Nuclear Structure and Reactions - IV

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10-12 June 2013

MICHIGAN STATE UNIVERSITY

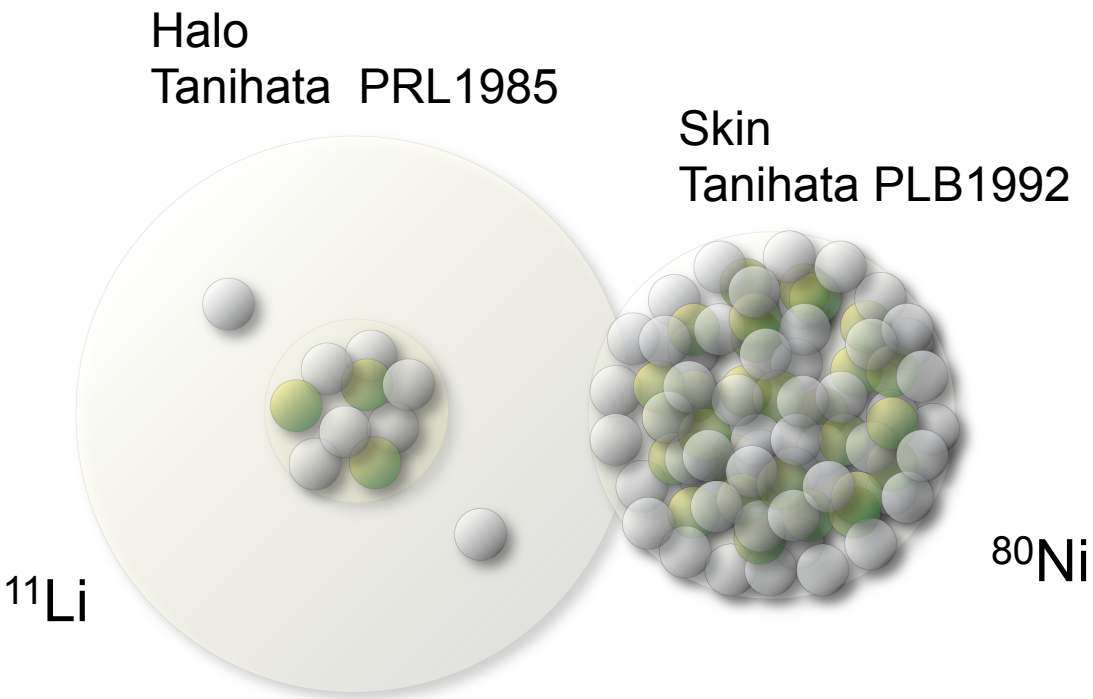
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline of my six lectures

- One of HUGS goals is to introduce students to “topics of interest in nuclear physics”. My lectures will attempt to describe what is interesting in the study of nuclei.
- Lecture 1: Search for the limits of nuclear binding and production of new isotopes
- Lecture 2: Attempts to model atomic nuclei I
- Lecture 3: Attempts to model atomic nuclei II
- **Lecture 4: Nuclear Reactions**
- Lecture 5: The origin of atoms – Nuclear Astrophysics I
- Lecture 6: The origin of atoms – Nuclear Astrophysics II

It is important for you to ask questions.

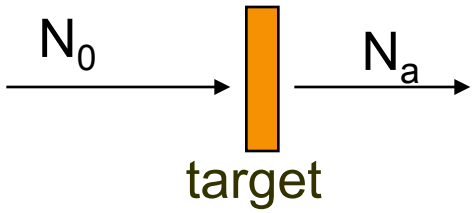
Weakly bound isotopes have unique features



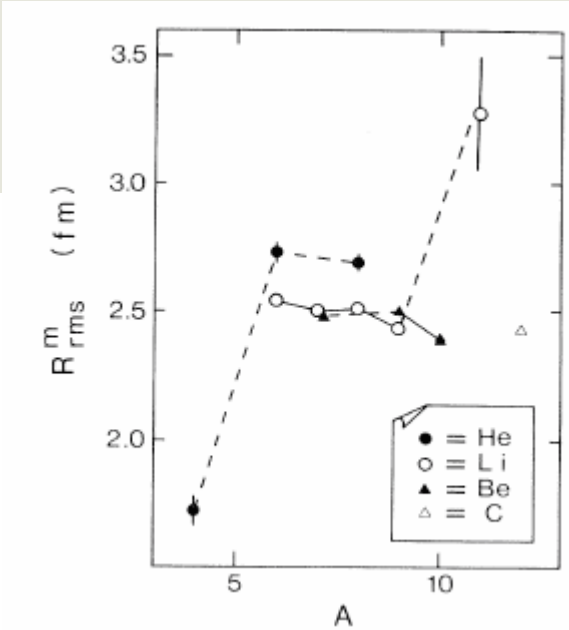
<u>Science:</u> Pairing in low-density material, new tests of nuclear models, open quantum system, interaction with continuum states - Efimov States - Reactions

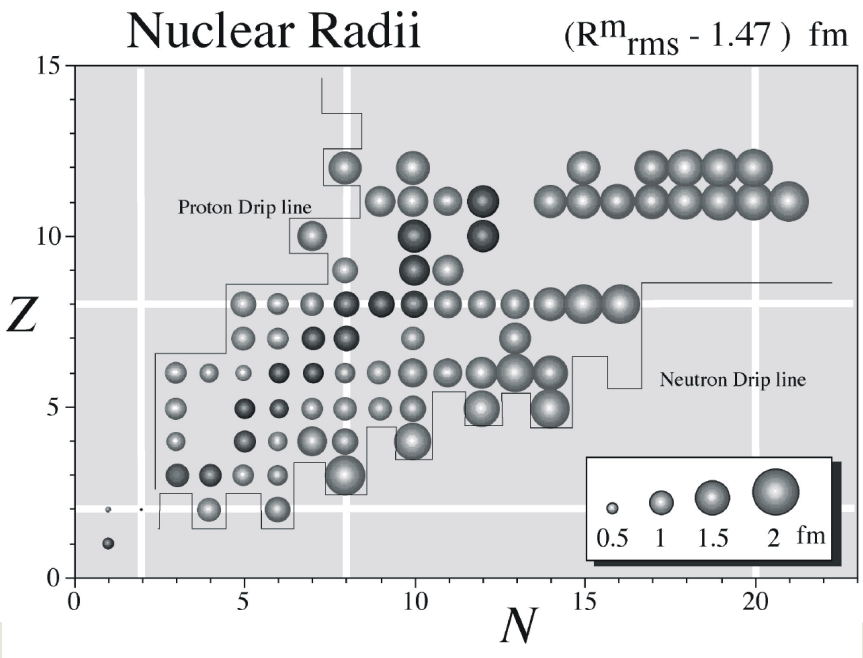
Experimental "Discovery"

- Evidence for the size of ^{11}Li was found from total interaction cross section measurements (Tanihata PRL1985)
- One of the first thing we learn about nuclei is that Nuclear radii follow the formula: $r = r_0 A^{1/3}$ (Equation 1.2 Wong *Introductory Nuclear Physics*
- This is incorrect



$$\sigma_{interaction} = -\mu \ln(N_a/N_0)$$

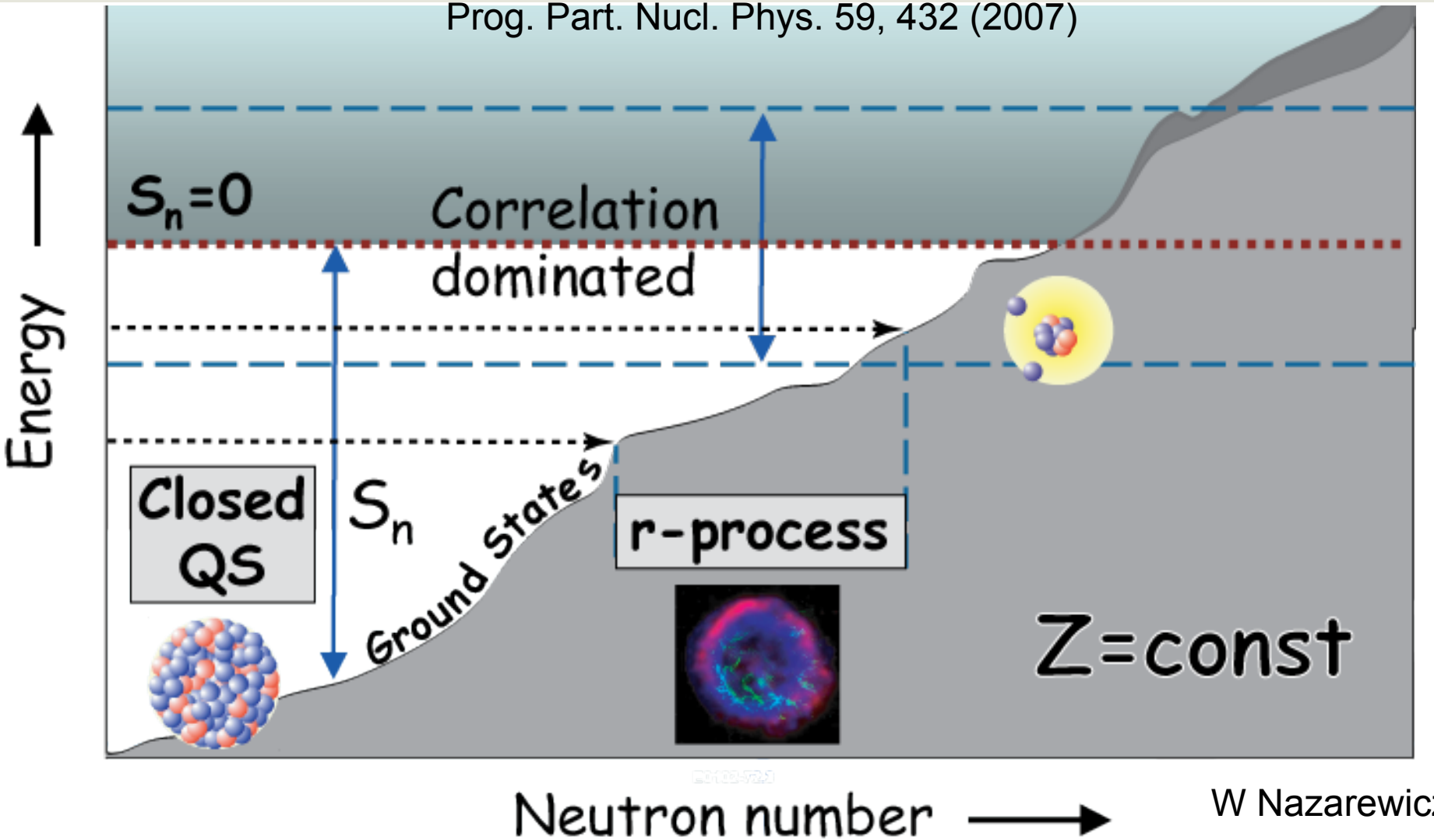




I. Tanihata, OSAKA

Weakly Bound Nuclei are Open Quantum Systems

Prog. Part. Nucl. Phys. 59, 432 (2007)



W Nazarewicz

What we now know about atomic nuclei

- Nuclear can be approximated by protons, neutrons, and their pair-wise interactions
- Nuclear radii follow the formula $r = r_0 A^{1/3}$ (Equation 1.2 Wong *Introductory Nuclear Physics*)
- The nuclear force has a saturation property where each nucleon can only interact with a few of its neighbors and the total binding energy increases linearly with A.
- Nuclei obey a shell model with magic numbers 2, 8, 20, 28, 50, etc.
- Resonance properties, etc.

- Three body forces are important
- Only true for N~Z nuclei; ^{11}Li has valence orbits as large as ^{208}Pb
- This is only true for the stable isotopes found in nature. Some heavy isotopes of mid-mass nuclei may accept 20+ nuclei with no change in BE
- Magic numbers change depending on relative A/Z
- Neutron number can dramatically change the values away from stability

Cool Questions

- How good is the approximation of neutrons and protons in the nucleus?
- How much are neutrons and protons modified in the nucleus and how is this reflected in nuclear structure?
- What are the interactions at pay in a nucleus and how do we understand them from the underlying QCD?
- Is there a standard model for nuclear structure and what is it? Are there forces and interactions beyond this nuclear standard model?

Types of Nuclear Reactions

- Transfer (strong interaction)
  - $^{15}N(p,\alpha)^{12}C$ $\sigma \sim 0.5$ b at E= 2.0 MeV
- Capture (electromagnetic interaction)
  - $^{3}He(\alpha,\gamma)^{7}Be$ $\sigma \sim 10^{-6}$ b at E= 2.0 MeV
- β-decay or electron capture (weak interaction)
  - $p(p,e^{+}\nu)d$ $\sigma \sim 10^{-20}$ b at E= 2.0 MeV

adopted from KH Langanke

Types of nuclear reactions

Direct
Compond

- Elastic Scattering – projectile and target stay in their ground state
- Inelastic scattering – projectile and/or target are left in an excited state
- Transfer reaction – one or more nucleons move
- Breakup (nuclear or Coulomb) – projectile is broken into pieces (target is normally ignored
- Charge Exchange – atomic mass, A, of target and projectile remain the same, but the atomic charge, Z, changes
- Knockout – one or more nucleons are removed from a nucleus (could be target or projectile)
- Spallation – a light ion breaks (spalls) pieces of a nucleus
- Deeply inelastic – highly excited states are produced; many nucleons are transferred
- Capture – beam is absorbed and nucleus deexcites
- Fusion (incomplete, fusion-fission, fusion-evaporation) – nuclei stick together

Types of nuclear reactions

Two types of reactions:

1. Nuclei can coalesce to form highly excited Compound nucleus (CN) that lives for relatively long time.

   Long lifetime sufficient for excitation energy to be shared by all nucleons (> 10^{-20} s). If sufficient energy localized on one or more nucleons (usually neutrons) they can escape and CN decays. Independence hypothesis: CN lives long enough that it loses its memory of how it was formed. So probability of various decay modes independent of entrance channel.

2. Nuclei make 'glancing' contact and separate immediately, said to undergo Direct reactions.

   Short interaction time (≈ 10^{-22} s)Projectile may lose some energy, or have one or more nucleons transferred to or from it.

Nomenclature

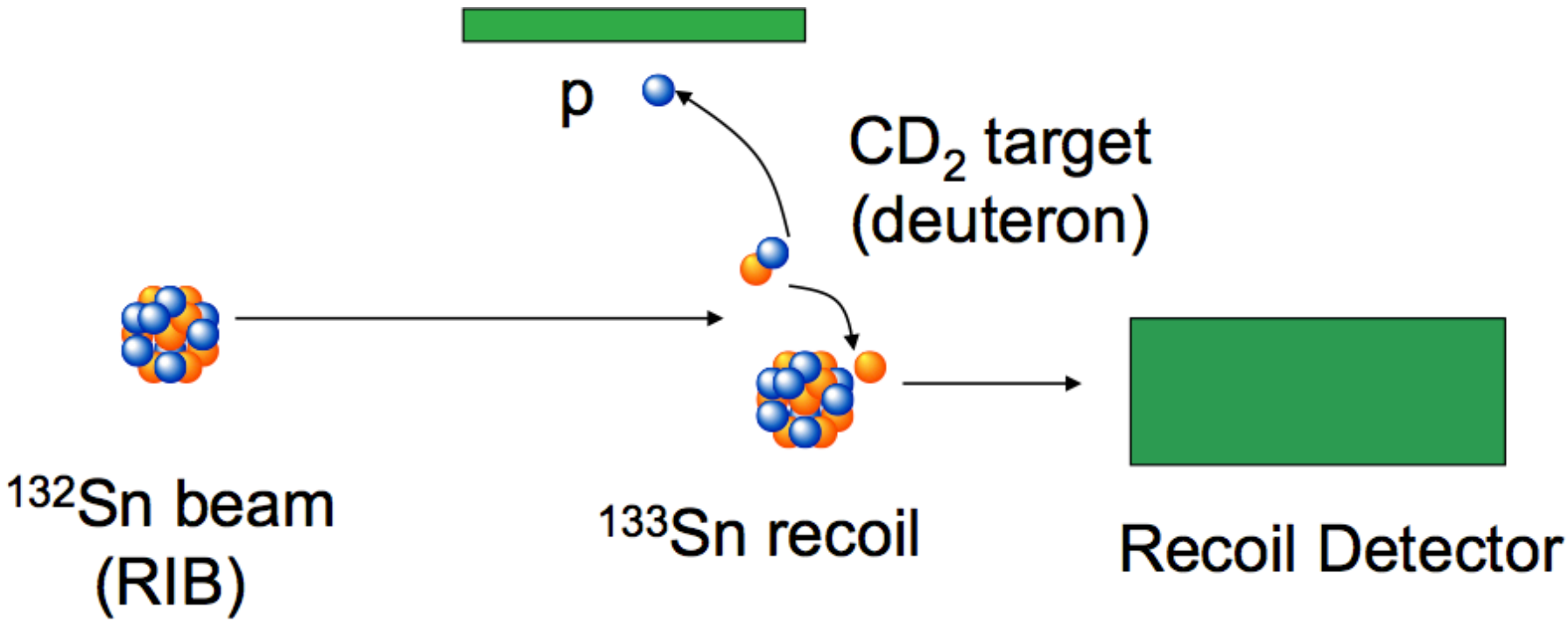
- ^{12}C (beam) + ^{12}C (target) ➔ ^{13}C (detected) + ^{11}C (residual)
- This reaction would be written as $^{12}C(^{12}C,^{13}C)^{11}C$
- Target(Beam, Product/Detected) Residual
- Example: One nucleon stripping reaction

$^{40}Ca(^{2}H,^{1}H)^{41}Ca$

- Example: Nucleon knockout reaction

$^{9}Be(^{40}Ca,^{39}Ca)X$

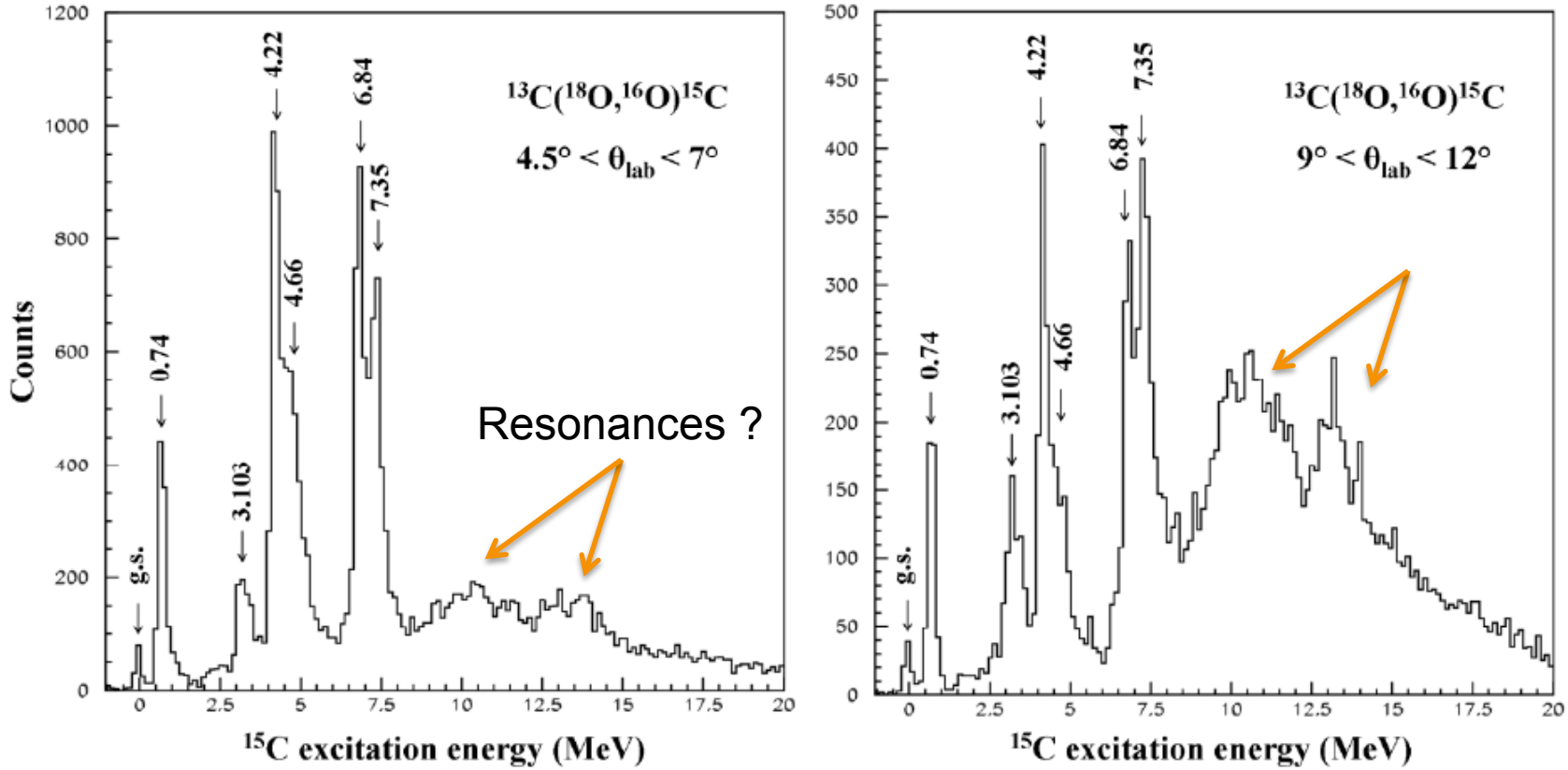
Cartoon of a modern stripping experiment



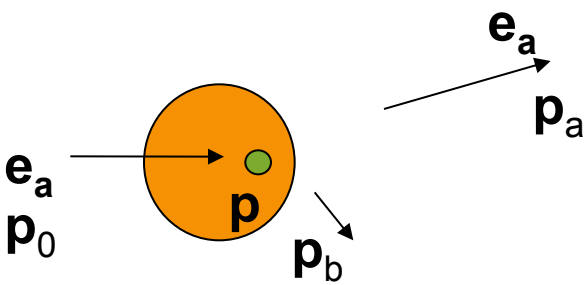
Nuclear response to two-neutron transfer via the $^{13}C(^{18}O,^{16}O)$ reaction – *D. Carbone et al*

- INFN with MAGNEX Spectrograph

Giant Pairing Vibrations (GPV) – Broglia and Bes

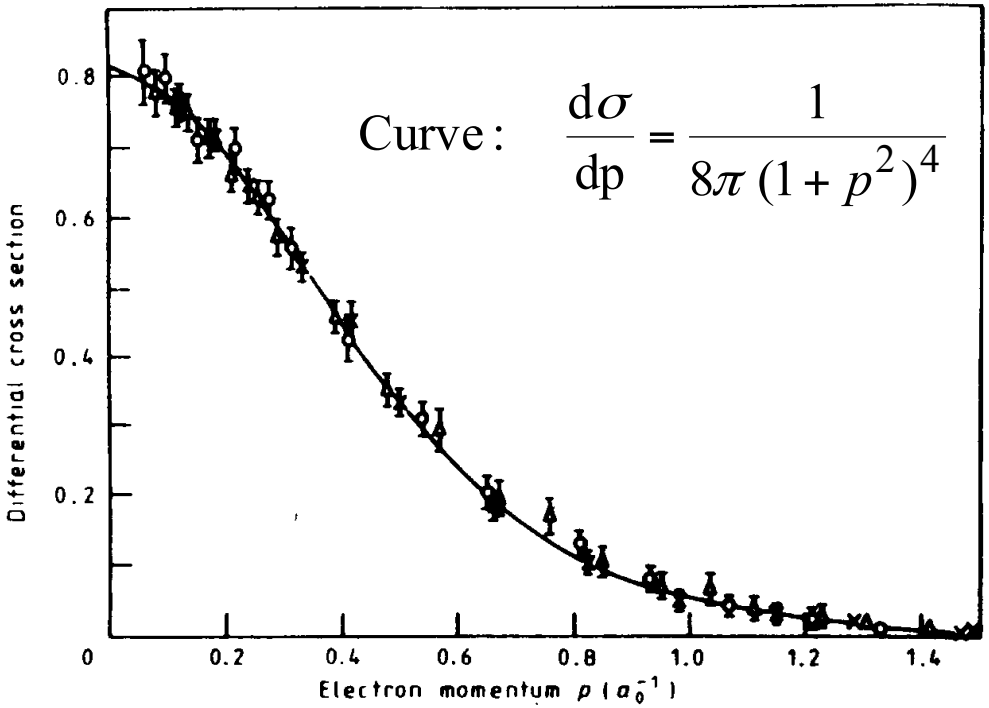


Knockout Reactions Atomic Physics



$p = p_0 - p_a - p_b$
"missing momentum"

Example: 0s state in atomic hydrogen



I.E. McCarthy and E. Weigold, Rep. Prog. Phys. 51 (1988) 299

Concept of Spectroscopic Factor

- One-nucleon overlap functions - capture and transfer reactions of a nucleon on/to a target nucleus with mass A is determined by the one-nucleon overlap function

$$O(r) = \left\langle A+1 \middle| a^{+}(r) \middle| A \right\rangle$$

- Definition of the Spectroscopic Factor – SF is the norm of the overlap function (how much is the occupancy of a single-particle orbital

$$S_{nlj} = \int_{0}^{\infty} \left| O(nlj;r) \right|^{2} r^{2}\, dr$$

- Asymptotic normalization C for r > $R_{nucleus}$

$$S_{nlj}^{1/2} \varphi_{nlj}(r) \rightarrow C_{nlj} \frac{W_{-\eta, j+1/2}(2\kappa r)}{r}$$

Reality: Nucleons in the single orbits

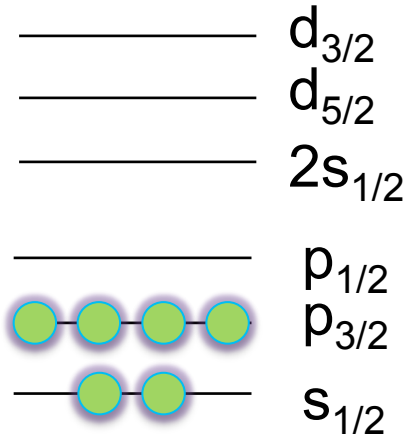
$$\left|{}^{12}C(\text{g.s.})\right\rangle = a^{+}_{1p_{1/2}}\left|{}^{11}\text{B}(\text{g.s.})\otimes 1p_{1/2}\right\rangle + a^{+}_{1p_{3/2}}\left|{}^{11}\text{B}(g.s.)\otimes 1p_{3/2}\right\rangle + \ldots$$

$$S_{\ell sj} = \left|a^{+}_{\ell sj}\right|^{2}$$

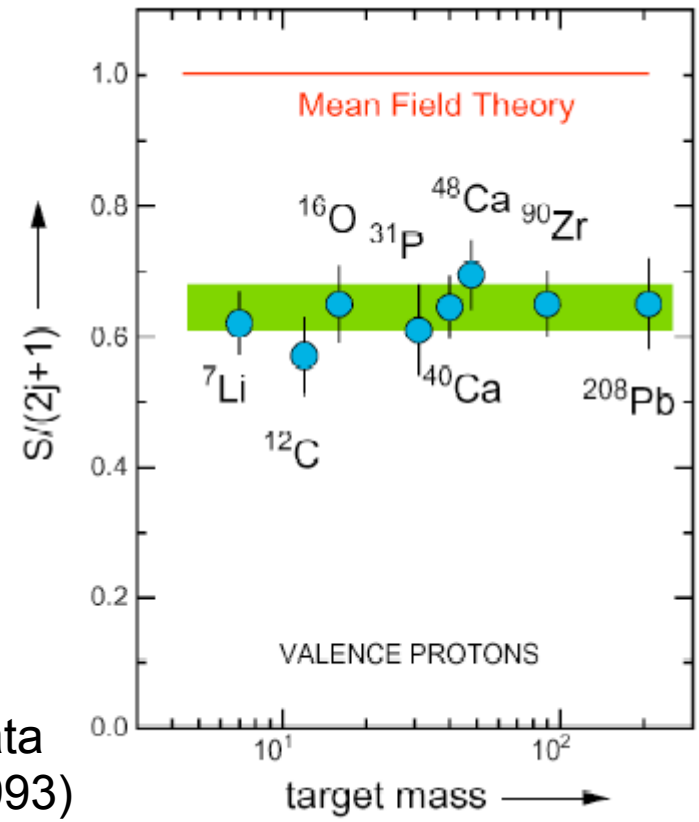
Shell Model

^{12}C

$Z = 6$



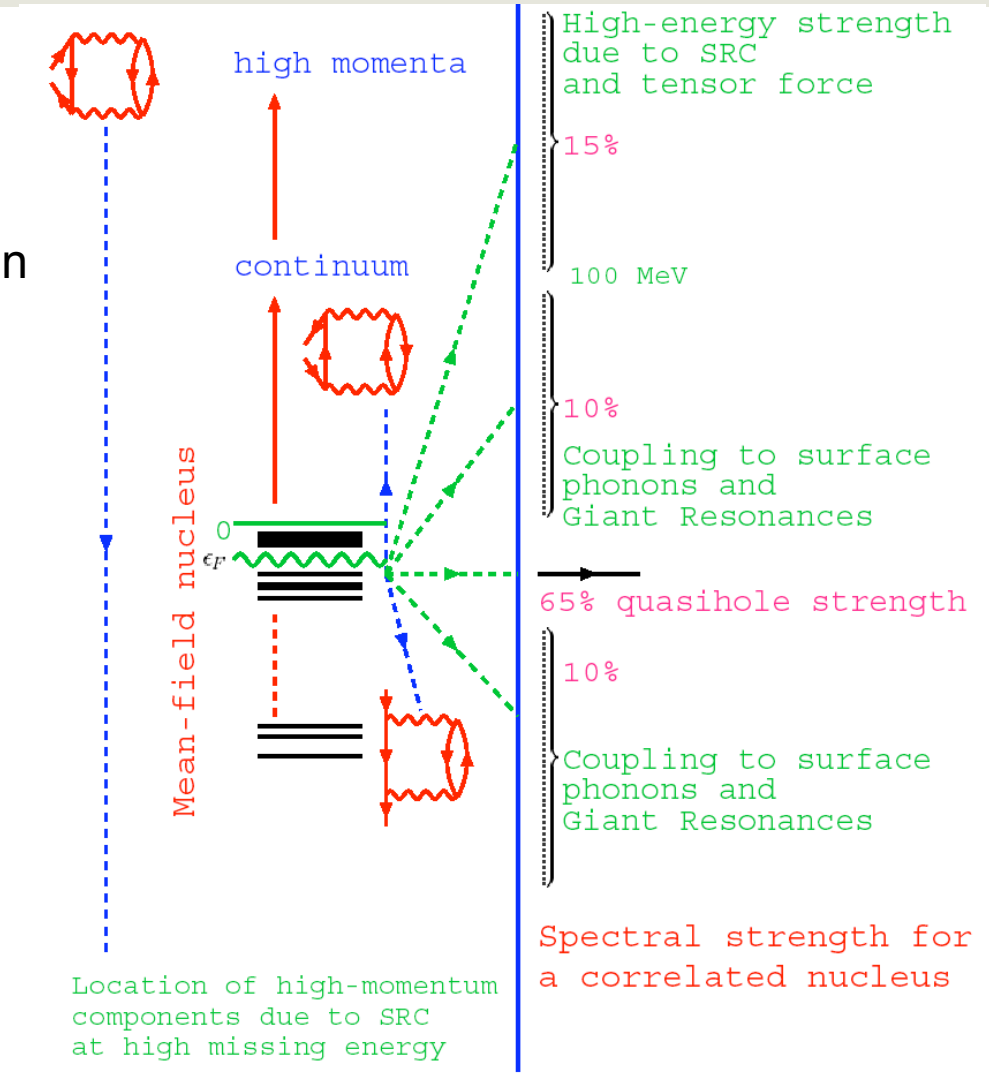
protons



Electron Scattering (e,e'p) NIKHEF data
L. Lapikás, Nucl. Phys. A553,297c (1993)

Location of proton single-particle strength in ^{208}Pb

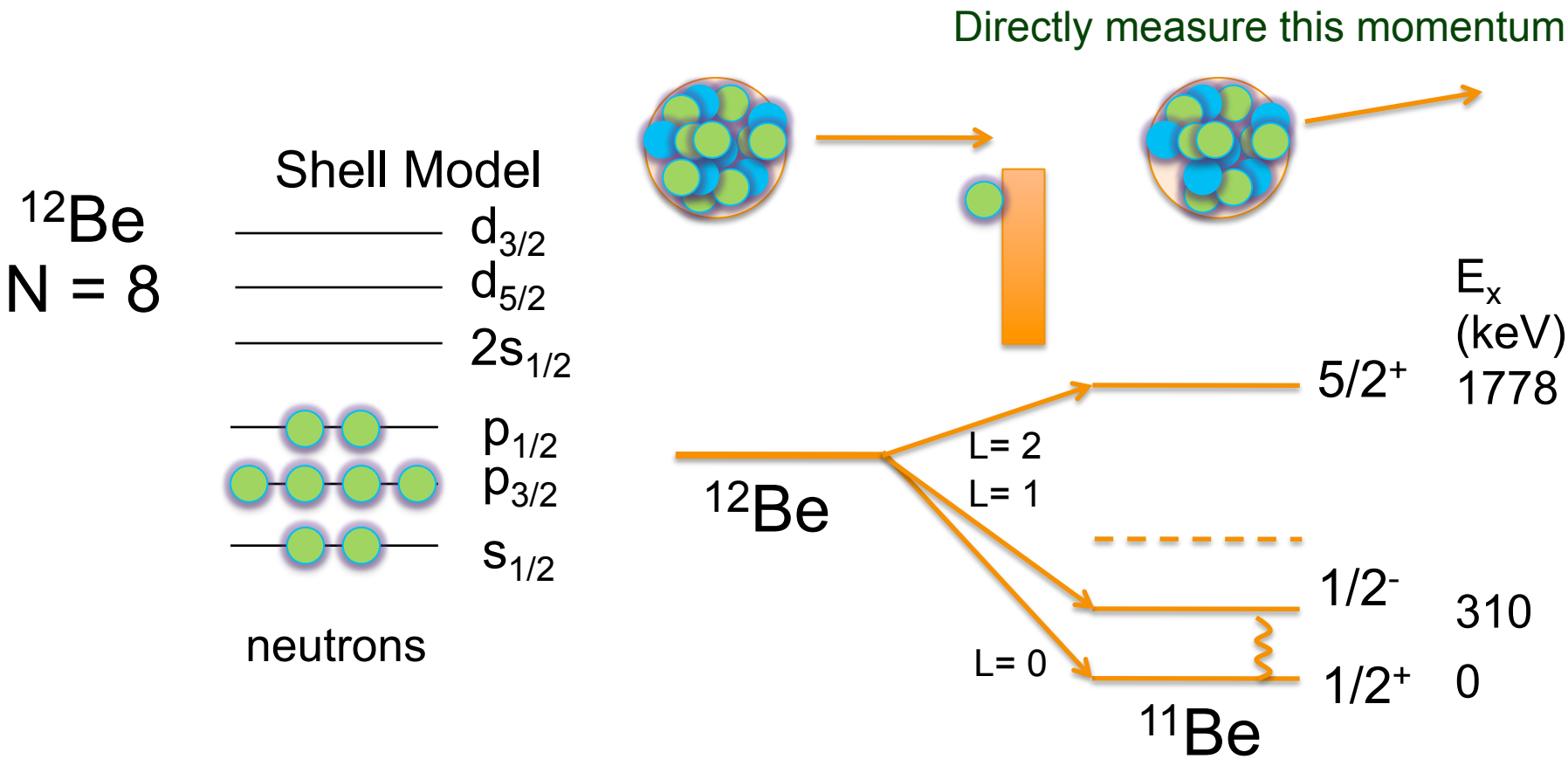
Wim Dickhoff - “We now essentially know what all the protons are doing in the ground state of a “closed-shell” stable nucleus !!!”



W.Dickhoff and C. Barbieri, Prog. Part. Nucl. Phys. 52, 377 (2004)

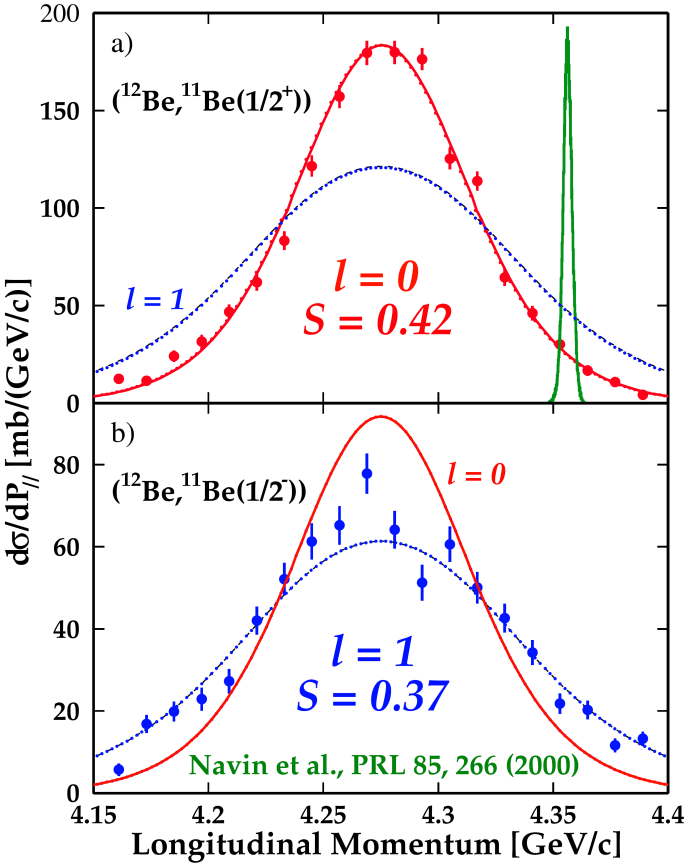
C. Barbieri, *et al.* PRL 103, 202502 (2009)

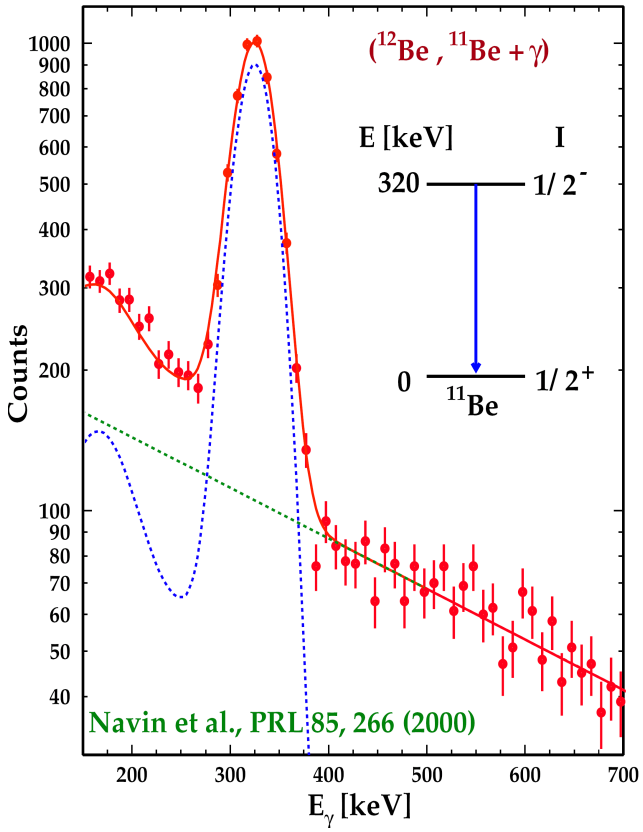
Nucleon knockout technique to measure wave functions



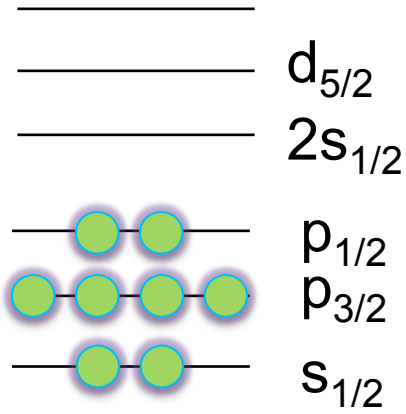
P. G. Hansen and J. A. Tostevin, Annu. Rev. Nucl. Part. Sci. 53, 219 (2003).

Recoil momenta show which orbit the nucleons came from





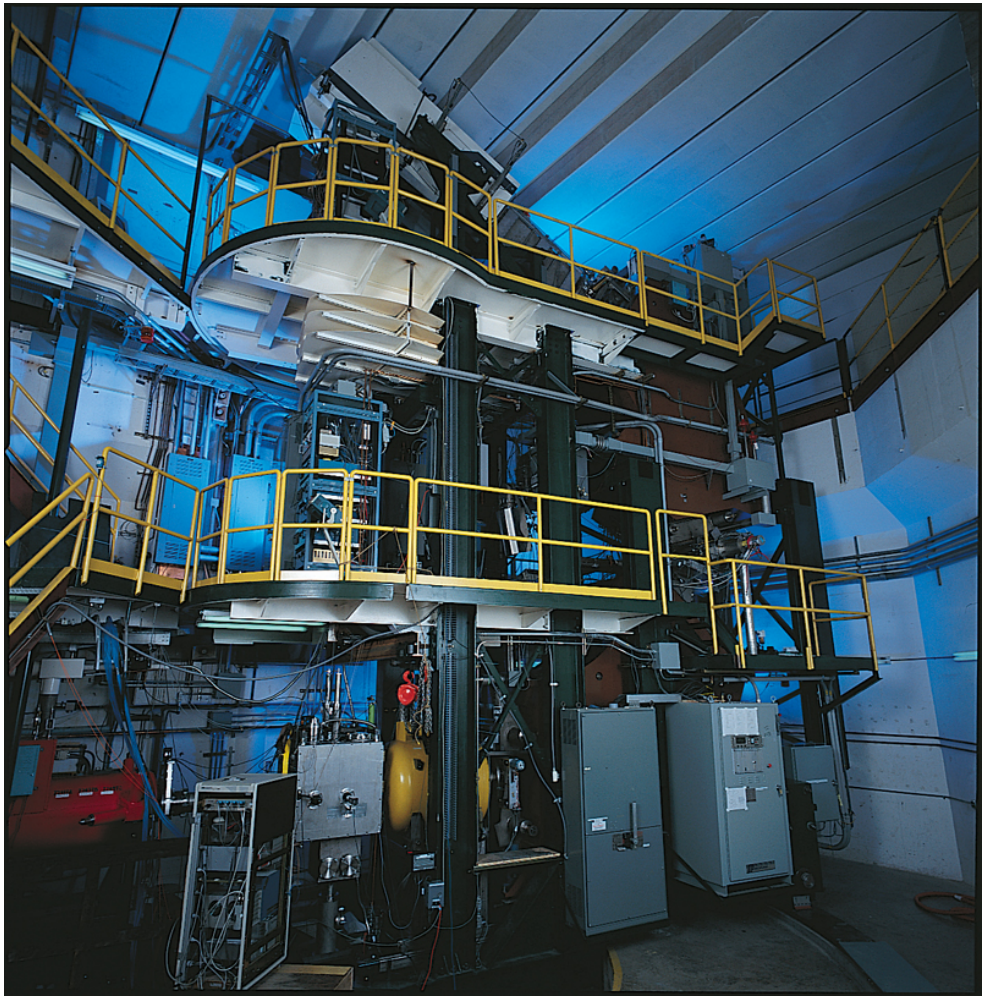
Shell Model
100% $(0p)^2$



neutrons

N=8 is not a shell closure in ^{12}Be: It is just about the opposite with the wave function of 32% $(0p)^8$, 34% $(1s)^2$, 34% $(0d)^2$

How do we measure the recoil fragment?

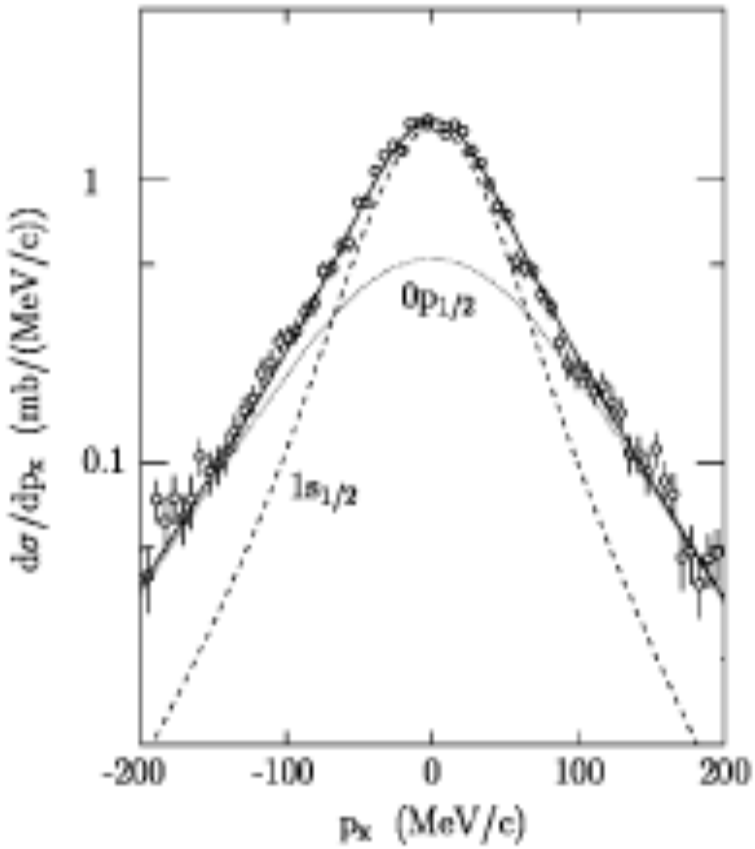


S800 Spectrograph
1.2 GeV/c,
High resolution: 1 in 20,000
Large acceptance: 20 msr

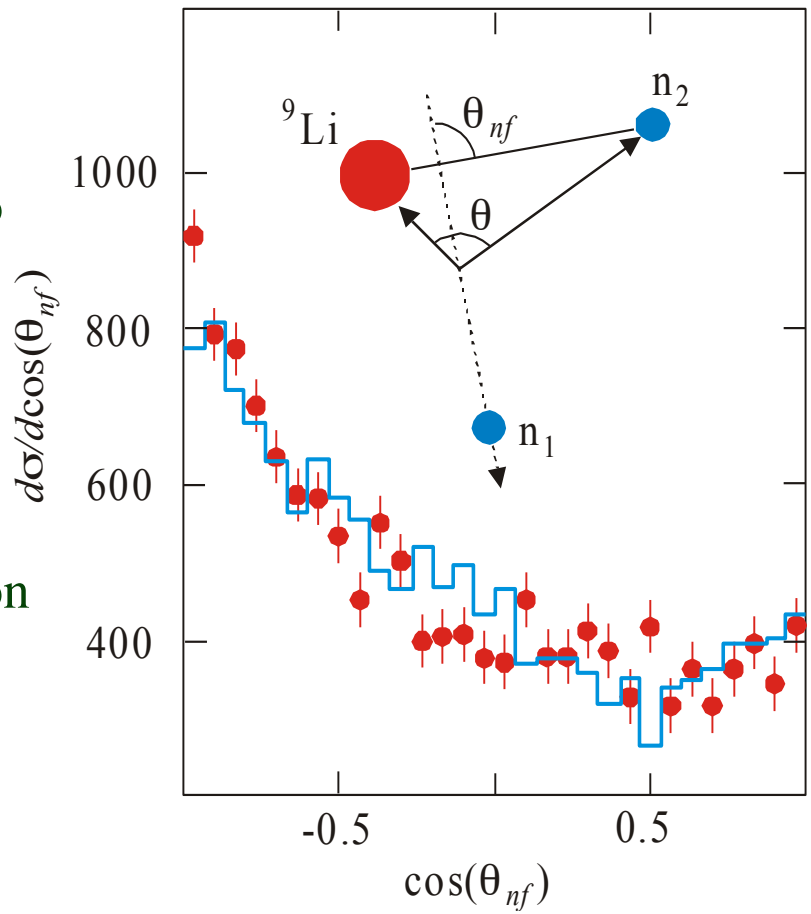
Admixture of s and d components in ^{11}Li

H Simon et al. Phy. Rev. Lett 83 (99) 496

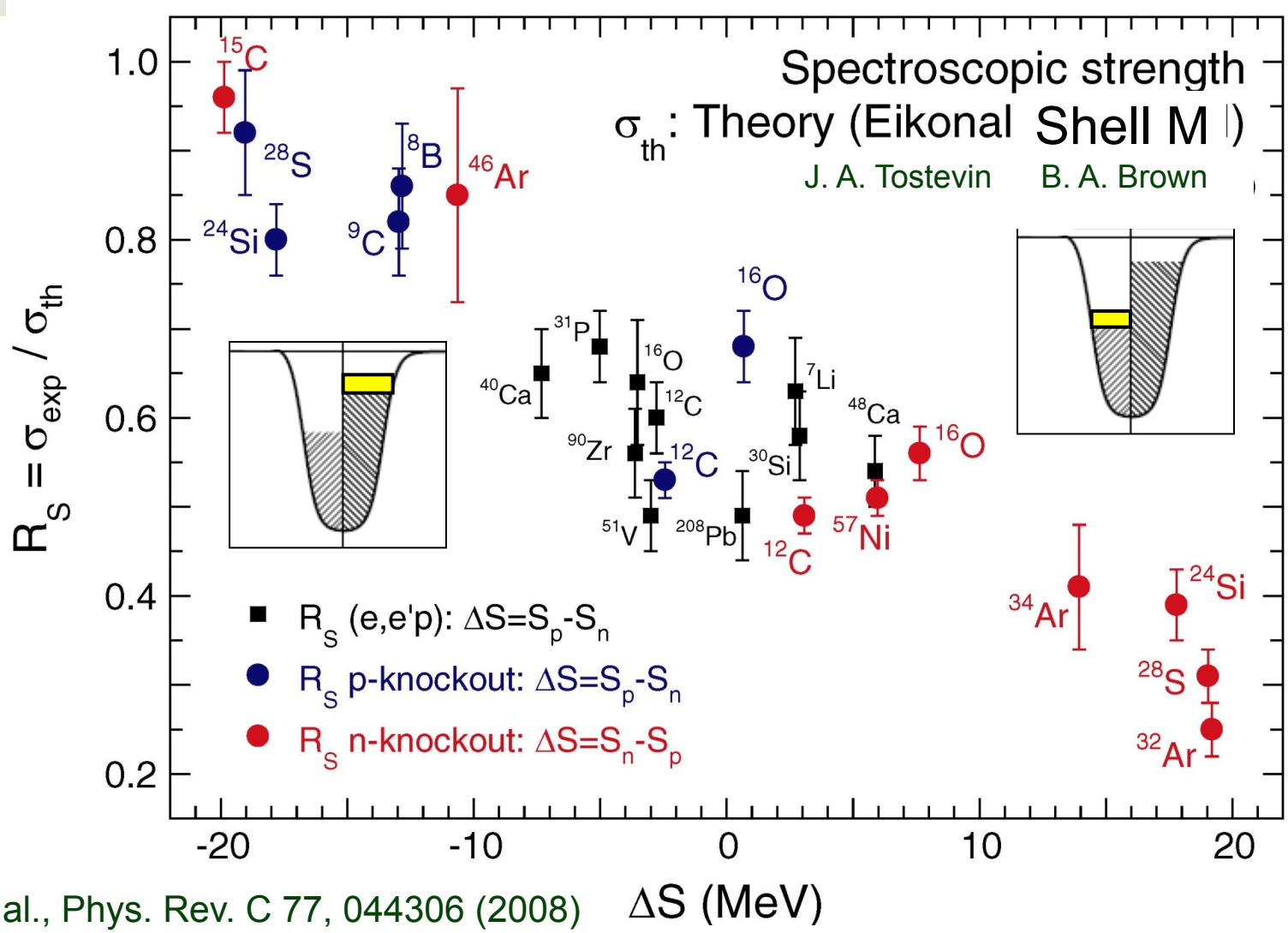
^{11}Li + C at 287 MeV/u



- Knockout shows s and p-wave contributions to the ^{11}Li ground state.
- Angular correlations between the removed neutron and ^{10}Li shows interference effects.

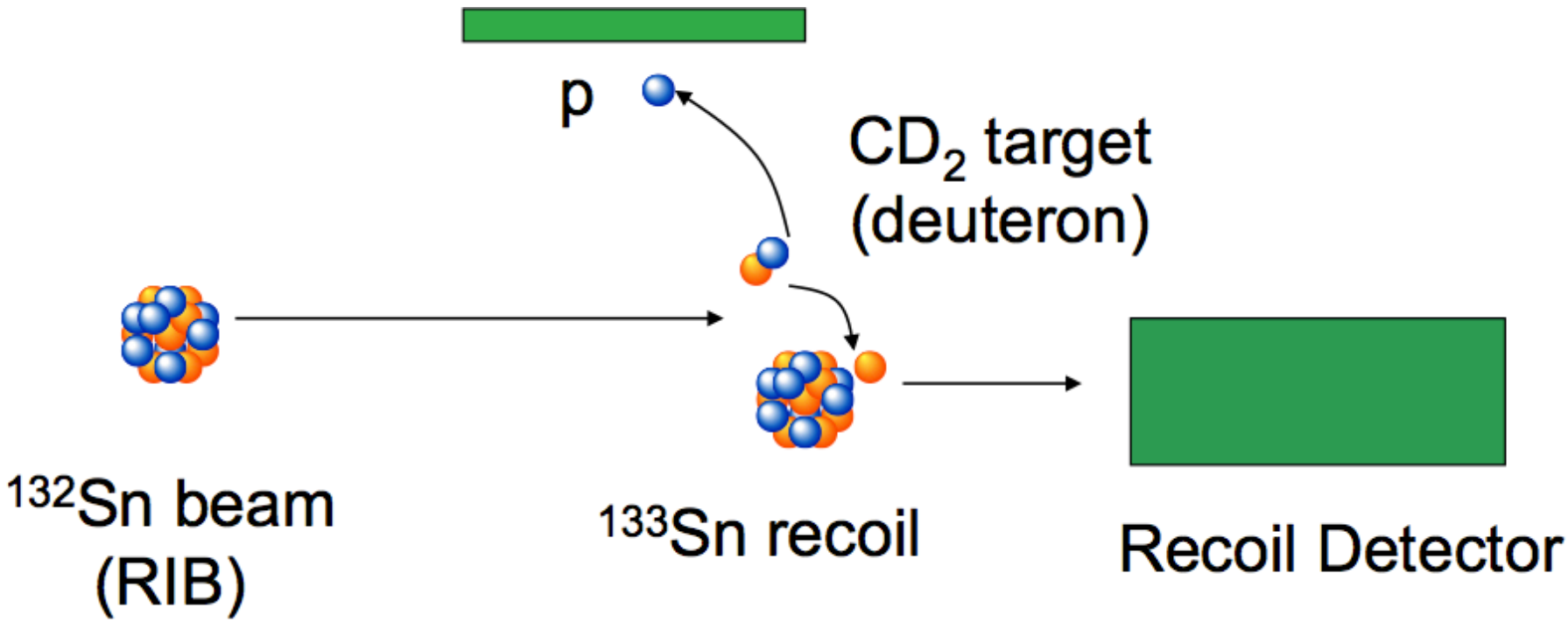


Occupation in rare isotopes – an open issue



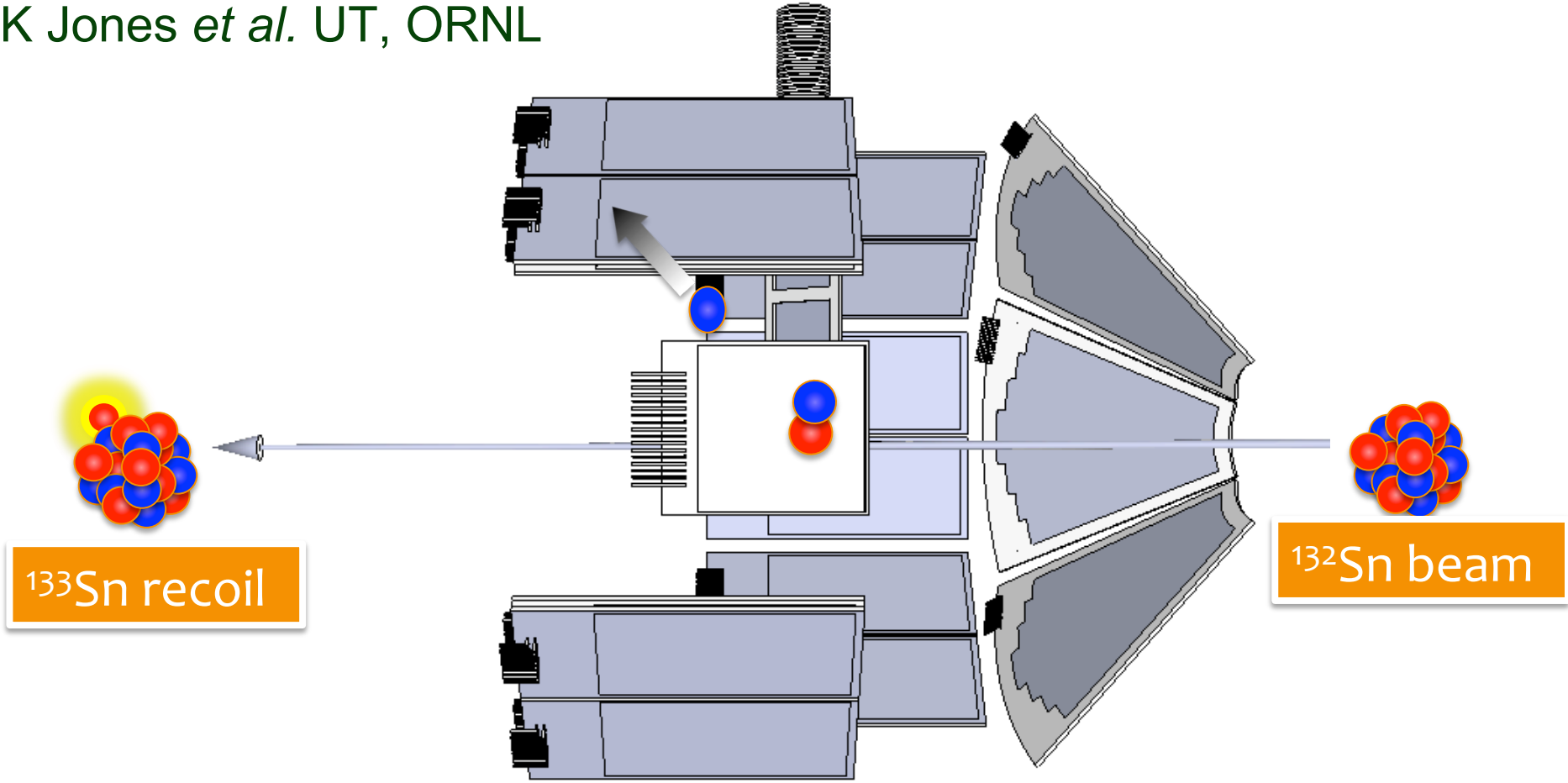
A. Gade et al., Phys. Rev. C 77, 044306 (2008)

Spectroscopic Factors from Transfer Reactions

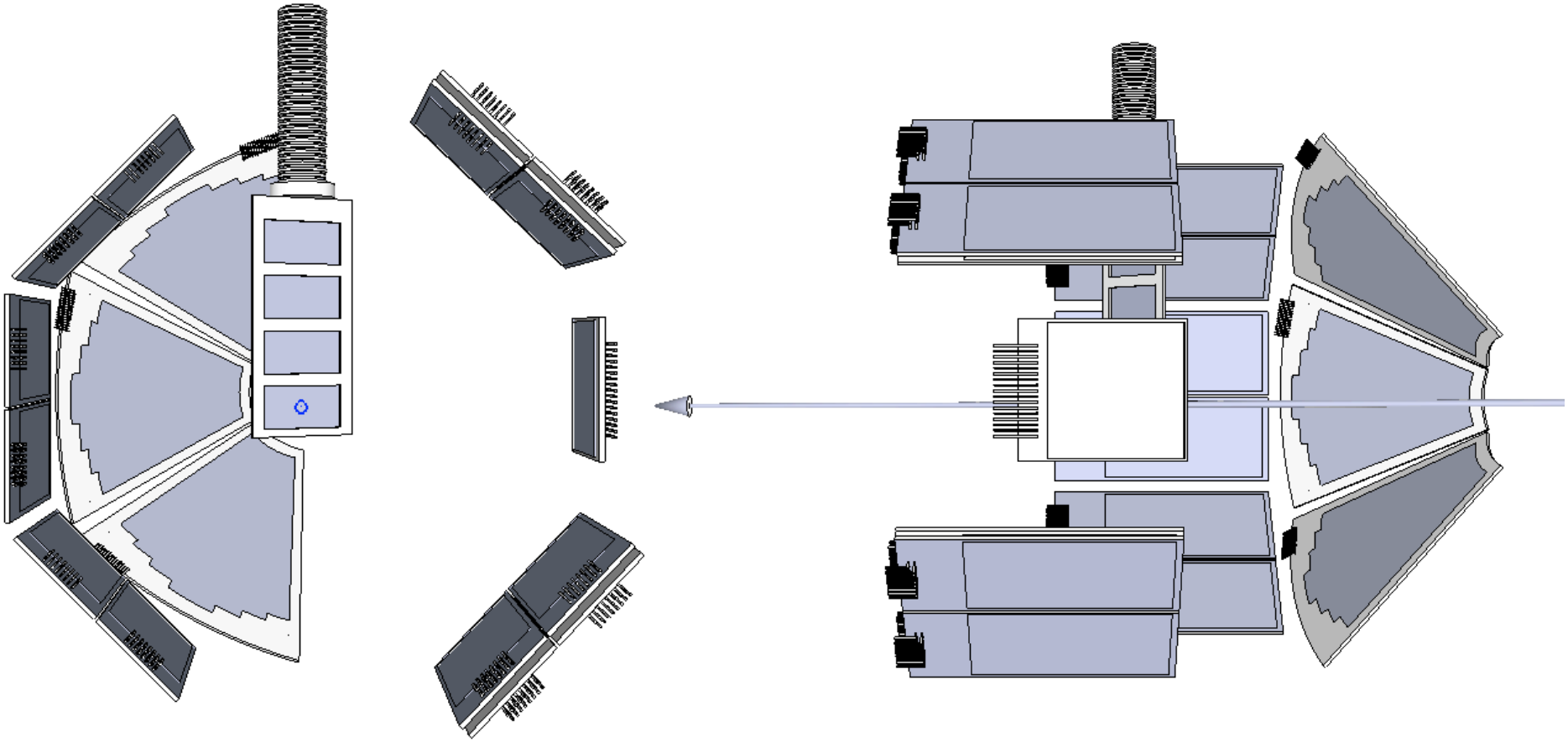


Example: ^{132}Sn(d,p) experiment

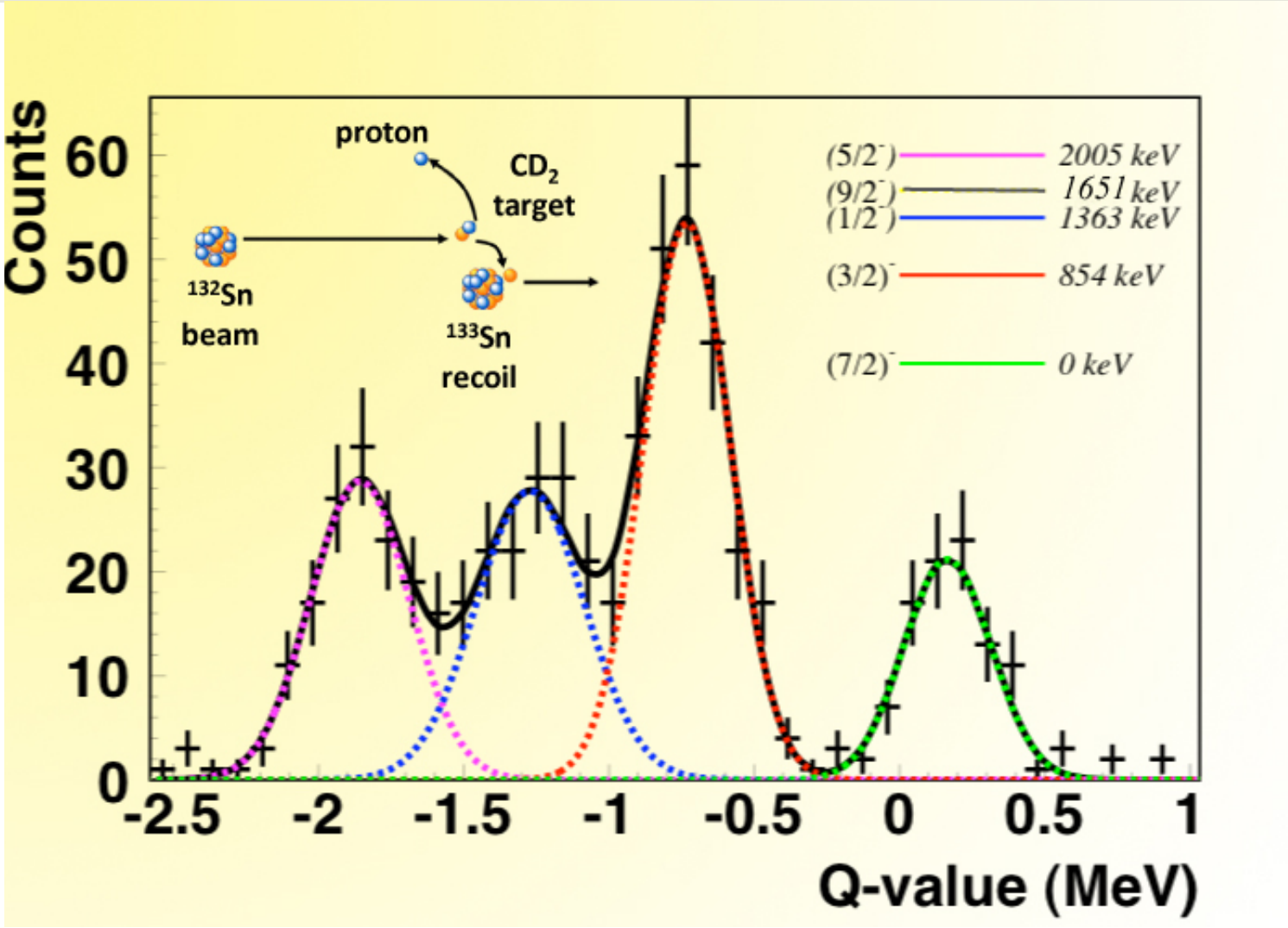
- Array of Si-strip detectors used to detect the scattered protons, p
- K Jones *et al.* UT, ORNL



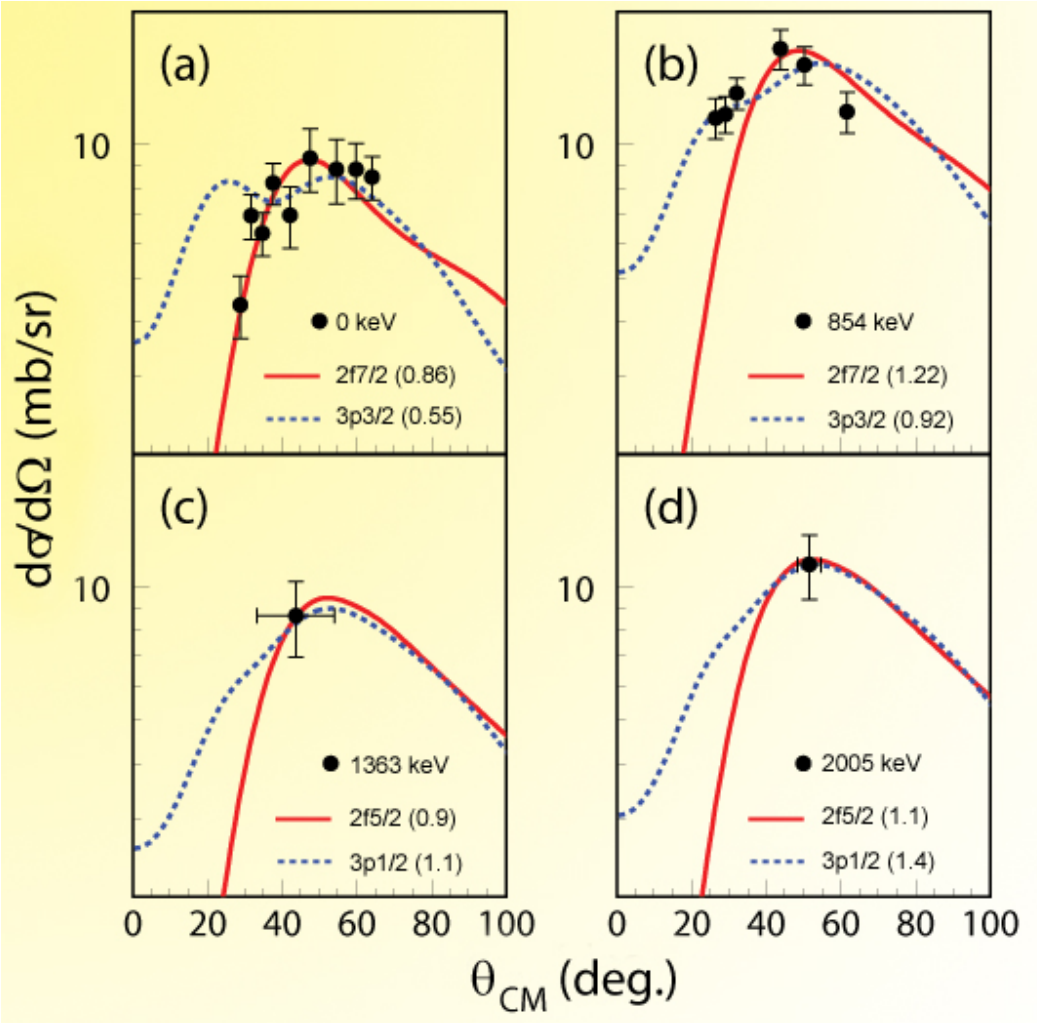
^{132}Sn(d,p)setup



^{133}Sn Q-value spectrum



^{133}Sn Angular Distributions

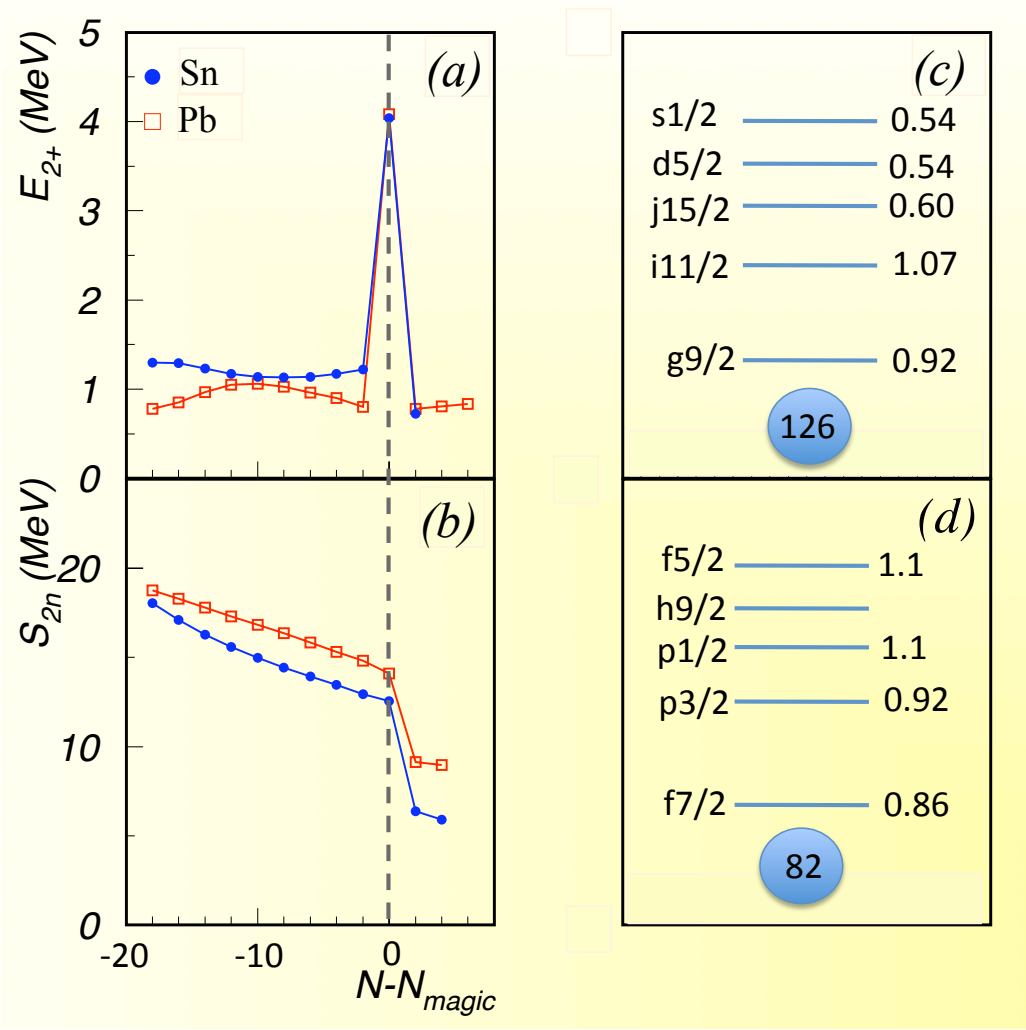


Theory from Filomena Nunes (NSCL)

Spectroscopic factors for ^{133}Sn from DWBA

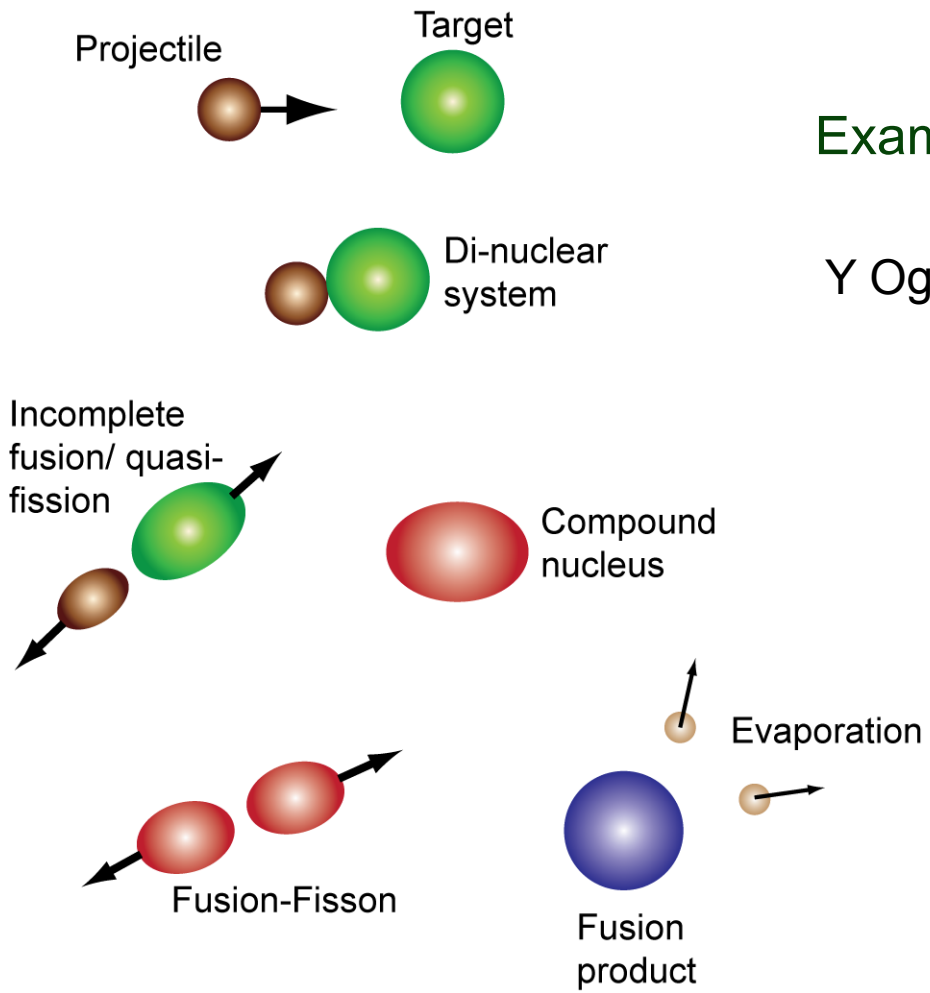
Ex (keV)	J^{π}	Configuration	SF	C^2 (fm^{-1})
0	$7/2^-$	$^{132}Sn_{gs} \otimes \nu_{f7/2}$	0.86 ± 0.16	0.64 ± 0.10
854	$3/2^-$	$^{132}Sn_{gs} \otimes \nu_{p3/2}$	0.92 ± 0.18	5.61 ± 0.86
1363±31	$(1/2)^-$	$^{132}Sn_{gs} \otimes \nu_{p1/2}$	1.1 ± 0.3	2.63 ± 0.43
2005	$(5/2)^-$	$^{132}Sn_{gs} \otimes \nu_{f5/2}$	1.1 ± 0.2	$(9 \pm 2)\times 10^{-4}$

Magicity of ^{132}Sn



K.L. Jones *et al.* Nature **465** 454 (2010)

Fusion-Evaporation



Example $^{48}Ca+^{237}Np$

Y Oganessian et al

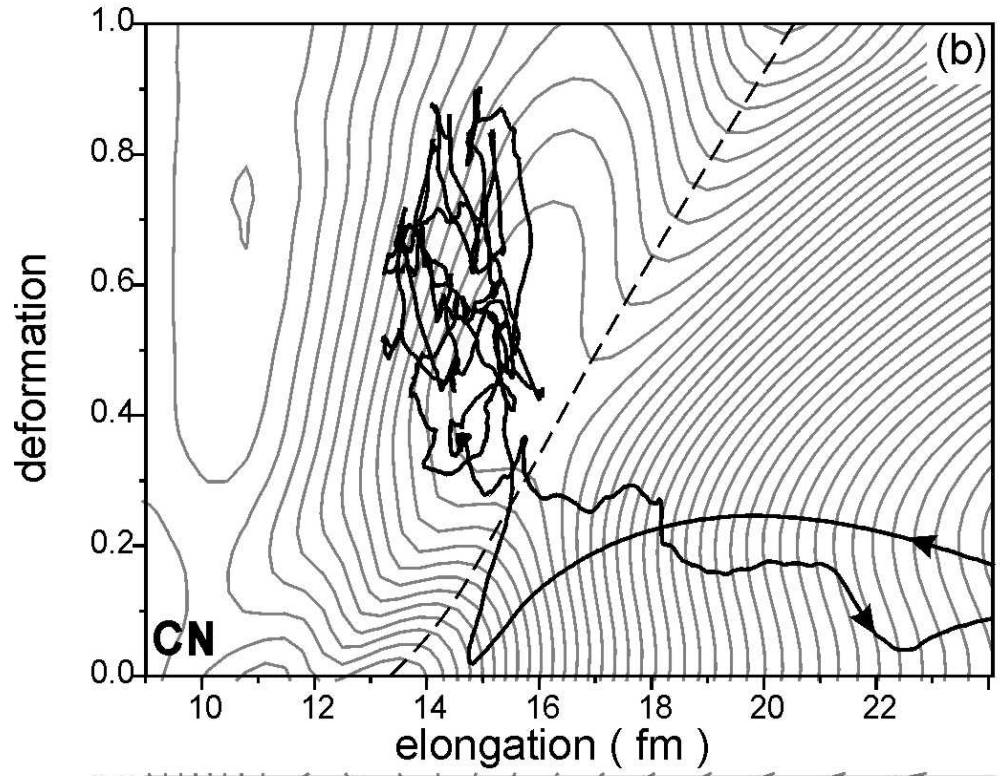
In new element searches fusion happens only 1 in 10^{18}

Calculation of Fusion-Evaporation

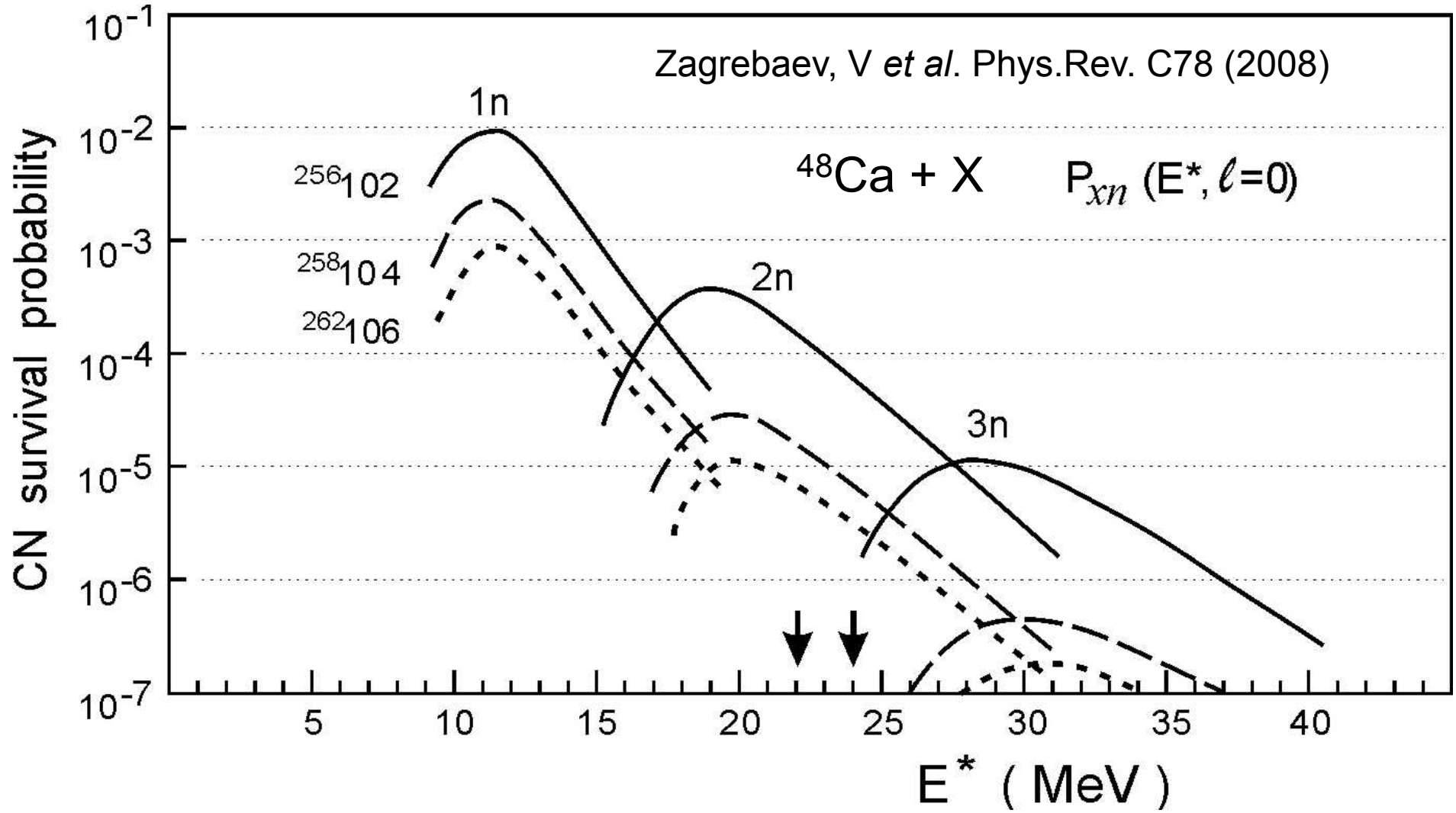
Zagrebaev, V *et al*. Phys.Rev. C78 (2008) 034610

$^{48}Ca + ^{248}Cm$ at $E_{c.m.}$=210~MeV

Potential energy surface calculated by the interactions of the nuclei as they approach.

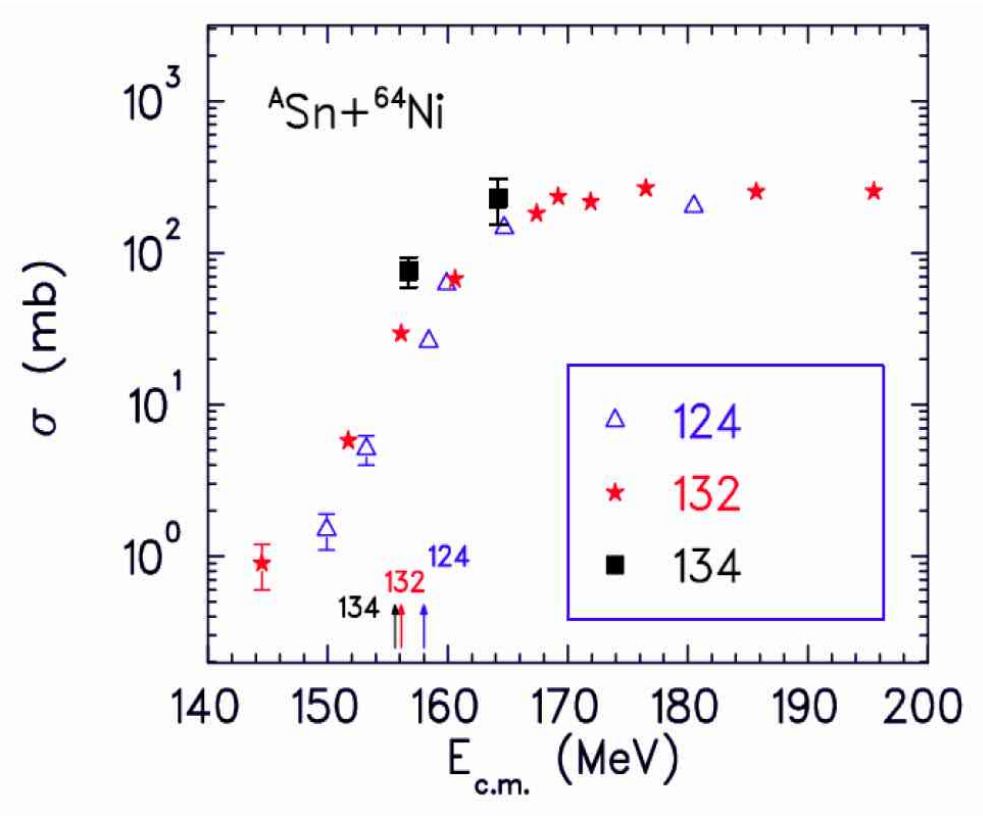


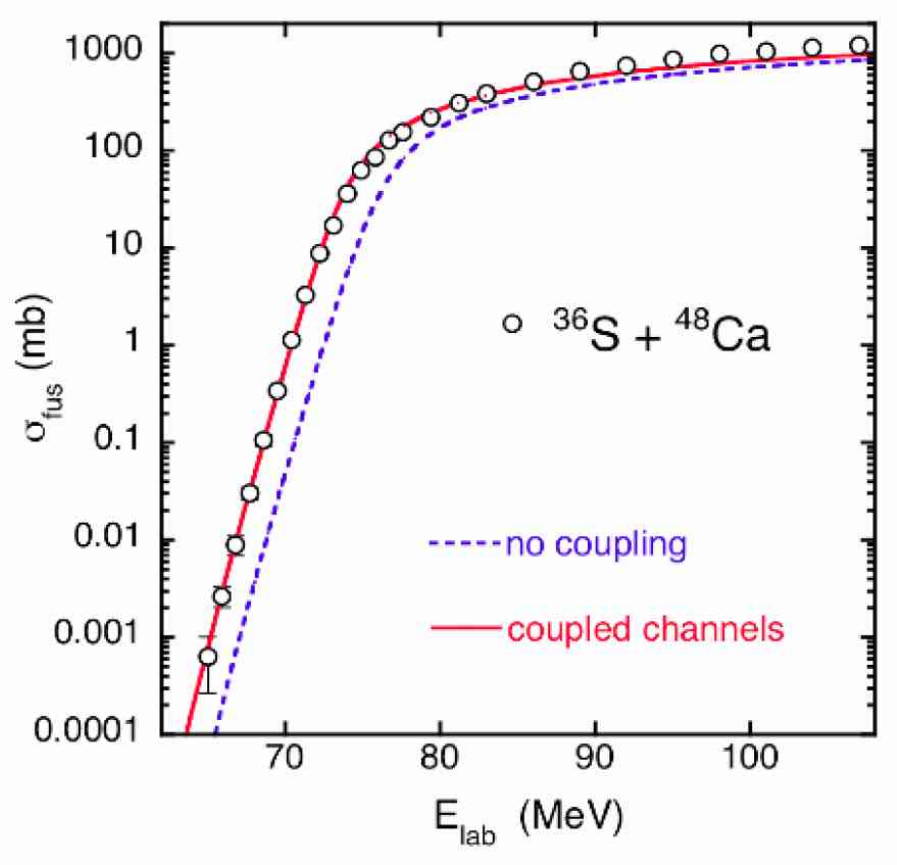
Fusion-Evaporation



Experimental Example

http://web2.infn.it/spes/index.php/what-is-spes/physics-case/50-physics-case





Open Questions

- What is the most accurate way to probe the nuclear wave function?
- How can we determine the neutron skin and halo in weakly bound isotopes?
- How can we understand nuclear fission?
- What reaction mechanism is the best to produce any given nuclide (nuclide is a given proton and neutron number)?
- What mechanism do we use to discover more elements and isotopes?

References

- Nuclear Reaction Theory - **Nuclear Reactions for Astrophysics: Principles, Calculation and Applications of Low-Energy Reactions**; Thompson and Nunes ISBN-10: **0521856353** | ISBN-13: **978-0521856355**
- Electron scattering and knockout - http://www.jlab.org/hugs/archive/Schedule2003/03_Ulmer.pdf
- Nuclear knockout - P.G. Hansen and J.A. Tostevin Ann Rev. Nucl Part Sci., 53 (2003) 219; http://www.nucleartheory.net/DTP_material/lectures/Balkan_School.pdf
- Transfer reactions - http://www.nscl.msu.edu/~zegers/ebss2011/thompson.pdf
- Nuclear fusion-evaporation reactions – Theory: R. Broda, J. Phys. G 32, R151 (2006); Experiment: G. D. Dracoulis et al. Phys. Rev. C 87, 014326 (2013)