Quasi-free scattering from radioactive ion beams

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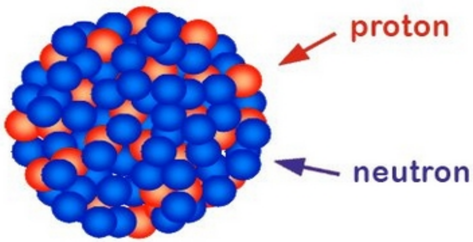
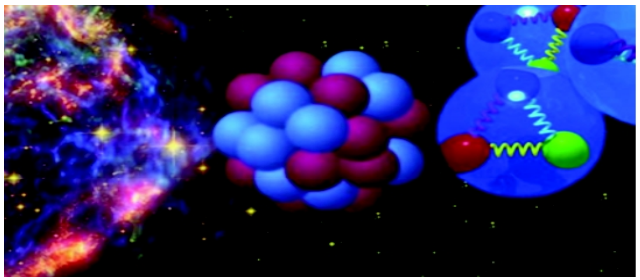
Layout

- The atomic nucleus and the shell model
- An experimental insight into the nucleus: Quasi-free scattering and stable nuclei
  - study of single-particle state properties
  - role of NN correlations
- Production and study of asymmetric nuclear matter
- Quasi-free scattering and exotic nuclei
  - R3B at GSI: experimental challenges
  - the ^{12}C case: proof of concept
  - first experimental campaign with RIB
- The R3B@FAIR setup and the CALIFA calorimeter
  - paving the road towards FAIR
- Summary and Outlook

The atomic nucleus and the shell model

The atomic nucleus is a strongly-correlated, bound, quantum many-body system formed by p and n (themselves compound many-body structures).



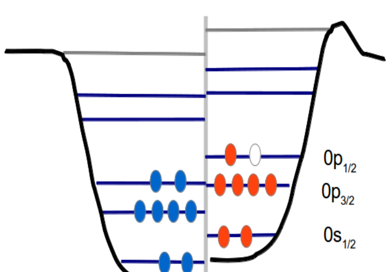


A century after its discovery we still miss a global theory able to explain the nuclear structure of all species in the nuclear chart.

Probably, the most popular nuclear structure model is the shell model based on the assumption that the motion of each single nucleon (i) is governed by an average potential given to i by the presence of all the other A-1 particles (mean field).

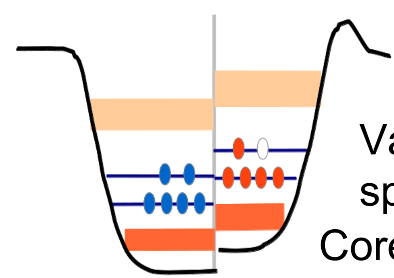
In the independent particle picture nucleons do not with each other and are only subject to the Pauli principle.

In the interacting picture on top of the mean field 1p-1h or 2p-2h in the allowed valence space can be considered.



$$H = \sum hi$$

$$hi = \frac{pi}{2m} + Ui$$

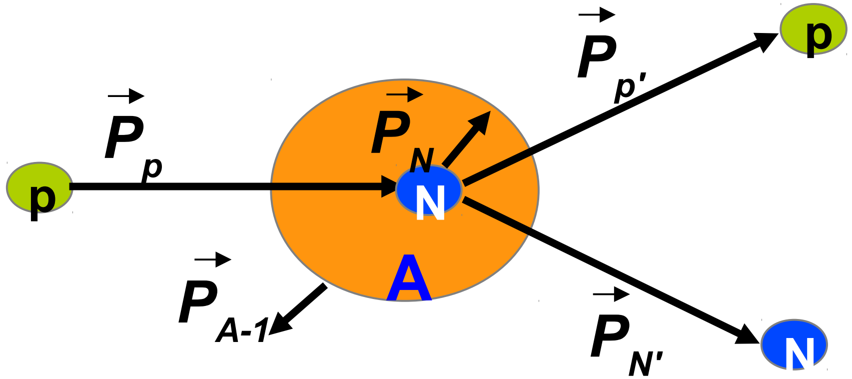


The Quasi-Free Scattering (QFS)

The shell model helps to interpret the structure of known nuclei and also to predict the structure of new (non measured) ones, improving our knowledge on the nuclear force.

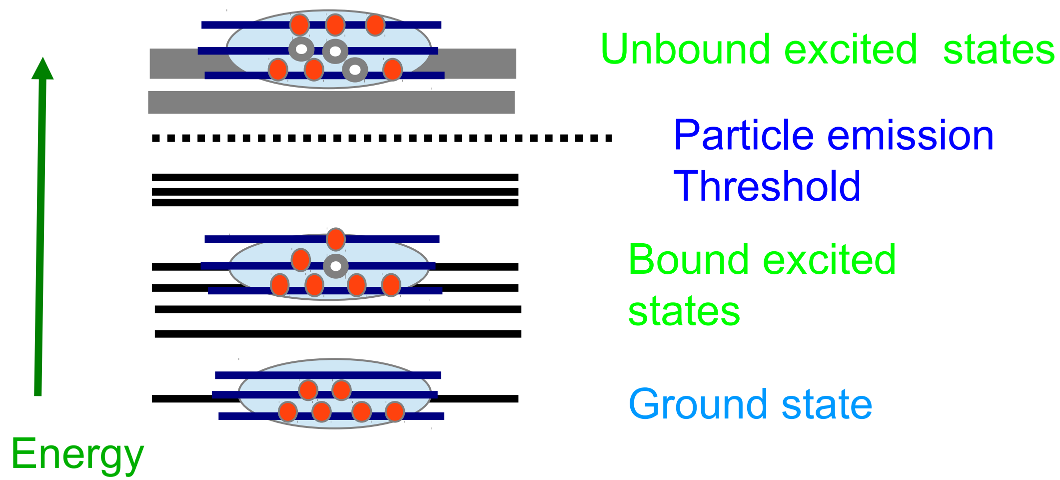
The use of direct reactions, such as QFS is an important tool in this titanic task.

A simplified picture of the QFS reaction mechanism



QFS have allowed traditionally:

- ✓ to perform spectroscopic studies of single particle states
- ✓ to understand the nature of nuclear these states



QFS with stable nuclei : single-particle vs. correlations

Along 1950-60's many (p,2p) experiments were performed

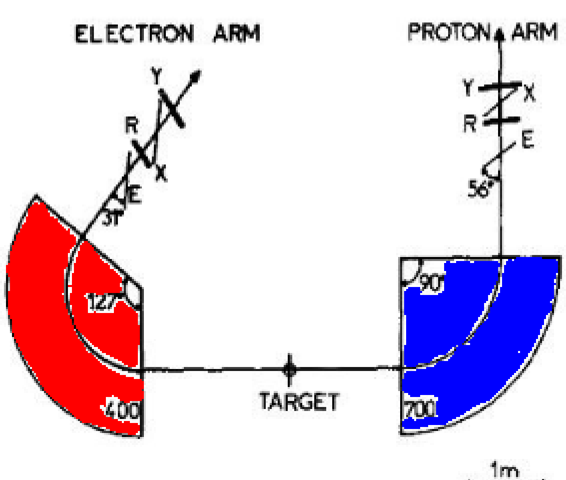
- Hadron probe → nuclear absorptions
- limited detection resolution → study to light nuclei

O.Chamberlain et al PR 87 (1952)
J.B. Gladis et al PR87 (1952)
J. Berggren et al Anu. Rev. Nucl. Sc. 16 (1966)
J. Jacob et al. Rev. Mod. Phys, 38 (1966)

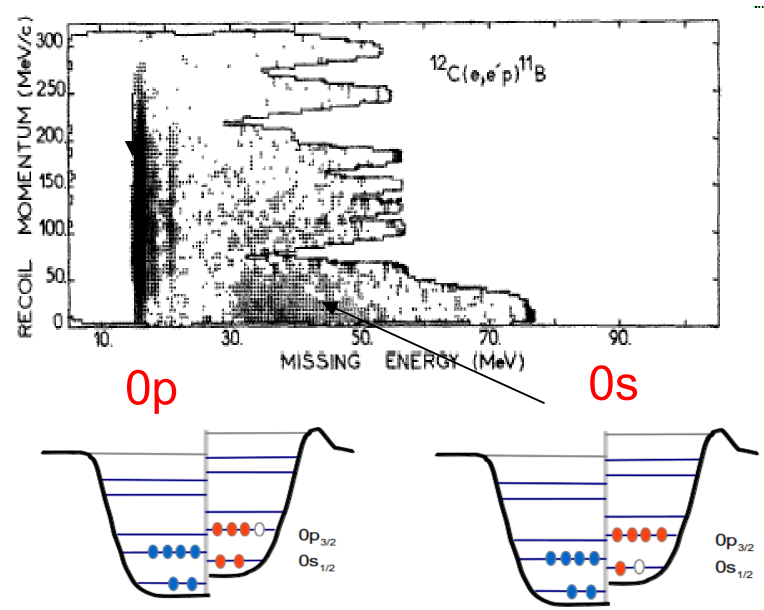
They were replaced by the study of (e,e'p) reactions

electrons are transparent and reduce the outgoing particle distortion
- demanded the development of powerful electron detectors
- made use of improved experimental setups

$^{12}C(e,e'p)\,^{11}B$



J. Mougey et al NPA 335 (1980)

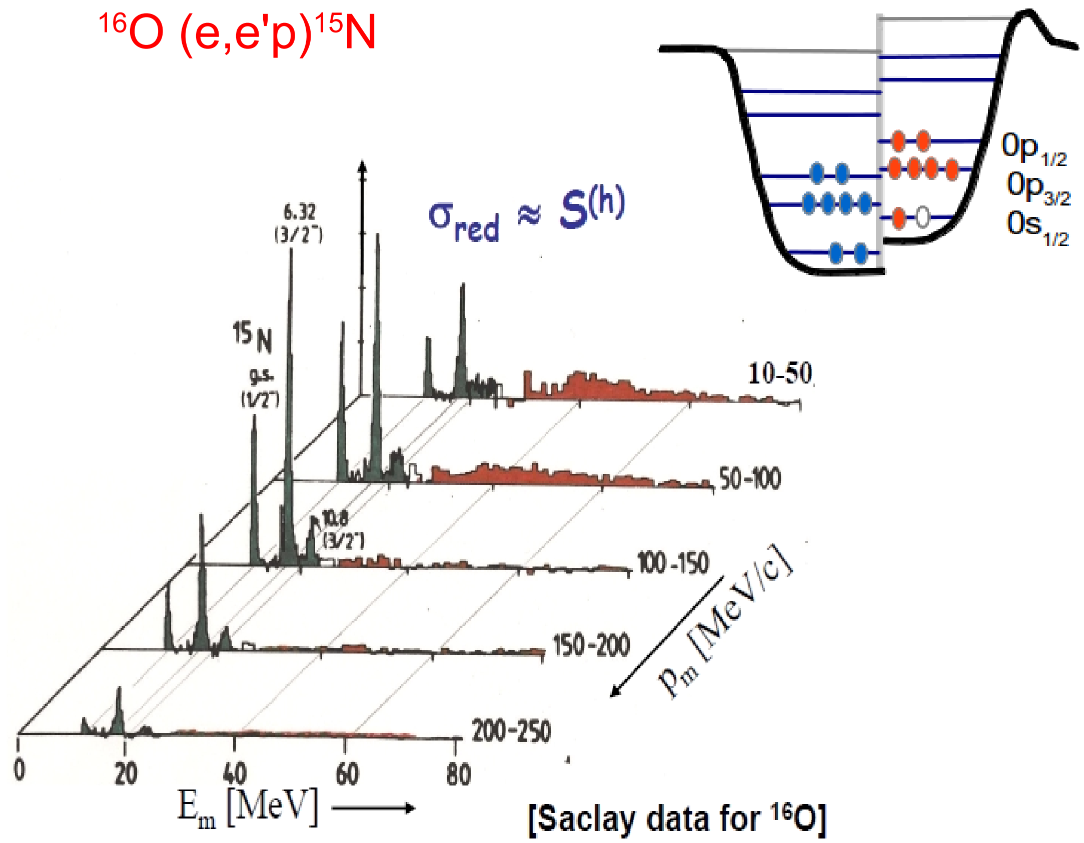


D. Cortina, EuNPC 2015, Gröningen

QFS with stable nuclei : single-particle vs. correlations

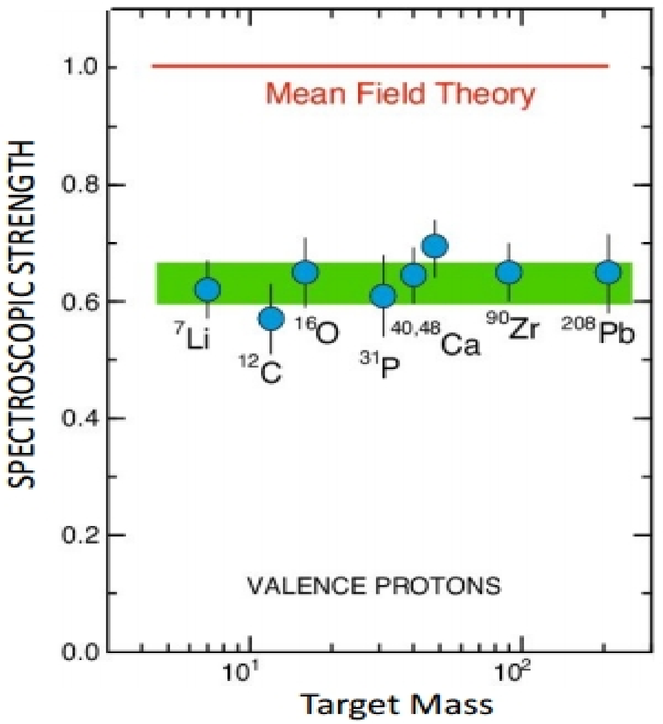
Determination of spectral function: probability of finding a proton with energy E and momentum p in the nucleus of interest

$^{16}O\ (e,e'p)^{15}N$



L. Lapikas and P.K.A. de Witt Huberts Jou. of Phys.

NPA A553 (1993) 297c

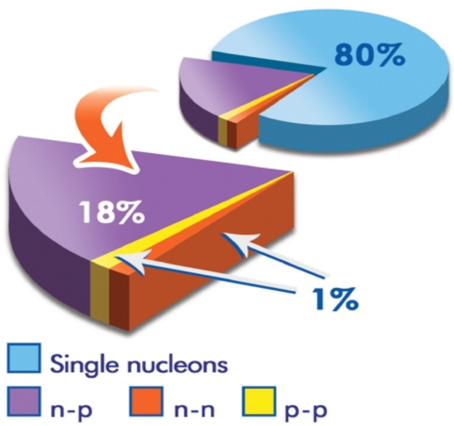


Deviation from single particle picture

- Data exhibit a considerable quenching
- NN correlations playing an important role

NN correlations and multiparticle coincidence experiments

The issue of NN correlations needed of multiparticle coincidence experiments (e,e'2p), (e,e'pn)...



^{12}C(e,e'pN)

Protons and neutrons form in the nuclear ground state strongly correlated nucleon pairs (SRC).

In ^{12}C np pairs are ~ 20 times as prevalent as pp or nn → consequence of NN tensor force

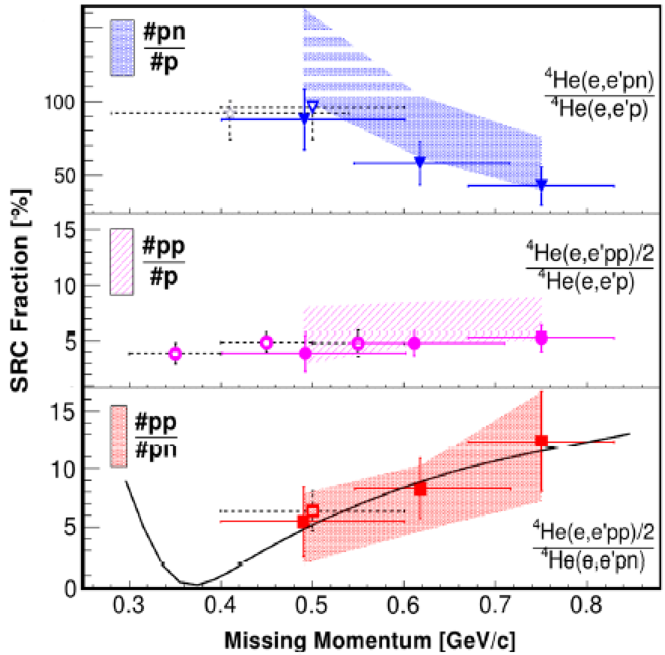
R. Subedi et al., Science 320 (2008) 1476 and references therein

^{4}He(e,e'pN)

Changes in the pair isospin composition as a function of the missing momentum → the reduction of np/pp ratio with p_{mis} increasing

Reduce contribution from a tensor component and constant from the scalar component of the NN force

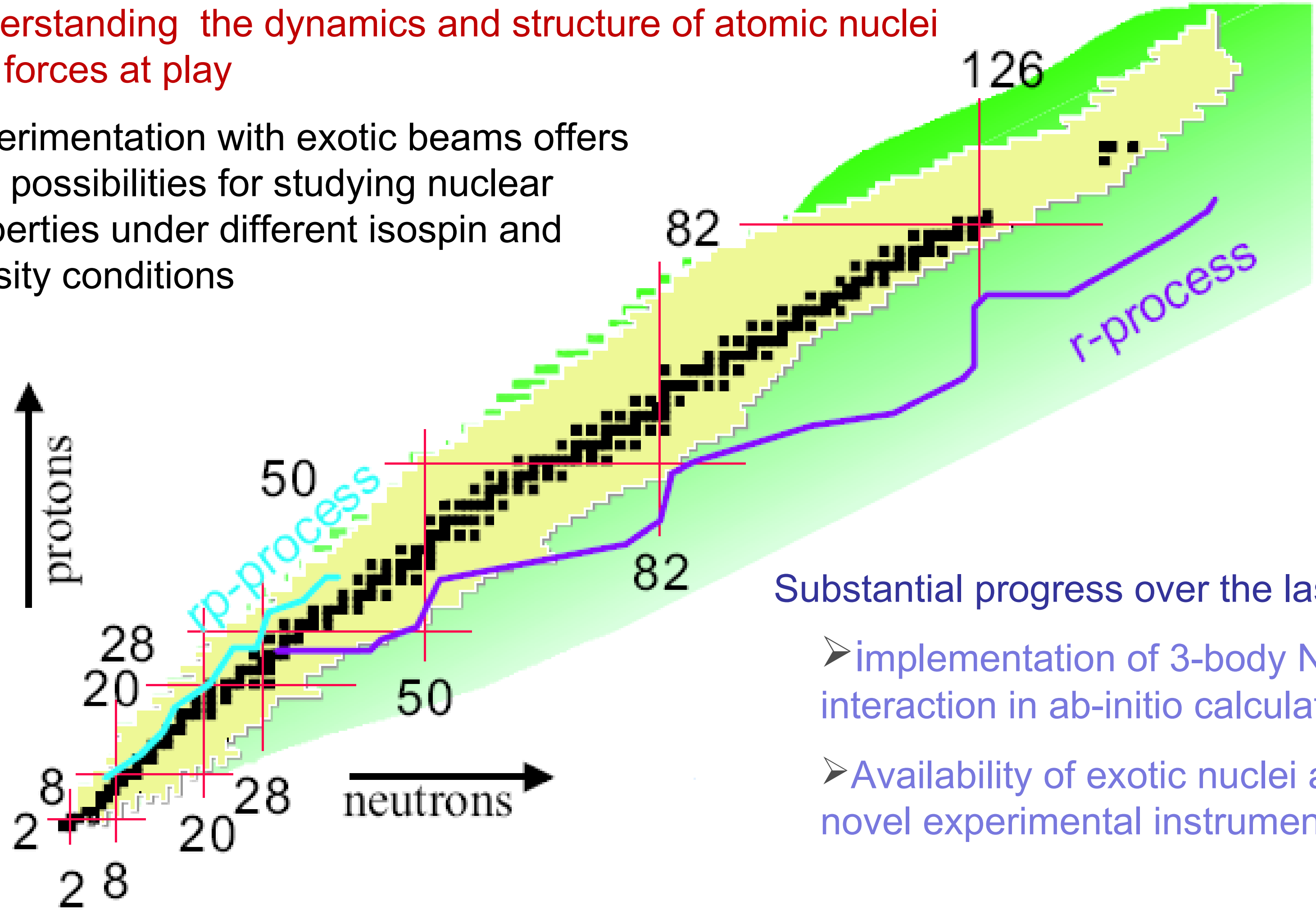
I. Korover et al., Phys. Rev. Lett. 113 (2014) 022501



Radioactive Ion Beams: access to asymmetric nuclear matter

Understanding the dynamics and structure of atomic nuclei and forces at play

Experimentation with exotic beams offers new possibilities for studying nuclear properties under different isospin and density conditions



Substantial progress over the last decades

- implementation of 3-body NN interaction in ab-initio calculations
- Availability of exotic nuclei and novel experimental instruments

Radioactive Ion Beams: access to asymmetric nuclear matter

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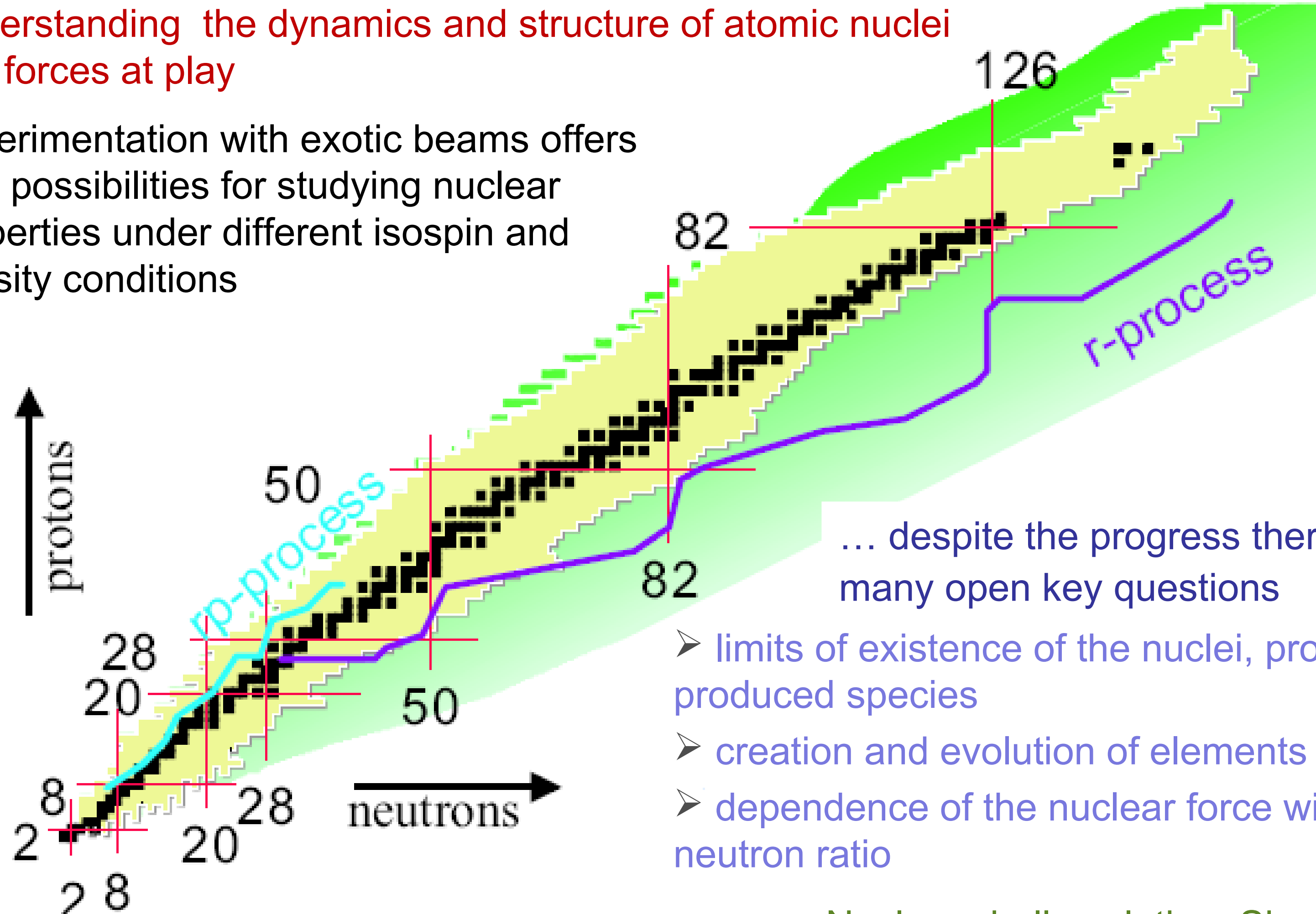


… despite the progress there are still many open key questions

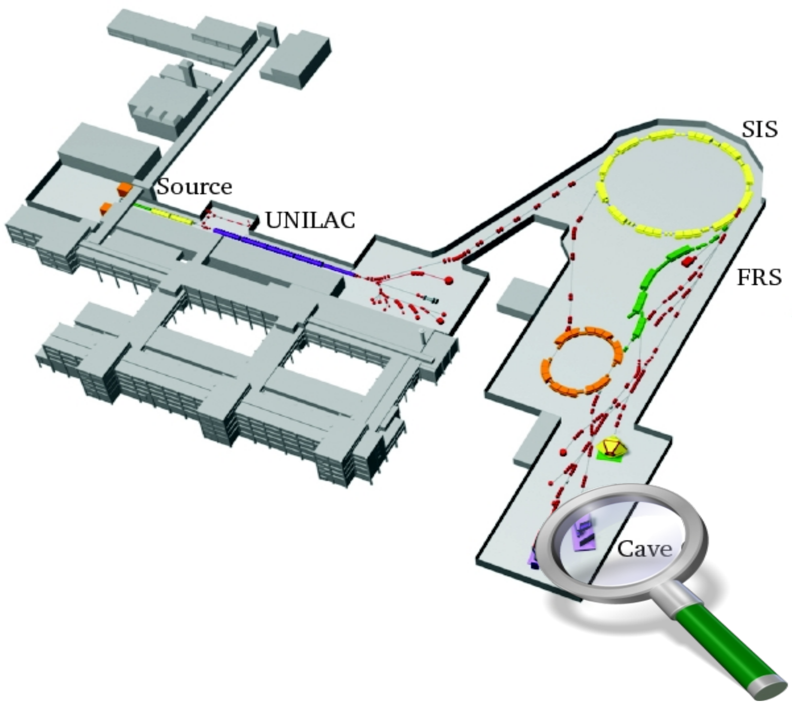
- limits of existence of the nuclei, properties of newly produced species
- creation and evolution of elements in the universe
- dependence of the nuclear force with the proton-to-neutron ratio

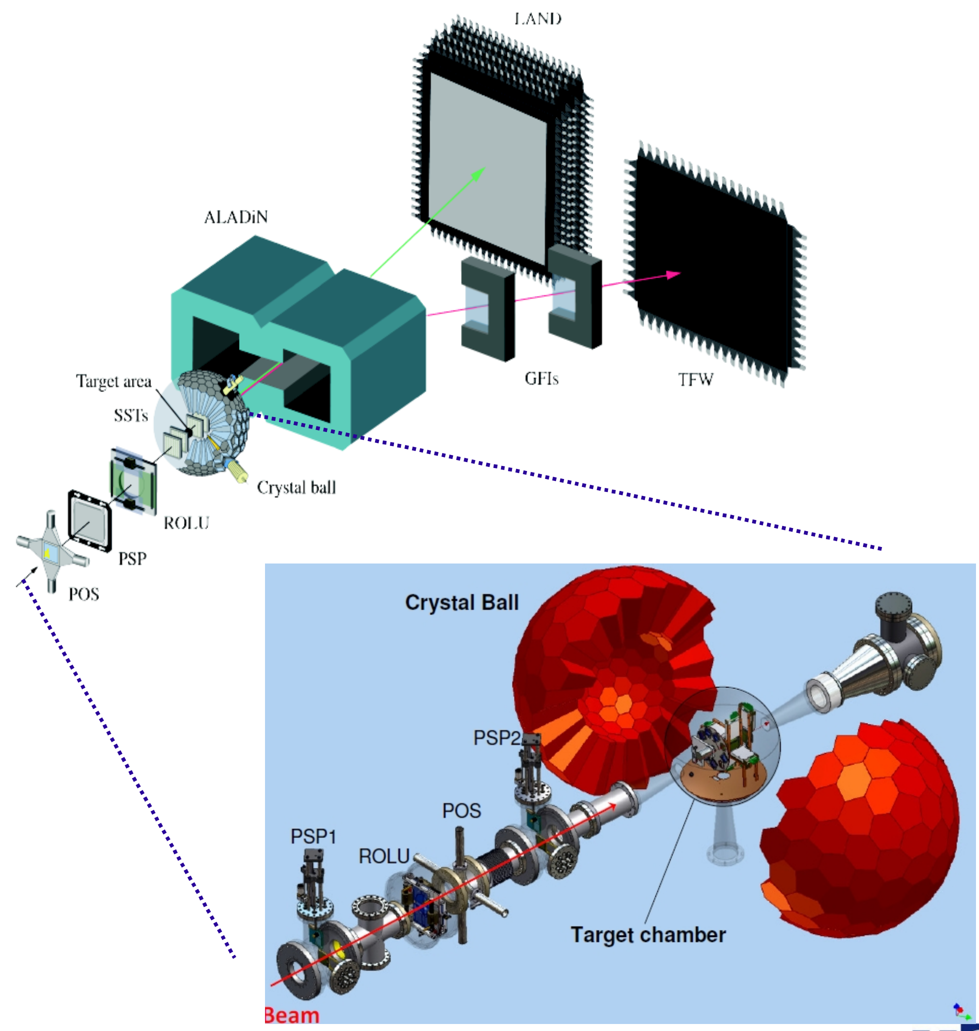
  - Nuclear shell evolution: Single-particle properties far from stability
  - Role of NN correlations in asymmetric nuclear matter

The R3B collaboration: Our experimental approach

R3B stands for Reacctions with Relativistic Radioactive Beams

- In-flight production of nuclei far from stability. RIB at relativistic energies
- Study of nuclear reactions induced by these secondary beams in inverse kinematics





- NUSTAR/FAIR sub-collaboration
- Construction of a large acceptance, high resolution experimental device for studying reactions induced by RIB
- Step approach from GSI/FRS and Aladin/LAND to R3B/FAIR

The R3B experimental program: The QFS from RIB case

EM excitations: Low-liying transition strengths, resonances in the continuum, GDR, determinationif astrophysical S factors, ...

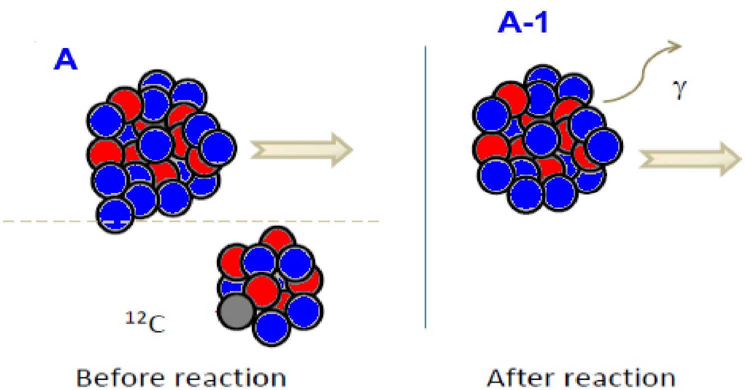
Total absorption/Elastic scattering: nuclear radius, nuclear density, …

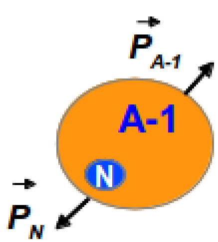
Spallation, fragmentation, multifragmentation Fission: structural and dynamic properties, ...

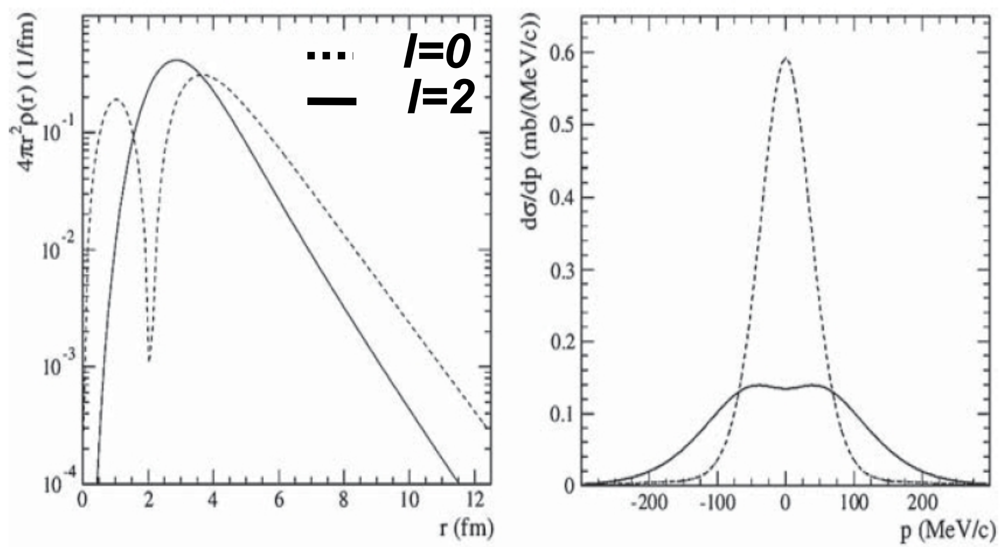
Knockout/QFS: evolution of shell structure, N-N correlations, cluster structure, states beyond dripline

One nucleon knock-out

Exotic projectiles at high energy







Explore the external part of the wave function

- sensitivity to *l*

The R3B experimental program: The QFS from RIB case

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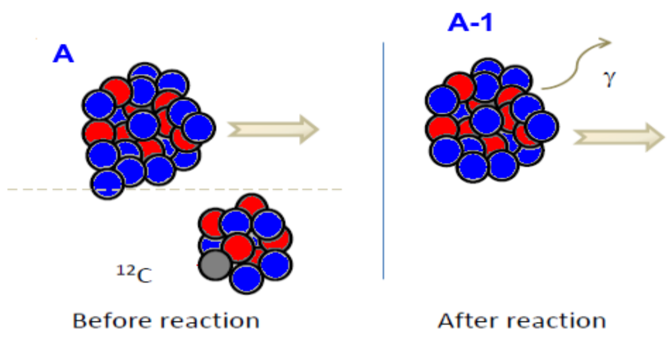
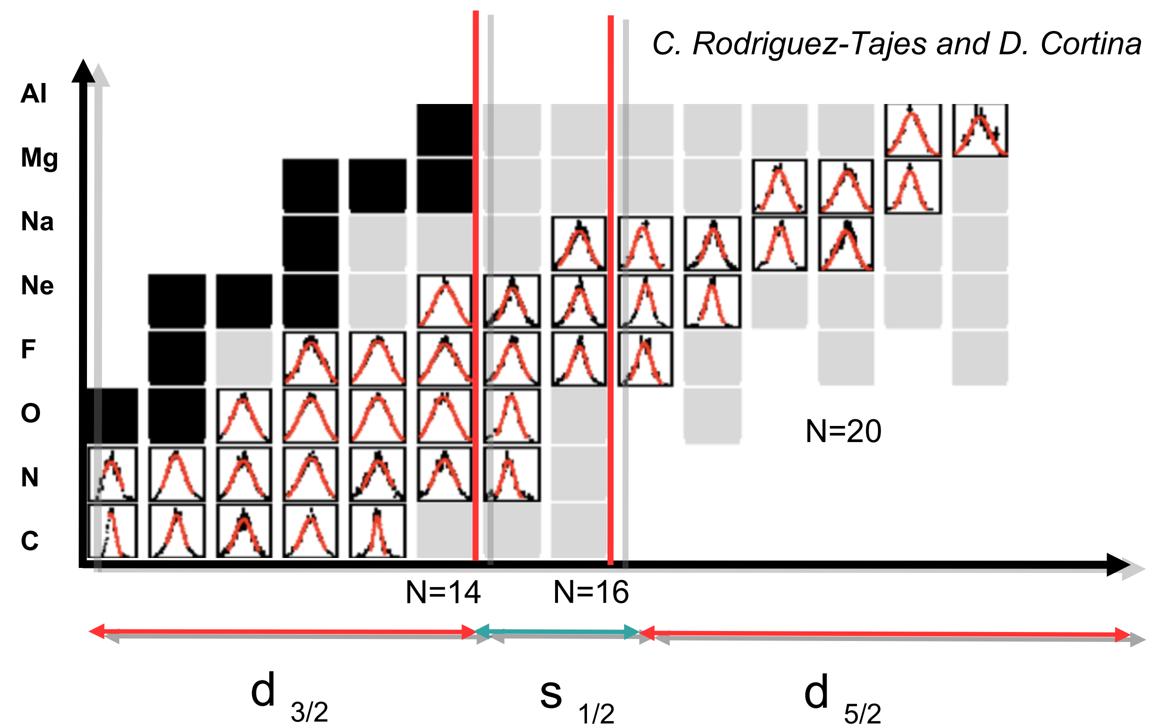


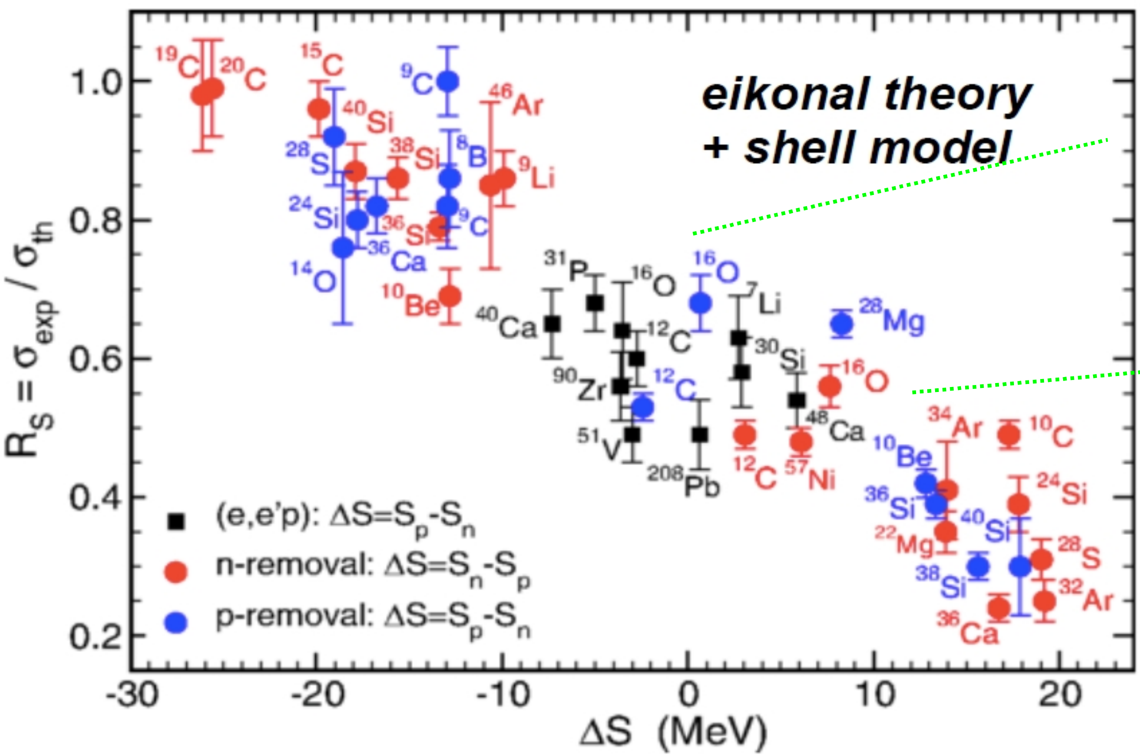
C. Rodriguez-Tajes and D. Cortina

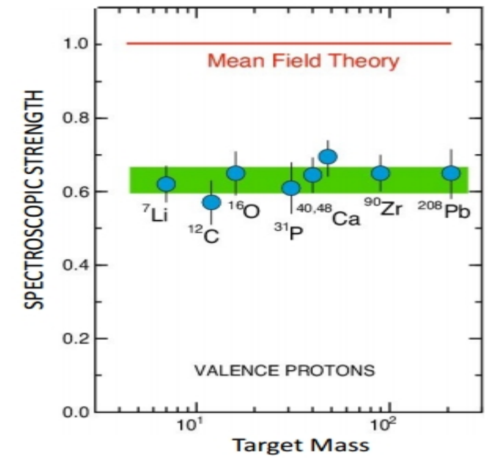


Evolution of the nuclear structure

The R3B experimental program: The QFS from RIB case

A. Gade et al., Phys. Rev C 77, 044306 (2008)



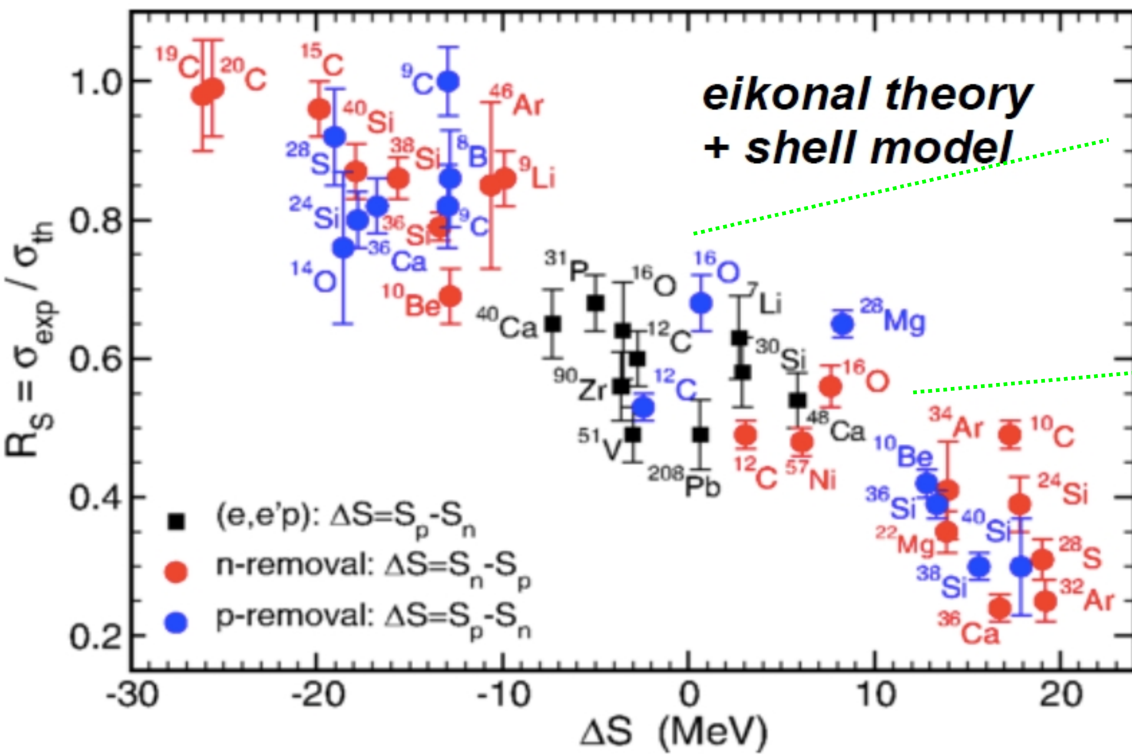


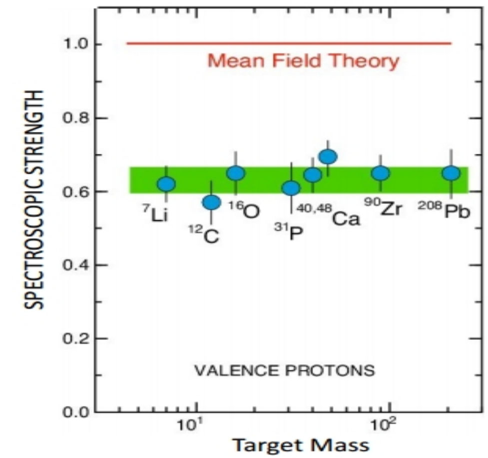
Enhancement of correlations in asymmetric nuclear matter (strongly bound valence nucleon)

suported by O. Jensen et al Phys. Rev. Lett. (2011) 032501

The R3B experimental program: The QFS from RIB case

A. Gade et al., Phys. Rev C 77, 044306 (2008)

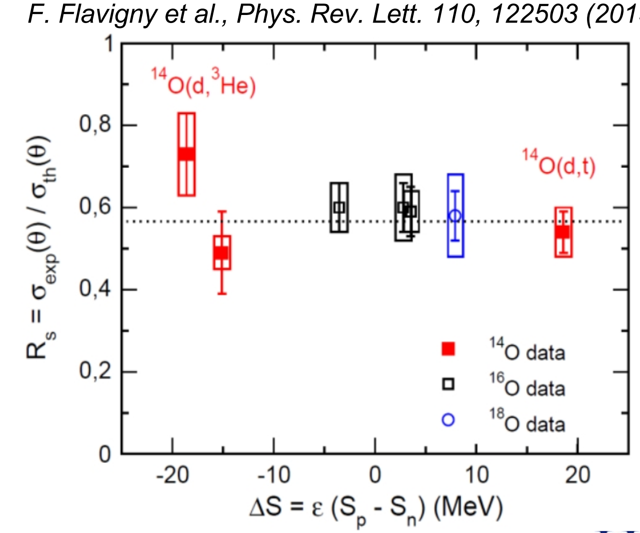




Comparison with transfer reactions

F. Flavigny et al., Phys. Rev. Lett. 110, 122503 (2013)

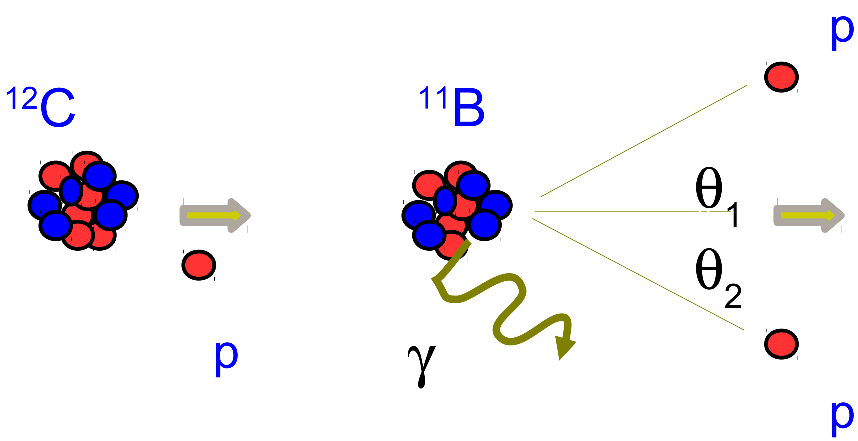
Disagreement



The use of QFS induced by exotic projectiles at high energy can bring to light this topic

D. Cortina, EuNPC 2015, Gröningen

The QFS in inverse kinematics: ^{12}C a proof of concept

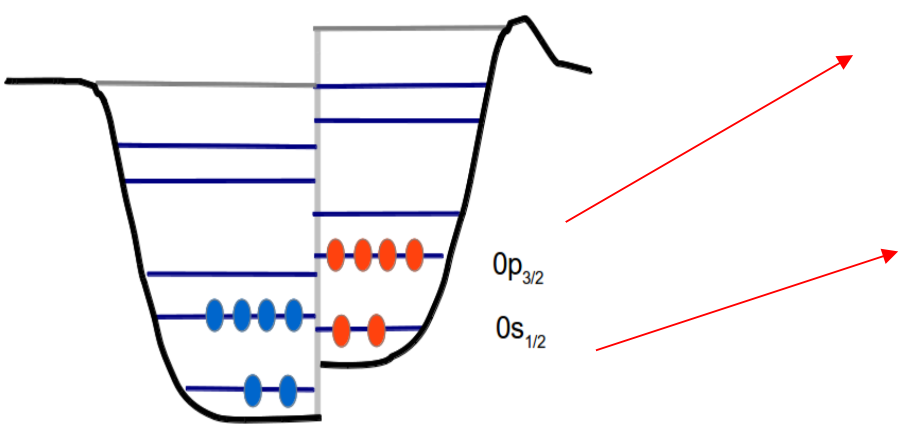


Use of inverse and complete kinematics

Large acceptance detectors

→ reduces the experimental limitation

→ it provides better information on the scattering process and structure of the SP states.



* p-Knockout from external $p_{3/2}$ →

Observation of bound state

$S_p < [Q_p(^{12}C) + Q_a(^{11}B)] = 24{,}61$ MeV

* p from a deep $s_{1/2}$ shell →

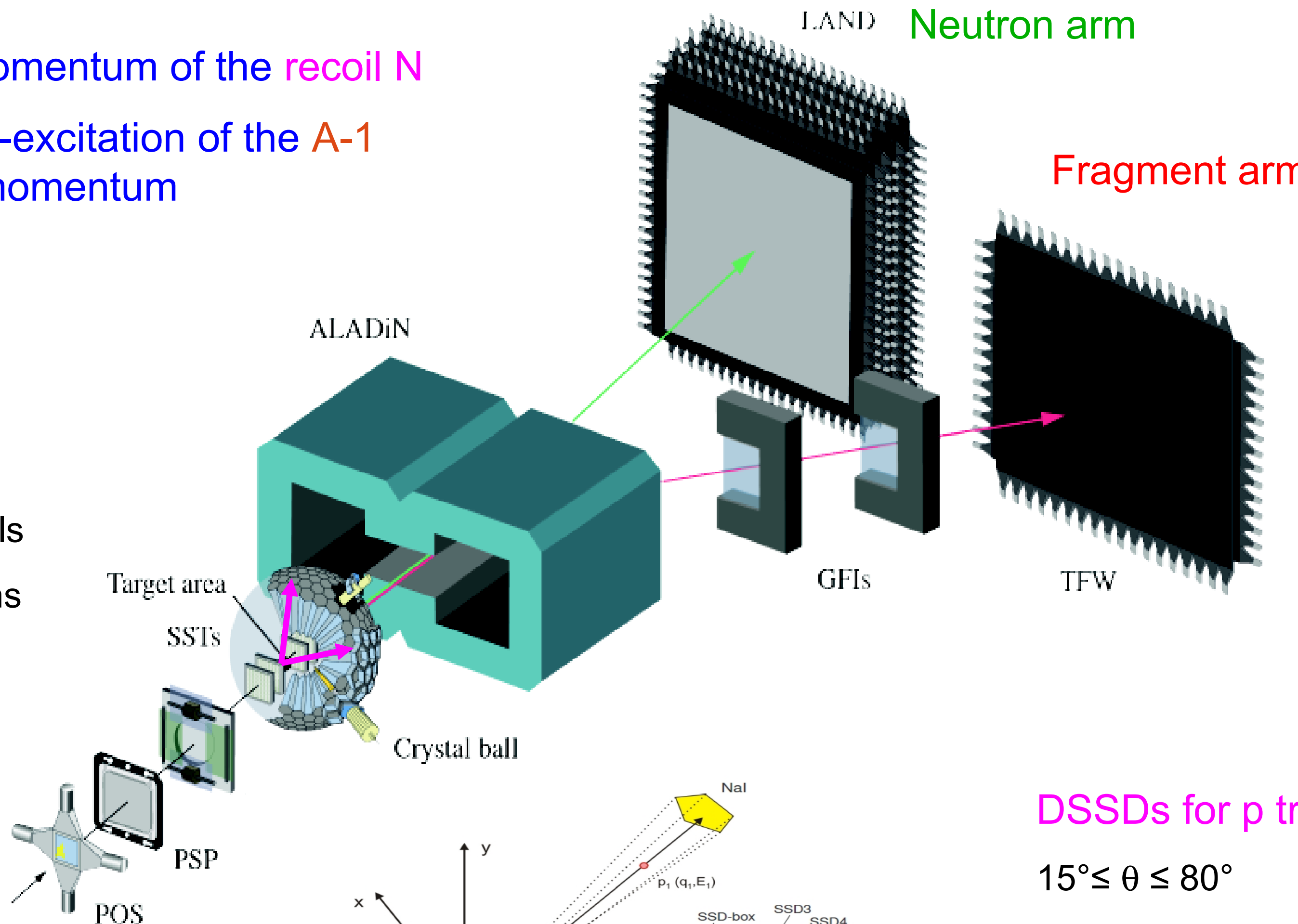
Observation of unbound states $^{11}B^*$

$S_p > [Q_p(^{12}C) + Q_n(^{11}B)] = 27{,}41$ MeV

$$Sp = Qp + Ex$$

The R3B setup at Cave C

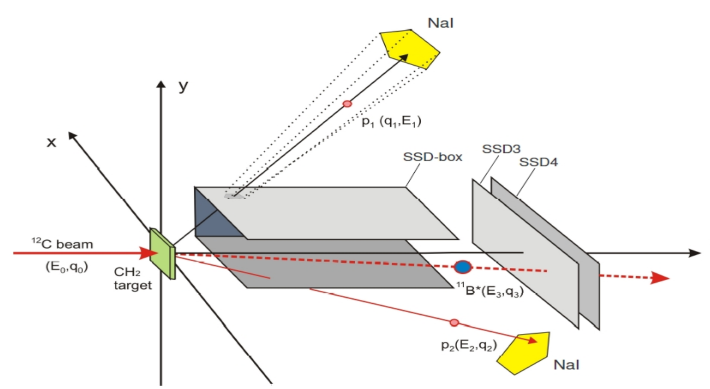
- Measuring the momentum of the recoil N
- Measuring the de-excitation of the A-1 fragment and its momentum



Crystal Ball:

162 NaI(Tl) crystals

$4\Pi\ \gamma$, 2Π protons



DSSDs for p tracking

$15° \leq \theta \leq 80°$

$\Delta x \sim 100\ \mu m$;

$\Delta E \sim 50$ keV

100 keV < E < 14 MeV

$^{12}C\ 10^4$ pps@ 400 A Mev

214 mg/cm^2 CH_2,

$^{12}C(2,2p) \rightarrow$ 2 p angular correlation + outgoing fragment

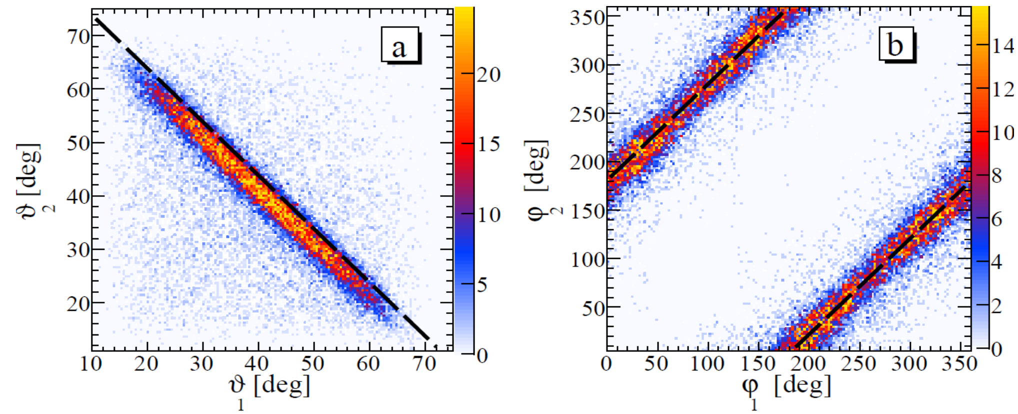
V. Panin and J. Taylor PhD Submitted to PLB

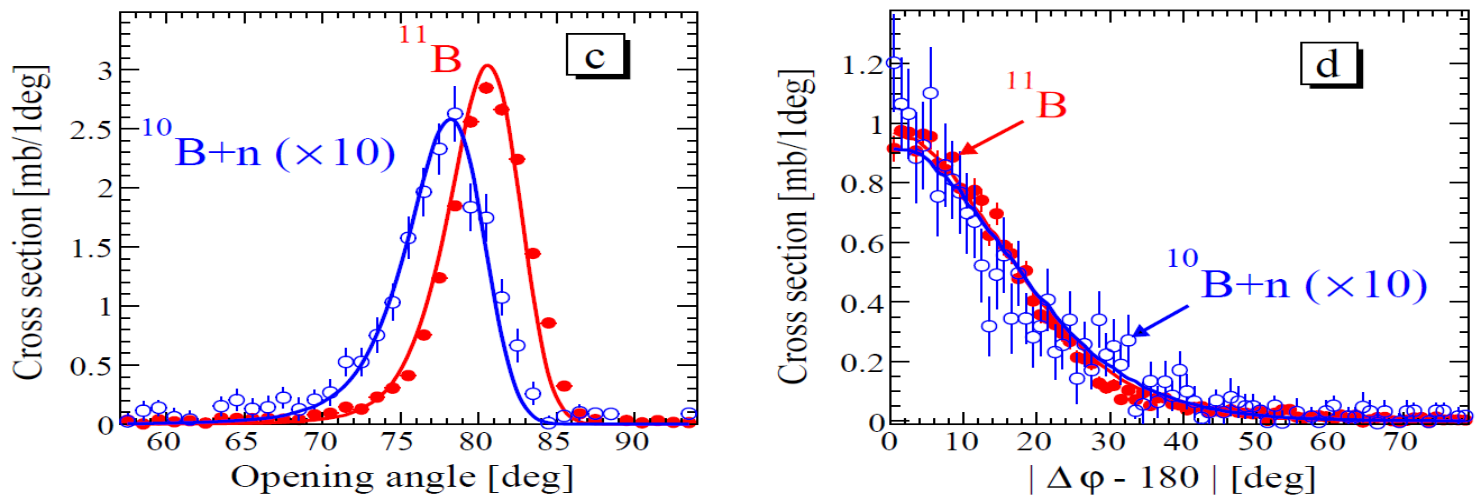
Signature of the $^{12}C(p,2p)$

→ strong spacial correlation

a) opening angle $\theta \sim 90$

b) enhanced coplanarity $\Delta\Phi$-180 = 0





The difference in Sp between bound and unbound states is observed in the protons opening angle

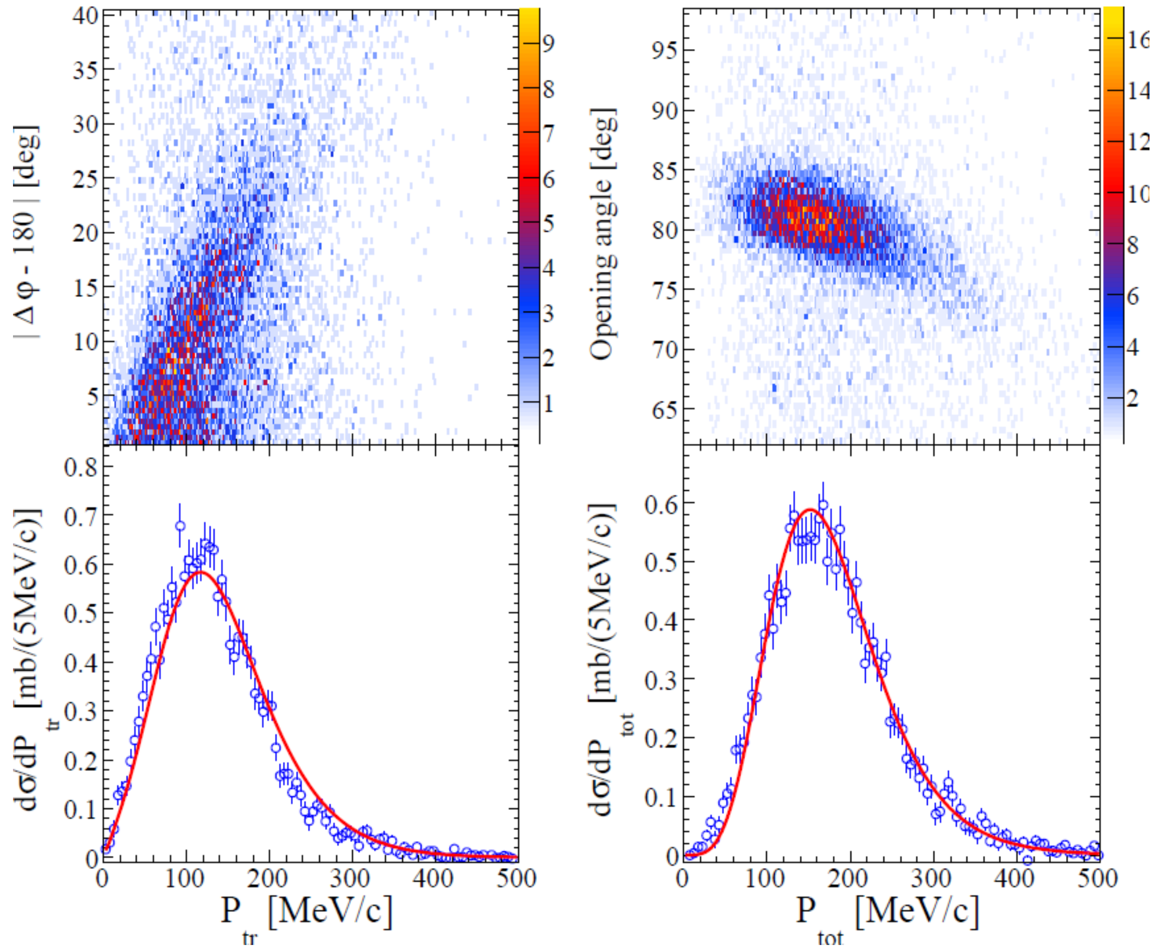
Kinematical simulations for both states

L.Chulkov NP A759 (2005) 43

$^{12}C(2,2p) \rightarrow {}^{11}B$ bound states inclusive momentum

V. Panin and J. Taylor PhD Submitted to PLB

The ^{11}B bound states can be tracked and their momentum distributions determined



Eikonal calculation

→ assuming a $0p_{3/2}$ proton

→ nuclear absorption included

T. Aumann, C. Bertulani and J. Ryckebusch PRC 88 (2013) 064610

Non co-planar events associate with larger momentum

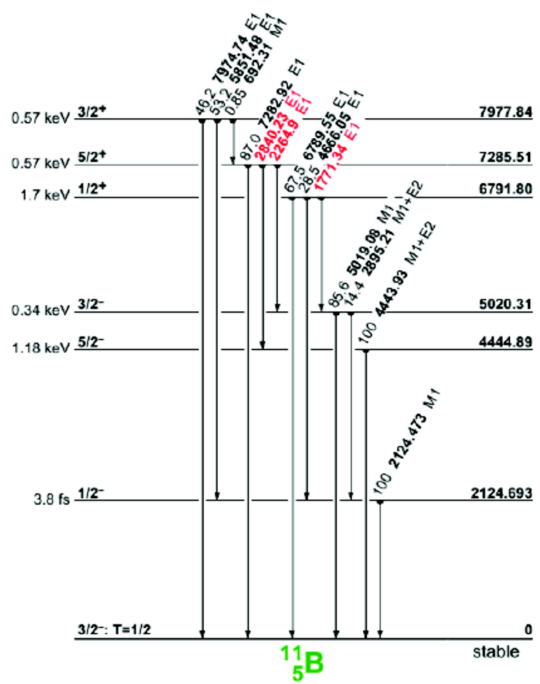
^{12}C(2,2p) →^{11}B bound states γ de- excitation

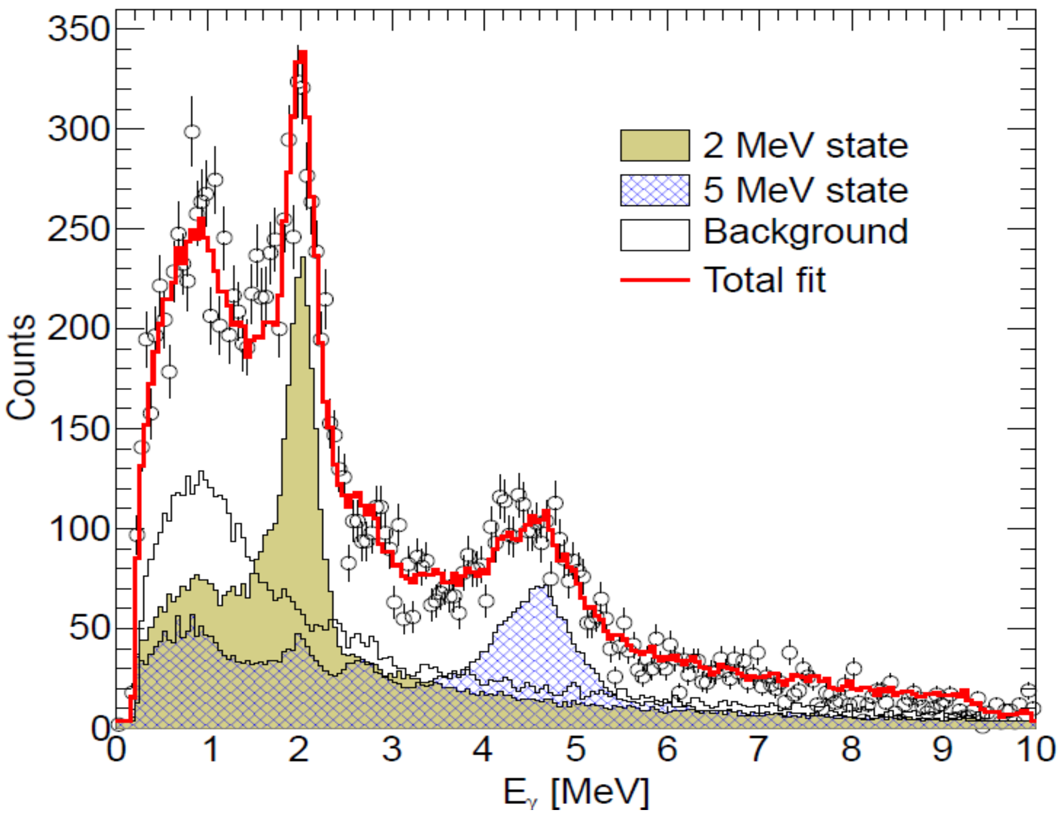
V. Panin and J. Taylor PhD Submitted to PLB

Following the ^{12}C(p,2p) reaction, one can reconstruct the excitation energy.

Depending on the excitation energy ^{11}B

* Bound states





$^{12}C(2,2p) \rightarrow ^{11}B$ bound states γ de- excitation

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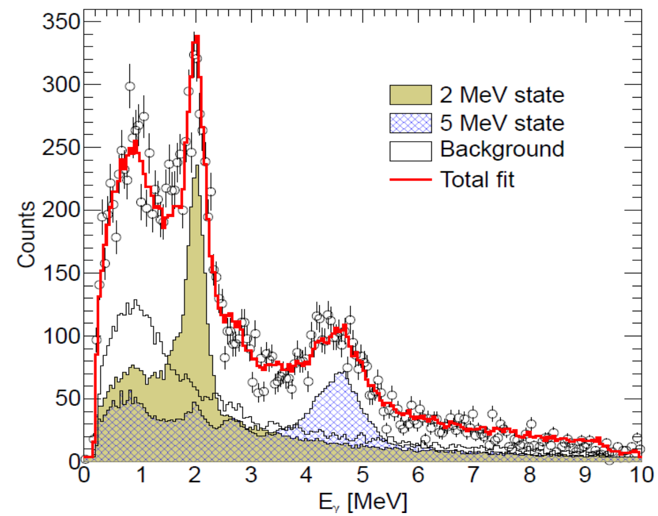
V. Panin and J. Taylor PhD Submitted to PLB



12C(p,2p)11B Exclusive Cross-sections

E_x [MeV], J^π	$\sigma_{\rm exp}$, mb	$\sigma_{\rm SP}$, mb	S(exp)	$S(e,e'p)$	$S(p,2p)$	$S(d,^3{\rm He})$
0.0 (G.S.), $3/2^-$	15.8(18)	7.5	2.11(24) [0.82]	1.72(11) [0.79]	2.02 [0.76]	1.72 [0.82]
2.125, $1/2^-$	1.9(2)	7.4	0.26(3) [0.10]	0.26(2) [0.12]	0.33 [0.12]	0.27 [0.13]
5.02, $3/2^-$	1.5(2)	7.2	0.21(3) [0.08]	0.20(2) [0.09]	0.33 [0.12]	0.11 [0.5]
Total:	19.2(22)		2.58(30) [1.00]	2.18(15) [1.00]	2.68 [1.00]	2.1 [1.00]

This work

T. Aumann et al
PRC 88 (2013)

G. Steenhoven et al
NPA 480 (1988)

D.W Devins et al
A Jou,Phys 32 (1979)

G J Kramer et al
NPA 679 (2001)

R = 0.65 ± 0.02

Overall good agreement

$^{12}C(2,2p) \rightarrow$ Excitation energy

V. Panin and J. Taylor PhD Submitted to PLB

Following the $^{12}C(p,2p)$ reaction, one can reconstruct the excitation energy.

Depending on the excitation energy ^{11}B

* Bound states

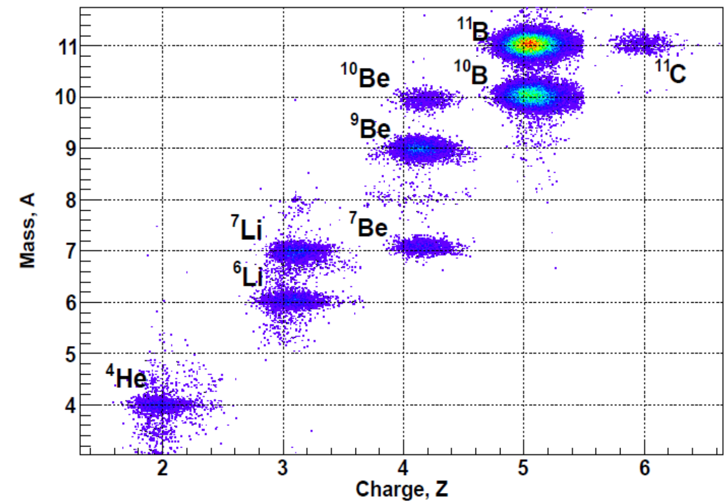
* Unbound states

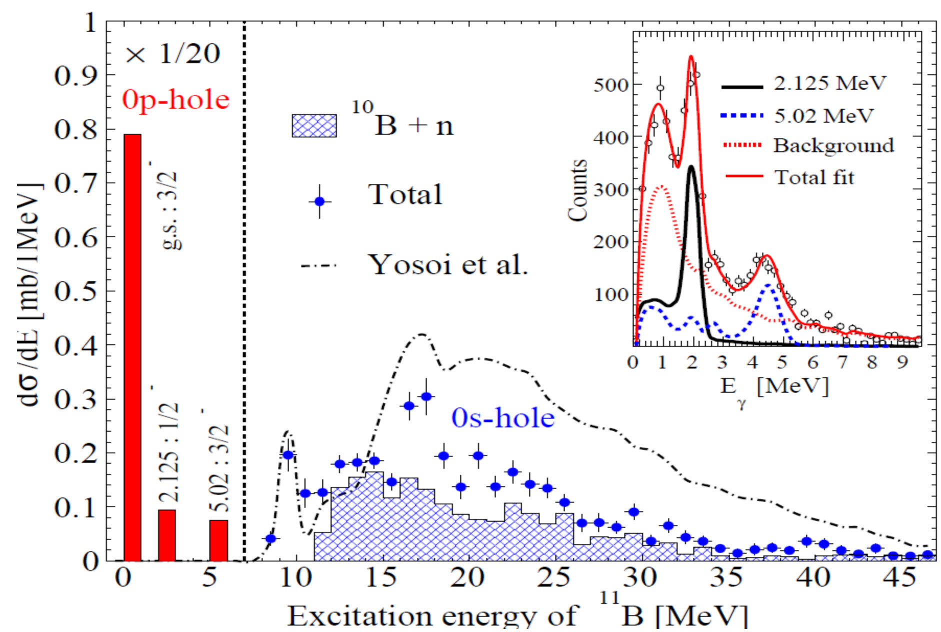
$^{10}B + n$

$^{9}Be + ^{2}H$

$^{7}Li + ^{4}He$

….





In rather good agreement with recent (p,2p) experiments in direct kinematics (E_p= 390 MeV)

Y. Yosoi et al. PLB 351 (2008)

The QFS in inverse kinematics: S393 experiment

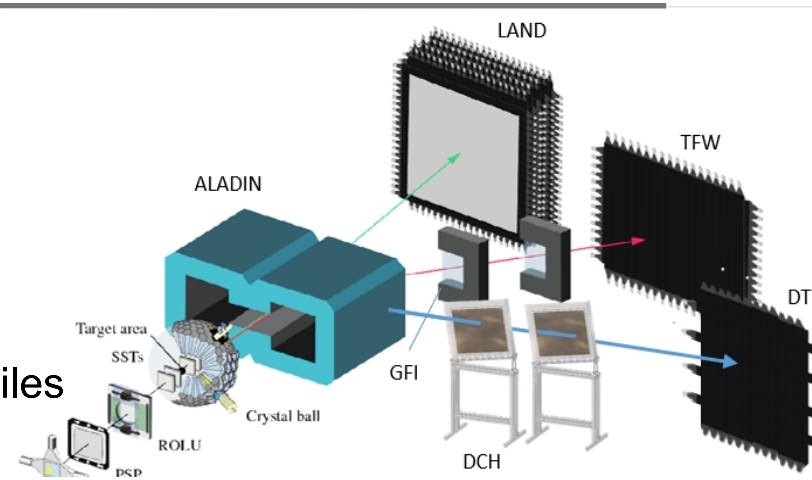
^{40}Ar primary beam @ 490 A MeV

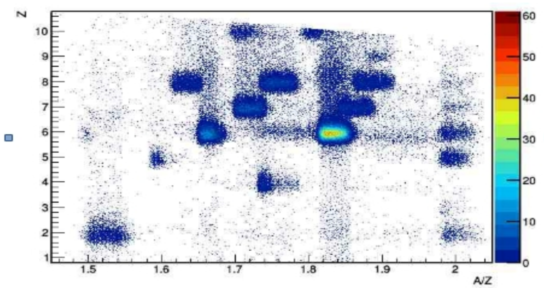
Exotic projectiles raning from Z=4 to Z=8

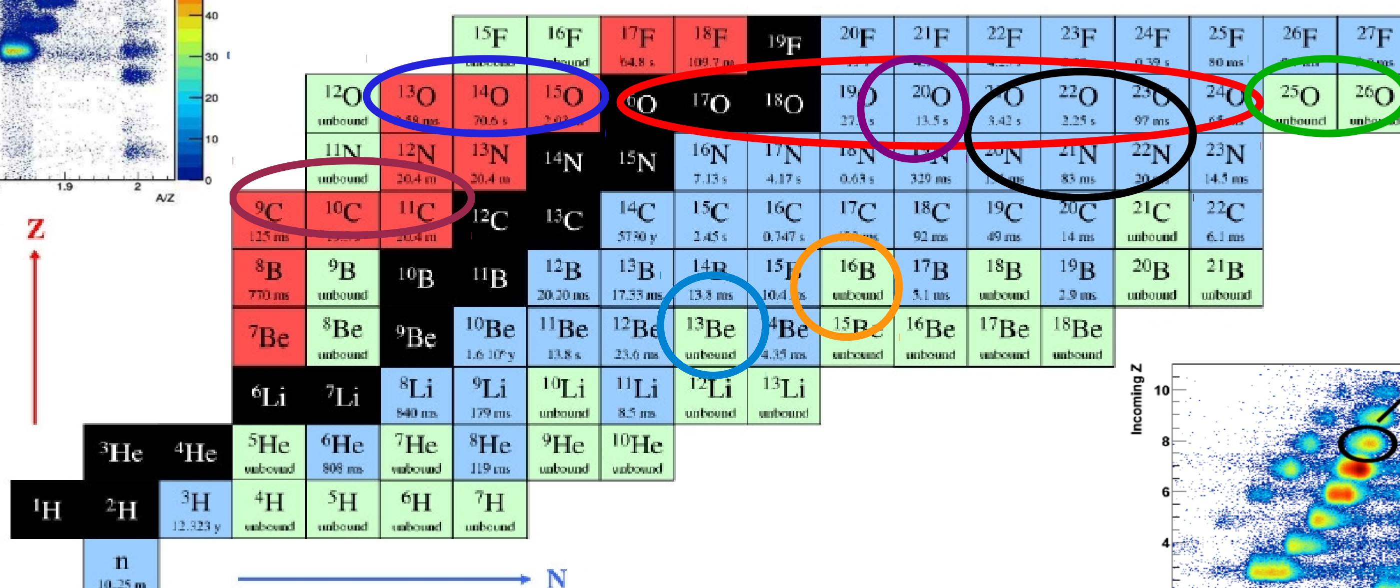
Spaning over N/Z

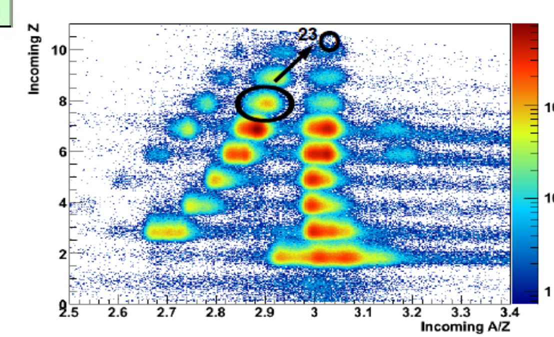
Different reaction targets Pb, C, CH_2

→ study of (p,2p) reactions induced by exotic projectliles









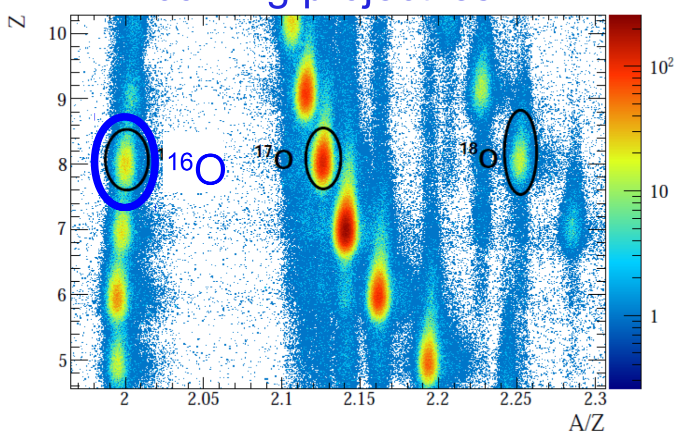
L. Atar
P. Díaz
JM. Boillos
C. Caesar
M. Holl
N. Al Nafaj
G. Ribero
R. Thies

- Role of nucleon correlations in nuclei
- Detailed spectroscopy, deeply bound states
- Study of unbound states beyond the dripline → invariant mass methode

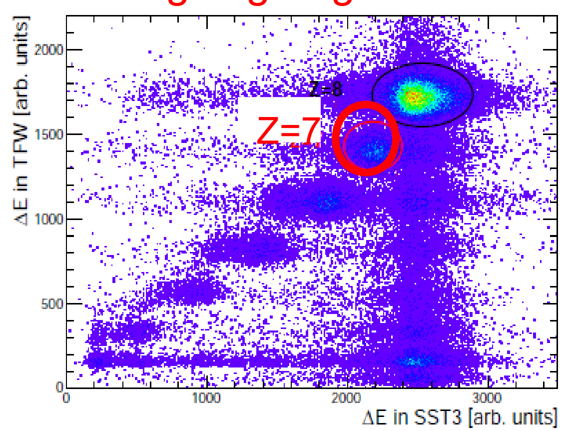
$^{16}O(p,2p)^{15}N$ analysis

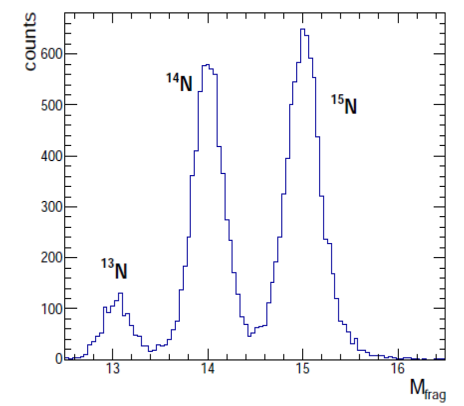
Stable oxygen isotopes were also produced by nuclear fragmentation of ^{40}Ar *L. Atar PhD*

Incoming projectiles



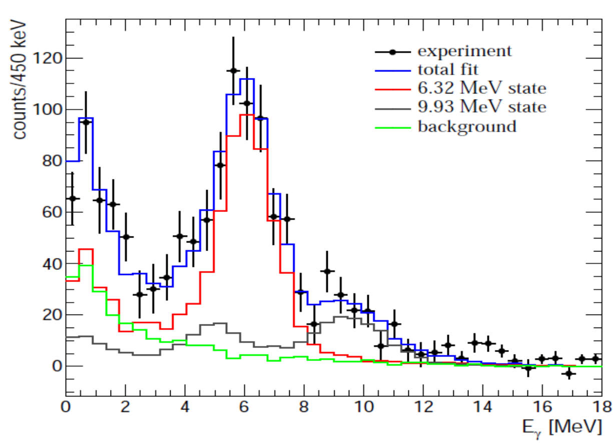
Outgoing fragments



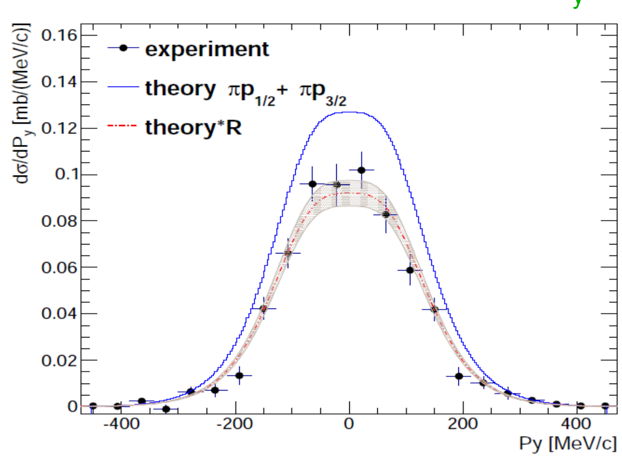


$^{16}O(p,2p)^{15}N$

γ de-excitation of ^{15}N bound states



^{15}N transversal momentum p_y



Eikonal calculation

T. Aumann, C. Bertulani and J. Ryckebusch PRC 88 (2013) 064610

R = 0.73 ± 0.03

In agreement with (e,e'p) experiments

Paving the road towards FAIR

Facility for Antiproton and Ion Research

•Primary beam intensity: Factor 100 – 1000

Secondary beam intensities radioactive nuclei: up to factor **10,000**

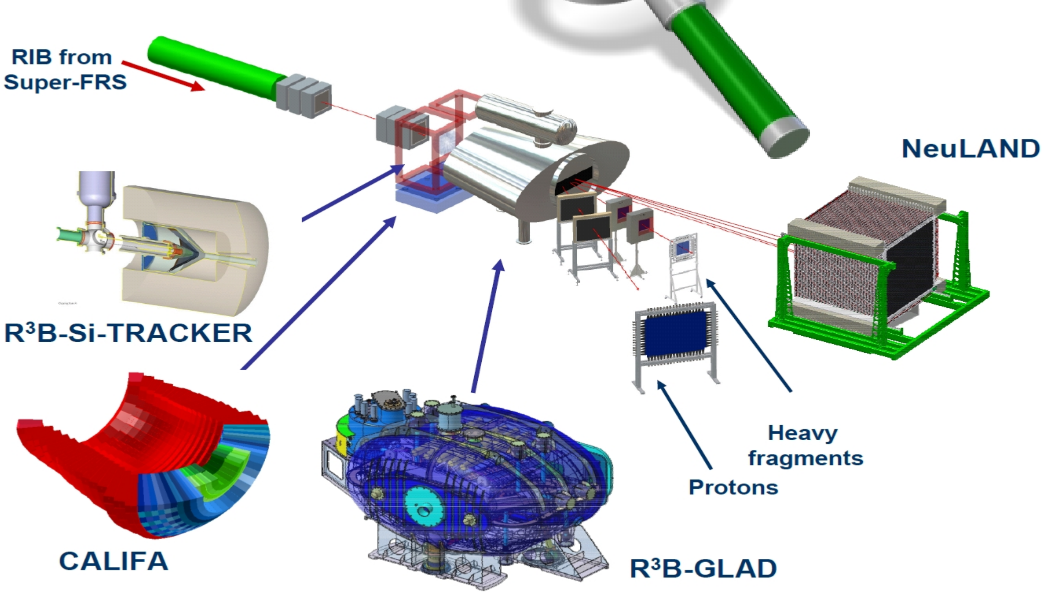
Beam energy: Factor 15

→ 20 Tm
1 A. GeV

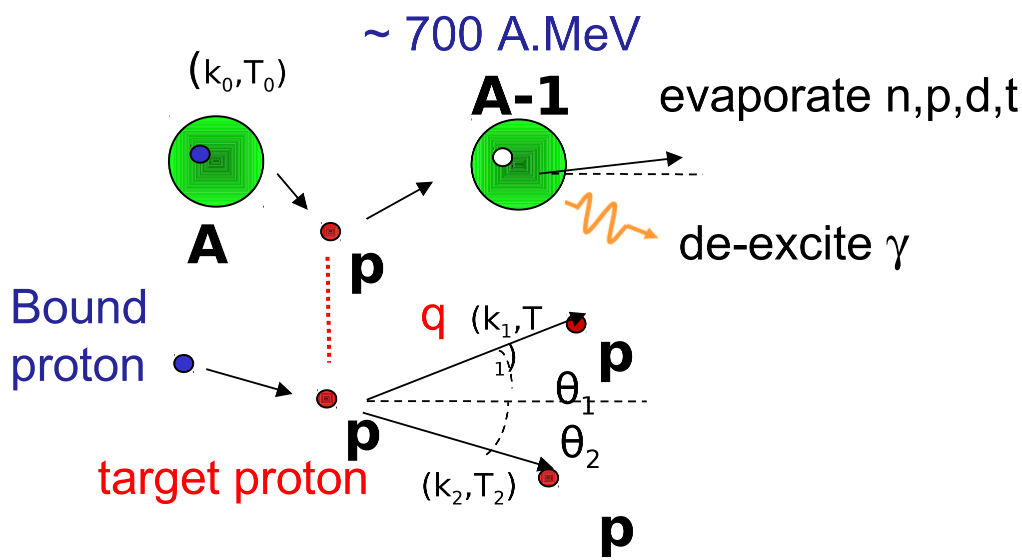
Large acceptance

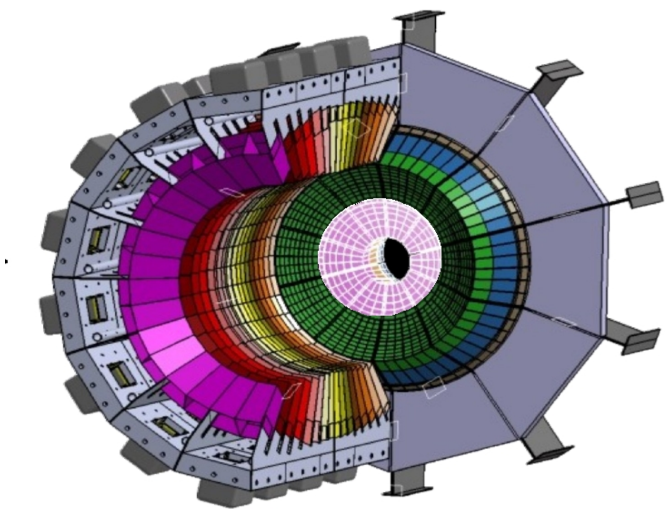
High resolution

High efficiency



Paving the road towards FAIR





CALIFA

Simultaneous p and γ detection

Physics imposes the technical choices

- Huge dynamic range
  100keV γ-rays – 700 AMeV charged particles
- high efficiency, good resolution
- high granularity → Doppler correction
- particle identification

θ (deg)	E_p (MeV)	CsI(Tl) range (cm)	Efficiency (%)
7	686	71,8	15%
20	592	59,7	...
40	356	26,4	50%

~ 3000 detection units
CsI(Tl) +LAAPD
LaBr/LaCl + PMT

D. Cortina convener; TDR approved 2015

Conclusions and Outlook

- Nuclei are complex systems, a century of research has not been enough to understand in detail the nuclear force.

- The availability of RIB for experimentation, opens bright perspectives to advance in this subject: isospin and density.
→ QFS from RIB, appear as a clean experimental probe to explore nuclear shell evolution and the role of NN correlations

- The R3B collaboration is working on the design and construction of a versatile experimental setup to study reactions induced by relativistic radioactive beams.
→ fulfills the stringent requirements that met in QFS

- First experiments with stable beams have been successfully performed.
→ validation of the experimental approach

- The continuation of this work with the fantastic beams and intensities of FAIR combined with the improved capabilities of the detection system looks very promising.

Thanks to R3B collaborators for the work
and thank you for your attention