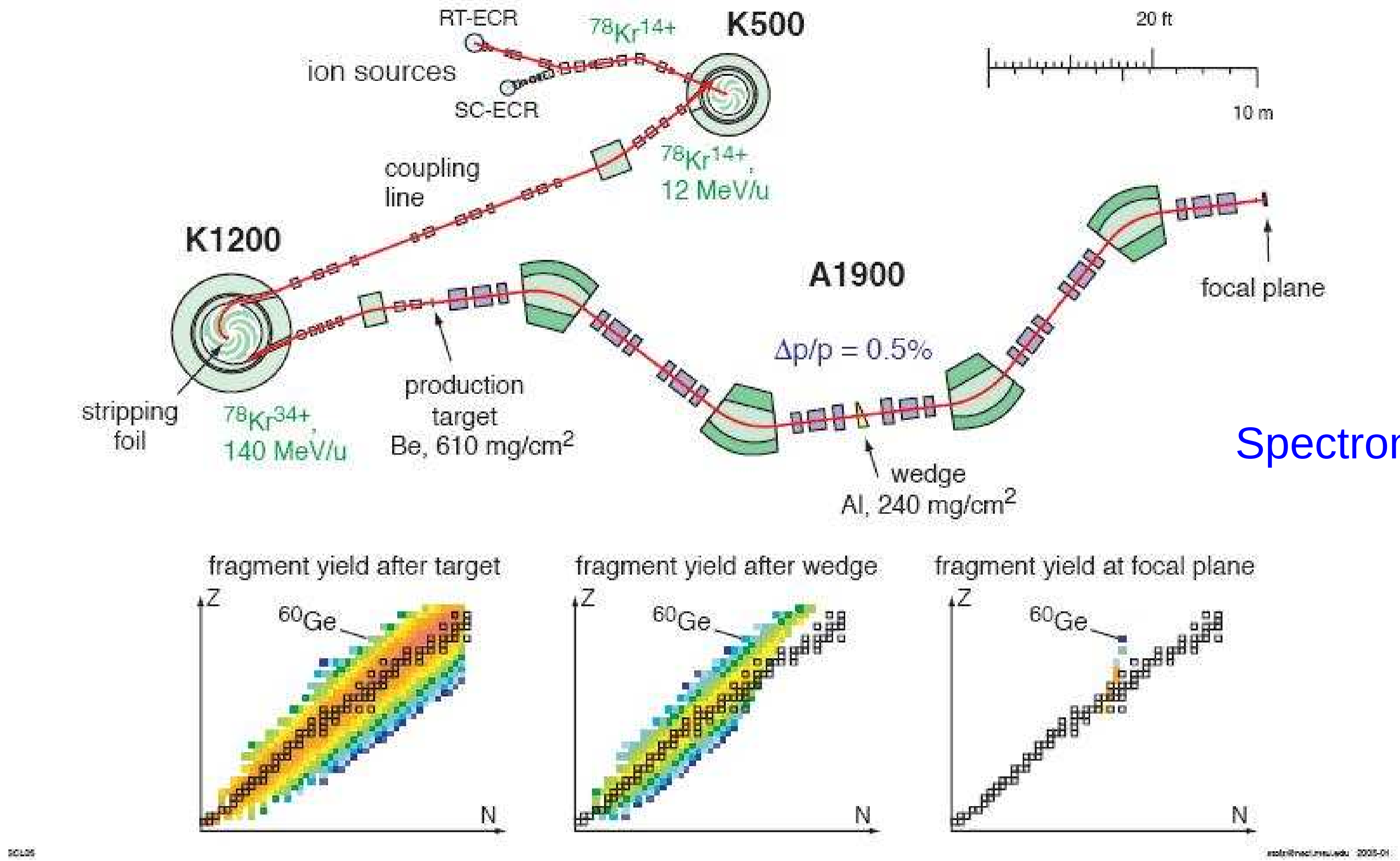
GANIL

Inverse kinematics: Fragment emmission is forward focussed

- Results from a MOCADI (http://www.gsi.de) simulation
- dependence on the primary beam energy



Cocktail beams



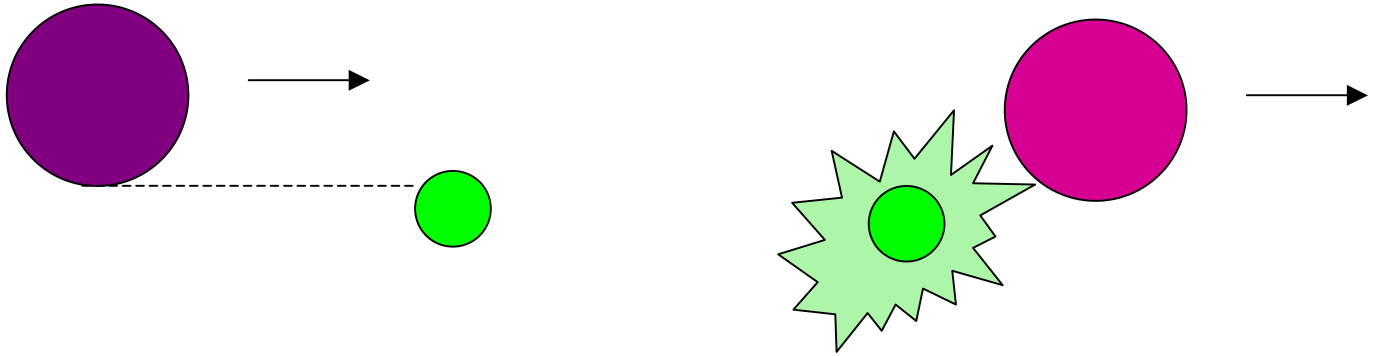
Spectrometer

Cocktail beams

From NSCL webpage

nucleon-knockout reactions

Fast projectile A has a peripheral collision with a light target.



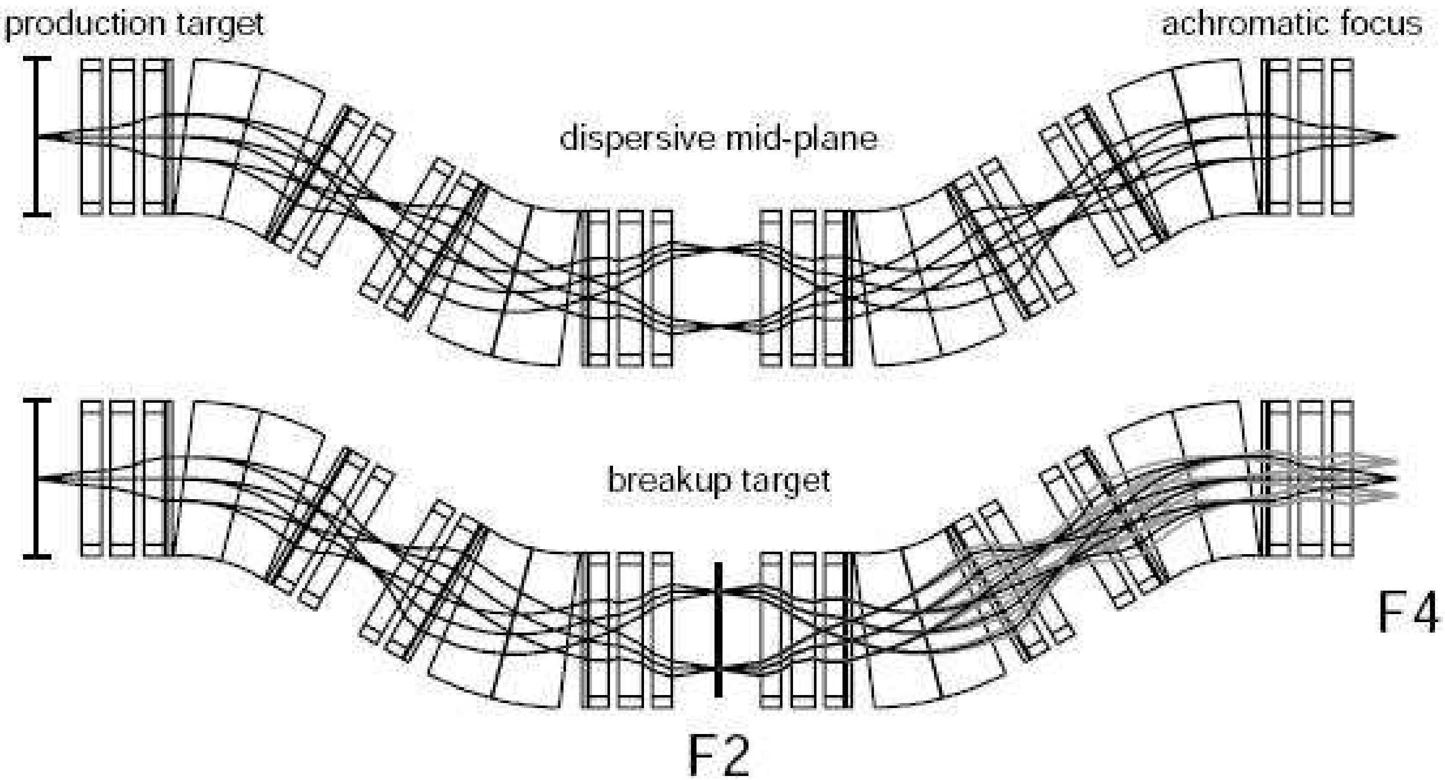
We detect the A-1 fragment

Measure the A-1 fragment momentum → the component parallel to the incident beam

- ✓ The projectile carries momentum (~ 10 GeV/c for A~30 and E~80 MeV/nucleon)
- ✓ The momentum width introduced after a single-particle hole creation ~ 50-300 MeV/c ➔ 50 MeV/c / 10 GeV/c → a resolution better than 0.5 % is needed.
- ✓ In addition the momentum spread of a secondary beam is ~ few %

Spectrometer

Use of spectrometer in the energy loss mode.



Measure the momentum change introduce in the target

rather than the absolute value

$\Delta B\rho / B\rho = 10^{-4}$

H. Geissel et al, NIMB 70 (1992)

Detector Setup : Projectile and Fragments

Identification

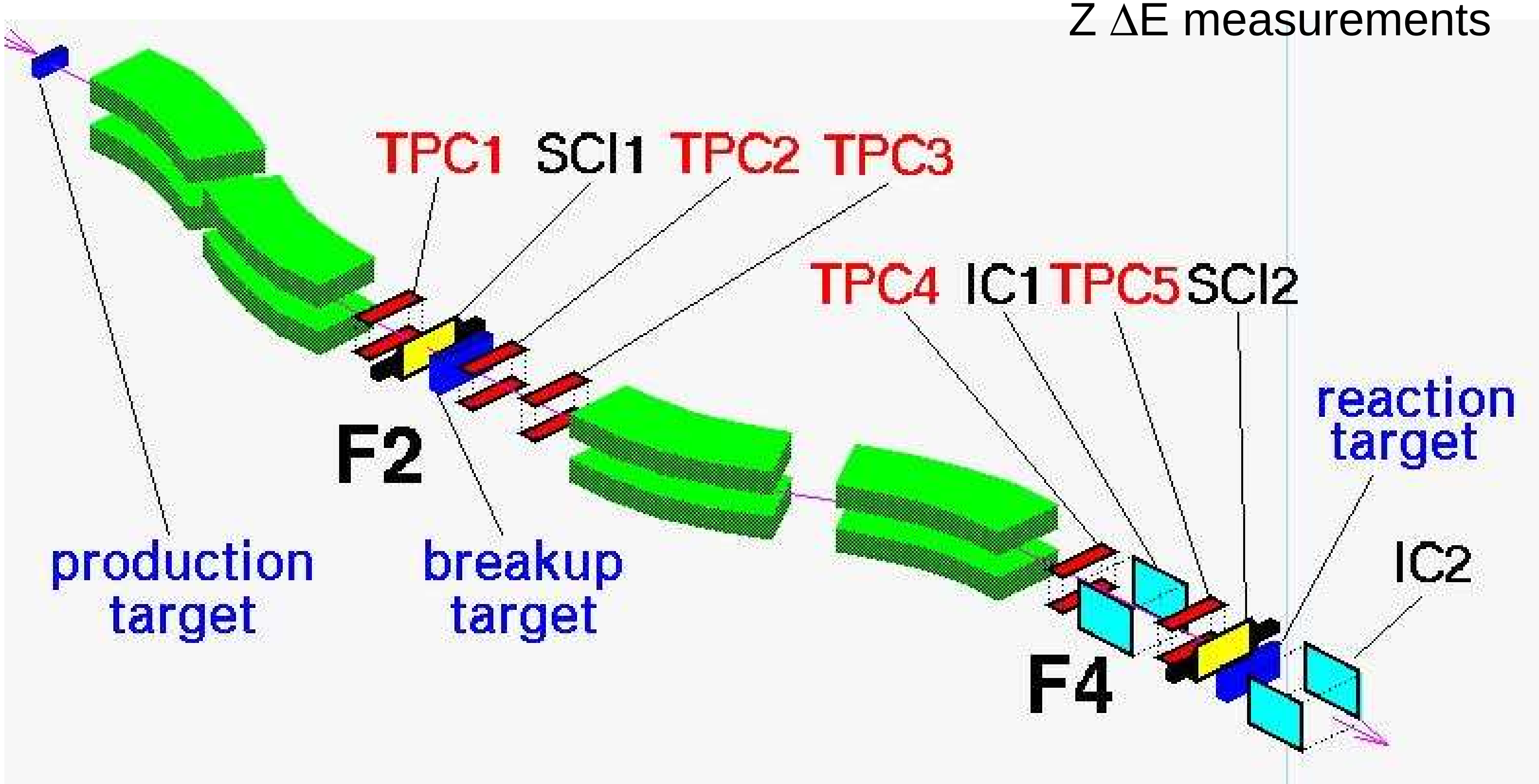
Tracking

$$\frac{A}{Z} = \frac{e}{m_u c} \frac{B\rho}{\beta\gamma}$$

Bρ from position measurements at focus

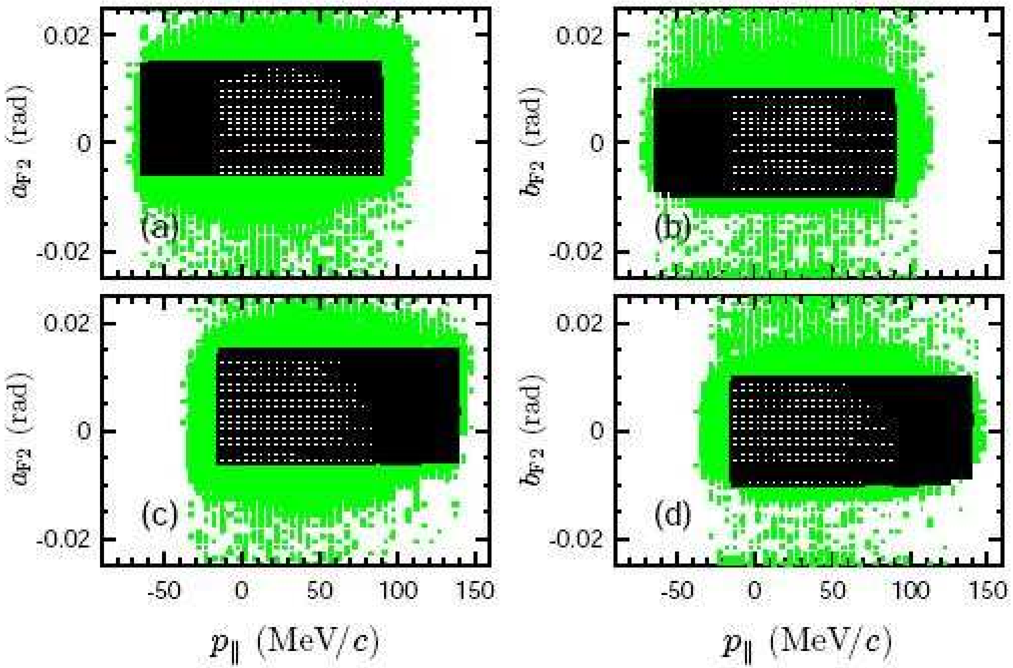
β ToF

Z ΔE measurements



Experimental setup at GSI (FRS)

Heavy fragment detection: spectrometer limited acceptance



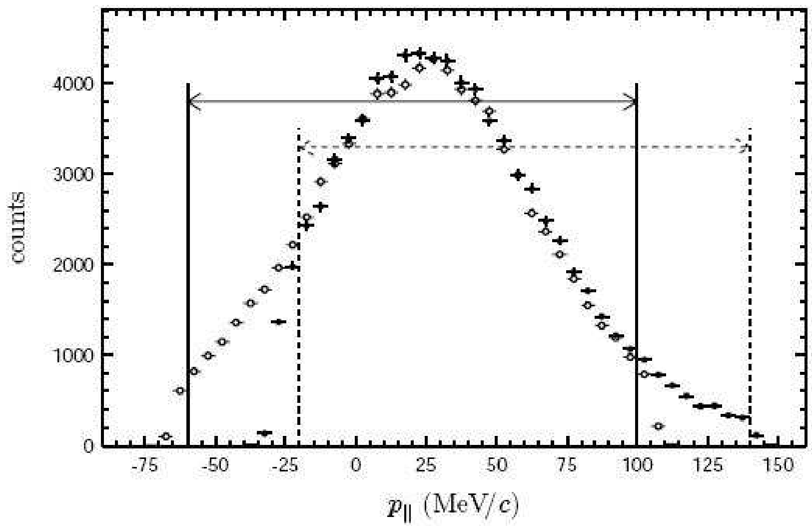
Pictures from T. Baumann PhD thesis

U. Giessen 1997

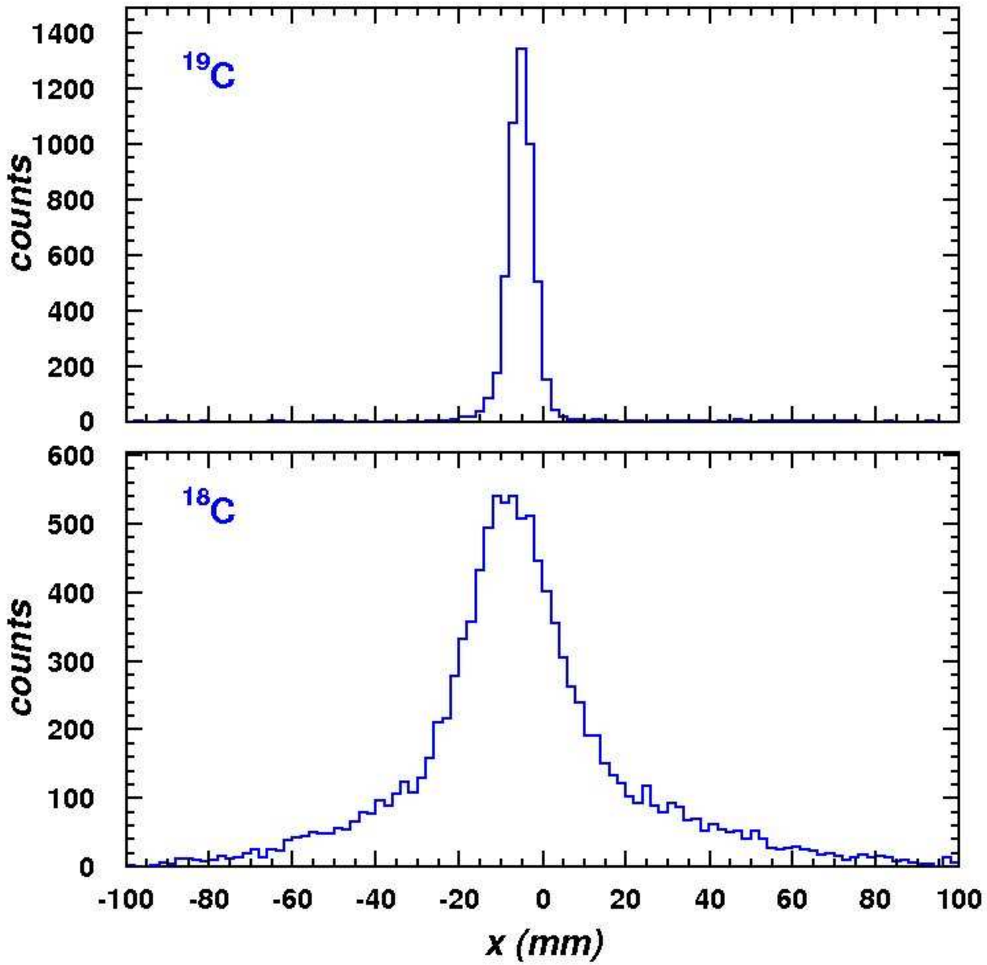
$p_F = P_o(1 + X_F/\delta)$

$P_{mov} = \gamma(P_F - \beta\ E_F/c)$

$E_F = (P^2c^2 + m^4c^4)^{1/2}$



Experimental resolution of the spectrometer



^{19}C at final focus(without target)

^{19}C → ^{18}C at final focus

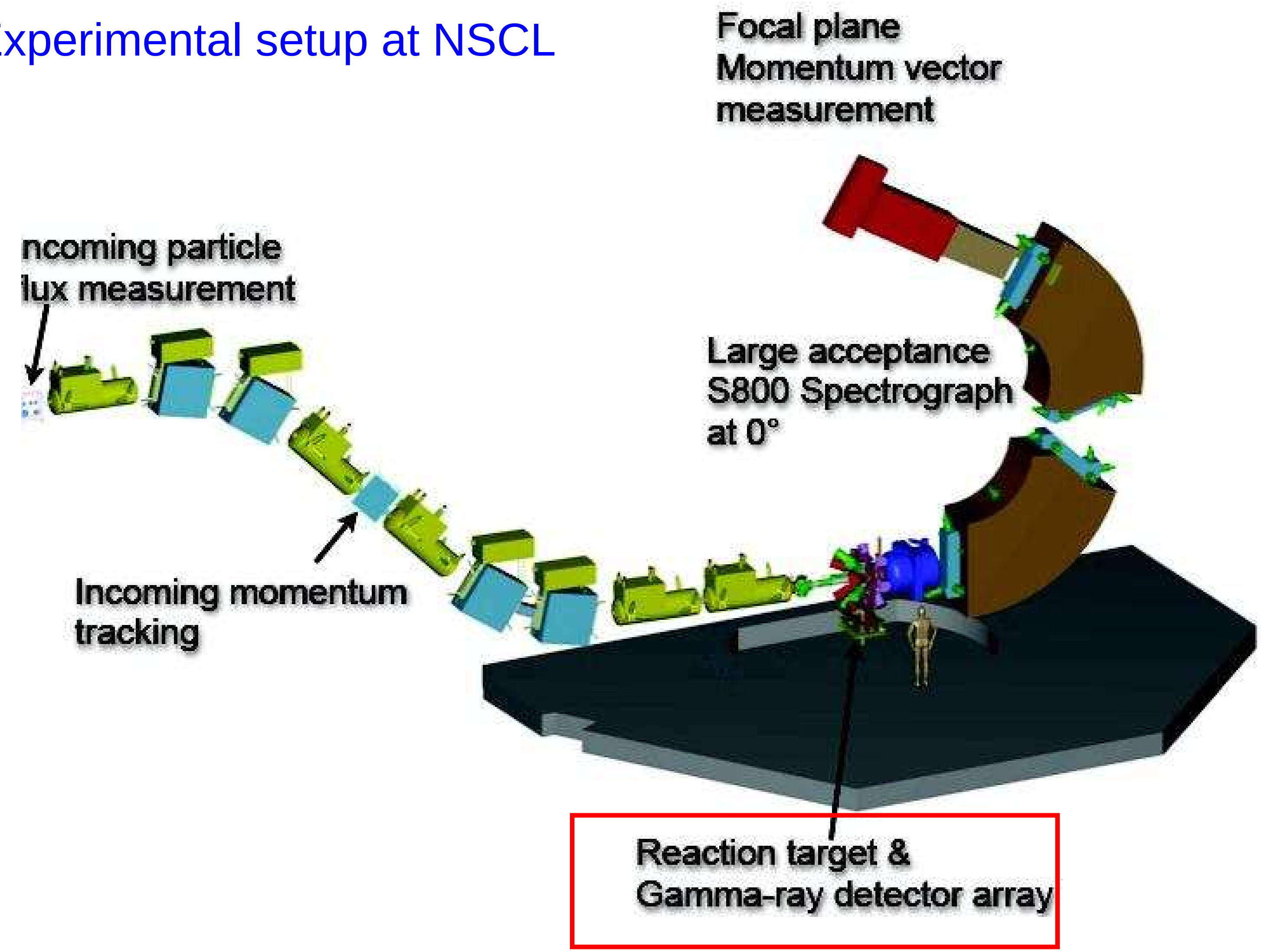
T. Baumann PhD thesis

U. Giessen 1997

Phys. Lett B 439 (1998)

Detector Setup : Gamma ray tagging

Experimental setup at NSCL



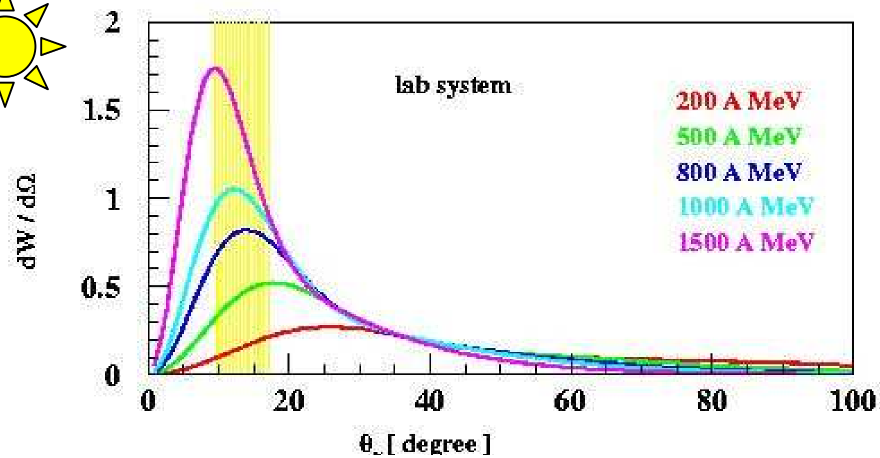
In-beam spectroscopy at high energies

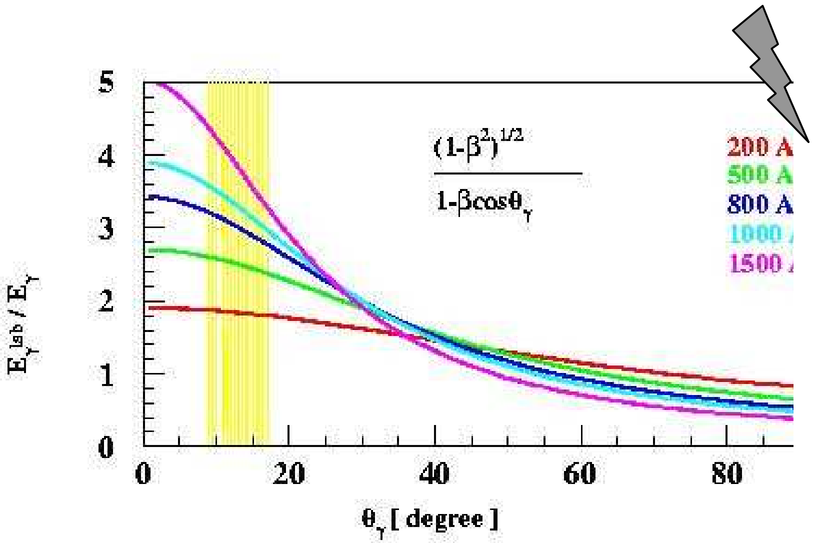
Relativist kinematics

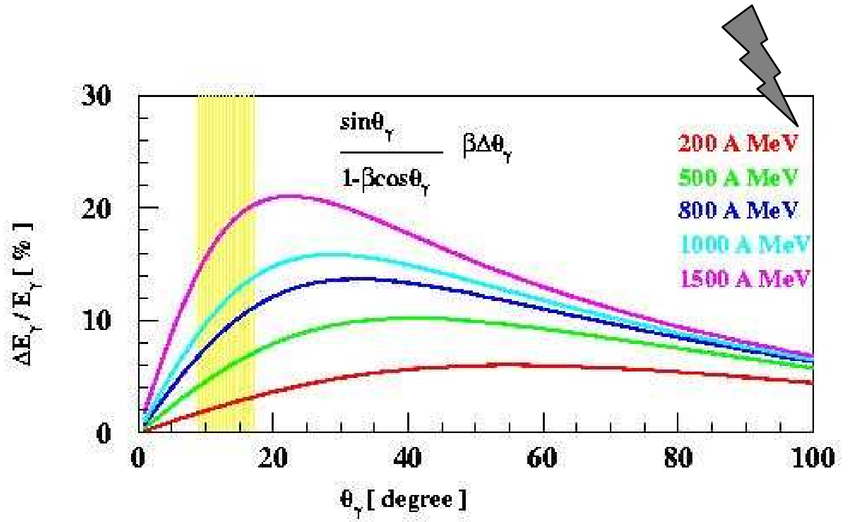
✓Kinematically forward focusing

✓Large Doppler effect

- Doppler shift (efficiency loss)
- Doppler broadening







⇩ **efficiency**

⇩ **energy resolution**

Experimental determination of the measured observables

What can affect the quality of the measurements : parallel momentum distribution of heavy fragment (l assignement) after nucleon removal and associated cross-section (spectroscopic factor)

* Detection of the heavy residue

  Detector efficiency

  Detector resolution

  System resolution

  Transmission → experimental device acceptance

INCLUSIVE

•Detection of gamma rays

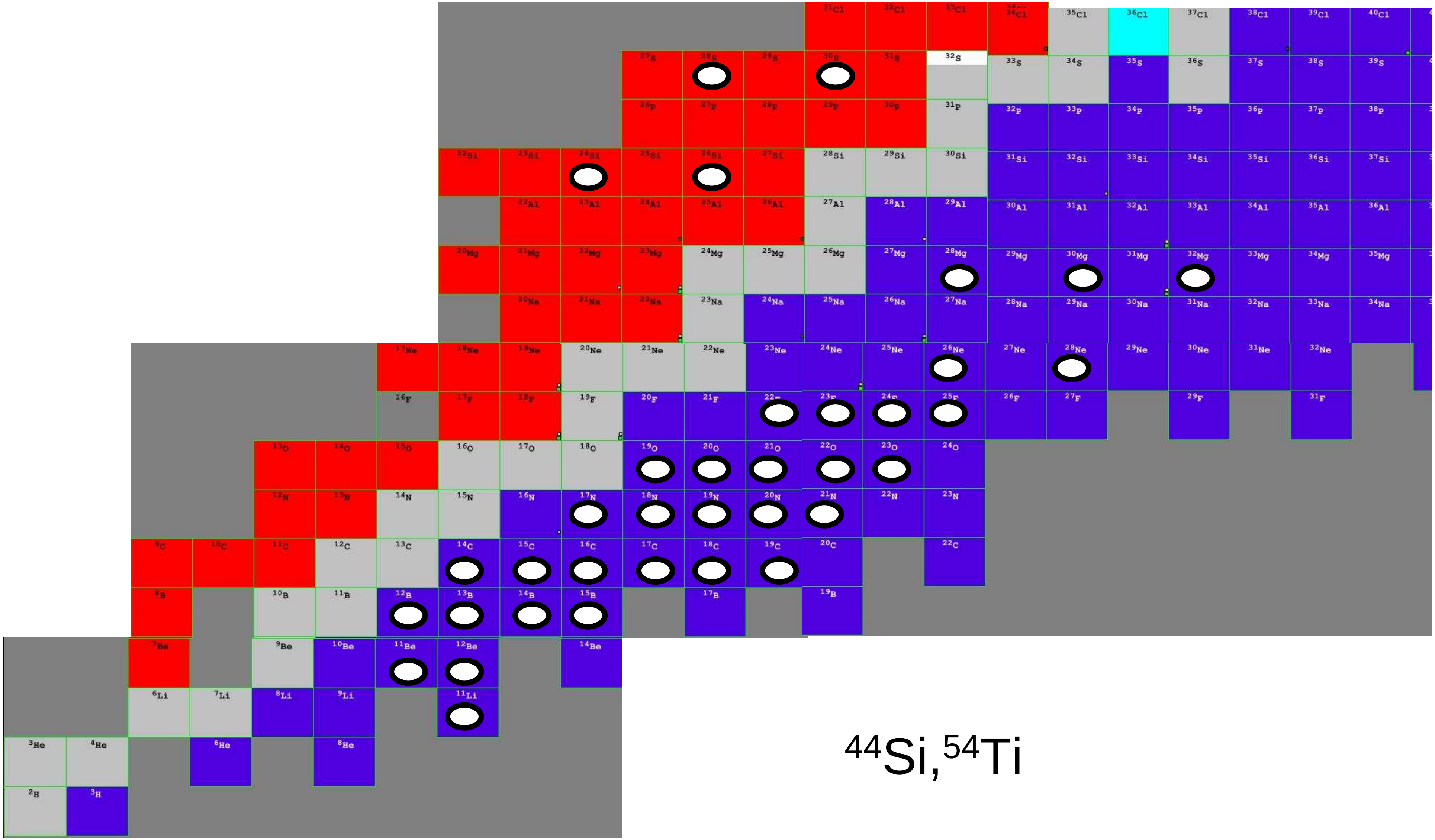
  Detector efficiency

  Detector resolution

EXCLUSIVE

We will discuss in this lecture only about inclusive measurements

Mesurements performed so far ….



$^{44}Si, ^{54}Ti$

The case of halo nuclei: ^{11}Be

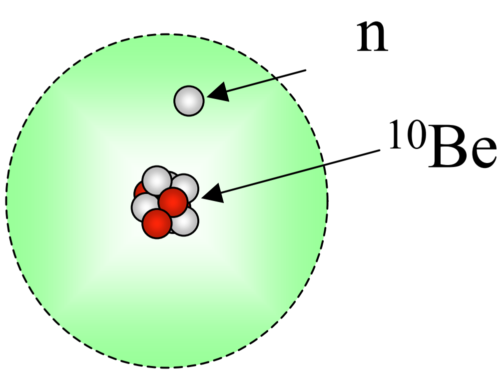
VOLUME 84, NUMBER 1 PHYSICAL REVIEW LETTERS 3 JANUARY 2000

One-Neutron Knockout from Individual Single-Particle States of ^{11}Be

T. Aumann,[1,2] A. Navin,[1,3] D. P. Balamuth,[4] D. Bazin,[1] B. Blank,[5] B. A. Brown,[1,6] J. E. Bush,[4] J. A. Caggiano,[1,6] B. Davids,[1,6] T. Glasmacher,[1,6] V. Guimarães,[7] P. G. Hansen,[1,6] R. W. Ibbotson,[1] D. Karnes,[1] J. J. Kolata,[7] V. Maddalena,[1,6] B. Pritychenko,[1,6] H. Scheit,[1,6] B. M. Sherrill,[1,6] and J. A. Tostevin[8]

- Sn = 0.504 Mev, It is n-halo in the g.s → unusual n WF spatial extension

1/2+ intruder state from the sd-shell



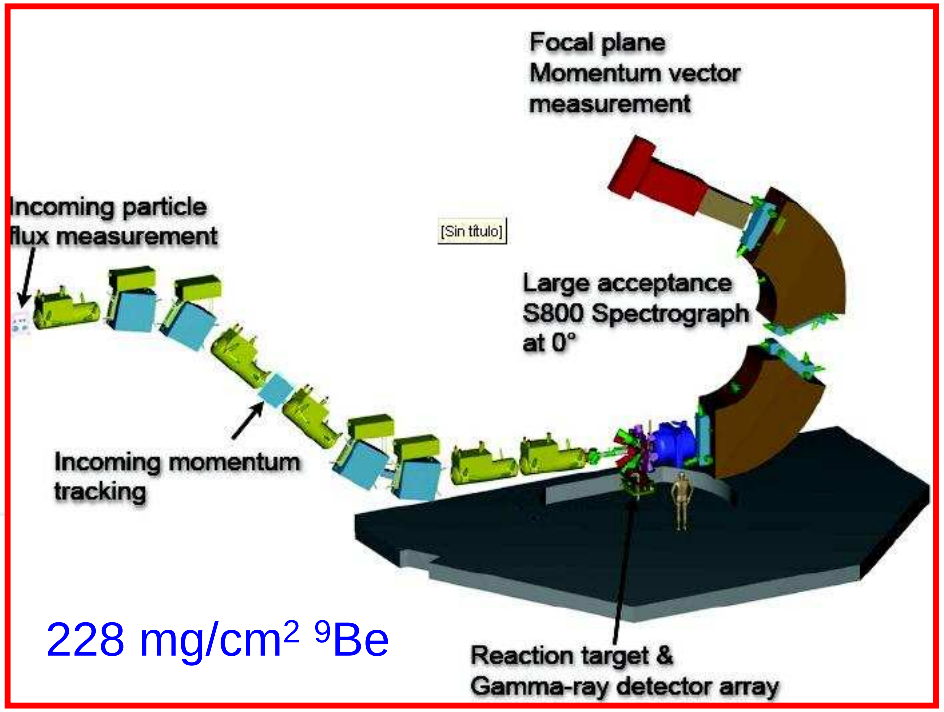
To which extent the picture of the inner core is right?

GS (J^π=1/2$^+$):

$$|GS\rangle = a\,|2s_{1/2} \otimes 0^+\rangle + b\,|1d_{5/2} \otimes 2^+\rangle$$

The case of halo nuclei: ^{11}Be

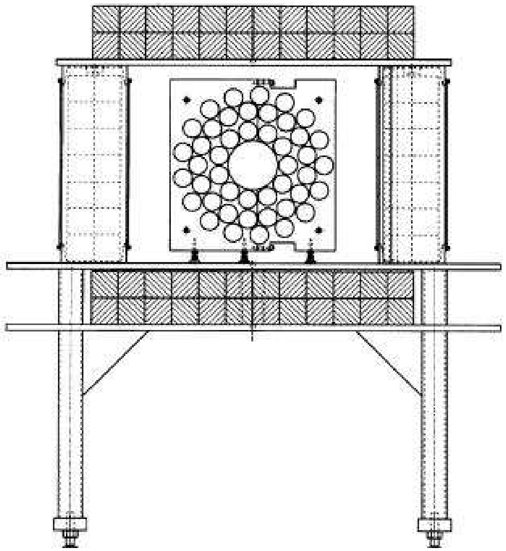
^{11}Be @60 MeV/nucleon

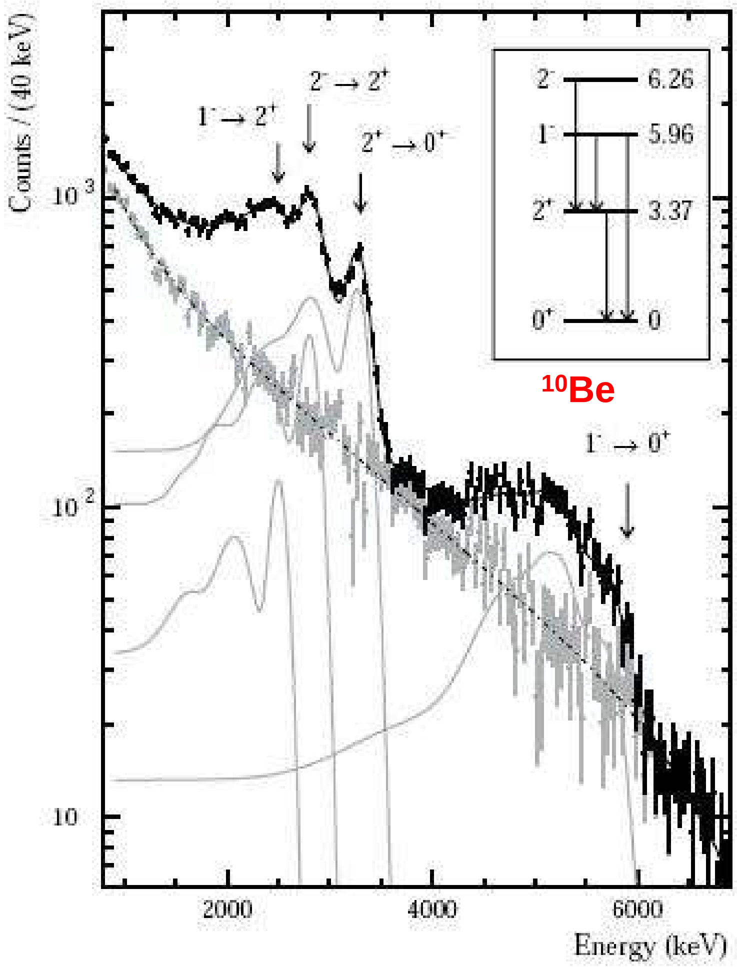


^{18}O @80 MeV/nucleon +
Be 79 mg/cm^2

228 mg/cm^2 ^9Be

The case of halo nuclei: ^{11}Be





Position sensitive NaI detectors

covering 60- 150 deg in cm system

Error sources

residue detector efficiency ~ 100% for g.s

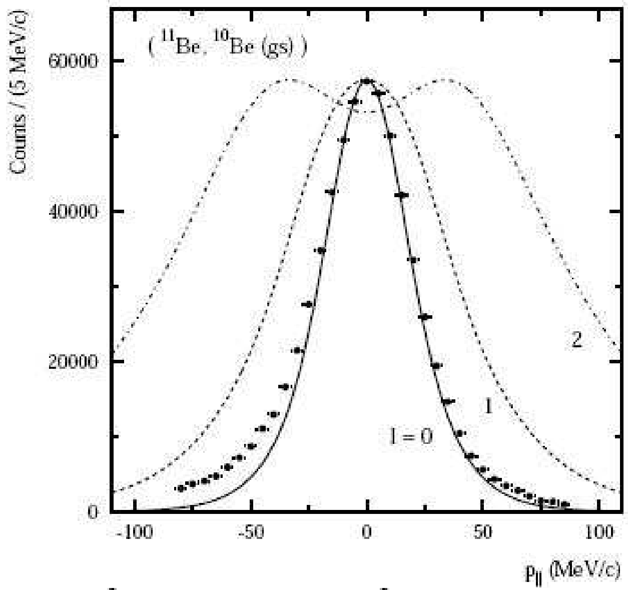
efficiency determination ~ 5%

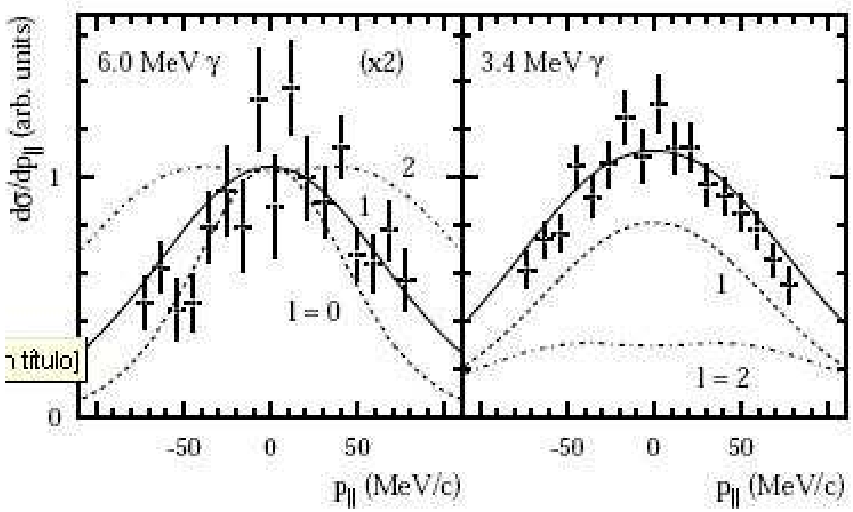
branching ratio determination ~ 10%

Error in cross- section ~ 15 %

The case of halo nuclei: ^{11}Be

FWHM 45.7 MeV/c





I^π	l	S	σ_{sp}^{knock}	σ_{sp}^{diff}	σ^{other}	σ^{theo}	σ^{expt}
0^+	0	0.74	125	98	10 [a]	172	203(31)
2^+	2	0.18	36	14	11 [b]	17	16(4)
1^-	1	0.69	25	9		23	17(4)
2^-	1	0.58	25	9		20	23(6)
Σ						224	259(39)

[a] Coulomb dissociation.

[b] Rotational excitation; spectroscopic factor is that of the 0^+ state (see text).

S_{exp}

→ **0.84**

$R_s = \sigma_{exp}/\sigma_{the} \sim 1.1$

✓ $^{10}Be|0+\rangle$ accounts for ~ 80%

✓ S_{exp} in good agreement with S_{theo}

The case of halo nuclei: ^{8}B

ELSEVIER
Physics Letters B 529 (2002) 36–41
PHYSICS LETTERS B
www.elsevier.com/locate/npe

Experimental evidence for the ^{8}B ground state configuration

D. Cortina-Gil [a,b], K. Markenroth [c], F. Attallah [b], T. Baumann [d], J. Benlliure [a], M.J.G. Borge [e], L.V. Chulkov [b,f], U. Datta Pramanik [b], J. Fernandez-Vazquez [a], C. Forssén [c], L.M. Fraile [e], H. Geissel [b], J. Gerl [b], F. Hammache [b], K. Itahashi [g], R. Janik [h], B. Jonson [c], S. Karlsson [c], H. Lenske [i], S. Mandal [b], M. Meister [c], X. Mocko [h], G. Münzenberg [b], T. Ohtsubo [b,j], A. Ozawa [k], Y. Parfenova [c], V. Pribora [f], K. Riisager [l], H. Scheit [m], R. Schneider [n], K. Schmidt [b], G. Schrieder [o], H. Simon [o], B. Sitar [h], A. Stolz [n], P. Strmen [h], K. Sümmerer [b], I. Szarka [h], S. Wan [b], H. Weick [b], M. Zhukov [c]

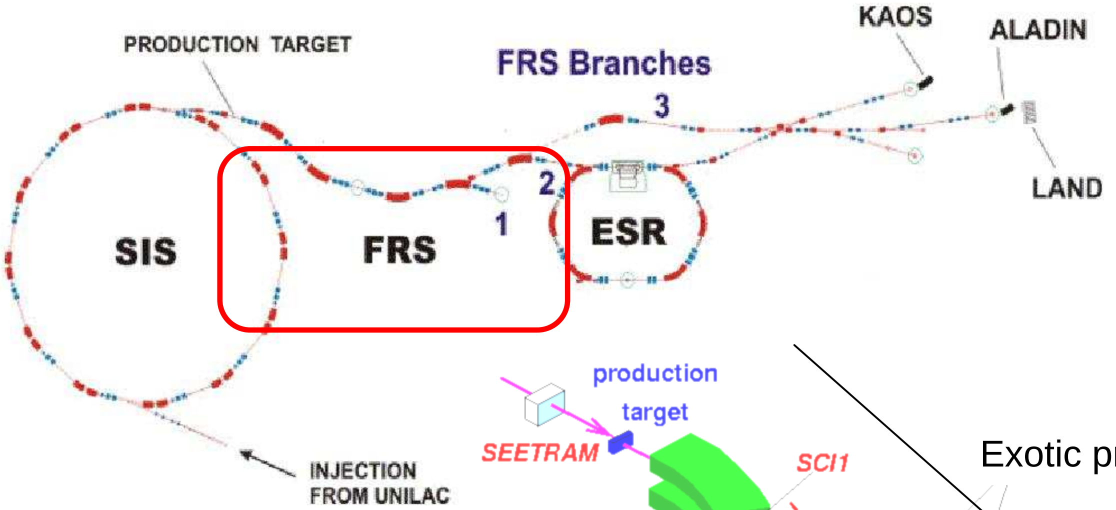
- Satisfactory description of its structure (3-body model)
- Sp = 0.1375 Mev, It is the single p-halo observed in the g.s and...

In the ^{8}B there are 3 possibilities to couple the core (^{7}Be) to the valence proton to obtain the known 2^{+} ground state:

Core	3/2-	3/2-	½-
Proton	3/2-	½-	3/2-

Which are the weights of these 3 possibilities in the ^{8}B ground state Wave Function ?

The case of halo nuclei: ^{8}B

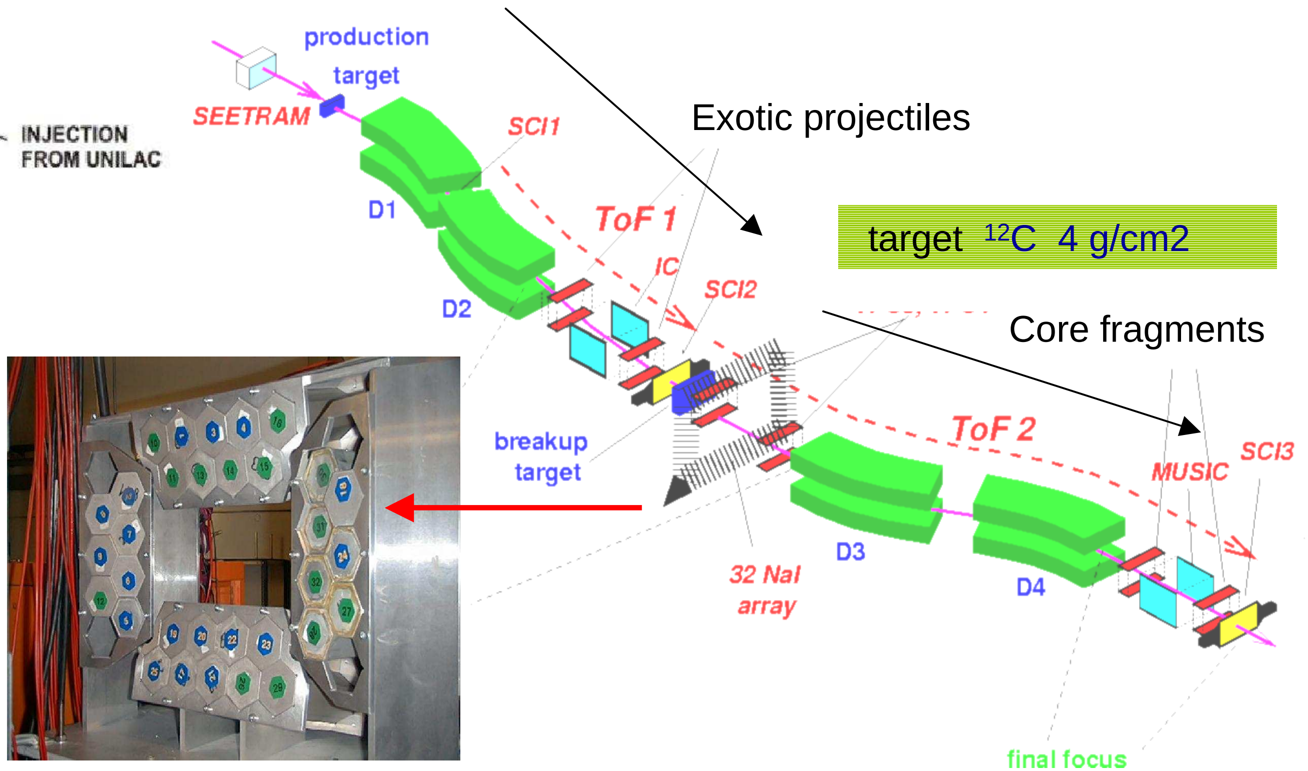


Primary beam

^{12}C @1 GeV/nucleon

Production target ,

^{9}Be 8 g/cm2



target ^{12}C 4 g/cm2

32 NaI

$\Delta E/E \sim 12\%$

$E \sim 3\%$

D.Cortina

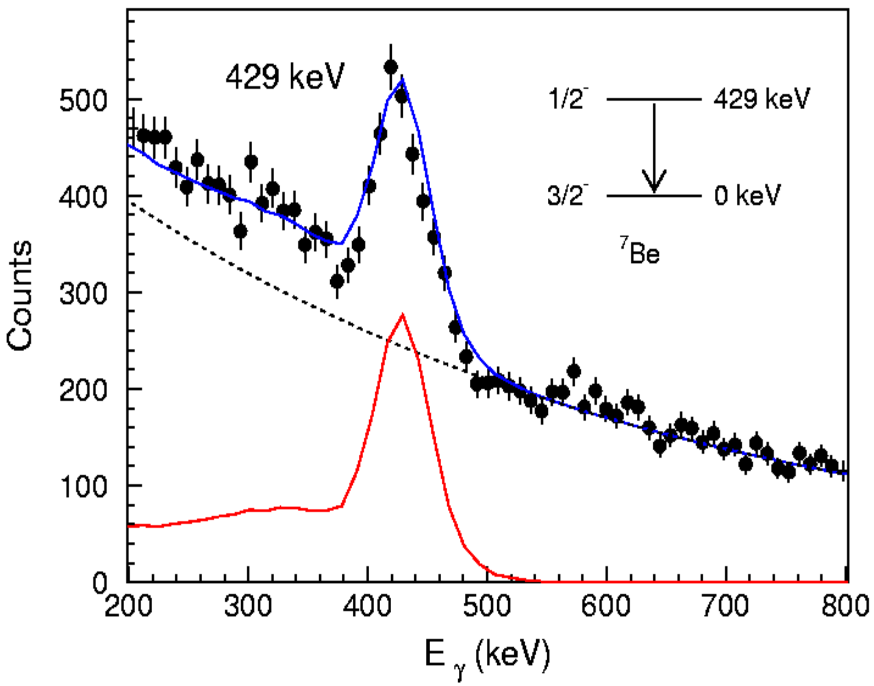
The case of halo nuclei: ^{8}B

•

GEANT simulation (red line)

background (dotted line)

blue line = red line + dotted line



✓ 7Be has a single bound excited state at 429 keV

The coincidence allow to distinguish between

a (3/2$^-$ ⊗ 1p 3/2 $^-$)

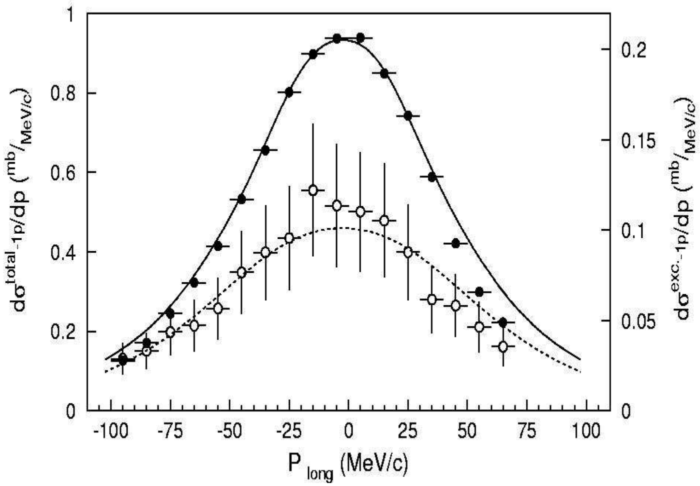
b (3/2$^-$ ⊗ 1p 1/2 $^-$)

c (1/2$^-$ ⊗ 1p 3/2 $^-$)

* check to the ^{8}B wave func.

* no selection on l in the P_{long}

The case of halo nuclei: ^{8}B

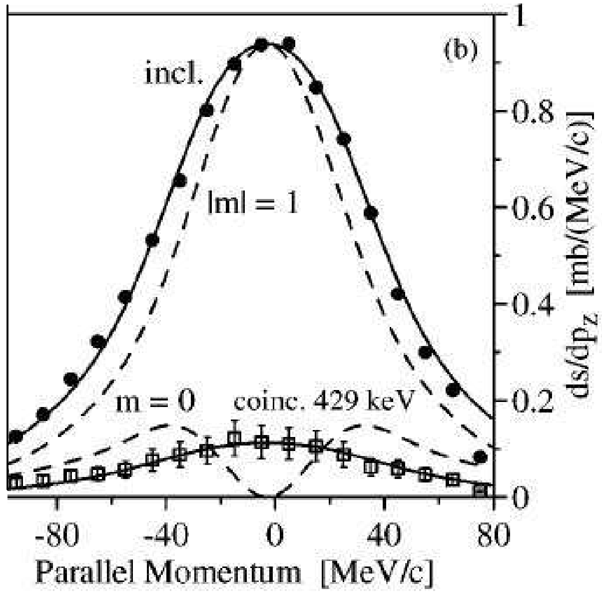


D. Cortina et al NPA 720(2003)3

3-body model+ Eikonal aproximation

	σ_{-1p} exp. (mb)	σ_{-1p} theo. (mb)	P_{long} exp. (MeV/c)	P_{long} theo. (MeV/c)
Total	94±9	81	95±5	99
Exc.	12±3	11	110±20	127

$Rs = \sigma_{exp}/\sigma_{the} \sim 1.09$



G. Hansen and J. Tostevin Ann. Rev. Nucl. Part. Sci. 53 (2003)

same data set

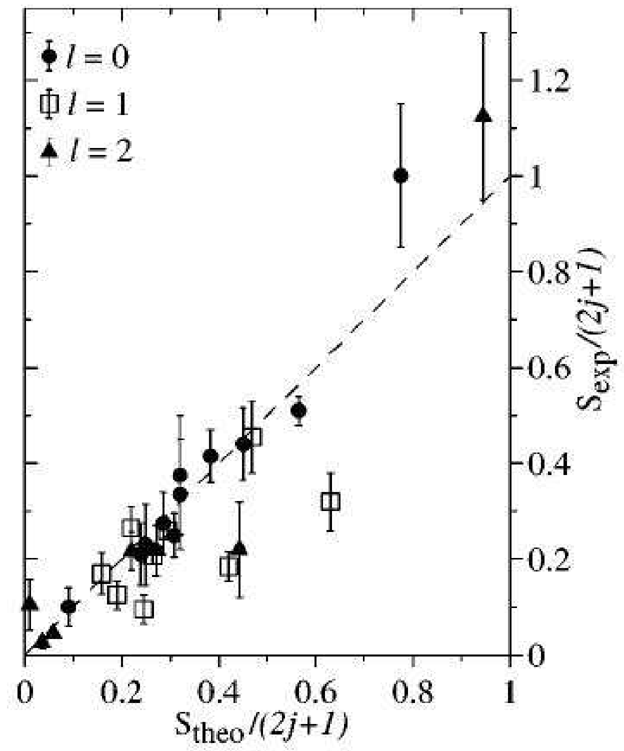
Overall very good agreement

➔ the reaction description is satisfactory as well as the nuclear structure information

Main error source ➔ gamma detection

Summary – Lecture 1

- We have explained the experimental technique
- We have analysed two selected cases : ^{11}Be, ^{8}B



Is it possible to extract spectroscopic information using this technique??

Puts together two models that are not directly conected : shell model and eikonal theory

Very good agreement for weakly bound nuclei

Discrepancies expected when the fundamental assumptions fail

- more complex reaction mechanism ➔ knockout neutrons from inner shells
- no so weakly bound nuclei

P.G. Hansen and J.A.Tostevin Ann. Rev. Nucl. Part. Sci. 53 (2003)

The ^{8}B case, experimental determination of diff/stripp cross sect

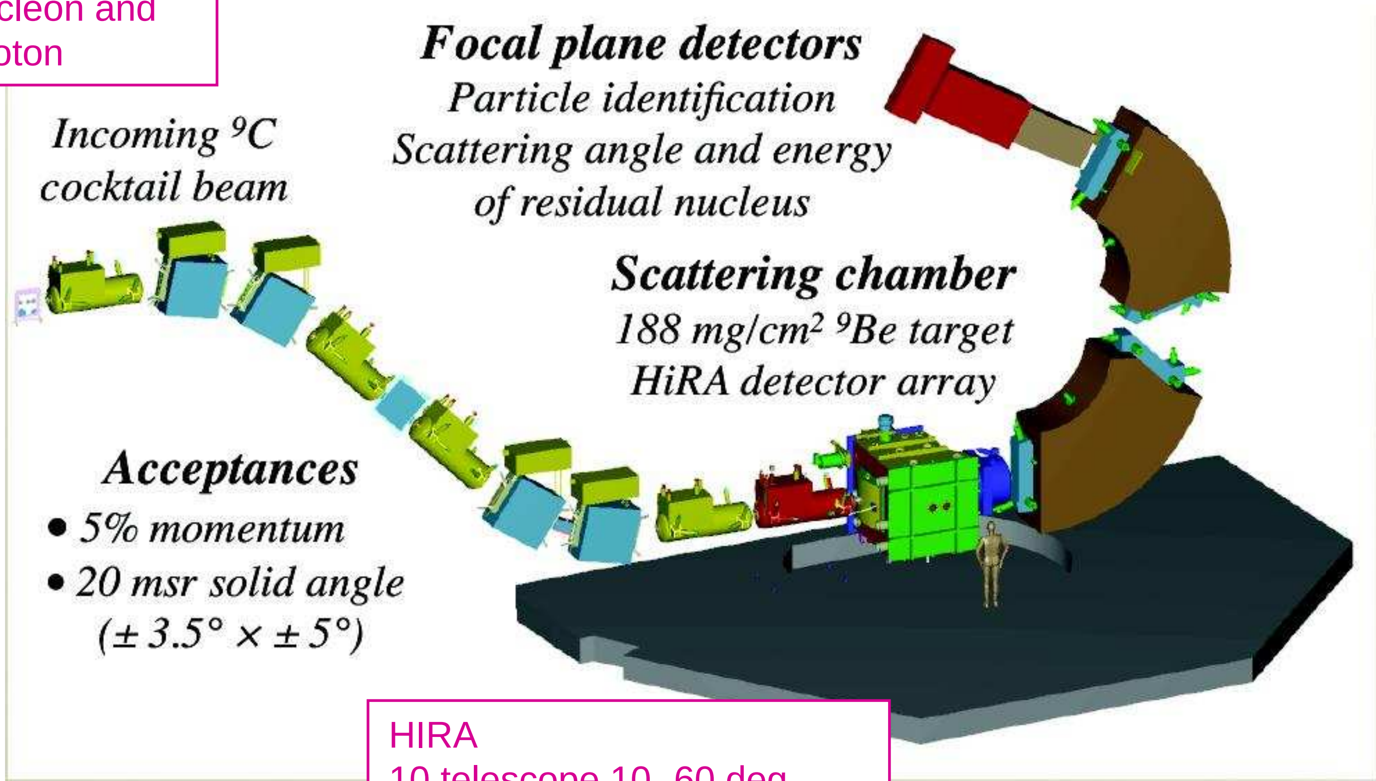
Experiment aimed to measure both contributions separately

^{9}C and ^{8}B One-proton removal in full kinematics

D. Bazin et al DREB 07 RIKEN 2007

$$\sigma = \sigma^{str} + \sigma^{diff}$$

Detection of both removed nucleon and knockout proton



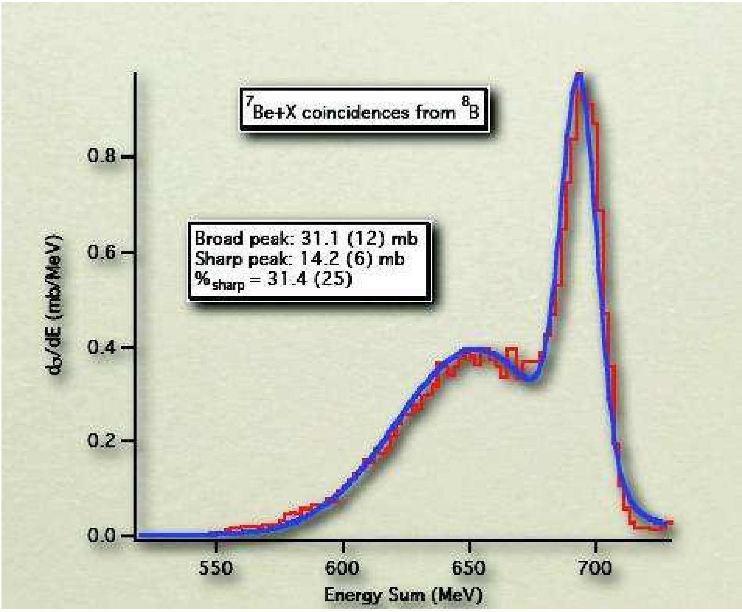
HIRA
10 telescope 10- 60 deg

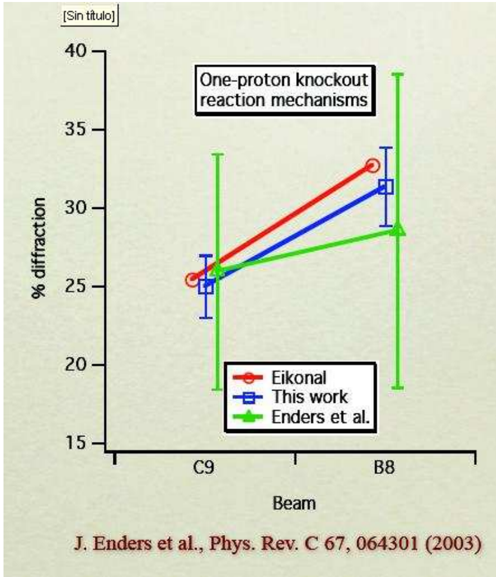
(32x32 DSSD + 4 CsI)

The ^{8}B case, experimental determination of diff/stripp cross sect

D. Bazin et al DREB 07 RIKEN 2007

The experimental results show contributions of ^{7}Be in coincidence with d





Initial state	Final state	S_p (MeV)	σ_{str} (mb)	σ_{diff} (mb)	S_{SM}	σ_{tot} (mb)	$\%_{diff/str}$
^{9}C (3/2$^-$)	^{8}B (2$^+$)	1.300	46.0	15.7	0.94	58	25.4
^{8}B (2$^+$)	^{7}Be (3/2$^-$)	0.137	61.5	30.5	1.036	111.8	32.7
^{8}B (2$^+$)	^{7}Be (1/2$^-$)	0.566	52.7	22.5	0.22		

École Internationale Joliot-Curie

RÉACTIONS DE DISSOCIATION:

-Aspects théoriques par D. Baye
-Aspects expérimentaux

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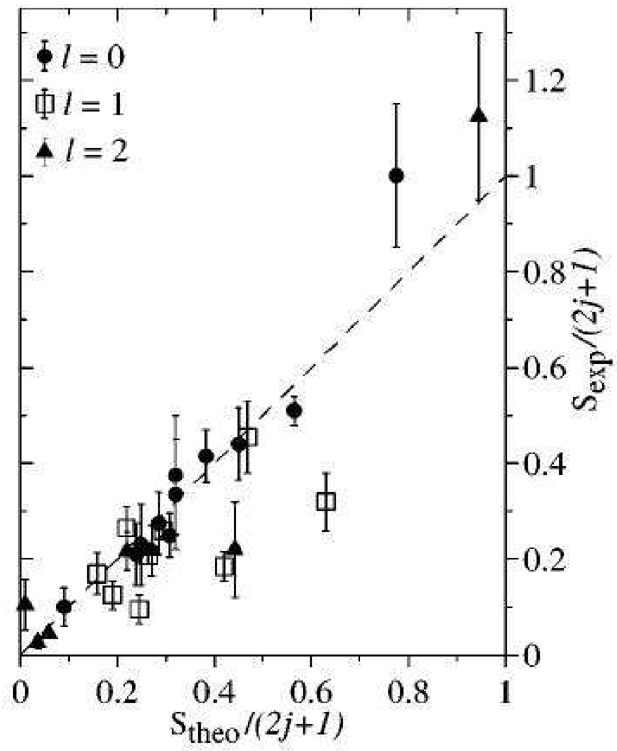
USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

GENP Grupo Experimental de Núcleos y Partículas

MAUBUISSON (France) 17-22 September 2007

Summary – Lecture 1

- We have explained the experimental technique
- We have analysed two selected cases : ^{11}Be, ^{8}B



P.G. Hansen and J.A.Tostevin Ann. Rev. Nucl. Part. Sci. 53 (2003)

Is it possible to extract spectroscopic information using this technique??

Puts together two models that are not directly conected : shell model and eikonal theory

Very good agreement for weakly bound nuclei

Discrepancies expected when the fundamental assumptions fail

- more complex reaction mechanism ➔ knockout neutrons from inner shells
- no so weakly bound nuclei

Layout

On the lecture's title

- Introduction: reactions with fast radioactive beams
- Experimental aspects associated: shopping list
- Experimental determination of the measured observables:
- Overview on the studied cases
- The case of halo states: ^{8}B and ^{11}Be
- Other selected cases
- Experimental determination of the spectroscopic information. Comparison with Coulomb dissociation experiments
- Two-nucleon removal
- Summary and conclusions
- Bibliography

Other more complex cases: ^{23}O

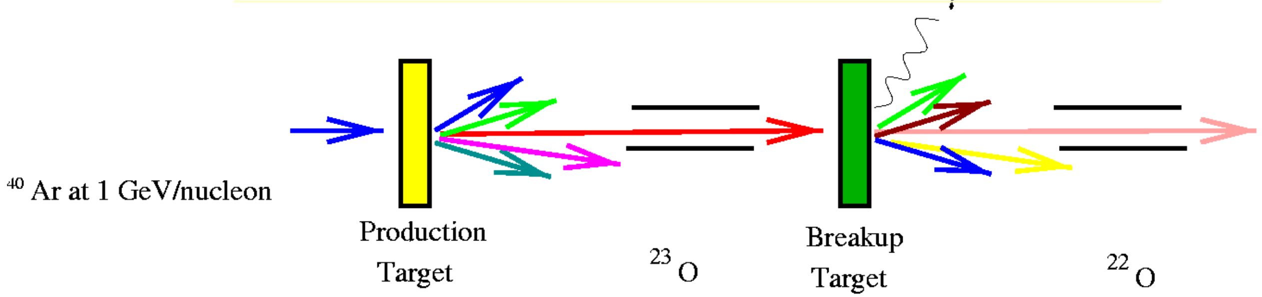
Determination of the ^{23}O shell structure — controversial results

Sauvan et al PLB 491(2000) g.s → **1/2 +**

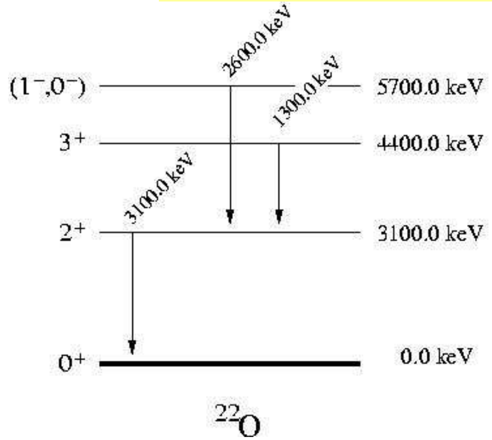
Kanungo et al PRL 88(2002) g.s → **5/2 +**

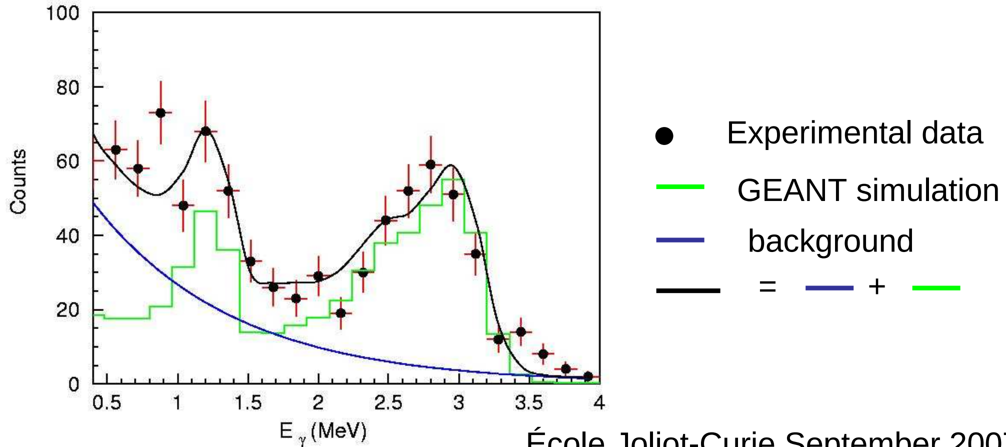
Presence of s wave in the total profile

Selectivity on the different configurations



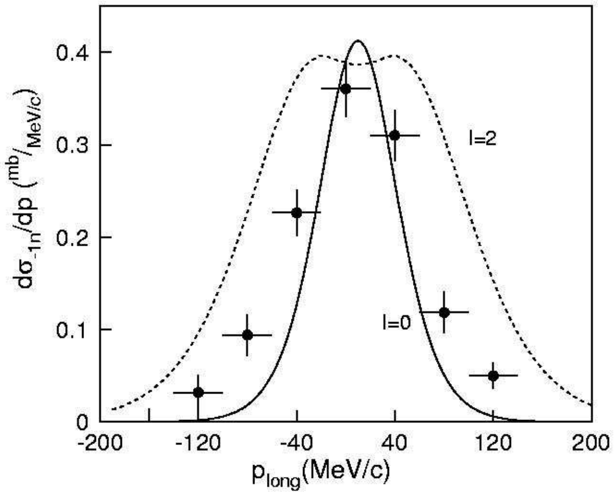
Information from the ^{22}O core-fragment de-excitation





Other more complex cases: ^{23}O

D. Cortina et al. PRL 93 (2004) 062501



● Experimental data

——— l = 0 ……… l = 2

From the comparison we assign **$J^\pi = 1/2^+$**

$|1/2^+\rangle = a|\,0^+ \otimes 2s_{1/2}\rangle + b|\,2^+ \otimes 1d_{5/2}\rangle$

σ_{exp} (mb)	σ_{theo} (mb)	S_{exp} $\sigma_{exp}/\sigma_{theo}$	C^2S_t
50±10	0^+ 51	0.97±0.19	0.8
10.5±4.5	2^+ 20	0.52±0.21	2.13
14±5	3^+ 18	0.77±0.27	3.08
10.5±4.5	$(1^-,0^-)$ 15	0.7±0.28	0.85
85±10	104.		

✓ Cross- section calculated separately for the individual single-particle configuration (eikonal approach) and then weighted with C^2S_t from Brown et al. PRL (2003)159201

✓ S_{exp} extracted from the ratio exp/calculated

➢Experimental evidence for a g.s **$J^\pi = 1/2^+$** for ^{23}O with a large C^2S for the **$0^+ \otimes |2s_{1/2}\rangle$**

➢Discrepancy for S_{exp} involving ^{22}O in any excited state

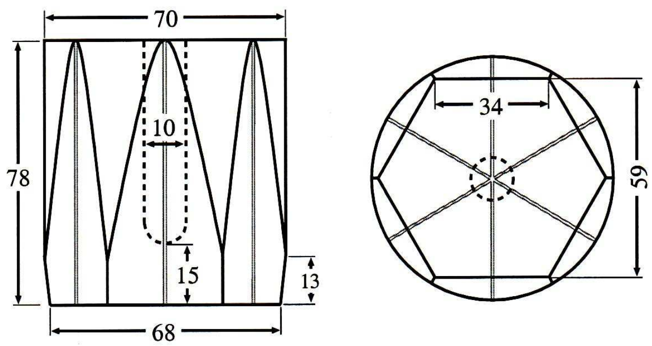
MINIBALL @FRS

Primary beam

Array of 24 Ge-crystals (MINIBALL[1])

8 clusters → 3 crystals → 6 segment

Average dimensions



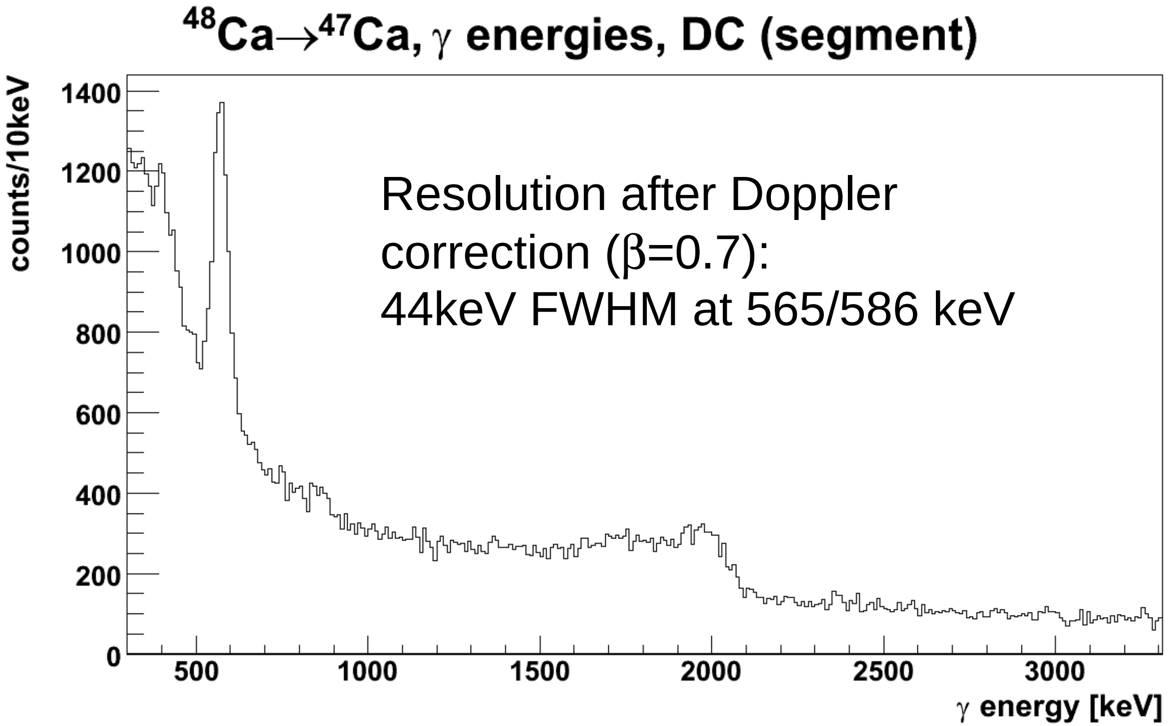
Covered solid angle ~ 11% 4Π and ~17% of the angular distribution for 700 A MeV moving gammas

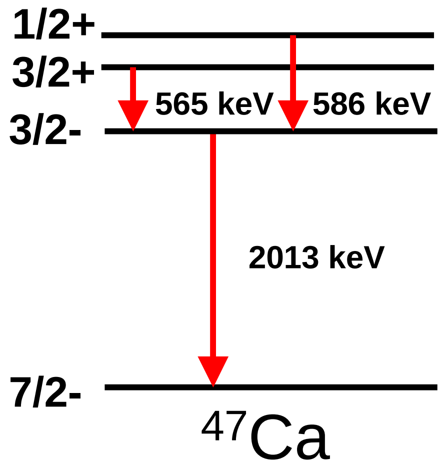
[1] J. Eberth et al., Progress in Particle and nuclear Physicas 46 (2001)389

Other more complex cases: ^{23}O

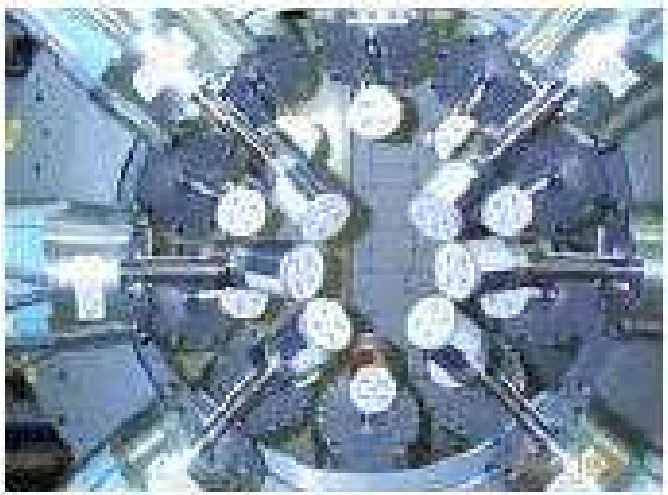
Probing the single particle structure around ^{54}Ca with one-neutron knockout- P. Maierbeck for S277 experiment

In calculations a shell closure at N=34 is predicted for calcium (Z=20)
as ^{54}Ca was out of the scope
→ measured other Ca isotopes





Other dedicated Ge- arrays



SEGA @ NSCL

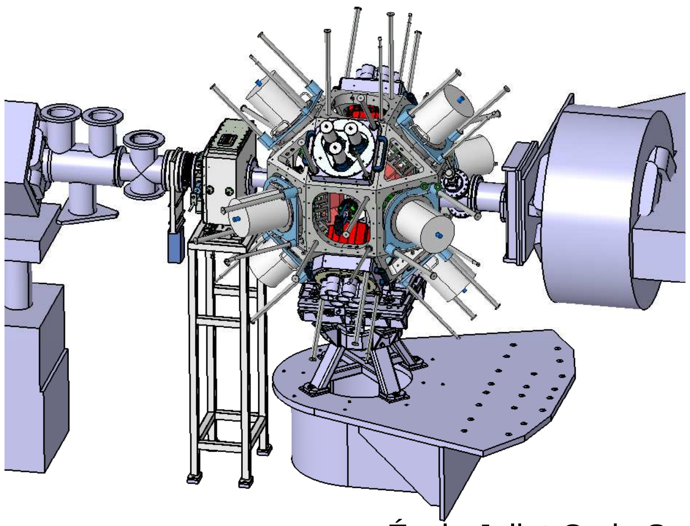
SeGA : 14 32-fold Ge detectors

20 cm from target

EXOGAM @ GANIL

8 exogam clusters

4x3 NaI detectors (14x20 cm)



More complex nuclei : Challenge to nuclear structure models

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Physics Letters B 640 (2006) 86–90

PHYSICS LETTERS B

www.elsevier.com/locate/physletb

Direct evidence for the onset of intruder configurations in neutron-rich Ne isotopes

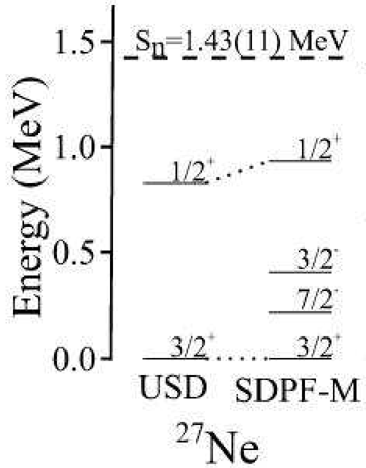
J.R. Terry [a,b,*], D. Bazin [b], B.A. Brown [a,b], C.M. Campbell [a,b], J.A. Church [a,b,1], J.M. Cook [a,b], A.D. Davies [a,b], D.-C. Dinca [a,b,2], J. Enders [b,3], A. Gade [b], T. Glasmacher [a,b], P.G. Hansen [a,b], J.L. Lecouey [b], T. Otsuka [d,e], B. Pritychenko [g], B.M. Sherrill [a,b], J.A. Tostevin [c], Y. Utsuno [f], K. Yoneda [b,4], H. Zwahlen [a,b]

<u>Island of inversion N ≥20 Z≤ 12</u>

Ground state dominated by intruder configurations

- Different effective interaction yield to very different predictions in the transitional region N=16-20

SDPF- M allows unrestricted mixing of particle-hole configuration across N=20 → they are already important at **N=17**



More complex nuclei : Challenge to nuclear structure models

Primary beam / Production target

^{48}Ca +376 mg/cm^2 Be

Secondary beam

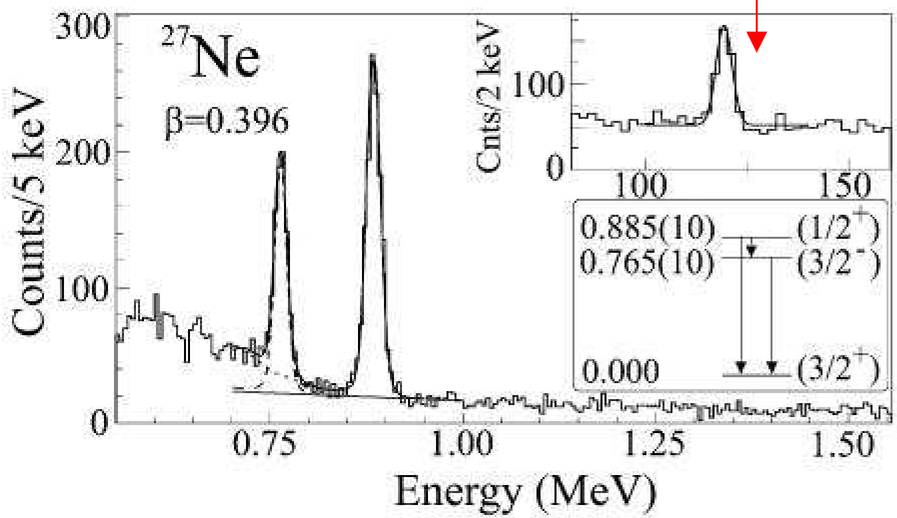
^{28}Ne @80 MeV/nucleon and 330 pps (10% purity)

SeGA 18 detectors (9 pairs 24-147 deg)

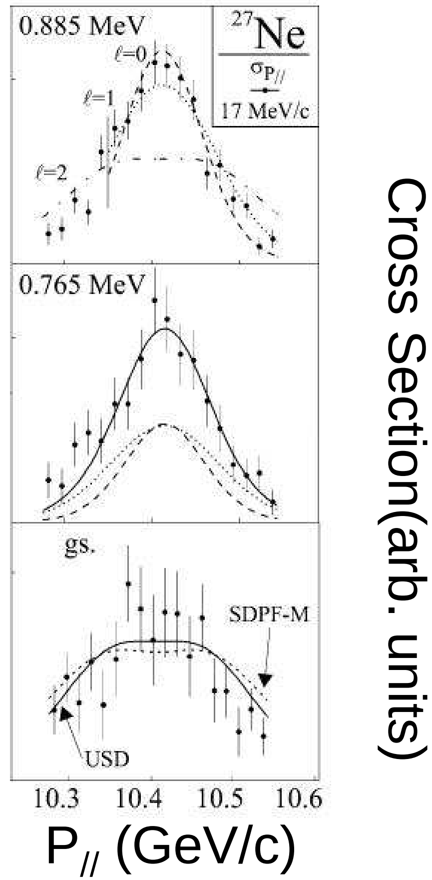
E_{ph}= 3% $\Delta E/E$= 2.4%

Observations contradic
USD in favour of SDPF-M

Never seen before

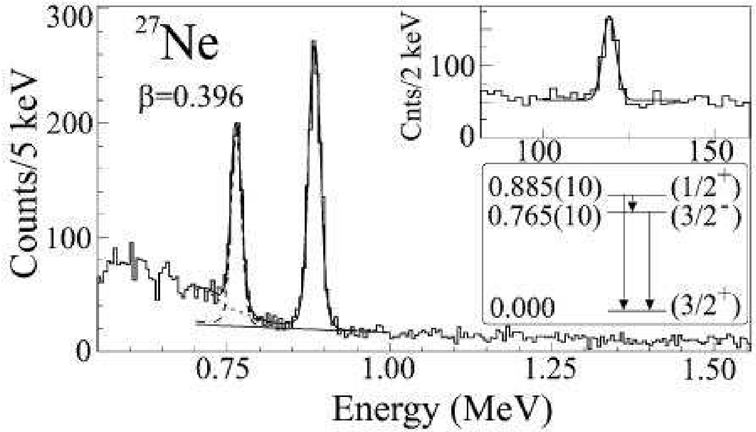


l=0,1



Consistent with the J^{Π} proposed

More complex nuclei : Challenge to nuclear structure models



No spectroscopic factors available with SDFP

E_{level} (MeV)	ℓ	σ_{exp} (mb)	σ_{sp} (mb)	C^2S exp	J^π	C^2S USD	$\langle n \rangle$ USD	$\langle n \rangle$ SDPF-M
^{9}Be(^{26}Ne, ^{25}Ne)X								
0.000	0	42(4)	30.8	1.4(1)	$\frac{1}{2}^+$	1.25	1.61	1.74
1.703	2	25(2)	19.3	1.3(1)	$\frac{5}{2}^+$	2.17	5.67	5.68
3.316	2	22(3)	17.7	1.2(2)		1.70		
2.090	2[a]	9(2)	18.7	0.5(1)	$\frac{3}{2}^+$	0.38	0.72	0.48
					$\frac{7}{2}^-$	–	–	0.08
					$\frac{3}{2}^-$	–	–	0.02
		$\sigma_{inc} = 98(5)$				$\sum = 8$	8	
^{9}Be(^{28}Ne, ^{27}Ne)X								
0.000		21(2)[b]			$\frac{3}{2}^+$	1.75	2.18	1.18
0.765	(0, 1)	10(1)	32.7	0.32(4)	$\frac{3}{2}^-$	–	–	0.24
0.885	(0, 1)	35(2)	32.7	1.07(7)	$\frac{1}{2}^+$	1.50	1.93	1.87
					$\frac{7}{2}^-$	–	–	0.89
					$\frac{5}{2}^+$	–	5.88	5.83
		$\sigma_{inc} = 66(3)$				$\sum = 10$	10	

2007

These kind of experiments provide spectroscopic information in the sense that are very convenient to determine experimentally J^{Π}

They represent a severe test for different nuclear models

More complex nuclei : Challenge to nuclear reaction models

PHYSICAL REVIEW C 74, 047302 (2006)

One-neutron knockout in the vicinity of the $N = 32$ sub-shell closure: $^{9}Be(^{57}Cr, ^{56}Cr+\gamma)X$

A. Gade,[1,2] R. V. F. Janssens,[3] D. Bazin,[1] B. A. Brown,[1,2] C. M. Campbell,[1,2] M. P. Carpenter,[3] J. M. Cook,[1,2]
A. N. Deacon,[4] D.-C. Dinca,[1,2] S. J. Freeman,[4] T. Glasmacher,[1,2] M. Horoi,[5] B. P. Kay,[4] P. F. Mantica,[1,6]
W. F. Mueller,[1] J. R. Terry,[1,2] J. A. Tostevin,[7] and S. Zhu[3]

Primary beam / Production target ^{36}Ge +423 mg/cm^2 Be

Secondary beam
57Cr @77 MeV/nucleon

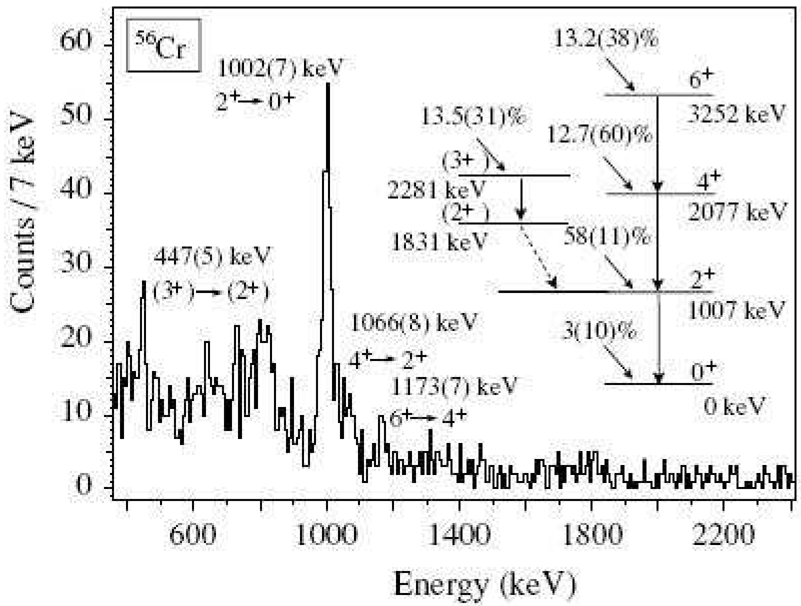
SeGA
E_{ph}= 2.2% at 1.33MeV

Very complex decay scheme→

Many higher E states not directly identify, but through 2$^+$ feeding

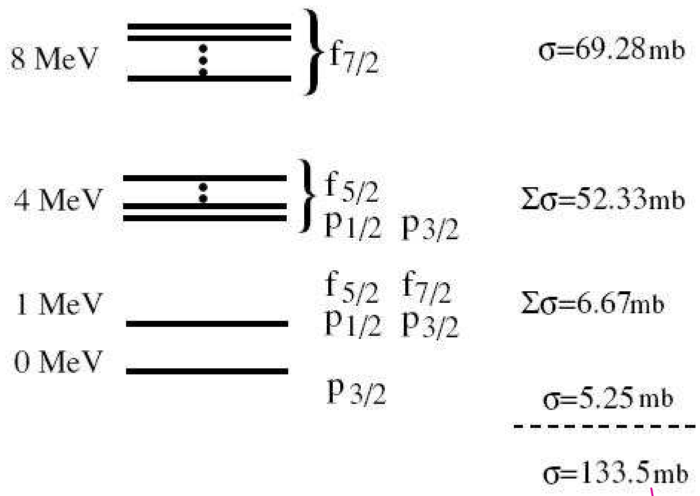
Proton-neutron monopole interaction →

shift in the ν5/2 whit the π7/2 filling →



More complex nuclei : Challenge to nuclear reaction models

Very fragmented spectroscopic strengh



Agreement with the experimental assuming large cross section going to higher E excited states

σ = 122(8) mb

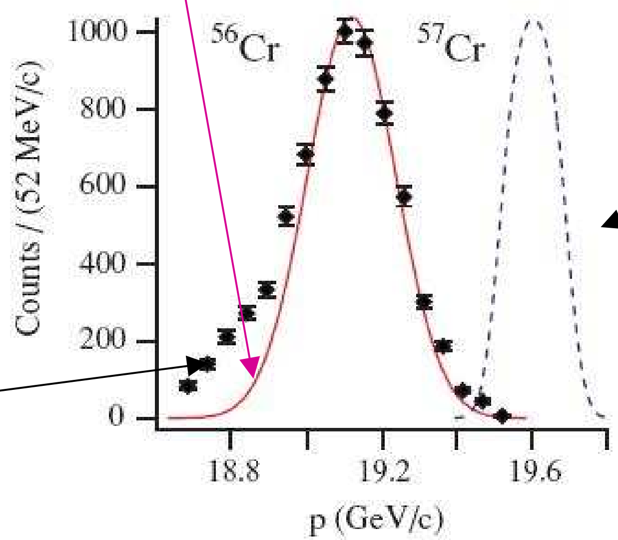
inclusive

No dispersion match mode → not so good system resolution

Asymmetry observed at lower momenta region

→ present in well-bound systems

→ deviation from eikonal reaction model



It is more and more difficult to extract precise spectroscopic information

→ information about deficiencies in the reaction mechanism

More complex nuclei : Deeply bound states in ^{32}Ar

VOLUME 93, NUMBER 4 PHYSICAL REVIEW LETTERS week ending 23 JULY 2004

Reduced Occupancy of the Deeply Bound $0d_{5/2}$ Neutron State in ^{32}Ar

A. Gade,[1] D. Bazin,[1] B. A. Brown,[1,2] C. M. Campbell,[1,2] J. A. Church,[1,2,*] D. C. Dinca,[1,2] J. Enders,[1,†] T. Glasmacher,[1,2] P. G. Hansen,[1,2,‡] Z. Hu,[1] K. W. Kemper,[3] W. F. Mueller,[1] H. Olliver,[1,2] B. C. Perry,[1,2] L. A. Riley,[4] B. T. Roeder,[3] B. M. Sherrill,[1,2] J. R. Terry,[1,2] J. A. Tostevin,[5] and K. L. Yurkewicz[1,2]

[1]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[2]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[3]*Department of Physics, Florida State University, Tallahassee, Florida 32306, USA*
[4]*Department of Physics and Astronomy, Ursinus College, Collegeville, Pennsylvania 19426, USA*
[5]*Department of Physics, School of Electronics and Physical Sciences, University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom*

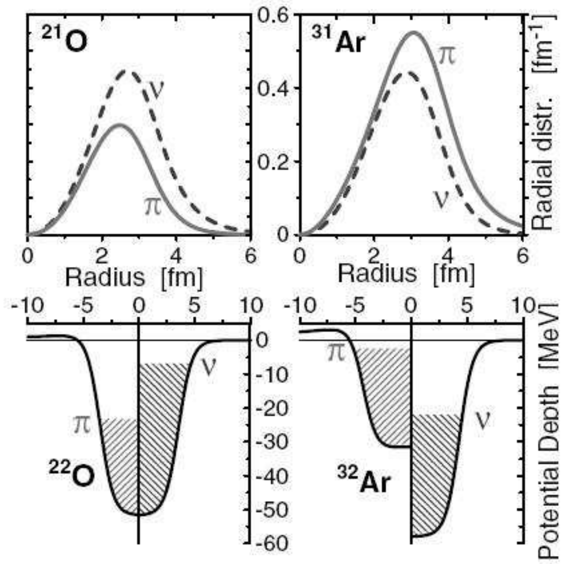
(Received 13 February 2004; published 19 July 2004)

Primary beam / Production target

^{36}Ar +1034 mg/cm^2 Be

Secondary beam

^{32}Ar @65 MeV/nucleon and 140 pps



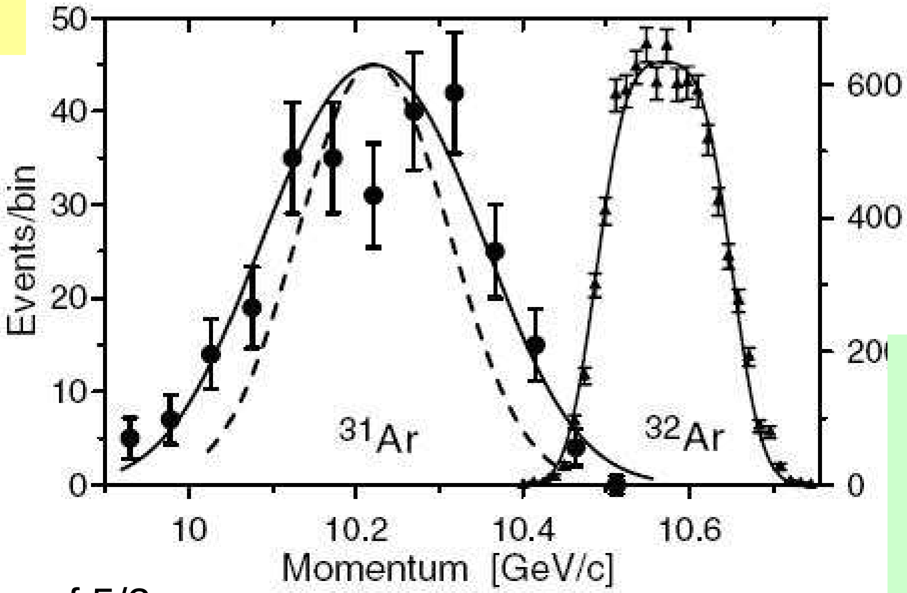
^{31}Ar proton dripline

Sn~ 21 MeV

5/2$^+$ single bound excited state

More complex nuclei : Deeply bound states in ^{32}Ar

inclusive



--- l=0

— l=2

➔confirmation of 5/2+ assignement

No dispersion match mode → not so good system resolution

Σ_{exp}=10.4 (13)mb

$\Sigma_{exp}=R_s\,(A/A-1)^2\,C^2S_j\,\sigma_{sp}$

C^2S_j =4.12

σ_{sp}=9.89 mb

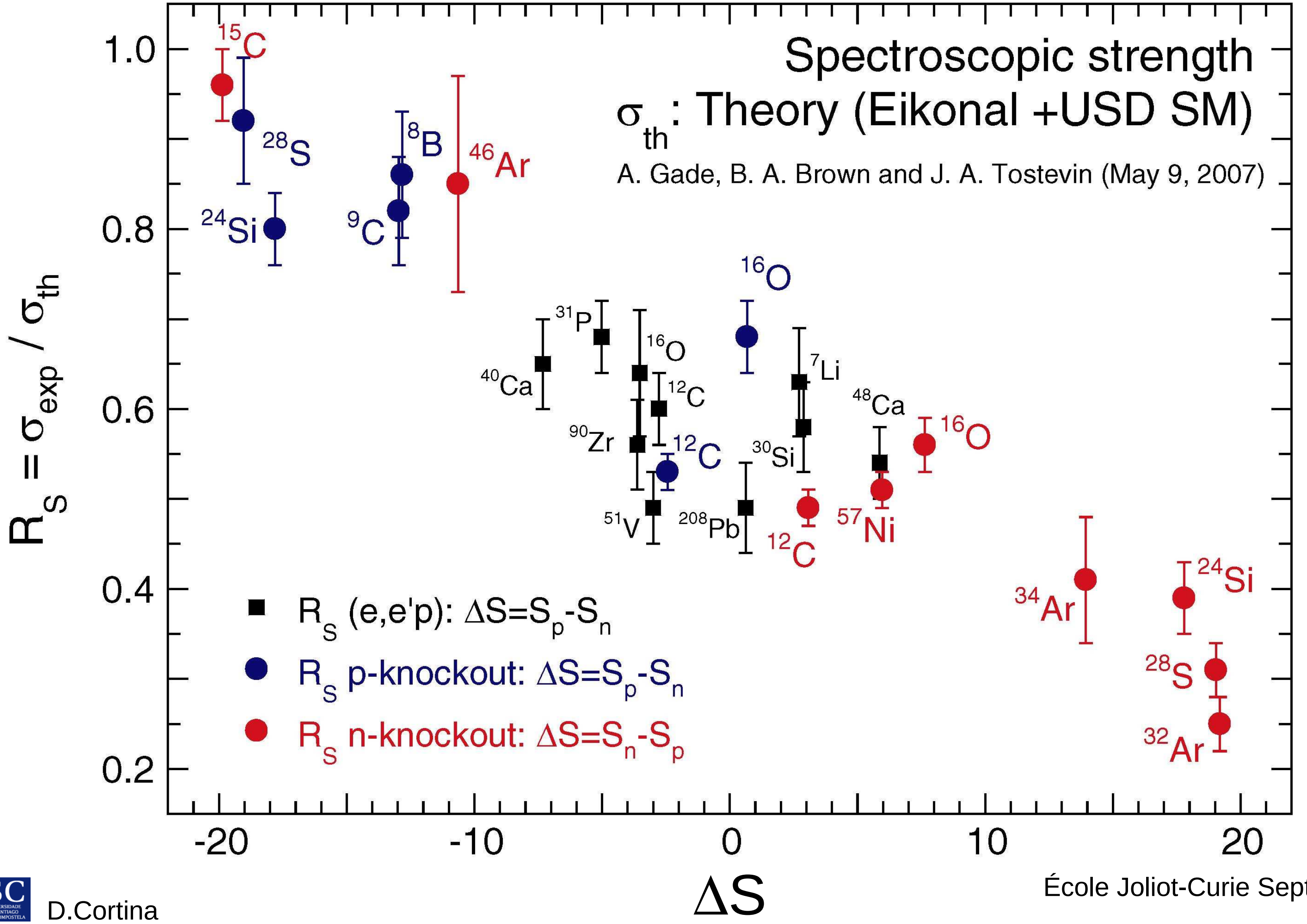
Experimental determination of the reduction factor

$Rs= \sigma_{exp}/\sigma_{the} = C^2S_{exp}/C^2S_{theo}$ = 0.2

→ open a question about spectroscopic factor determination in very asymetric nuclear matter

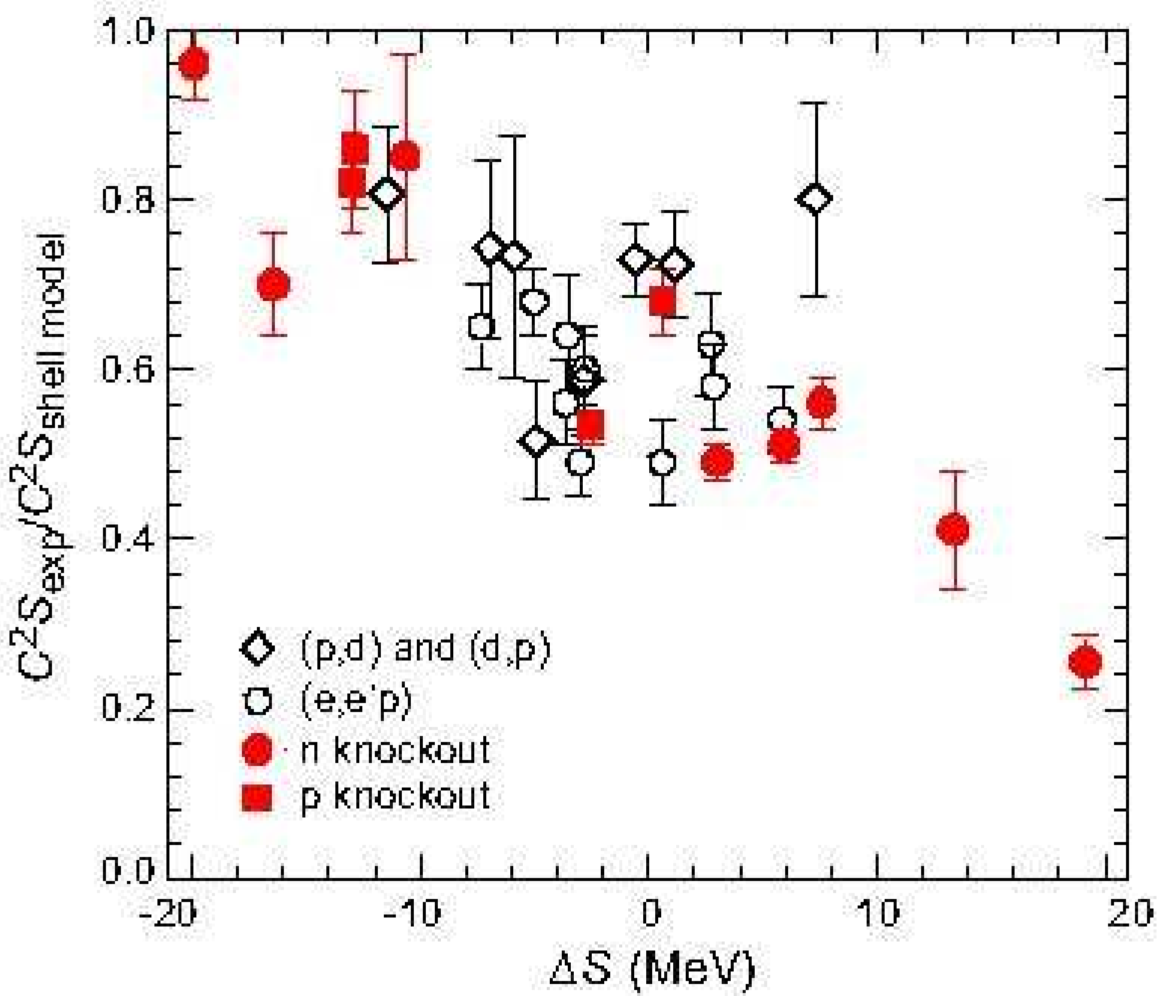
Spectroscopy with nucleon knockout reactions

J. Tostevin invited plenary talk at INPC07



Spectroscopy with nucleon knockout reactions

J. Tostevin et al.
http://www.nscl.msu.edu/future/isf

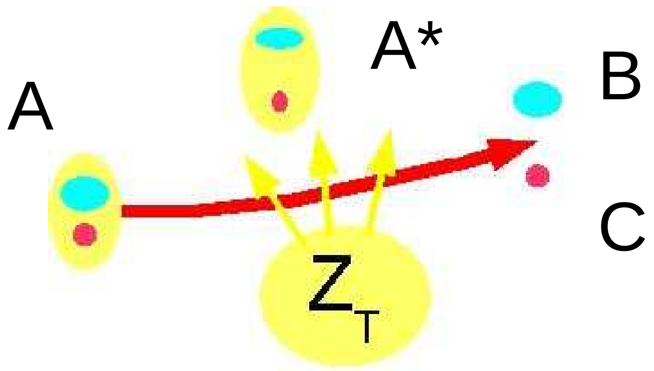


Alternative: to use “old-fashion” nuclear reactions →

First try of a (p,2p) measurement in the ALADIN-LAND experiment at GSI September 2007

Future → study of (e,e’p) at Elise@FAIR

Electromagnetical one-neutron removal



T. Aumann EPJA 26

The spectrospcopic information comes from the differential cross-section for the electromagnetic excitation → dominated by dipole transitions

Direct breakup model

N of photons

Calculated for individual sp states and weighthed

$$d\sigma(I_c^\pi)/dE_{rel} = \frac{16\pi^3}{9\hbar c} N_{E1}(E^*)\, S(I_c^\pi, nlj) \sum_m |\langle q | \frac{Ze}{A} r Y_m^1 | \Phi_{nlj} \rangle|^2$$

C^2S is calculated (like in knockout) by the ratio between experimental and theoretical cross section with unit C^2s, for each j state

well suited for halo states → huge cross-sections

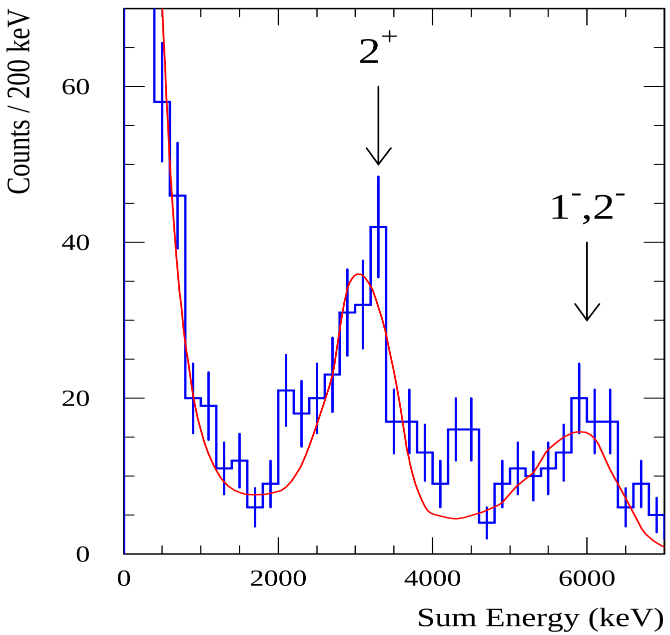
Well understood reaction mechanism

Nuclear versus Coulomb breakup : ^{11}Be at 520 MeV/nucleon

R. Palit et al., PRC 68 (2003) 034218

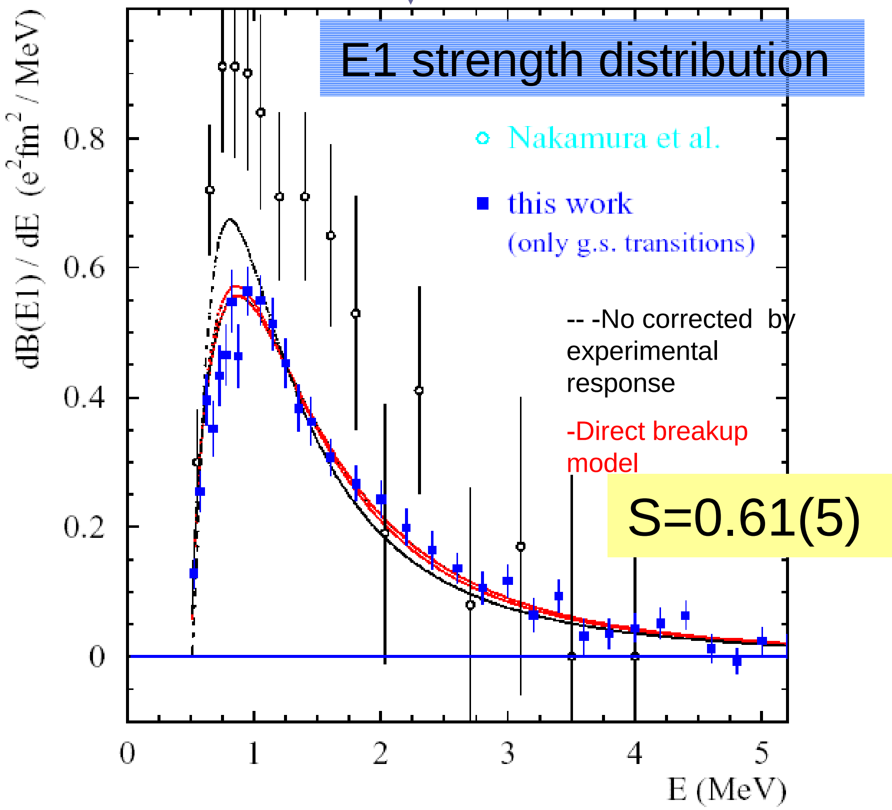
$$|^{11}\mathrm{Be}\rangle = \sqrt{S(2^+)}\,|^{10}\mathrm{Be}(2^+)\otimes 1d_{5/2}\rangle + \sqrt{S(0^+)}\,|^{10}\mathrm{Be}(0^+)\otimes 2s_{1/2}\rangle + \ldots$$

^{11}Be + Pb → ^{10}Be + γ + n



ph states at 6 MeV (inner shell p neutrons lifted into continuum)

^{11}Be → ^{10}Be(0$^+$)+n



Nuclear versus Coulomb breakup : ^{11}Be at 520 MeV/nucleon

Other Spectroscopic factor calculation

Analysis in the effective range approach: avoid choice of free parameter in the potential

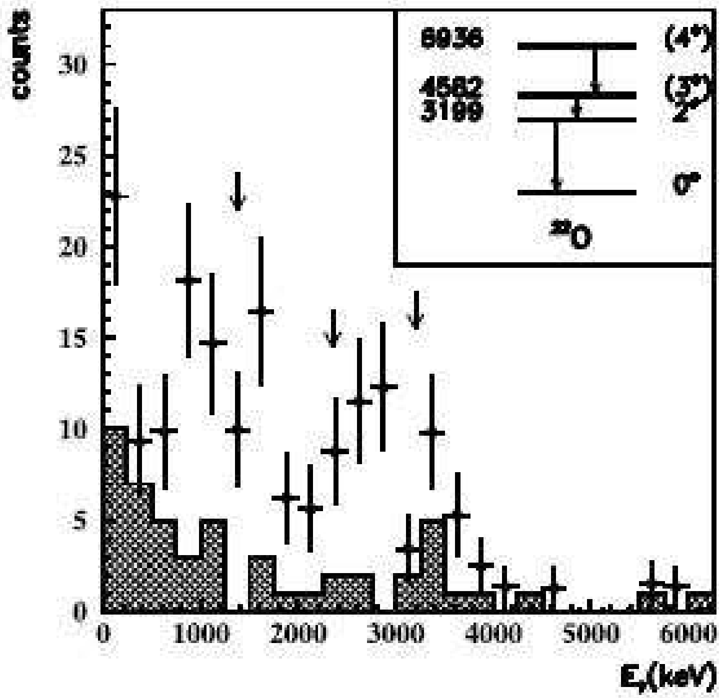
Only parameter is a reduced scattering-length→ interaction core- n , obtained from cross-section fit

$S(0^+)=0.70(5)$

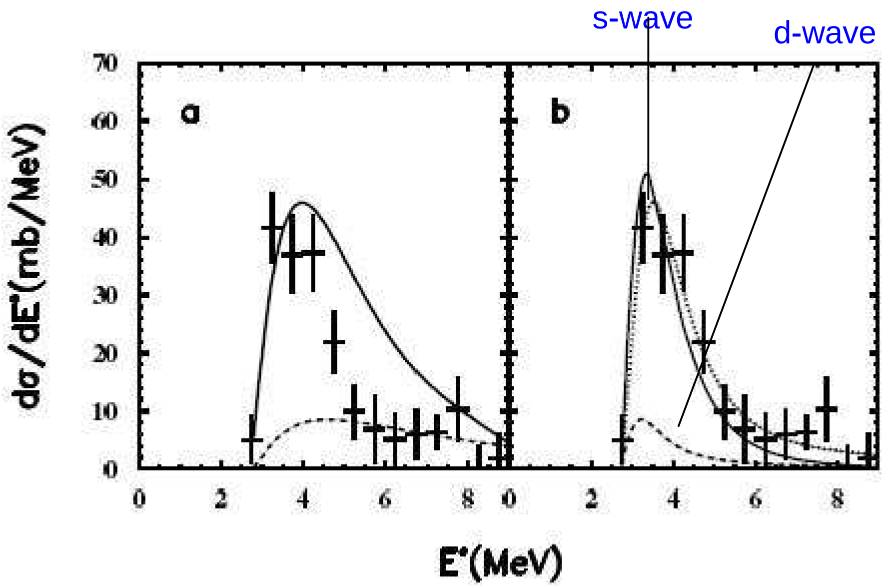
S. Typel, G. Baur, PRL **93** (2004) 142502

Nuclear versus Coulomb breakup: ^{23}O at 422 MeV/nucleon

C. Nocciforo et al., PRL B 605 (2005)



Smaller fraction of the cross-section populates excited states → selectivity for large core-neutron distances



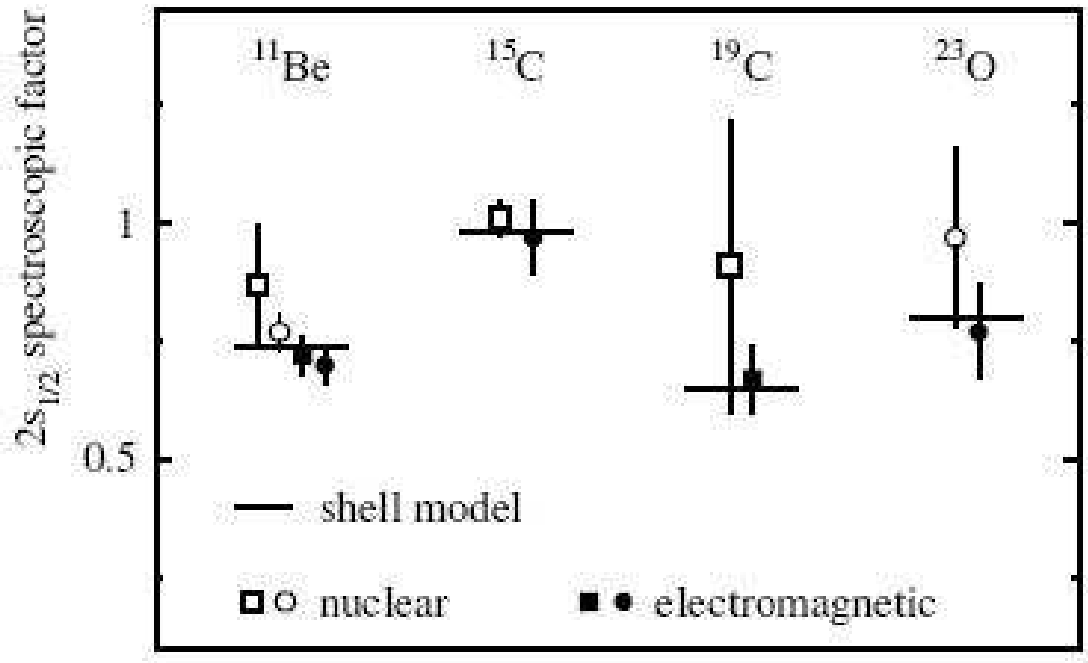
The sharp rise above the n threshold can only be reproduced by s-wave

$S(0^+)=0.77(10)$

Both experiments provide a consistent picture of ^{23}O g.s

Nuclear versus Coulomb breakup

T. Aumann, EPJ A 26 (2005)



Squared lower energies

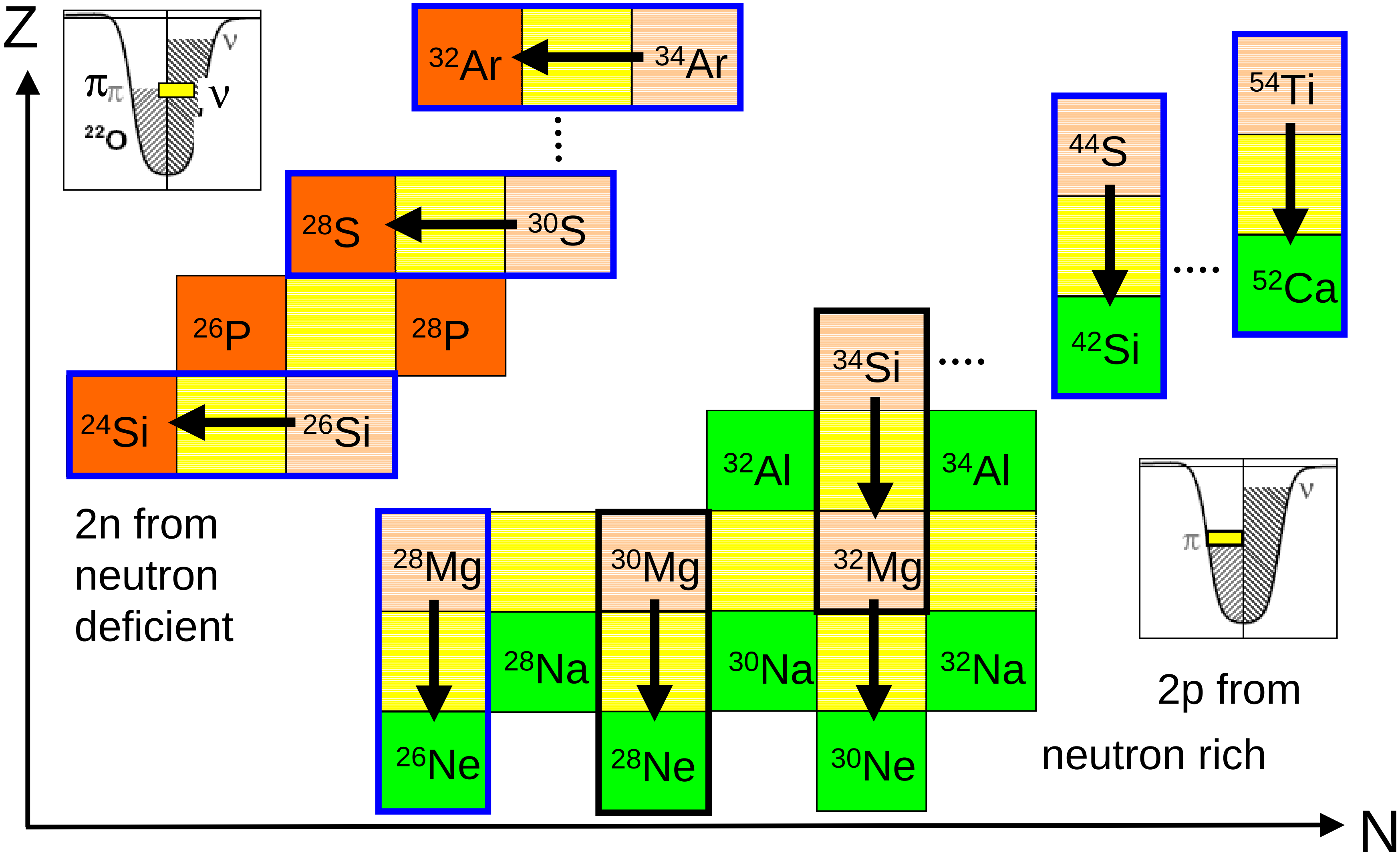
Circle higher energie

Complementary reaction mechanism

Comparison gives an estimation about spectroscopic factors estimation

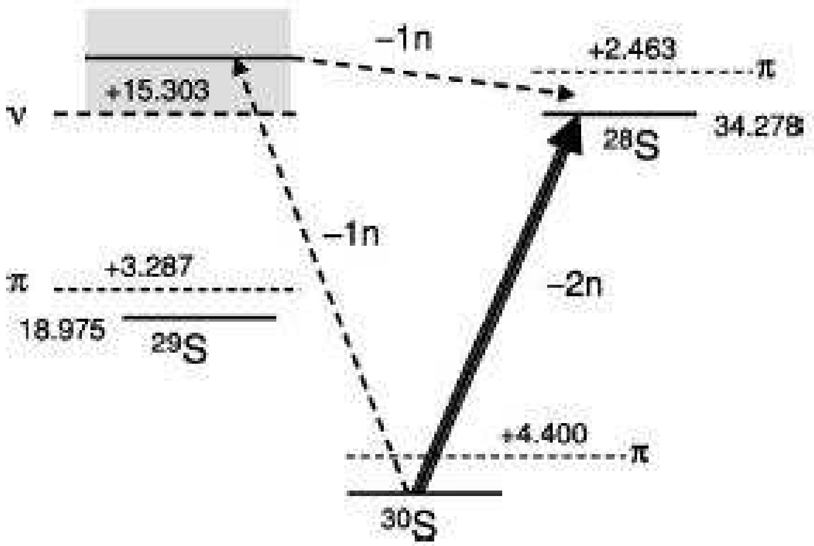
Both methods agree with 10-20% → estimation of the model systematical uncertainties

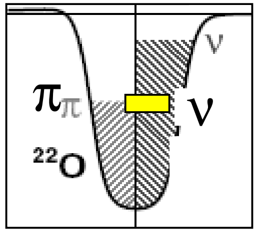
Two nucleon knockout – direct reaction set

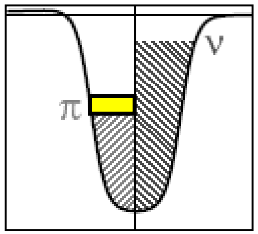


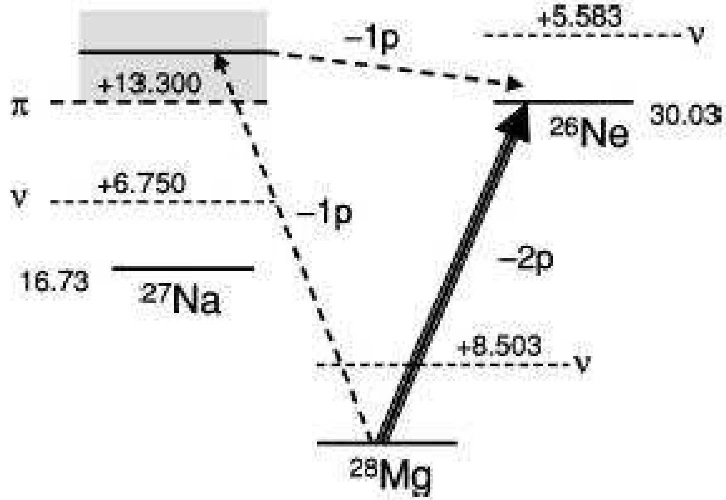
J. Tostevin, plenary talk INPC07 Tokyo

Direct process?









J. Tostevin et al PRC 70(2004) 064602

VOLUME 91, NUMBER 1 PHYSICAL REVIEW LETTERS week ending 4 JULY 2003

New Direct Reaction: Two-Proton Knockout from Neutron-Rich Nuclei

D. Bazin,[1] B. A. Brown,[1,2] C. M. Campbell,[1,2] J. A. Church,[1,2] D. C. Dinca,[1,2] J. Enders,[1,*] A. Gade,[1,2] T. Glasmacher,[1,2] P. G. Hansen,[1,2,†] W. F. Mueller,[1] H. Olliver,[1,2] B. C. Perry,[1,2] B. M. Sherrill,[1,2] J. R. Terry,[1,2] and J. A. Tostevin[3]
[1]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
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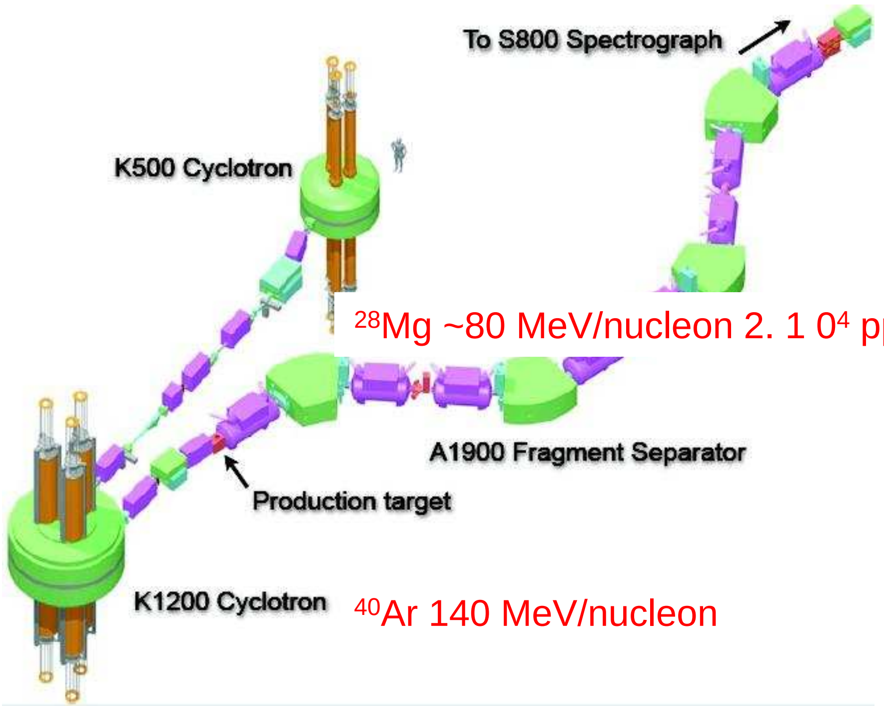
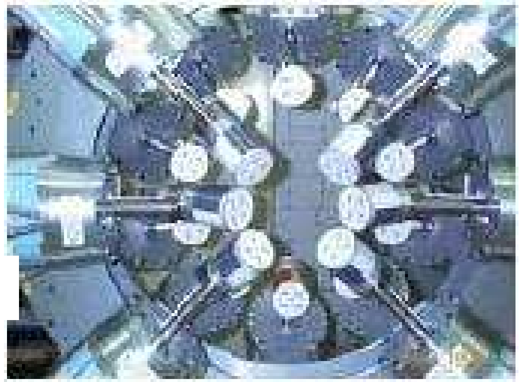
(Received 9 January 2003; published 30 June 2003)



^{28}Mg ~80 MeV/nucleon 2. 1 0^{4} pps

^{40}Ar 140 MeV/nucleon

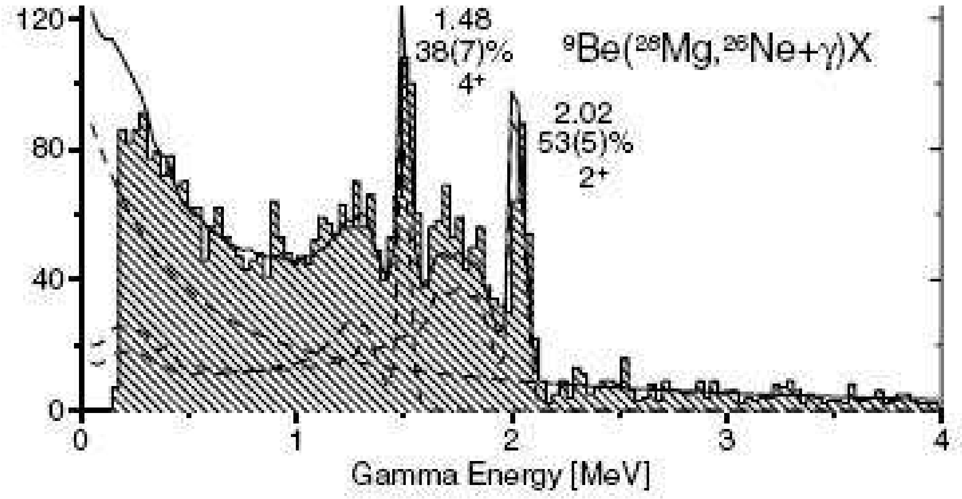


SeGA : 14 32-fold Ge detectors

20 cm from target

E_{ph}~ 2.5 % and ΔE/E ~2.5 %

Direct process?



D.Bazin et al PRL91(2003)012501

^{28,26}Mg assumed to be sperical N=16

Decay scheme known. Excess in the 1.7MeV line suggest other excited states at higher energies obseved in β decay

In agreement with USD predictions

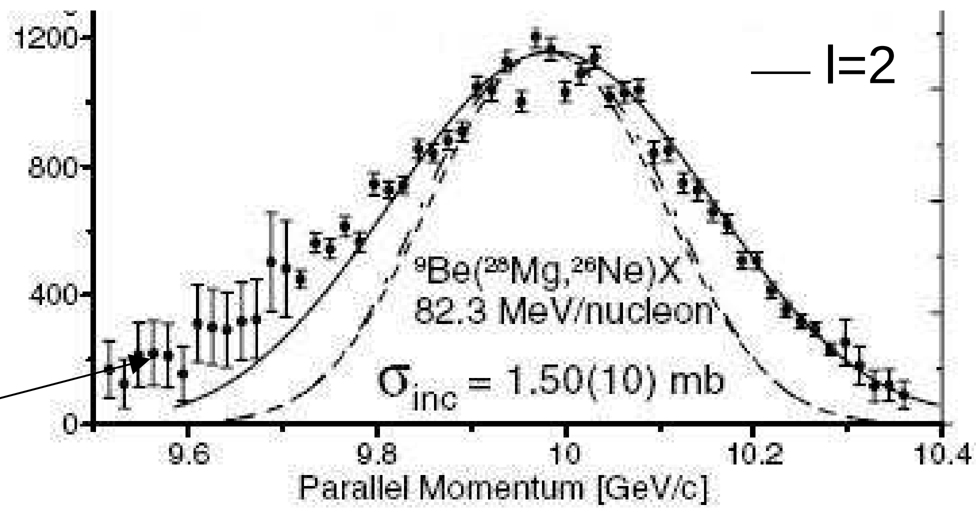
--- l=0

... l=1

— l=2

Small cross sections

Relatively broad momentum distributions (2 of knocked out)→ they do not bring quantitative information because they are wider by the 2 nucleon removal reaction



deviation from eikonal reaction model

Two-nucleon knockout: model development

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- the partial cross section for a given j channel factorizing into a part describing the contribution from many-body nuclear structure (''the spectroscopic factor'') and a part describing the reaction dynamics (''the single-particle cross section'') does no longer holds for the two-nucleon process.

-many two-particle components may, within each total-angular-momentum channel, contribute coherently

-First quantitative description : approximation

➢The **absolute cross section** is calculated in eikonal reaction theory assuming two **uncorrelated protons.**

➢ Same approximation for the **momentum distribution**. In the uncorrelated approximation: the distribution for two independent particles is simply given by the convolution of the separate distributions for the two nucleons

➢ Uncorrelated approximation assuming a **single active j shell**.

➢ Full diagonalization in the sd shell, **simplified reaction model**.

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Correlated two-nucleon stripping reactions

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Diffraction dissociation contributions to two-nucleon knockout reactions and the suppression of shell-model strength

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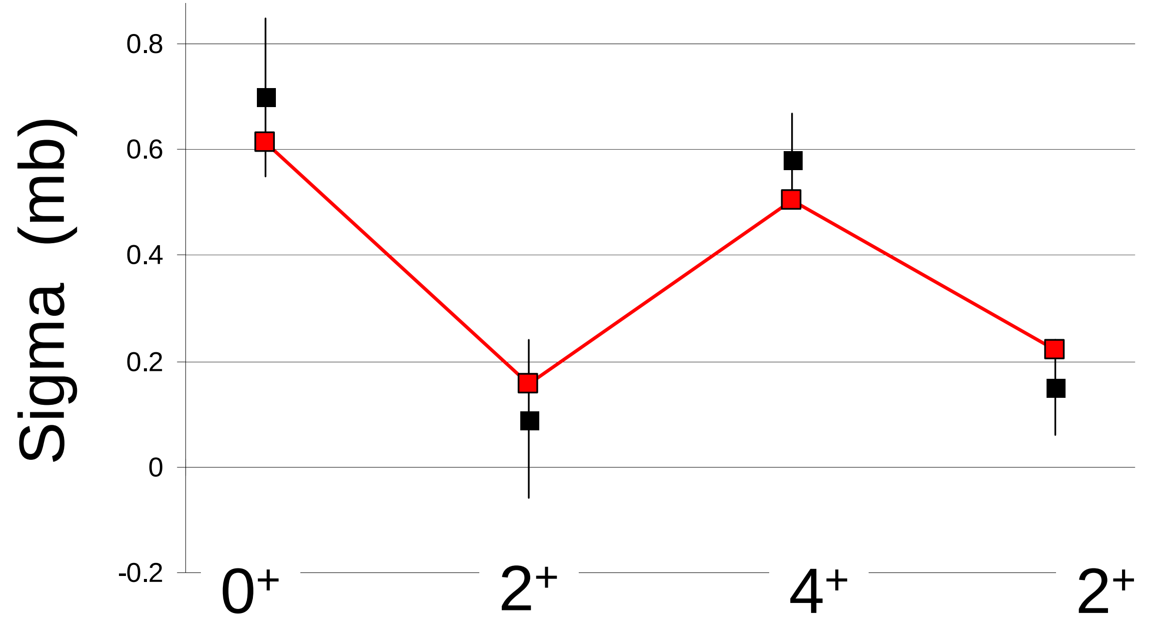
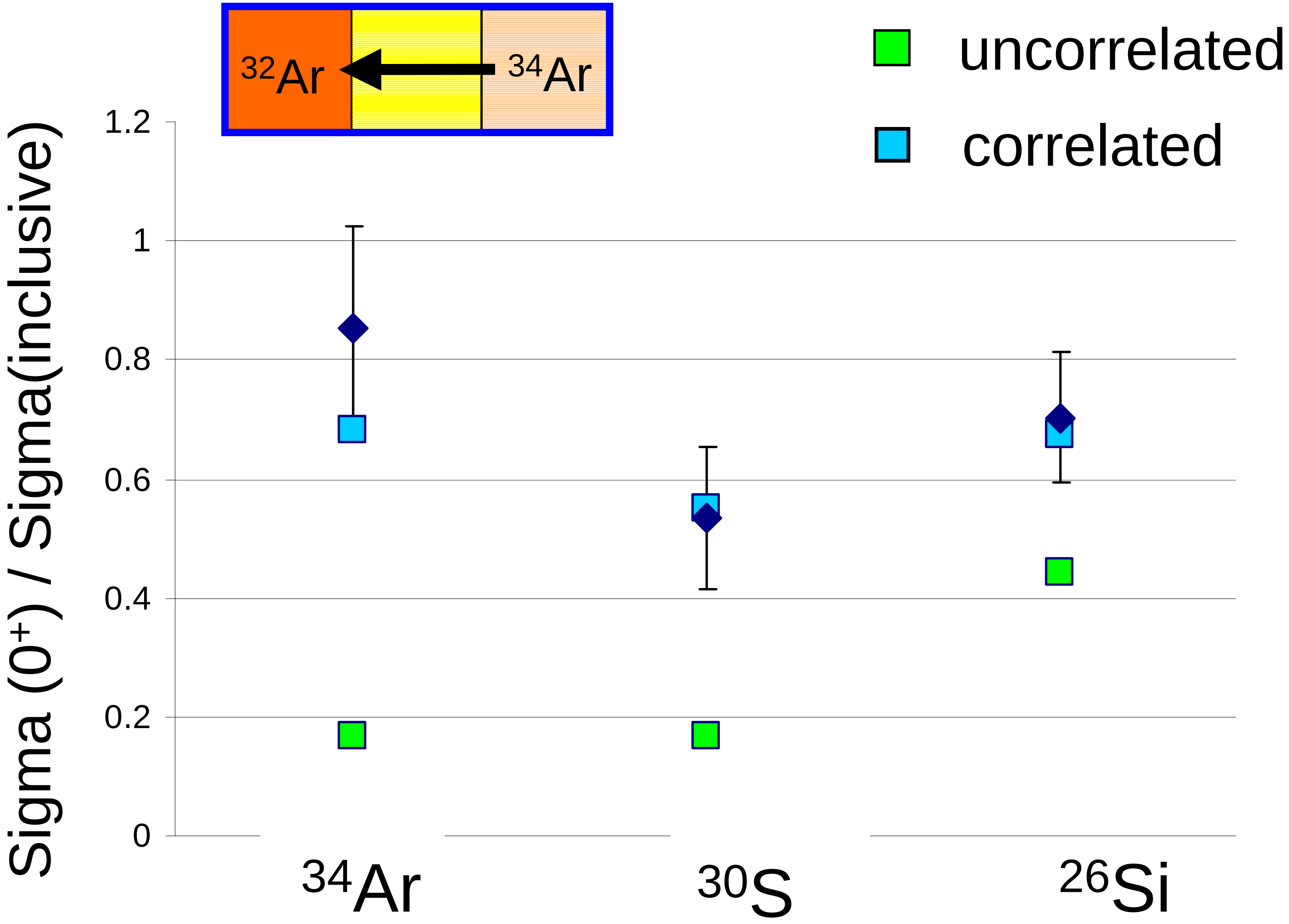
^{28}Mg $\rightarrow$ ^{26}Ne(0^+, 2^+, 4^+, 2_2^+)   82.3 MeV/u

$\sigma_{inc}(-2p)$=1.50(10) mb, $R_s(2N) = \sigma_{\rm exp}/\sigma_{\rm th} = 0.52(4)$



Other examples



Yoneda *et al PRC 74(2006) 021303*

Conclusions

- We have explained the experimental technique of nuclear knockout
- We have analysed two selected cases : ^{11}Be, ^{8}B → we can conclude that this technique provides precise spectroscopic information for these weakly boun nuclei
- When we go to more weekly bound nuclei is not trivial to obtain precise spectroscopic information but the technique is still valide to assign spins and parities
- For well bound nuclei we observe deviations from the eikonal model predictions → validity of the reaction mechanism ??
- Systematic measurements seem to show a dependence of the experimentally deduce quenching factor on mass asymmetry
- We have compare the spectroscopic information deduced by nuclear and coulom breakup for halo nuclei
- We have discussed the 2-nucleon removal as an alternative method
- **Future : study of (p,2p) (e,e'p)**

Selected Bibliography

❖ Review articles

P.G. Hansen and J.A Tostevin

Annual Review Nuclear Particle science 2003, 53: 219-261

T. Aumann

European Physical Journal A 26 (2005) 441-478

A. Gade and T. Glasmacher

Progress in Particle and Nuclear Physics (2007) unedited

And references therein

Recomended sources of informations

- school lectures (Joliot-Curie, Euroschool on exotic beams)