From Resonances to Continuum Transfer Reactions with stable and "exotic" beams

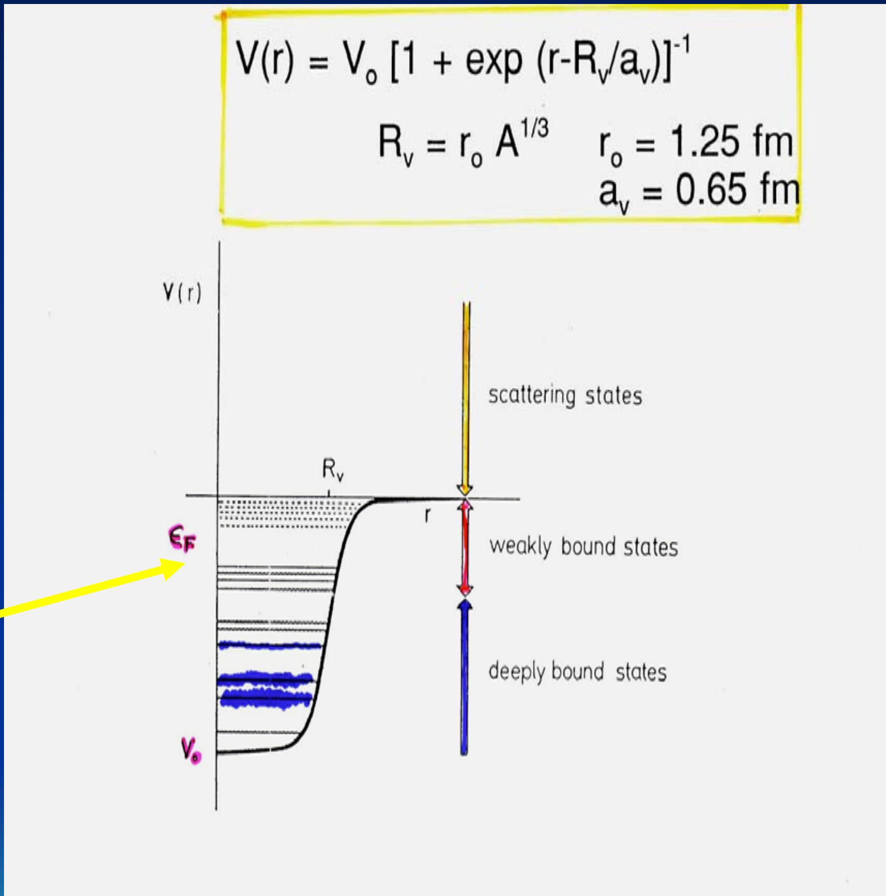
- I- Single-particle motion in nuclei
- Spectroscopic factors ,Sum-rules
- II- Experimental quest : One nucleon Transfer and e,e' p Knock out .
- III-Transfer to resonances in the continuum
- IV- Reactions with exotic beams
- V- Outlook

Nucleon-Nucleus mean field

°Mean field concept similar for bound (shell model) and scattering (optical model) states.

°°In real nuclei the mean field is non-local. V(r,r') velocity dependence Fluctuations of V give rise to collective modes . Coupling of s-p motion to Collective modes leads to V(r,r',E).

°°°Local equivalent



$V(r) = V_o\,[1 + \exp(r-R_v/a_v)]^{-1}$

$R_v = r_o\,A^{1/3}$ $r_o = 1.25$ fm

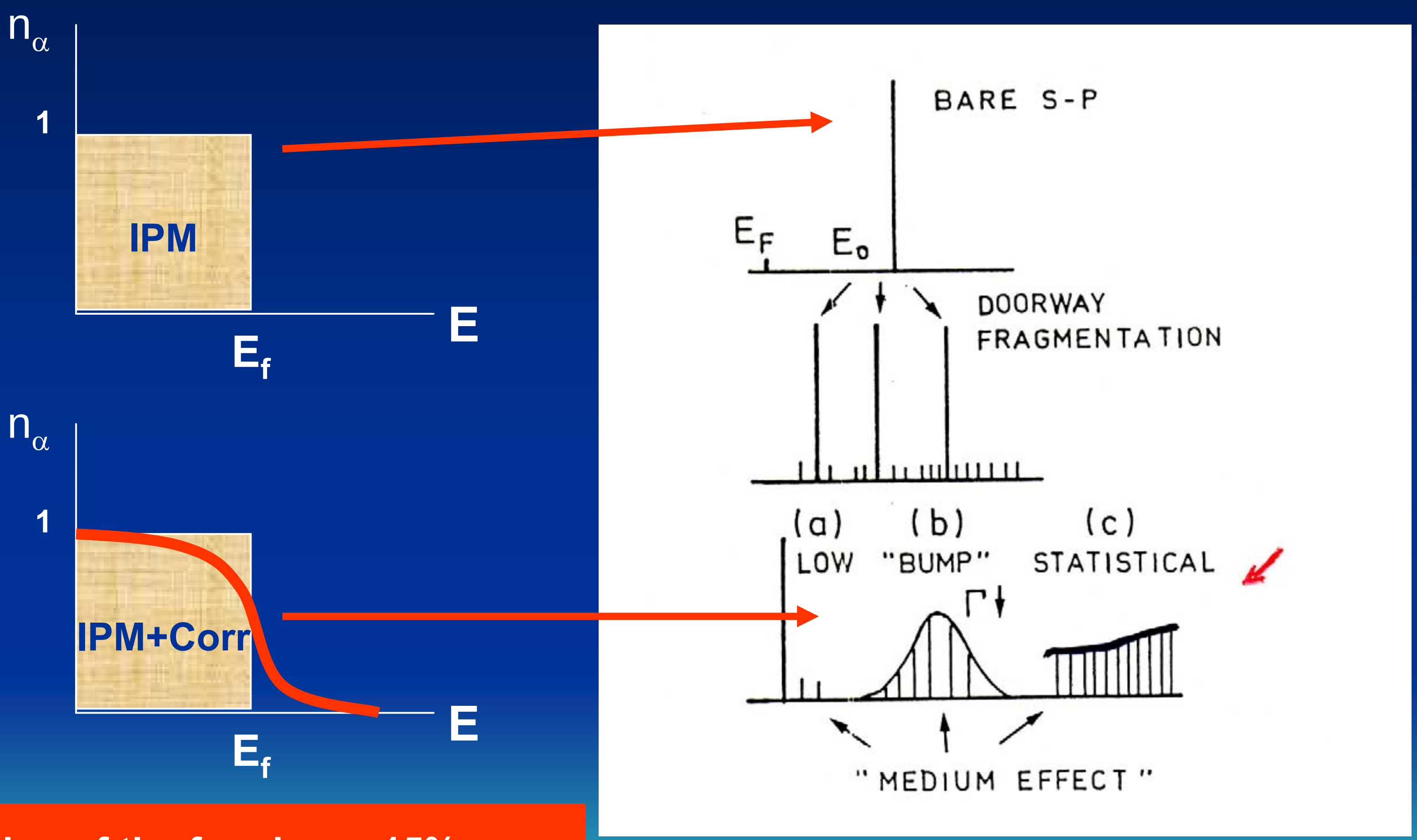
$a_v = 0.65$ fm

$$V(r,E)=V_{HF}\,(r,E)+\Delta V(r,E)$$

Dynamical content of IPM

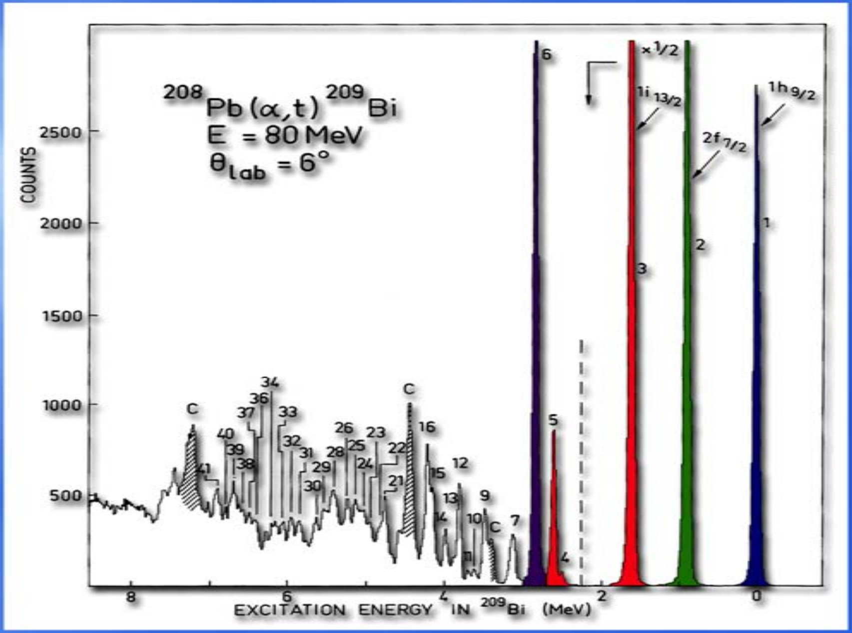
Potential depth A independent

Long Range Correlations Coupling to (1p-1h) ,…, (np-nh)

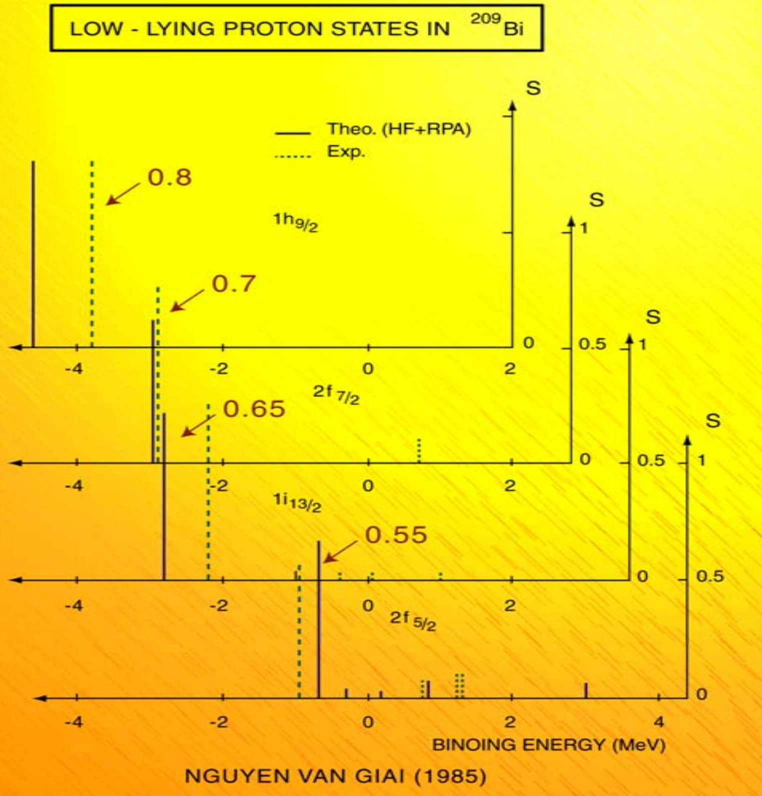


Depletion of the fermi sea 15%

Proton Stripping reaction
Single-particle states ^{208}Pb+1p



Proton S-P STATES ^{208}Pb+p



Above 2.5 MeV strong fragmentation of Single –particle strengths !!!

Spectroscopic Factors & sum-rule

Pick-up $S^{-}_{lj}(A,A-1)= /<\Phi_f(A-1)/a_{lj}\ /\Phi_0(A)>/^2$

Stripping $S^{+}_{lj}(A,A+1)= /<\Phi_f(A+1)/a^{+}_{lj}\ /\Phi_0(A)>/^2$

Sum-Rule

Sum of S^{lj} on all final sates f with lj quantum numbers give

$$\Sigma_f S_{lj} = < \Phi_0(A)/\ a^{+}a/\ \Phi_0(A)>= n_{lj}$$

number of nucleons lj in the ground state

Two obvious problems in deducing absolute values for this sum-rule

Sum of all final fragments limited in Energy short range correlations (up to high Ex)

Accuracy of reaction models
Cross-sections dependence on form factors ,
Optical parameters

Reaction model for one-nucleon transfer

- DWBA A+a → B+b b=a+/-1n one-step
- **$T_{BA}=\iint dr_{aA}\, dr_{bB}\, X_{b}^{-*}(k_b,r_{bB})\, F(r_{aA}, r_{bB})\, X_{a}^{+}(k_a,r_{aA})$**

OM elas channels

- EFR-DWBA

$$d\sigma/d\omega_{EXP}(\theta) = C^2S^{lj}.\ K.\ [T_{BA}]^2 = C^2S\ d\sigma/d\omega_{EFR\text{-}DW}(\theta)$$

. F contains

1) the V_{nb} interaction between the ejectile b and the transferred nucleon n (from n-n or n-b phase shifts at low energies)

Zero Range $V_{nb} = D_o\, \delta(r_{bn})\delta_{l0}$

2) the form factor $f_{lj}(r)$. Calculated in WS potential ,to reproduce correct binding (SE, energy dependence) . $d\sigma/d\omega_{DW}(\theta)$ displays strong dependence on the radius

Assymetry Measurements with polarized p and d beams

- Established 1975-1980 for single-nucleon transfe ,(p,d) ,(d,p) ,(d,t),(d,^{3}He)

Proton P=60-90%

$Ay(\theta) = N^+ - N^- / N^+ + N^-$

Deuton P_y =40-80% **$iT_{11}(\theta) = 1/$□$3.P_y.\ N^+ - N^- / N^+ + N^-$**

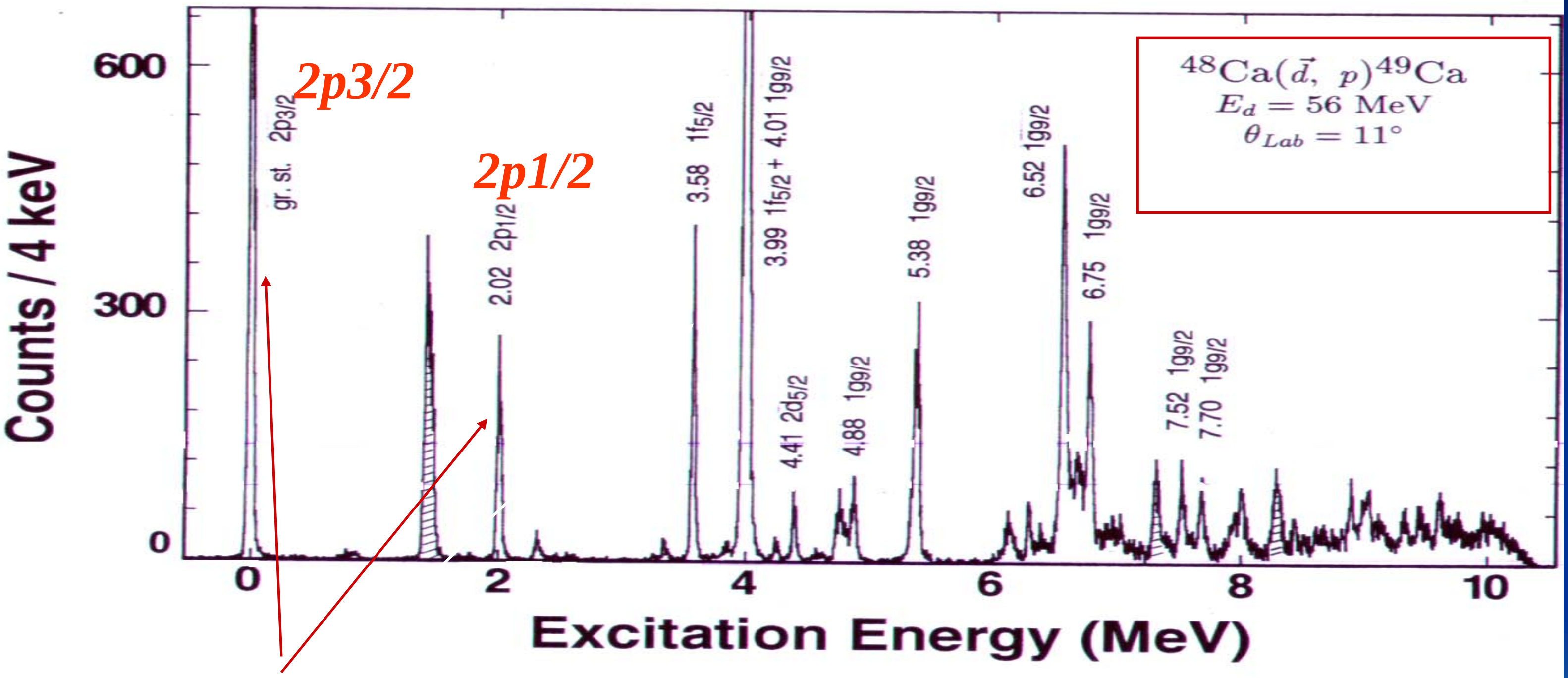
$\sigma(\theta)$ gives l =j+-1/2 for spin 0 target

$Ay(\theta)$# between l+1/2 and l-1/2

Therefore Ay perfect observable for spin-orbit partners

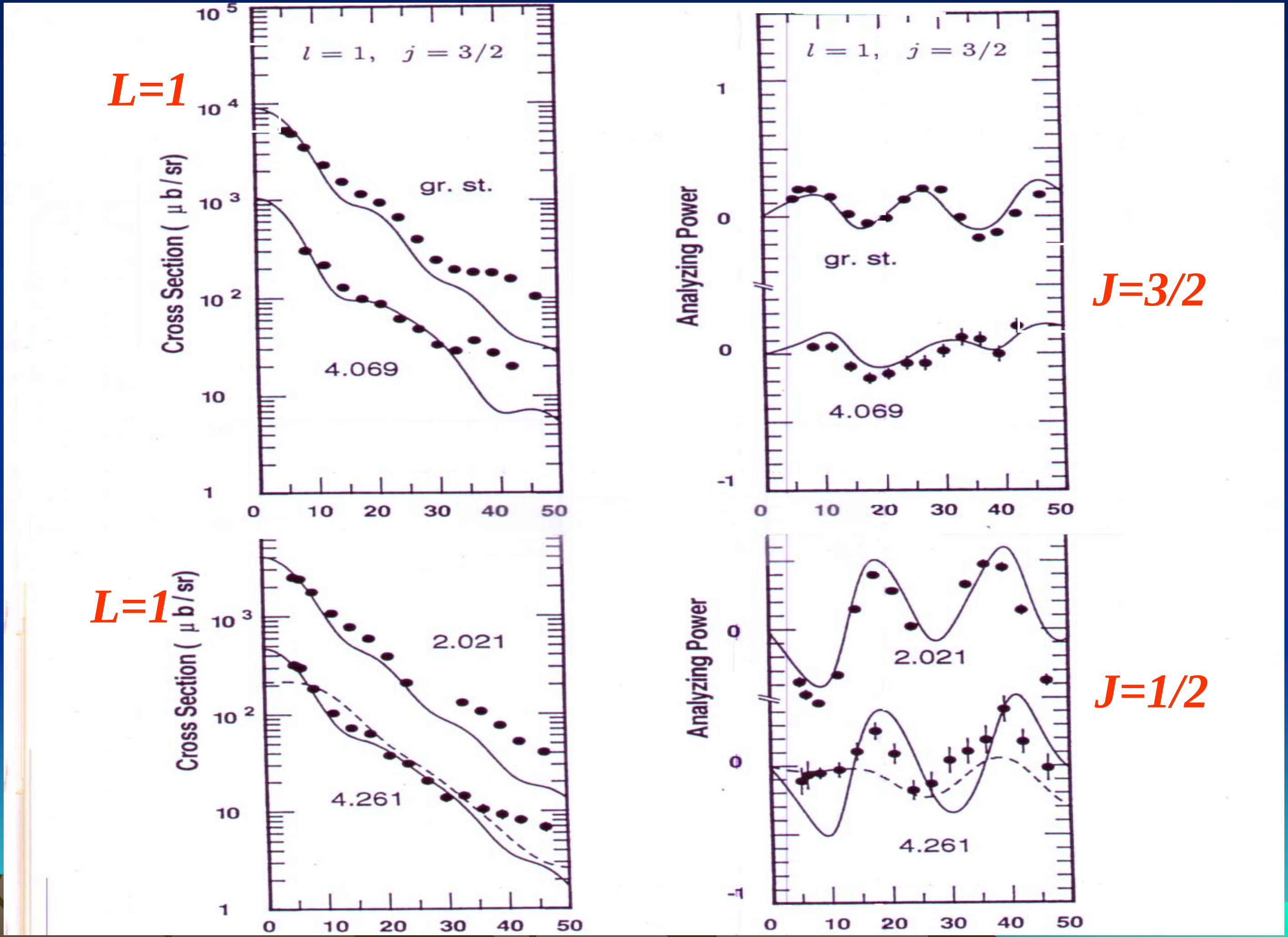
Bound states and polarized beams in transfer

State of the art **:OSAKA 1993**



P=80%
30KeV

Examples : Angular distributions and asymmetries $2p3/2$,$2p1/2$ in ^{49}Ca



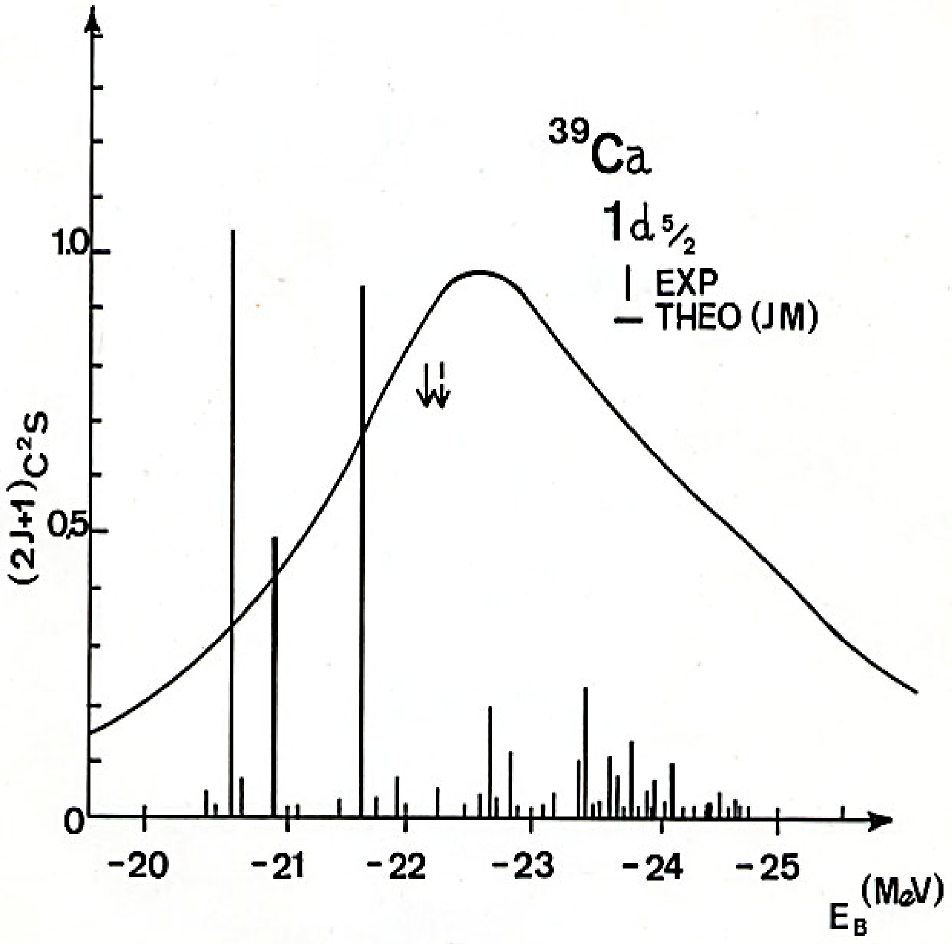
L=1

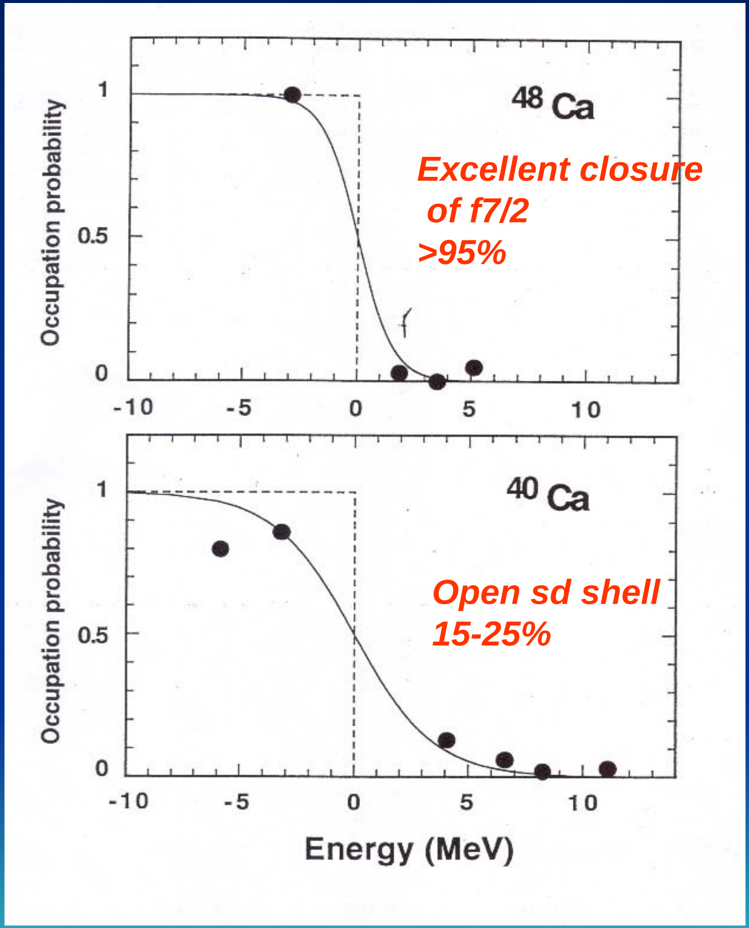
J=3/2

L=1

J=1/2

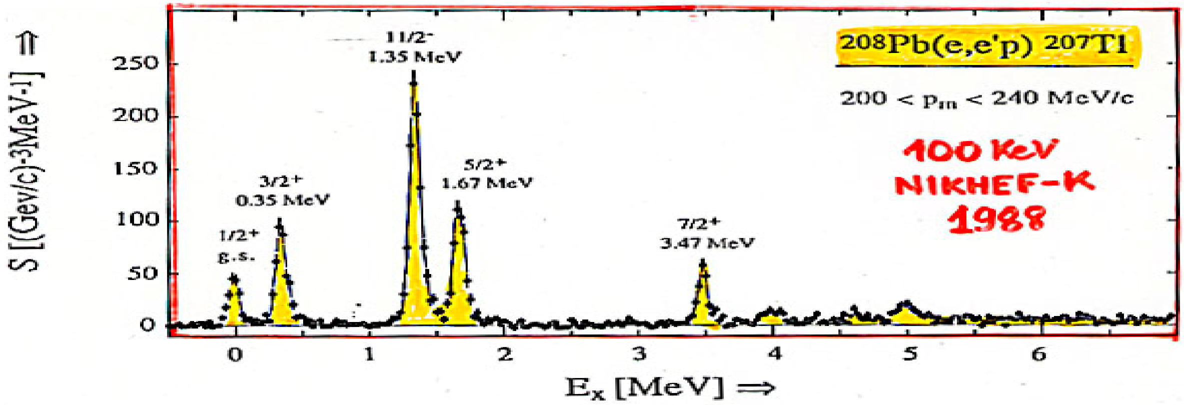
From stripping and pick-up :occupation numbers and shell closure





Excellent closure of f7/2 >95%

Open sd shell 15-25%



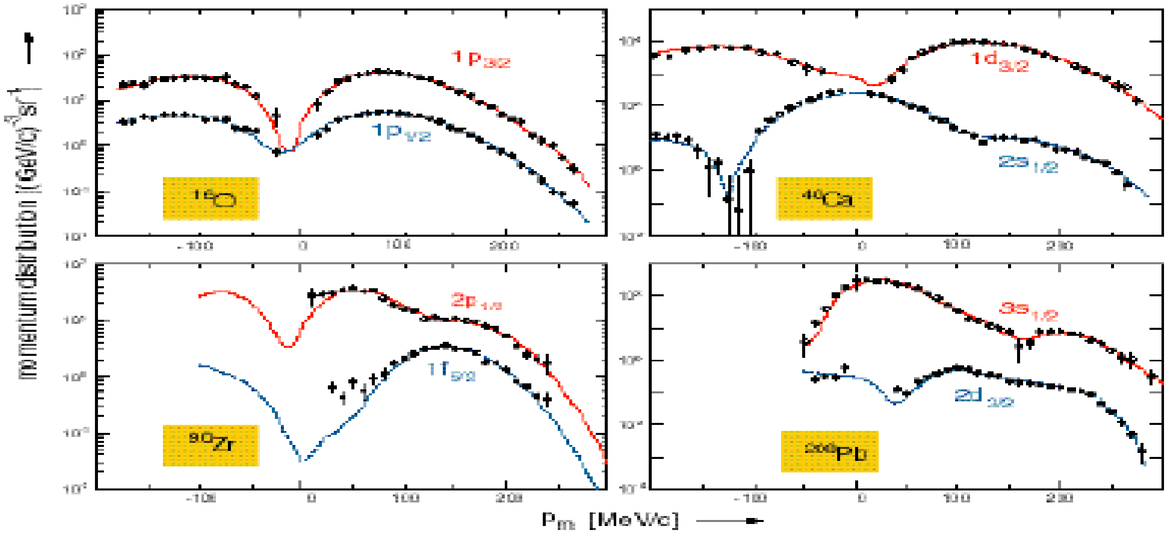
(e,e',p)
State of the art

Introduction
Some early (e,e'p) results

Spectroscopic strength with the reaction (e,e'p)

- seventies : pioneering experiments Frascati, Tokyo, Saclay
- eighties : high res. NIKHEF (e,e'p) program for nuclei A=2-209
  - spectral function at low (E_m, p_m)
  - Momentum distributions of valence orbits
- nineties –present : NIKHEF/Mainz/Bates also 2N knockout
- present : JLAB towards higher Q^2, larger p_m , E_m

NIKHEF RESULTS

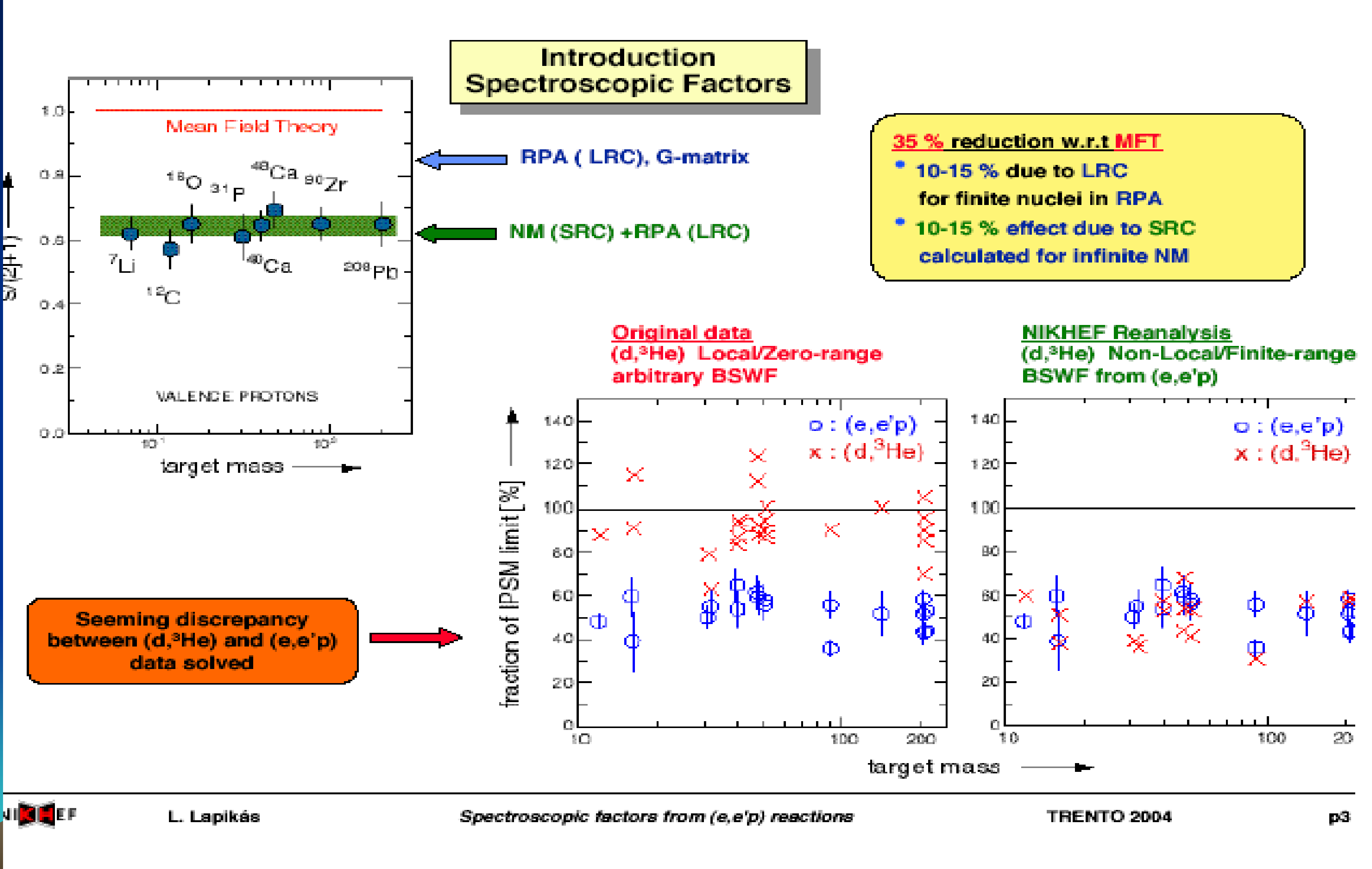


Results for valence orbits in closed-shell nuclei:

Curves scaled by about 0.65 wrt. mean field theory !!

Explanation : Effect of long-range and short-range correlations

LRC and SRC



Introduction Spectroscopic Factors

RPA (LRC), G-matrix

NM (SRC) +RPA (LRC)

35 % reduction w.r.t MFT

- 10-15 % due to LRC for finite nuclei in RPA
- 10-15 % effect due to SRC calculated for infinite NM

Original data
(d,³He) Local/Zero-range
arbitrary BSWF

NIKHEF Reanalysis
(d,³He) Non-Local/Finite-range
BSWF from (e,e'p)

Seeming discrepancy between (d,³He) and (e,e'p) data solved

NIKHEF L. Lapikás *Spectroscopic factors from (e,e'p) reactions* TRENTO 2004 p3

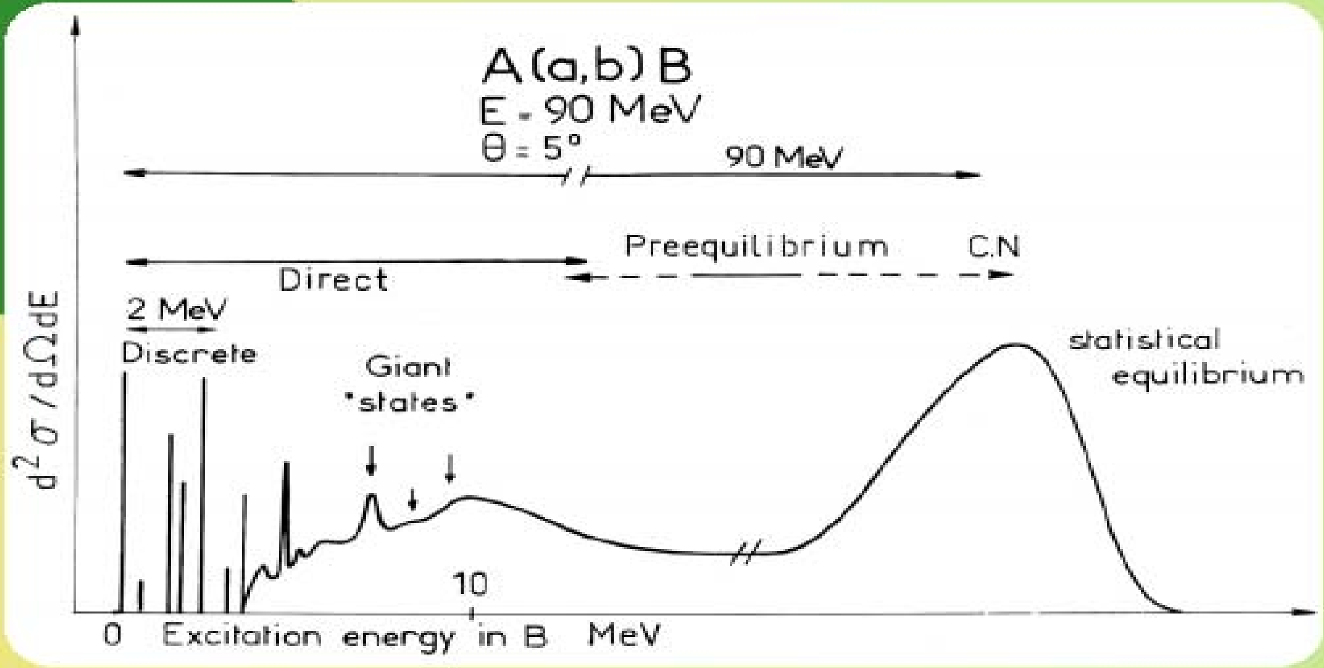
Persistence of s-p motion at high excitation energy ?

Transfer to the continuum

Inclusive single -particle spectra

Strength functions for resonance in the continuum

Exclusive experiments and decay properties.



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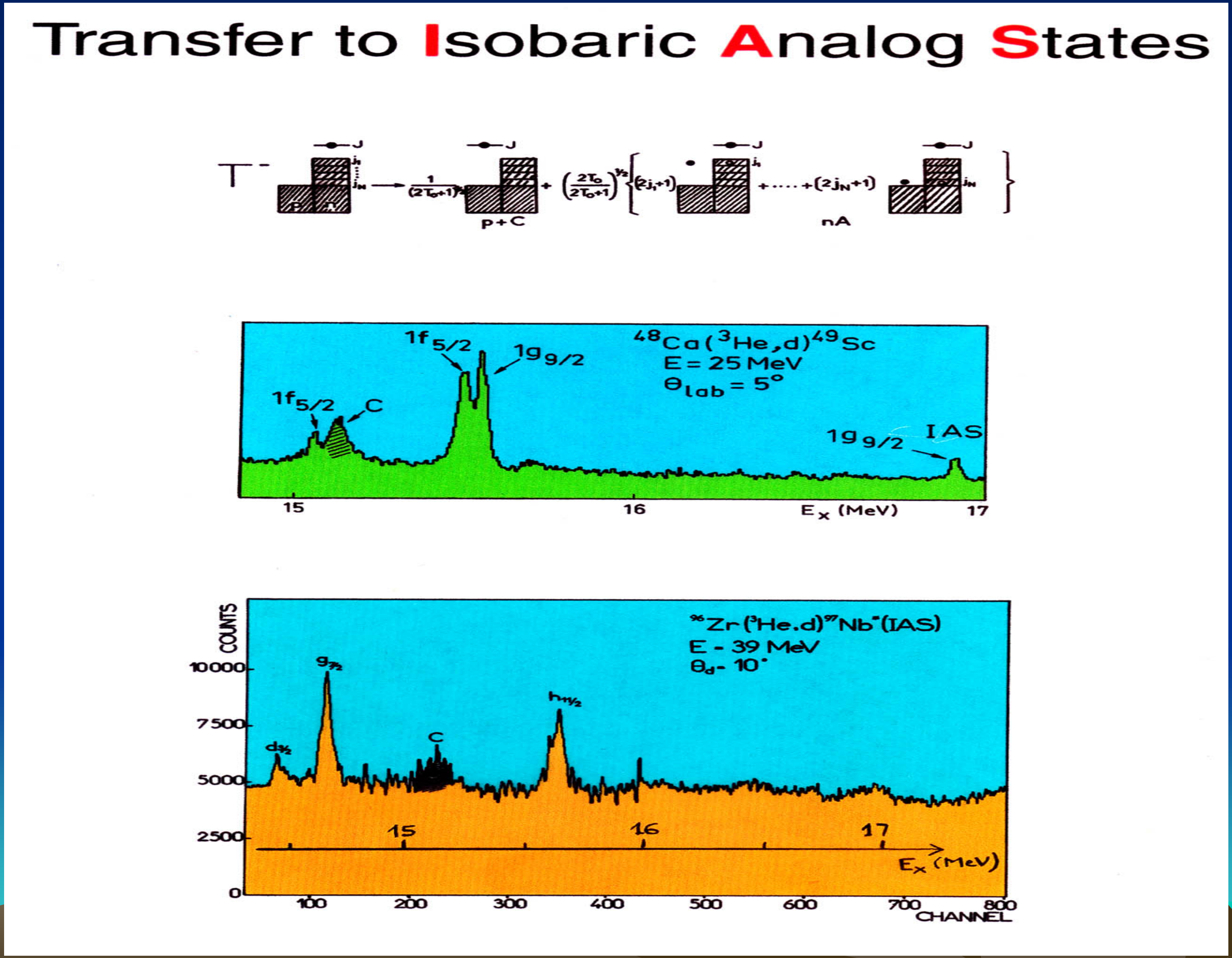
Persistence of s-p motion at high excitation energy ?

Single –Particle strenghts from IAS

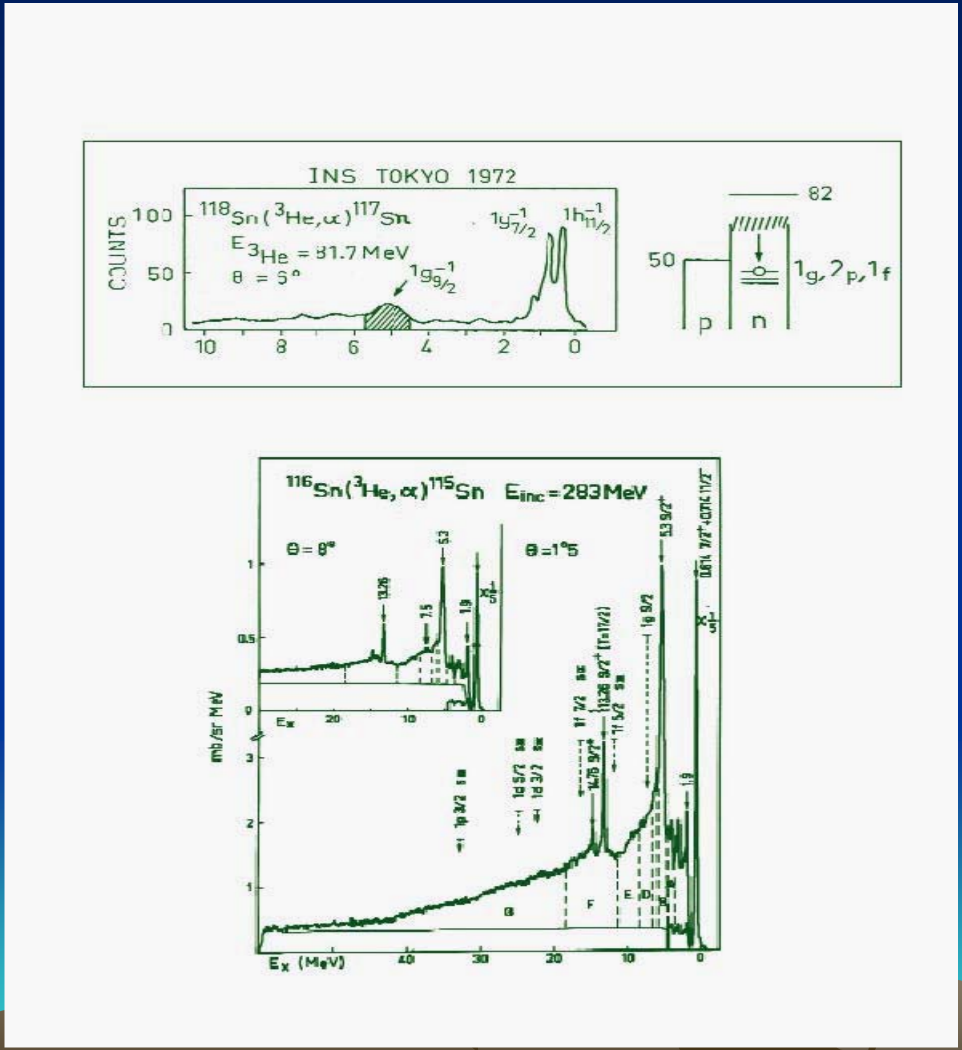


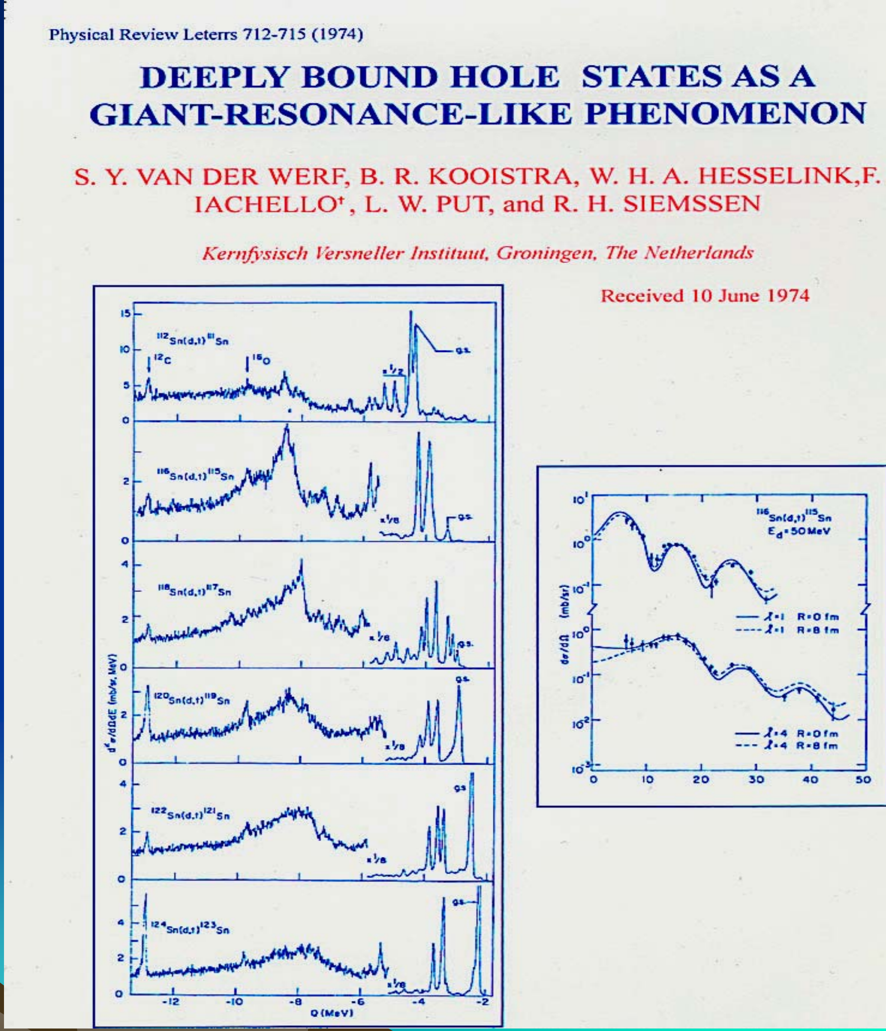
Transfer to **I**sobaric **A**nalog **S**tates

S. Gales et al

1976

Persistence of s-p motion at high excitation energy ? First evidence of deeply-bound hole states in heavy nuclei





Physical Review Leterrs 712-715 (1974)

DEEPLY BOUND HOLE STATES AS A GIANT-RESONANCE-LIKE PHENOMENON

S. Y. VAN DER WERF, B. R. KOOISTRA, W. H. A. HESSELINK,F. IACHELLO†, L. W. PUT, and R. H. SIEMSSEN

Kernfysisch Versneller Instituut, Groningen, The Netherlands

Received 10 June 1974

Selectivity for large L transfer (5-8)

TRANSFER CHANNELS

HIGH-LYING S-P NEUTRON STATES

outer subshells

$1j_{13/2}$

$1k_{17/2}$

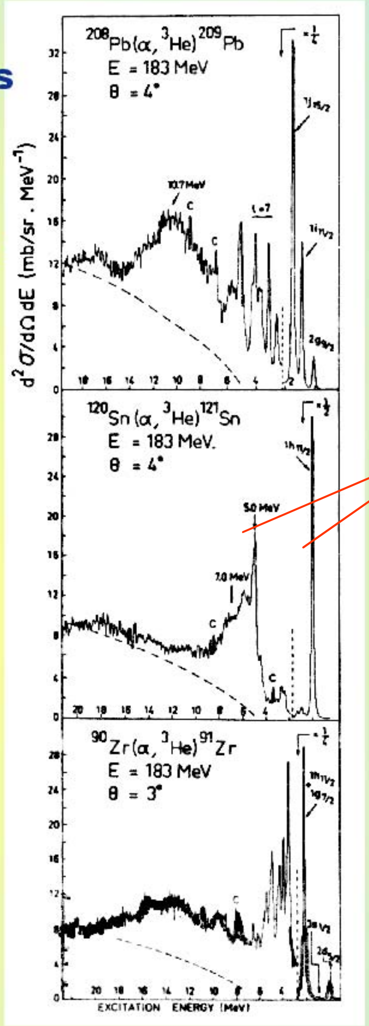
$1l_{19/2}$

$1i_{13/2}$

$1h_{9/2}$

$1i_{13/2}$

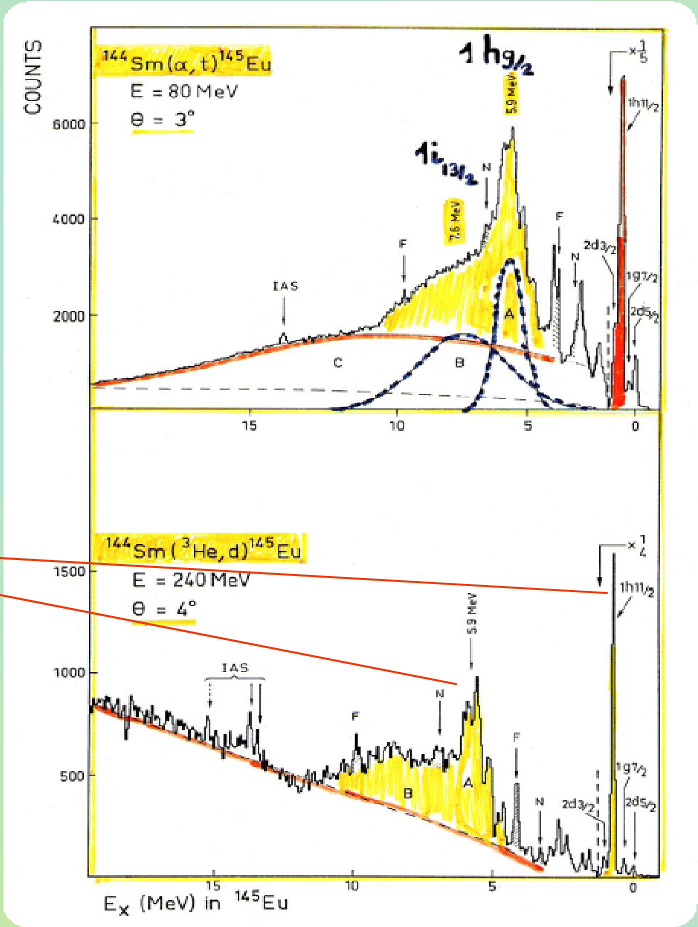
$1h_{9/2}$



(α, ^{3}He)
at 183 MeV
ORSAY K220 SC
(1984)

Direct observation of Spin-orbit partners

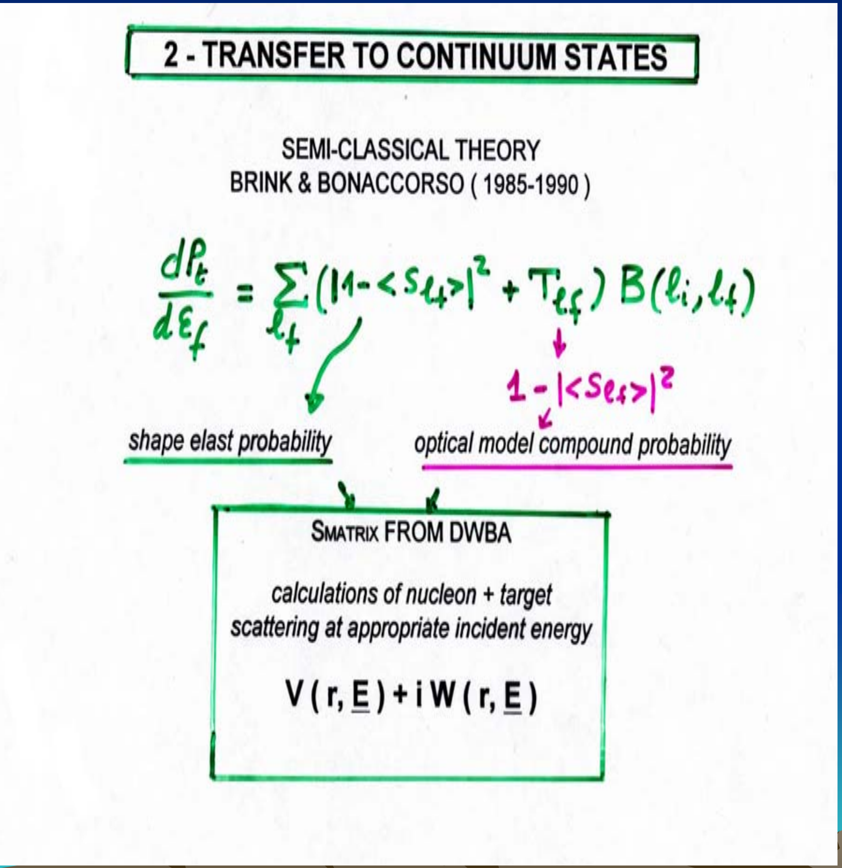
EXPERIMENTAL EVIDENCE OF S-P PROTON RESONANCES



The shape of fhe continuum is strongly dependant on the projectile

Break-up phase space (α, tp) or (^{3}He, dp)

III Beyond bound states :transfer to resonances in the continuum



2 - TRANSFER TO CONTINUUM STATES

SEMI-CLASSICAL THEORY
BRINK & BONACCORSO (1985-1990)

$$\frac{dP_t}{d\varepsilon_f} = \sum_{l_f} \left(|1-\langle S_{l_f}\rangle|^2 + T_{l_f} \right) B(l_i,l_f)$$

$$1-|\langle S_{l_f}\rangle|^2$$

shape elast probability

optical model compound probability

SMATRIX FROM DWBA

calculations of nucleon + target
scattering at appropriate incident energy

$V(r,\underline{E}) + i\,W(r,\underline{E})$

PHYSICAL REVIEW C VOLUME 38, NUMBER 4 OCTOBER 1988

Nucleon transfer to continuum states

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D. M. Brink
Department of Theoretical Physics, University of Oxford, Oxford OX1 3NP, United Kingdom

(Received 28 March 1988)

A semiclassical model is presented for the calculation of energy spectra of one nucleon transfer reactions to continuum states. Both isolated and overlapping resonances can be discussed. The theory is applied to medium energy heavy-ion reactions and the calculated spectra show general trends in agreement with the experimental data

I. INTRODUCTION

In this paper we present a formalism for studying single nucleon transfer reactions between heavy ions when the final state of the transfered nucleon is in the continuum. It is a natural extension of the formalism developed in$^{1-5}$ for nucleon transfer between bound states.

Nuclear reactions at incident energies well above the Coulomb barrier can lead to highly excited residual nuclei and in the case of a transfer reaction the transferred nucleon can have a continuous energy spectrum. Many approaches to the problem of calculating the cross section for such a reaction have been developed.$^{6-12}$ They are all based on extensions of the distorted-wave Born approximation (DWBA) theory to the case of an unbound final state. The work of Huby *et al.*^{9,10} is similar to ours since in both theories the final state for the unbound nucleon is represented by a scattering state with an appropriate normalization. Other approaches$^{6-8}$ are based on statistical compound nucleus theories. They require quite lengthy numerical calculations and do not determine the absolute normalization. McVoy and Nemes^{13} proposed a simple model based on the plane wave Born approximation to calculate both transfer to continuum and breakup. However, they obtained only very qualitative results.

A formula for the probability of transfer of a single neutron from an initial bound state to a final unbound state is obtained in Sec. II of this paper and the case of an isolated resonance is considered in Sec. III. In both the present approach and the one of Huby *et al.* it is found that the transfer probability is proportional to $|\sin\delta_f|^2$ where δ_f is the phase shift of the scattering wave function of the transferred nucleon by the final nucleus. The analysis in Secs. II and III is made for the case where the final state of the transferred nucleon is represented by a single-particle wave function but it can be generalized to more complicated situations. We discuss this generalization in Sec. IV of this paper and find that the transfer probability is proportional to $|1-S_{l_f}|^2$ where S_{l_f} is the elastic part of the scattering matrix for scattering of the transferred neutron by the final nucleus. If we take the energy average of this result the transfer cross section can be expressed in terms of the neutron optical-model S matrix. Some numerical results are presented in Sec. V.

II. TRANSFER TO CONTINUUM STATES

We begin the derivation from a formula for the transfer amplitude given in Ref. 4. The neutron makes a transition from a single-particle state ψ_1 with orbital angular momentum l_1,m_1 and energy ε_1 in the first nucleus to a state ψ_2 with angular momentum l_2,m_2 and energy ε_2 in the final nucleus. The two nuclei pass each other on classical orbits and the transfer amplitude is written as a surface integral over a surface Σ between the two nuclei. The relative velocity of the centers of the two nuclei at the point of closest approach is v and the z axis is chosen parallel to v. The surface Σ is parallel to the z-y plane. At the point of closest approach the center of the first nucleus is at a distance d_1 from Σ and the distance of the center of the second nucleus is d_2. The distance of closest approach between the two centers is $R=d_1+d_2$.

There are many equivalent ways of writing an approximate formula for the transfer amplitude. We start from Eq. (3.4) of Ref. 4

$$A_\lambda = \frac{i\hbar}{2\pi m v}\int_{-\infty}^{+\infty} dk_y\,(\eta^2+k_y^2)^{1/2} \times \tilde\psi_2^*(d_2,k_y,k_2)\,\tilde\psi_1(d_1,k_y,k_1)\ . \quad (2.1)$$

Here $\tilde\psi_\alpha(d_\alpha,k_y,k_z)$ is the double Fourier transform of the coordinate space wave function $\psi_1(\psi_2)$ of the initial (final) nucleon bound-state wave function

$$\tilde\psi(x,k_y,k_z) = \int\int dy\,dz\,e^{-i(k_y y+k_z z)}\psi(x,y,z)\ . \quad (2.2)$$

The quantity η in Eq. (2.1) is defined by

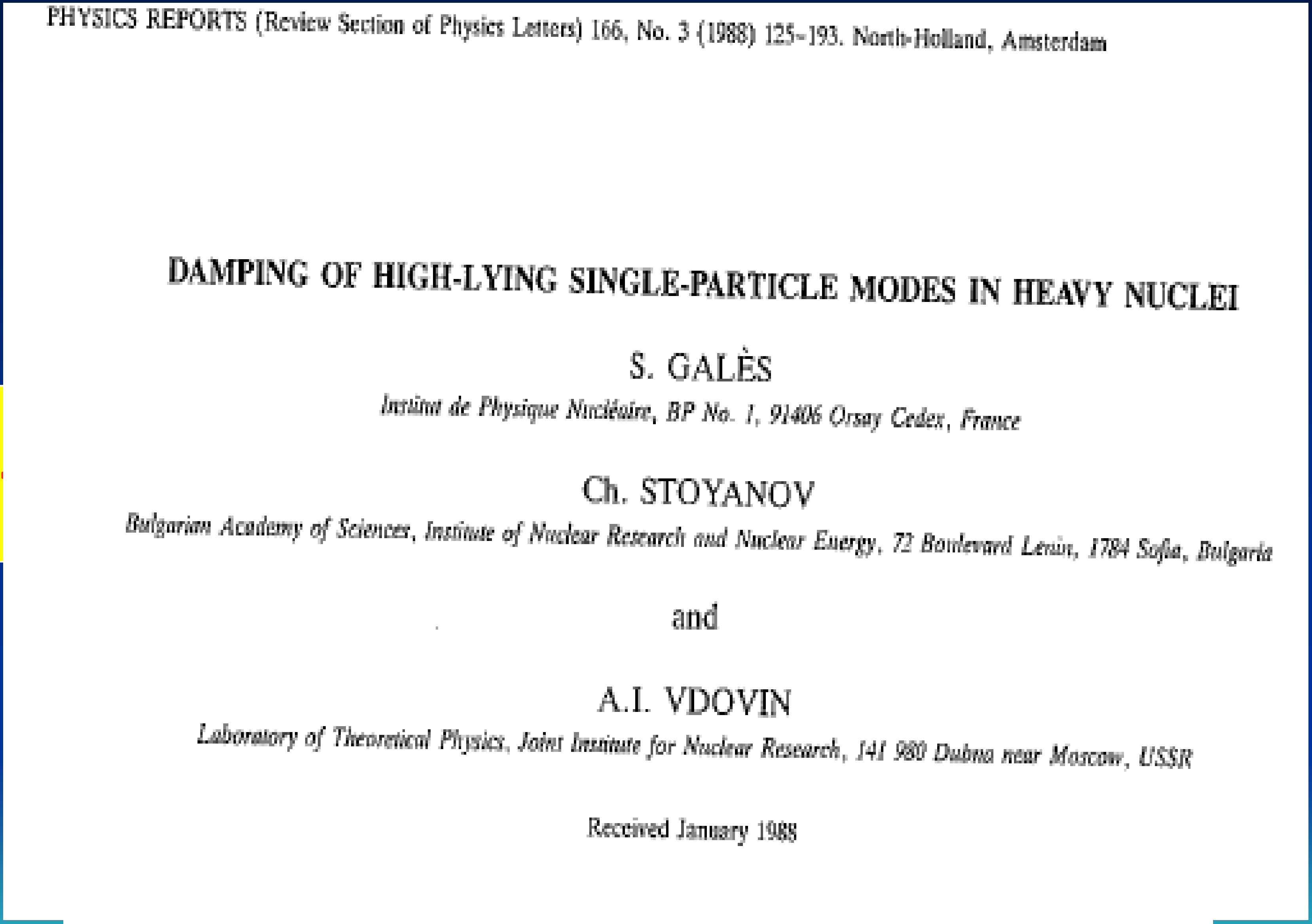
$$\eta^2 = k_1^2+\gamma_1^2 = k_2^2+\gamma_2^2\ , \quad (2.3)$$

where

$$\gamma_\alpha^2 = -\frac{2m\varepsilon_\alpha}{\hbar^2} \quad \text{for } \alpha=1,2 \quad (2.4)$$

and $\hbar k_1$ and $\hbar k_2$ are the z components of the momentum of the transferred neutron relative to the first and second

$\Gamma^{\downarrow} = 2\pi$



PHYSICS REPORTS (Review Section of Physics Letters) 166, No. 3 (1988) 125–193. North-Holland, Amsterdam

DAMPING OF HIGH-LYING SINGLE-PARTICLE MODES IN HEAVY NUCLEI

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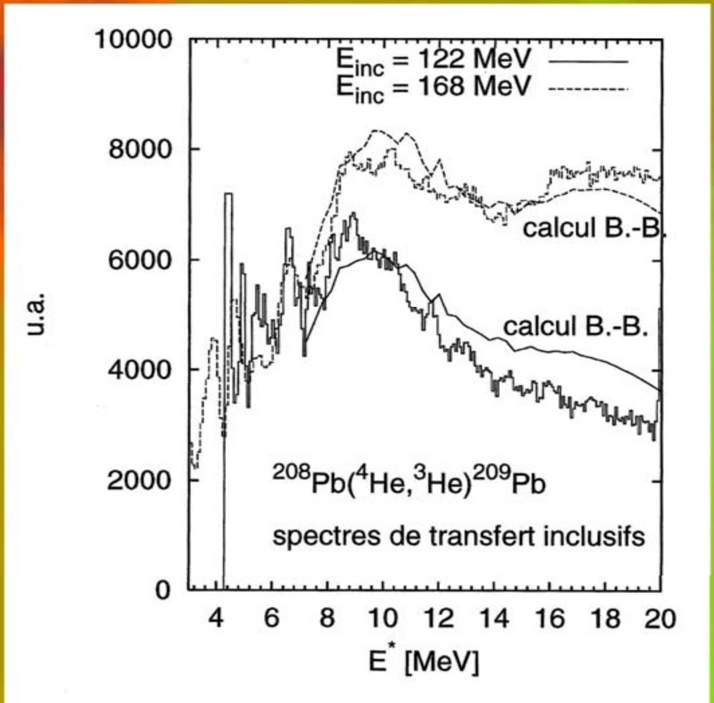
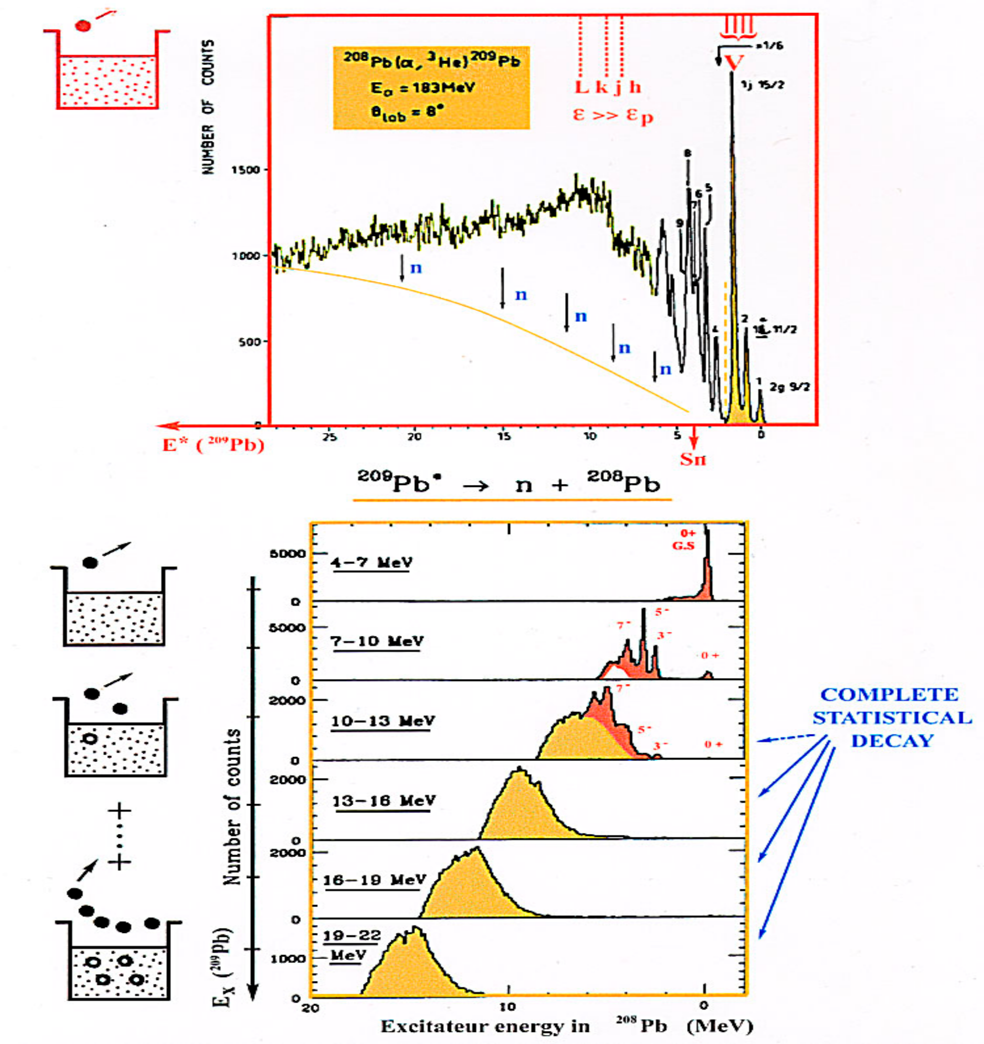
Received January 1988

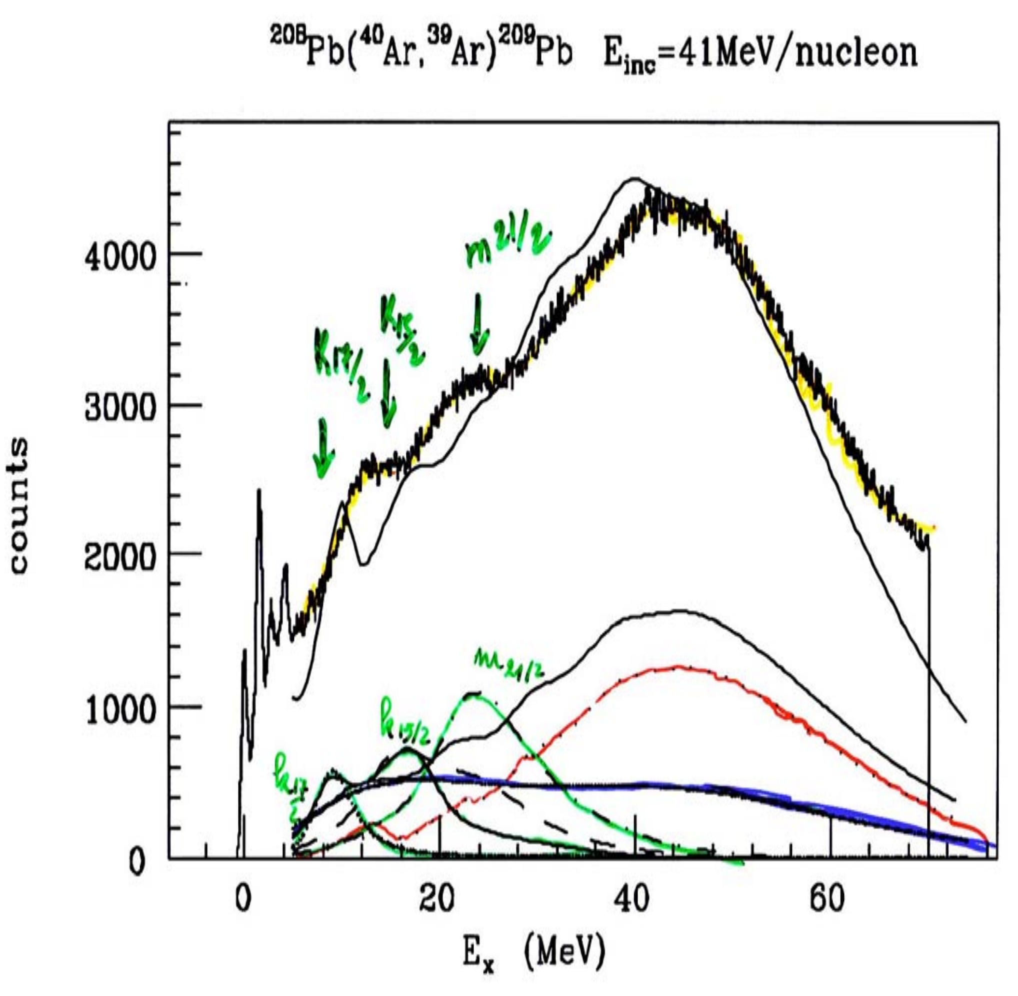
Experimental observation of the damping steps (1p-1h) to (np-nh)



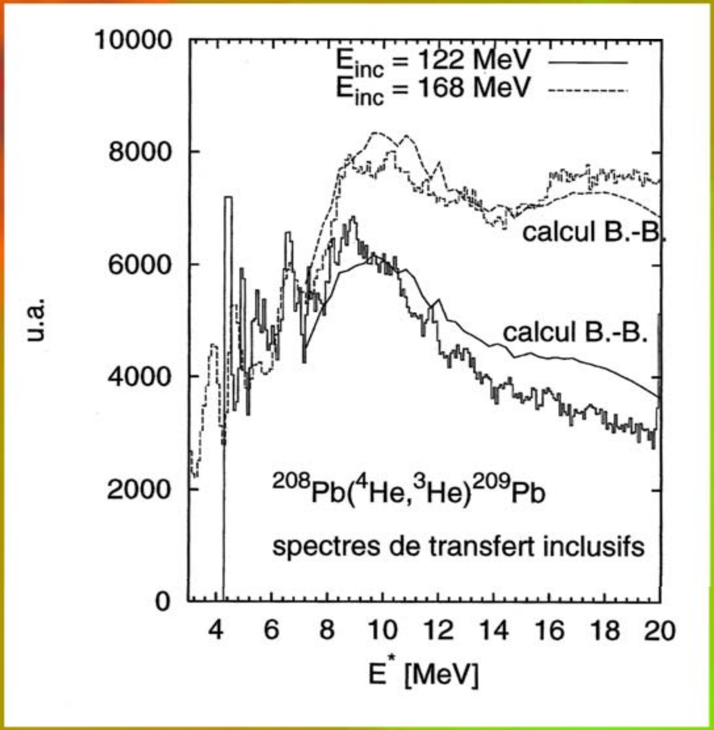


Sydney Gales ,Pisa NOV 3,2008

Transfer to continuum and reaction model Brink, Bonnacorso



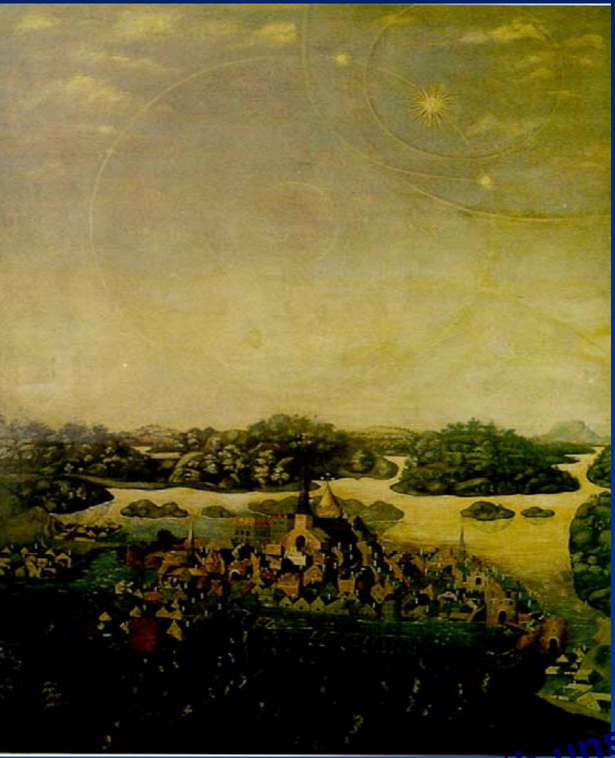
ORSAY 1987



I .LHENRY ,GANIL data,1992

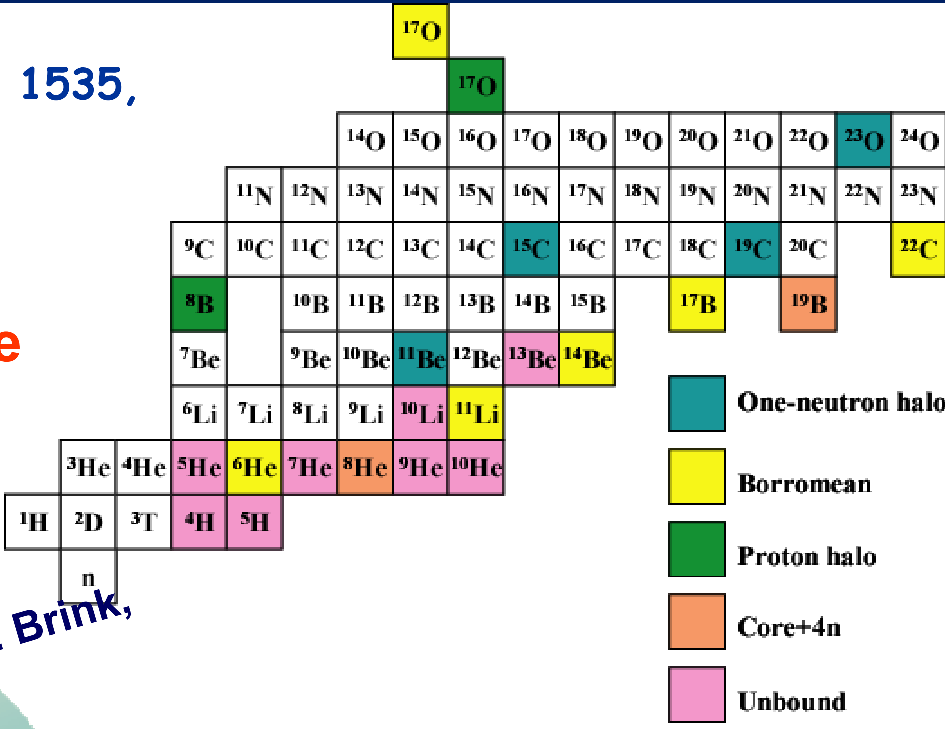
Single-particle motion far of stability

Interplay between structure and reaction aspects…bound vs. continuum…stronger than in any other part of the nuclear chart

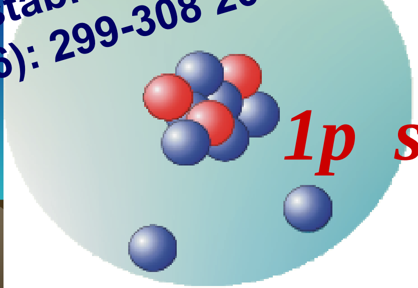


John Elbfas, 1535,
Storkyrkan,
Stockholm

Nuclei at the drip lines



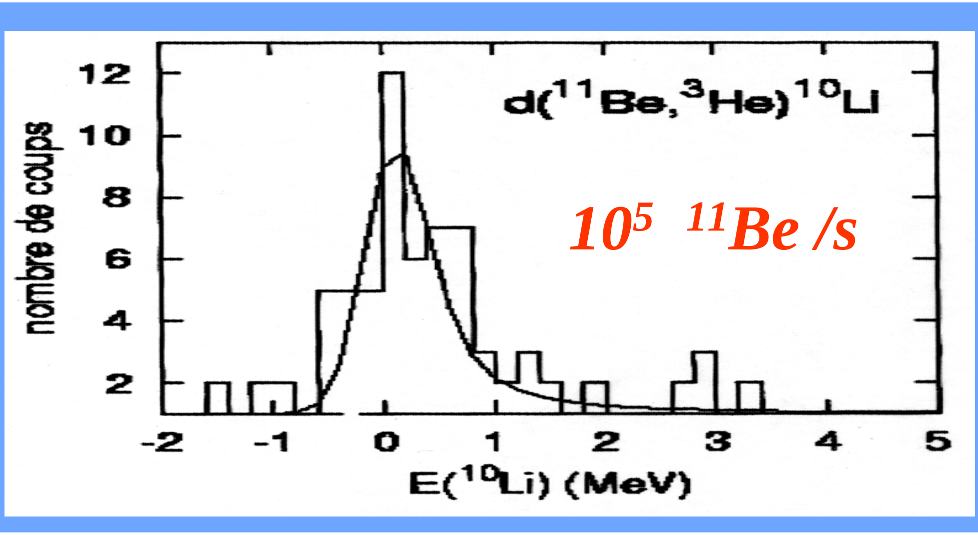
Low energy reactions with unstable nuclei, D. M. Brink, Prog. Theor. Phys. Supp. (146): 299-308 2002



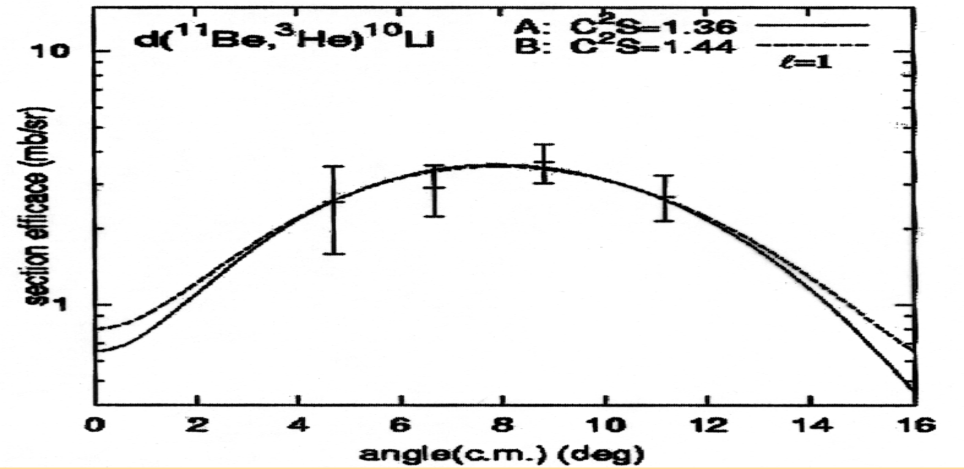
1p splitting , ^{8}He,$^{12-14}$Be,^{20}C,^{22}O (p,d) and (d,p)

S.Pita
PhD thesis
Orsay,2000

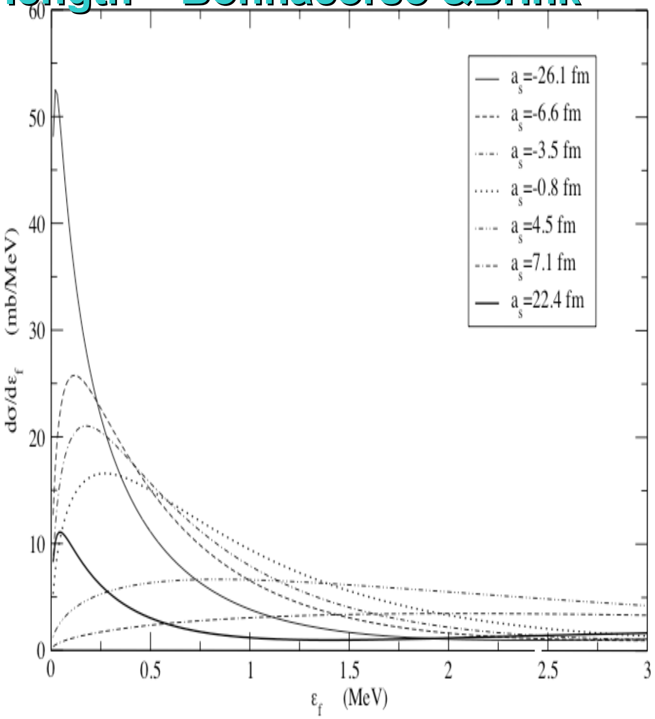
Structure of ^{10}Li G. S via transfer reactions



10^5 ^{11}Be /s



Sensitivity to the s-state scattering length Bonnacorso &Brink



Structural changes with neutron excess

Diffuse Nuclear Surface
Leads to vanishing
Spin-orbit splitting
and/or tensor effects

New « magic numbers »
Test cases
N=20, 1d splitting
^{32}Mg, ^{34}Si
Z=20 N=28-40
^{46}Ar
Z=28 N=28-40, 1f
^{56}Ni, ^{68}Ni

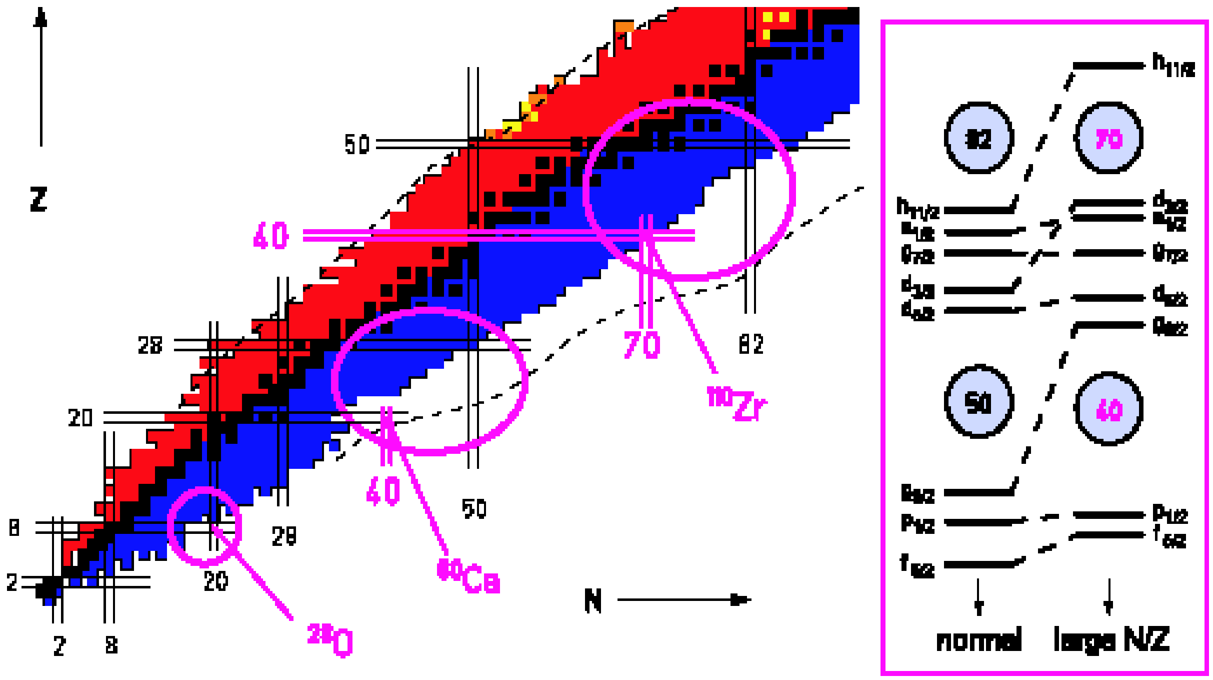
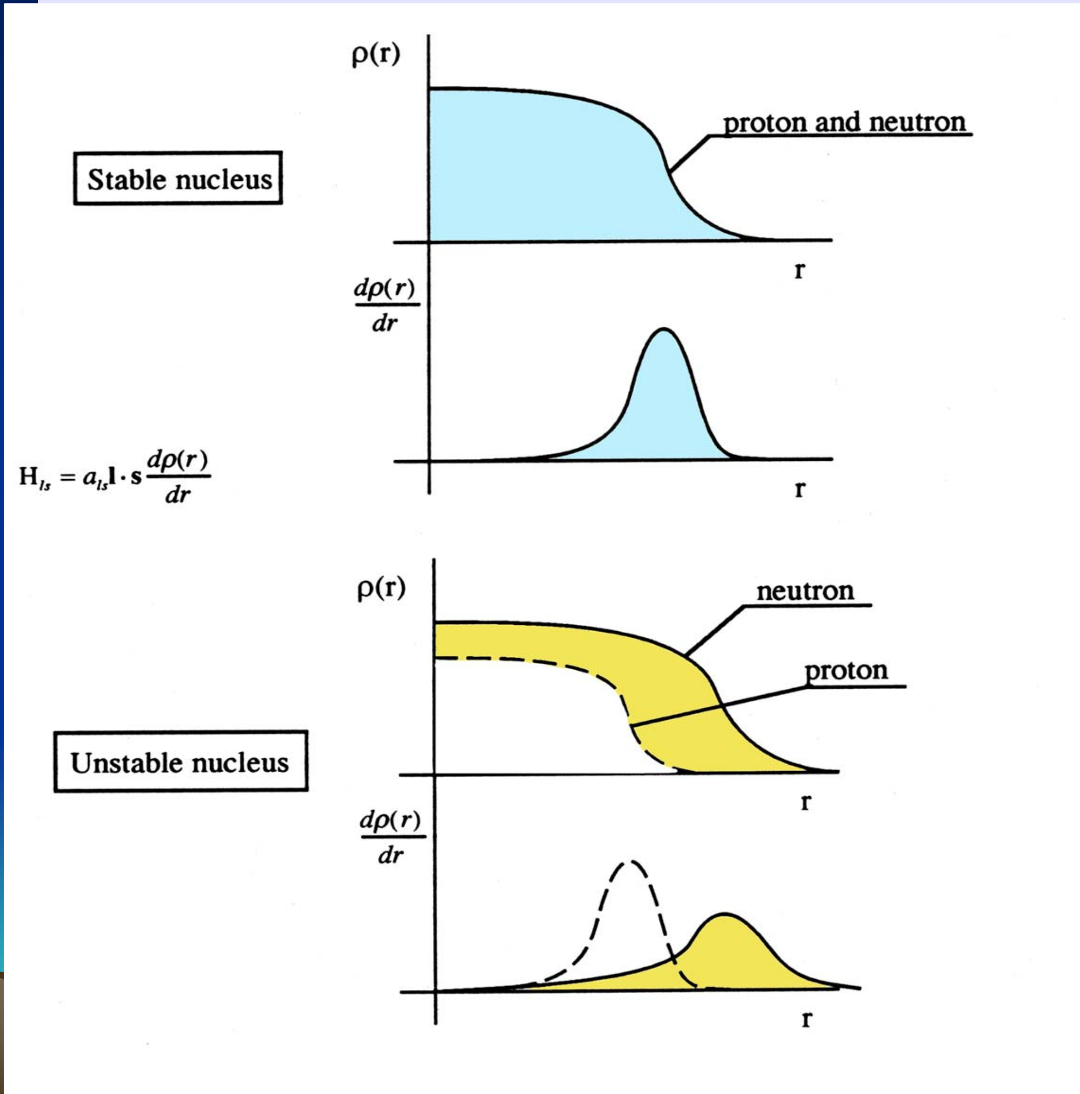


Fig. 16: Nuclear chart in the light- and medium-mass region. The circles indicate areas with possibly new magic numbers. The right-hand side shows the single-particle energies for nuclei close to stability and for nuclei with a large N/Z ratio.

Isopin dependence of spin-orbit interaction

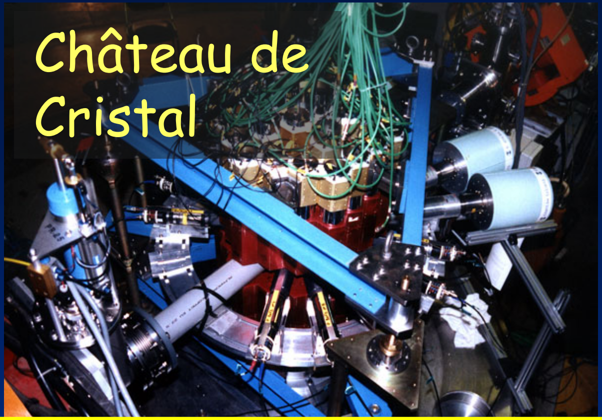


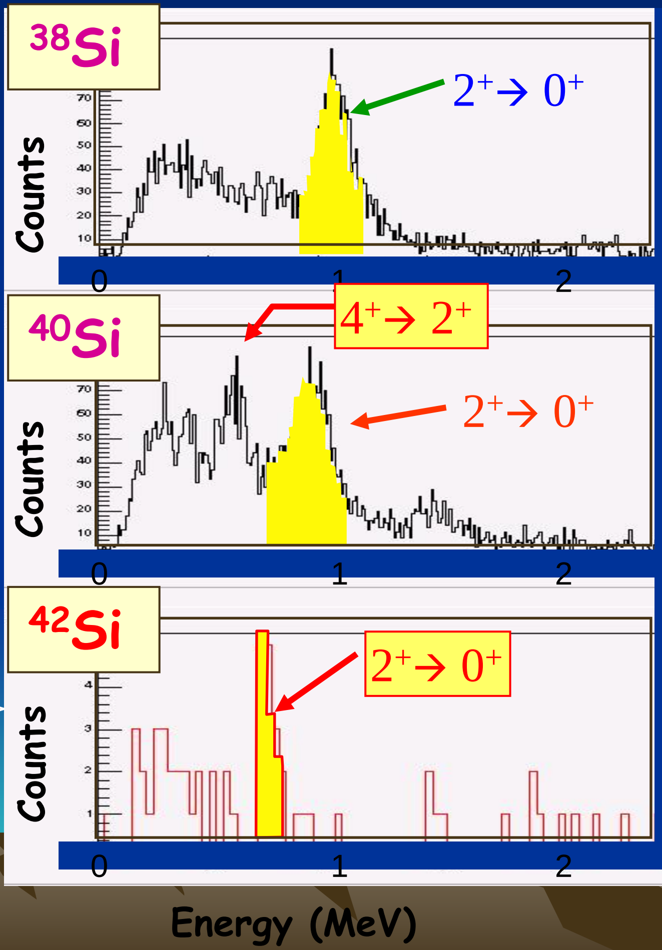
The Spin-orbit interaction is proportional to the nuclear distribution in a stable nucleus. In an unstable nucleus, the differential of the proton and the neutron distribution have peaks at different distances, therefore isospin dependence of the spin-orbit interaction becomes important

Shell Structure

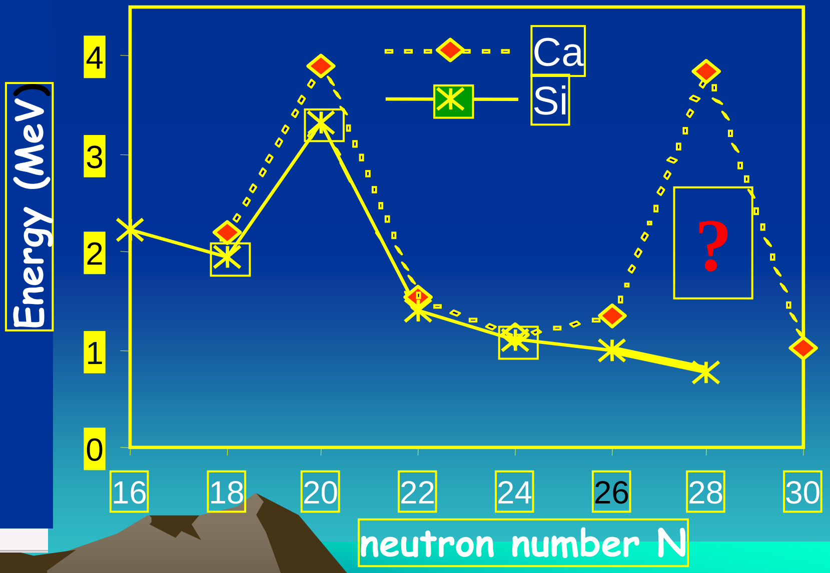
S. Grevy & al preliminary

- Magic Numbers





- Disappearance N=28
  - – ^{48}Ca => SISSI =>^{44}S /Target
  - ☐ γ => BaF$_2$; ^{42}Si => SPEG

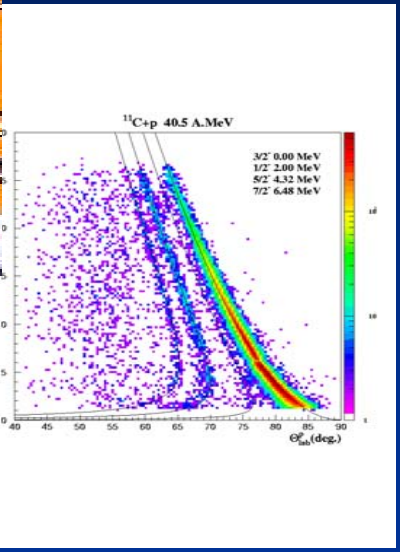


“ Nucleon Transfer in Inverse Kinematics

Detecting the target-like ejectile, e.g. in a Si array

Kinematically less favourable - need very large angular coverage
Spread in beam energy generally gives little effect on E_X measurement
Resolution limited to ~300 keV by both dE/dx(beam) and dE/dx(ejectile)
Target thickness limited to 0.5-1.0 mg/cm^2 to maintain resolution

MUST,Si Array



Detect decay gamma-rays *and* the light particles

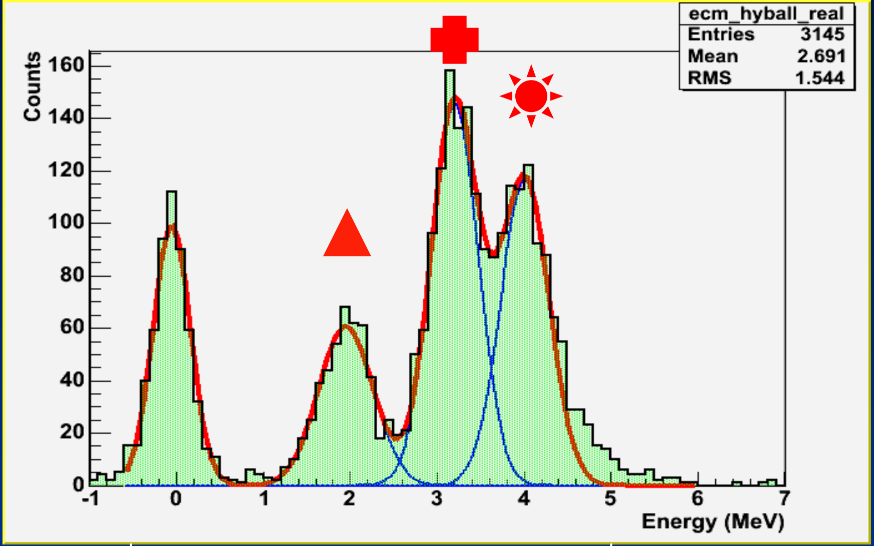
Need exceptionally high efficiency, of order > 25%
Resolution becomes acceptable; limited by Doppler broadening
Light particles give angular distribution and E_x of feeding, for gammas

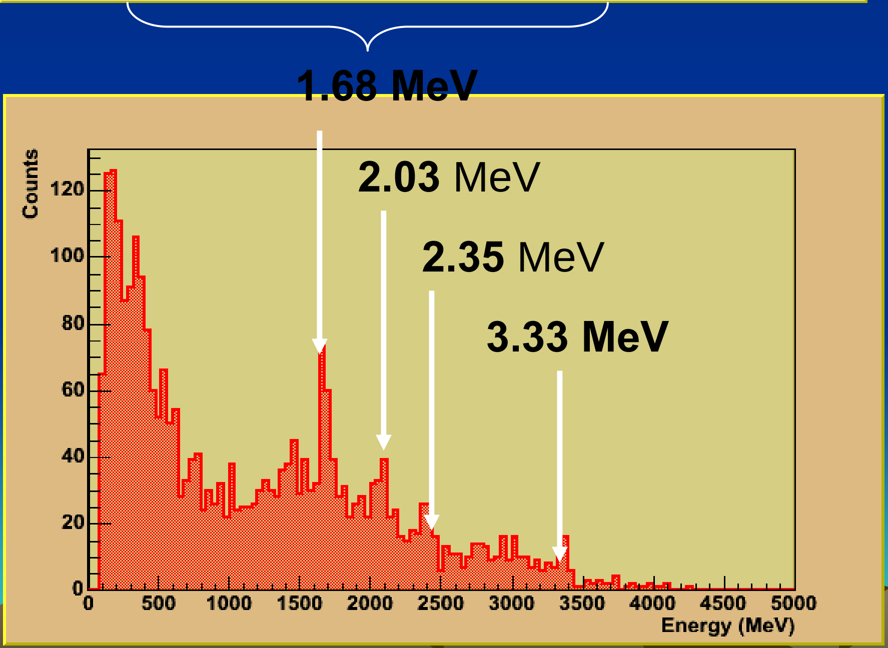
+ TIARA ★★★

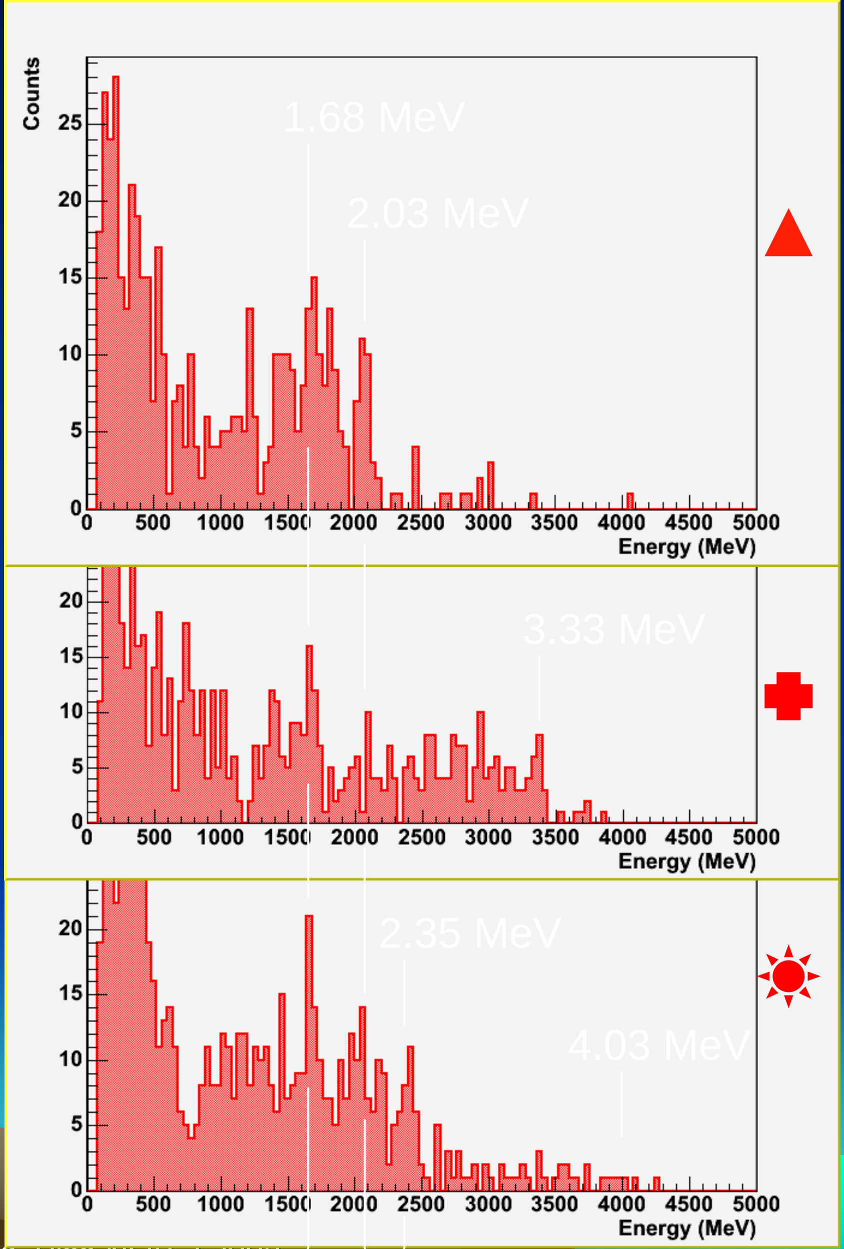
Sydney Gales ,Pisa NOV 3,2008

W.Catford ,ENAM2004

^{24}Ne (d,p γ) ^{25}Ne



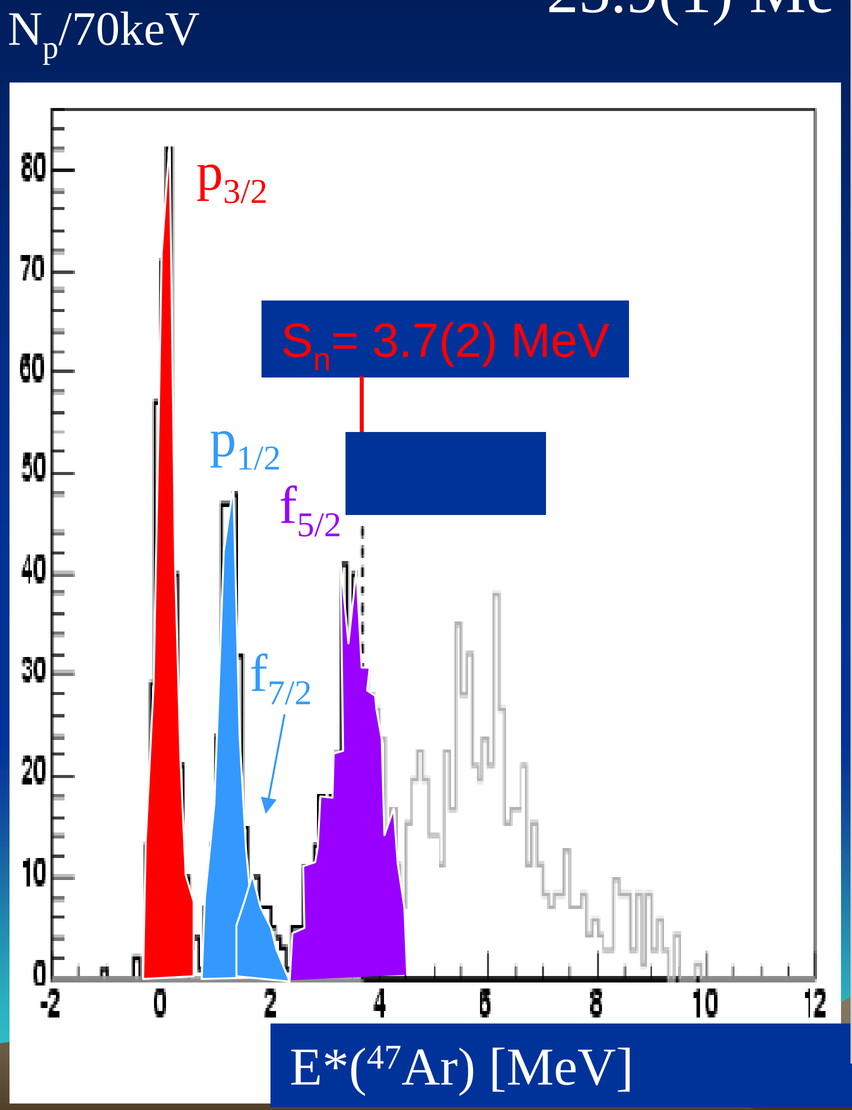


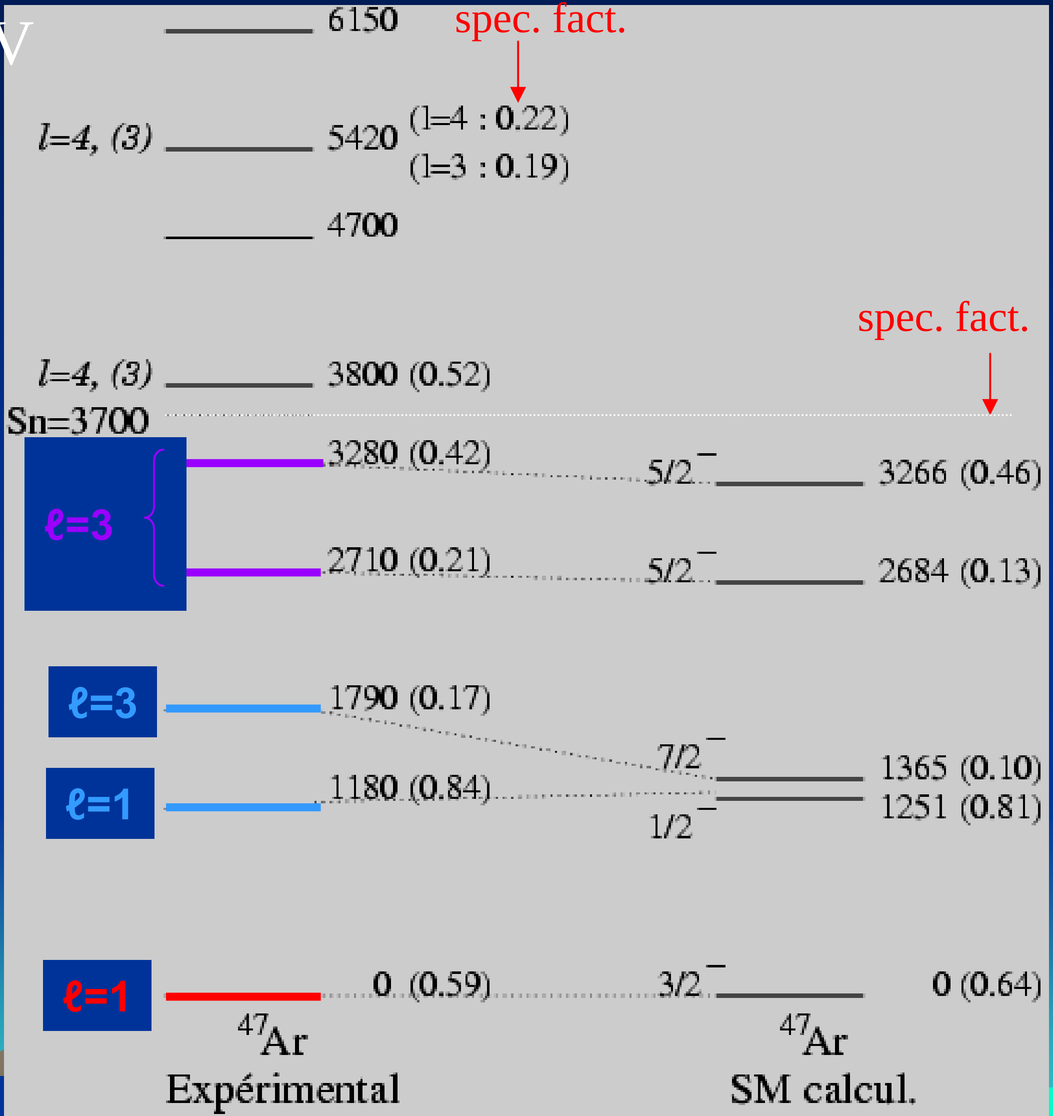


N=28 ^{46}Ar(d,p) ^{47}Ar as (n,γ) *O.Sorlin* *GANIL PRL 2007*

New $\Delta M(^{47}Ar)$ = -25.3(2)MeV

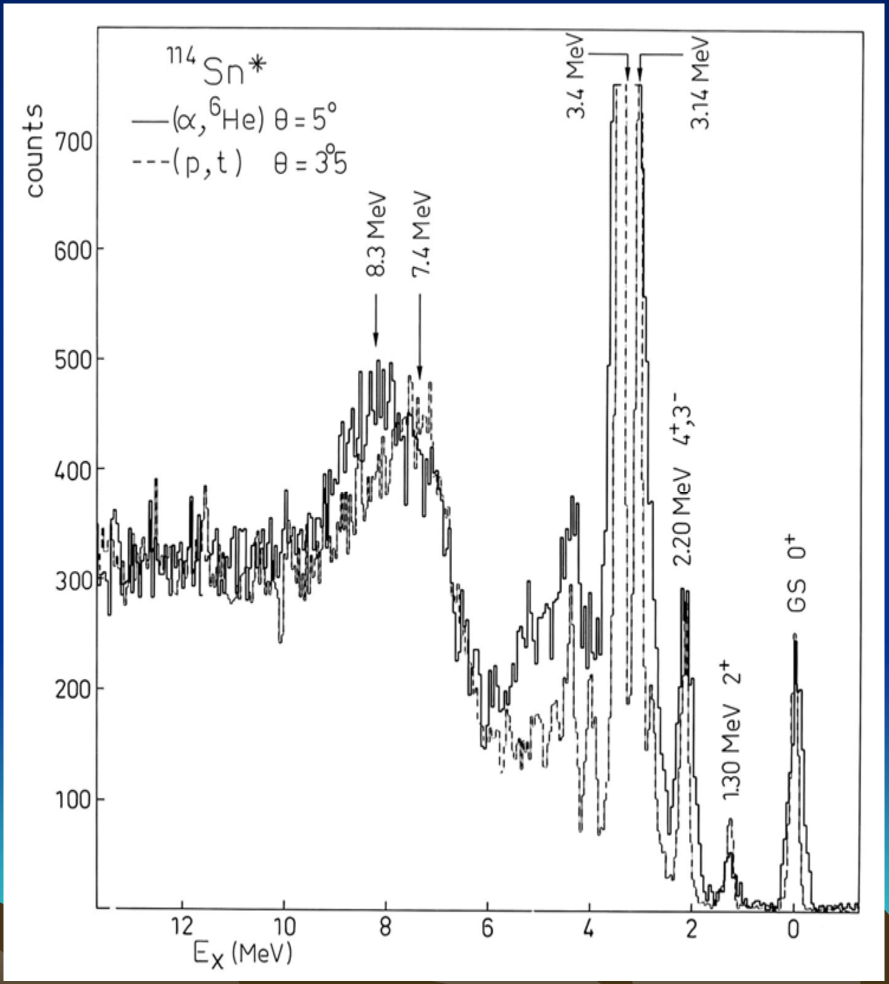
= -25.9(1) MeV





160 keV

Two-neutron pic-up at 218 MeV on 116Sn



A open question is how to treat pairing

How does the low-lying continuum and neutron excess impact the nature of superconductivity in nuclei?

METHOD:

Neutron-pair transfer on Sn isotopes

EXAMPLE:

^{138}Sn(t,p)^{140}Sn

Tritium target ~ 50µg/cm^2

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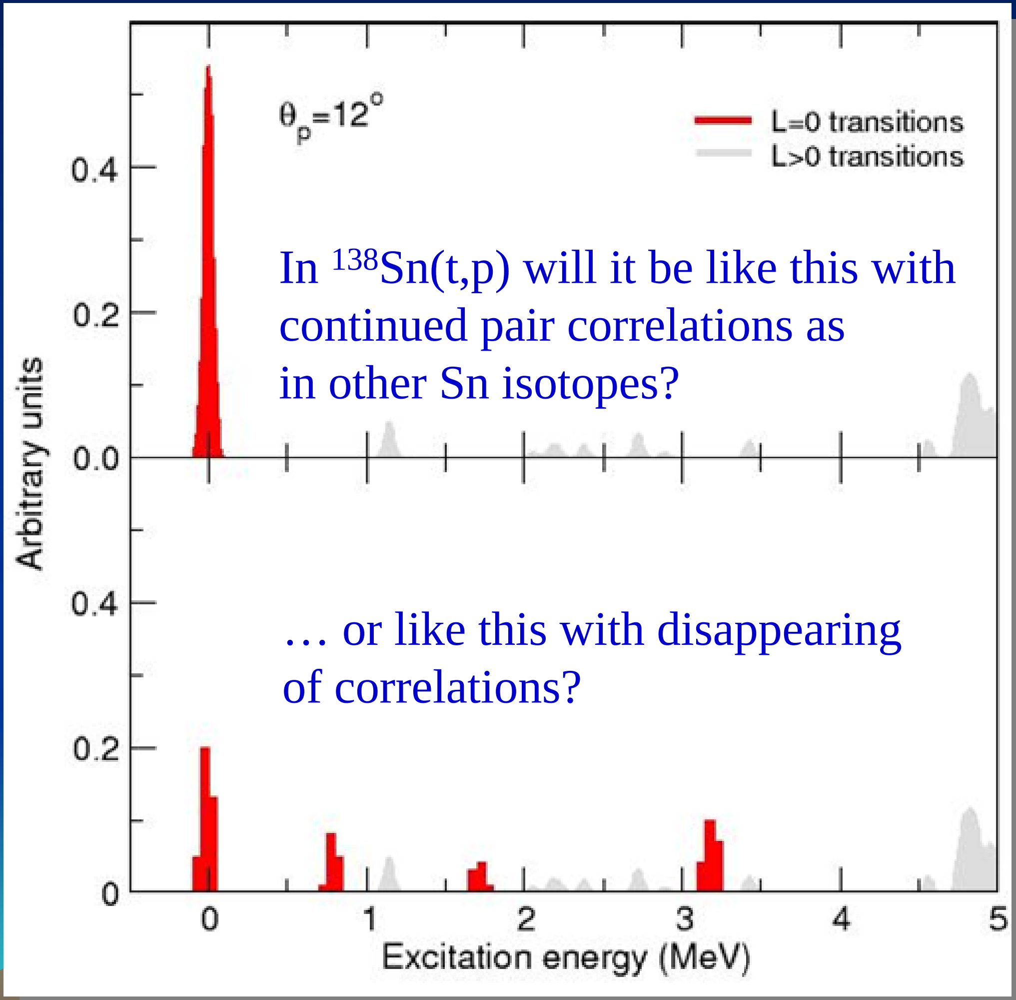
20 MeV/u beam

0.5 mb/sr over at least 1 sr:

~30 cts/wk for each state



In ^{138}Sn(t,p) will it be like this with continued pair correlations as in other Sn isotopes?

… or like this with disappearing of correlations?

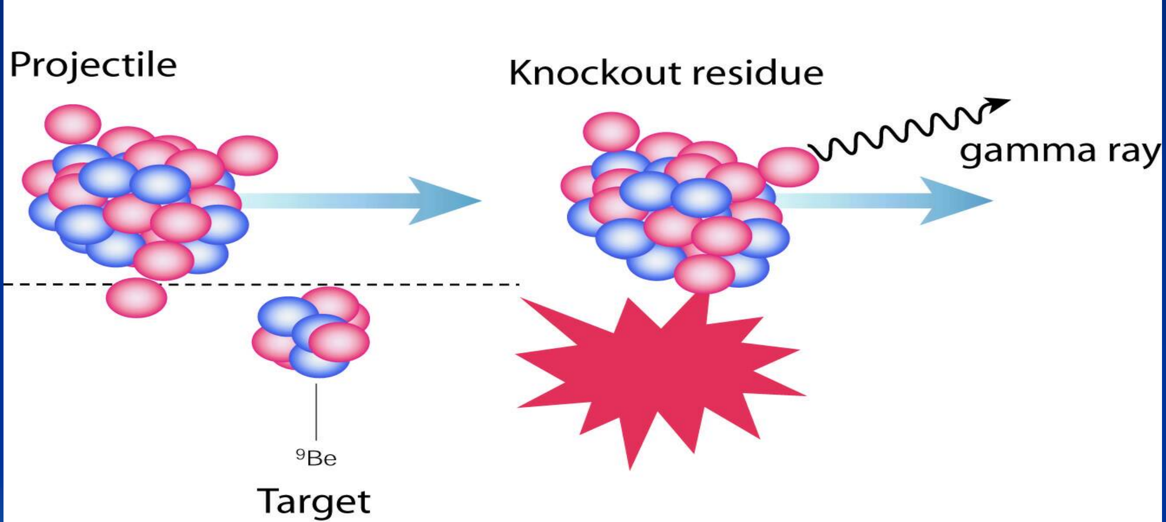
Spectroscopy of the wave function: One-nucleon knockout

- more than 50MeV/nucleon:

sudden approximation + eikonal approach (J.A. Tostevin, Surrey)

- Spectroscopic Factors

determined from the population of the residue with A-1



residue moment distribution

→ ℓ-value of knocked-out n

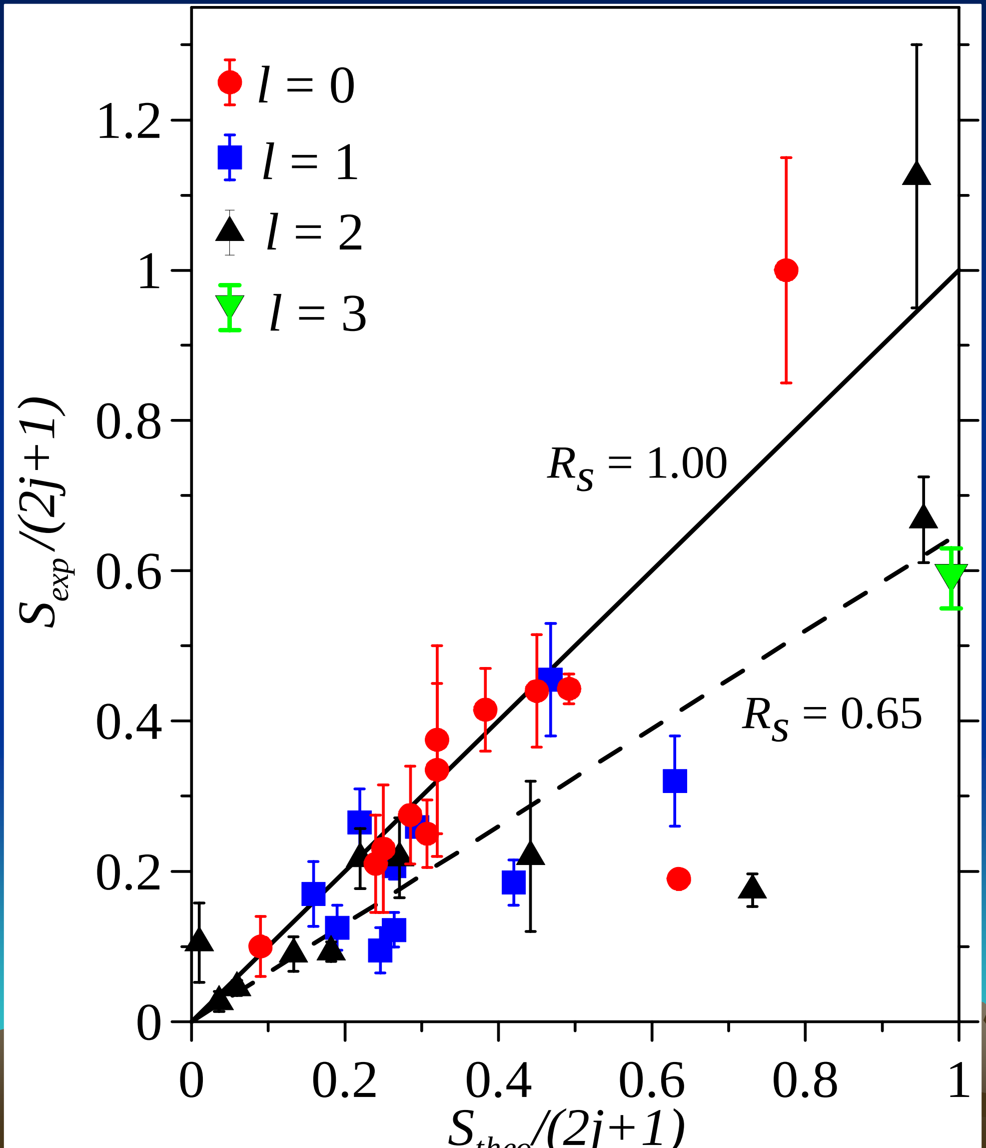
$$\vec{k}_3 = \frac{A-1}{A}\vec{k}_A - \vec{k}_{A-1}$$

$$\sigma(nI^\pi) = \sum_j C^2S(j,nI^\pi)\;\sigma_{sp}(j,B_n)$$

nuclear structure

P.G. Hansen and B.M. Sherrill, Nucl. Phys. **A 693**, 133 (2001).
P.G. Hansen and J. A. Tostevin, Annual Review of Nuclear and Particle Science **53**, 219 (2003)

Reduction factors from knockout



Measured vs. theoretical spectroscopic factors in units of the maximum sum-rule value

P.G. Hansen and B.M. Sherrill, Nucl. Phys. A 693, 133 (2001)

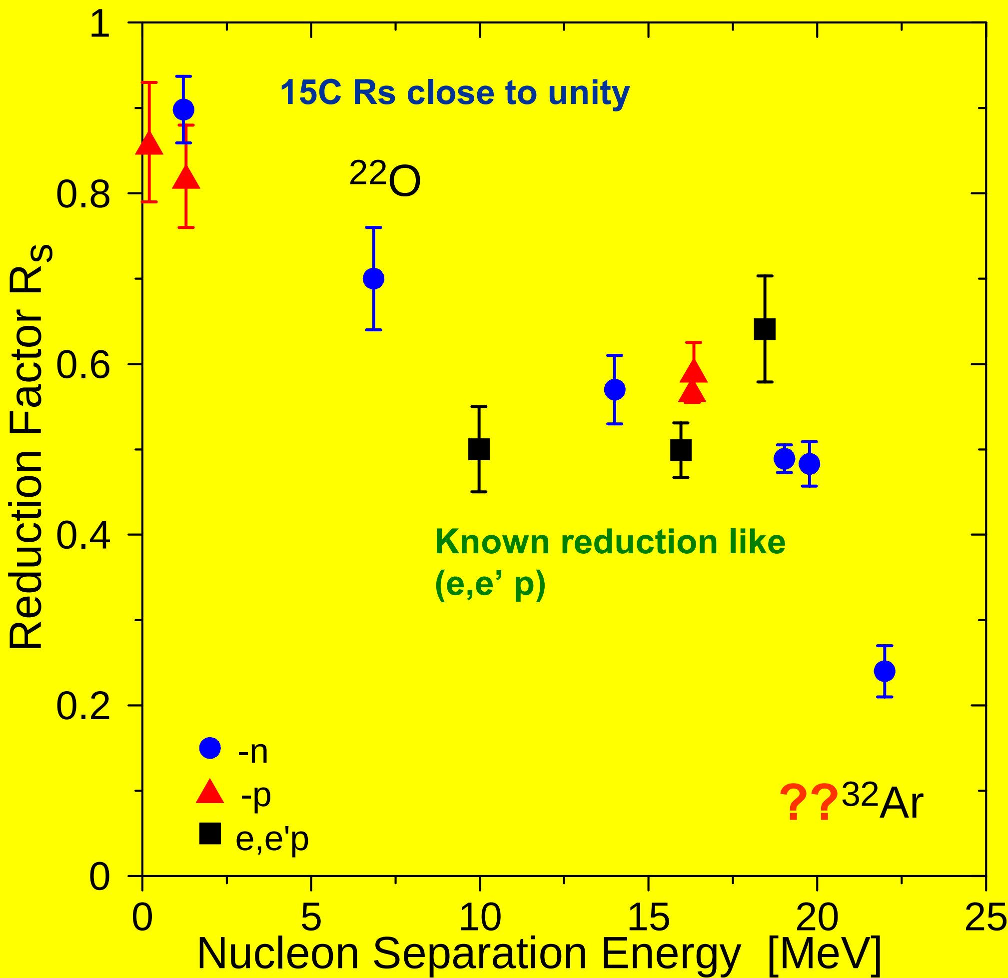
J. Enders et al., Phys. Rev. C 65, 034318 (2002)

P.G. Hansen and J.A. Tostevin, Annual Review of Nuclear and Particle Science 53, 219 (2003)

J.R. Terry et al. Phys. Rev. C, Phys. Rev. C 69, 054306 (2004)

A. Gade et al. , Phys. Rev. Lett., 93, 042501 (2004)

Reduction factors across the nuclear landscape



^{32}Ar and ^{22}O have the same neutron configuration but the reduction R_s is very different

Determination of the occupancies provides information on the presence of correlation effects beyond effective-interaction theory.

B.A. Brown, P. G. Hansen, B.M. Sherrill and J.A. Tostevin, PRC 65, 061601 (2002)
J.Enders *et al.,* Phys. Rev. C 67, 064301 (2003)
A. Gade *et al.,* PRL 93, 042501 (2004)
K.L. Yurkewicz *et al.,* to be published
J.R. Terry *et al.,* PRC 69, 054306 (2004)
B. Jonson, private communication, E. Sauvan et al., Phys. Lett. B 491, 1 (2000)

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GANIL facility

LIRAT

CIME Cyclotron
Acceleration of RI Beams
E < 25 MeV/n, 6-8 MeV/n for FF

Production building
C converter+UCx target
$\leq 10^{14}$ fissions/s

Heavy-Ion ECR source (A/q=3), 1mA

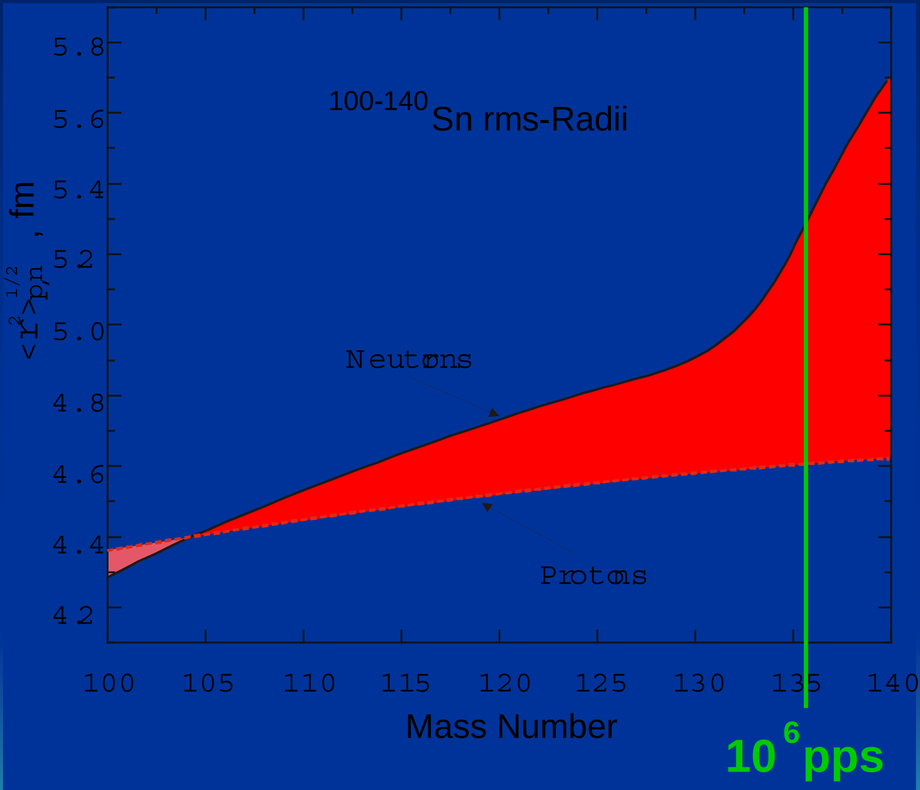
RFQ

Stable Heavy-Ion
Exp. Hall

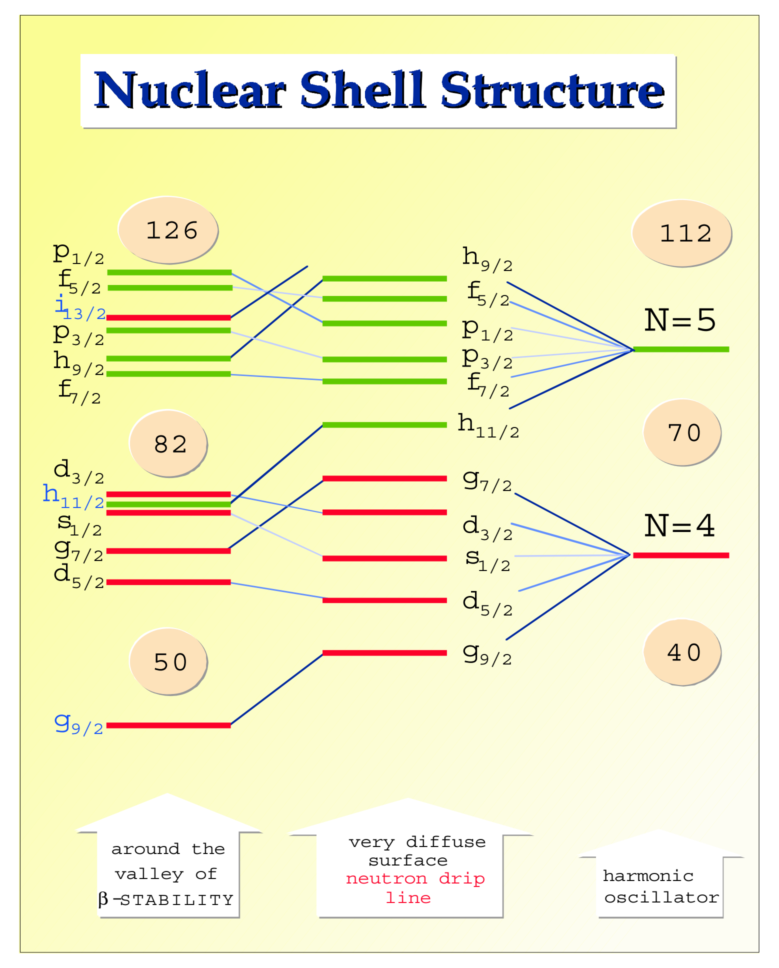
Super conducting LINAC

40MeV d ,5mA ,14MeV/n HI

Neutron skin with neutron excess

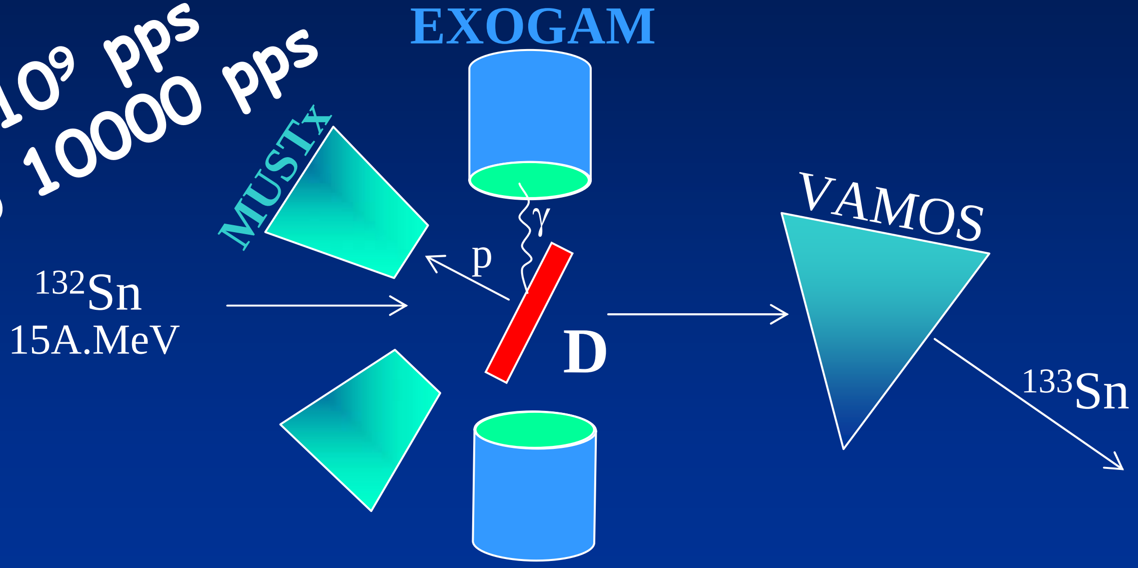


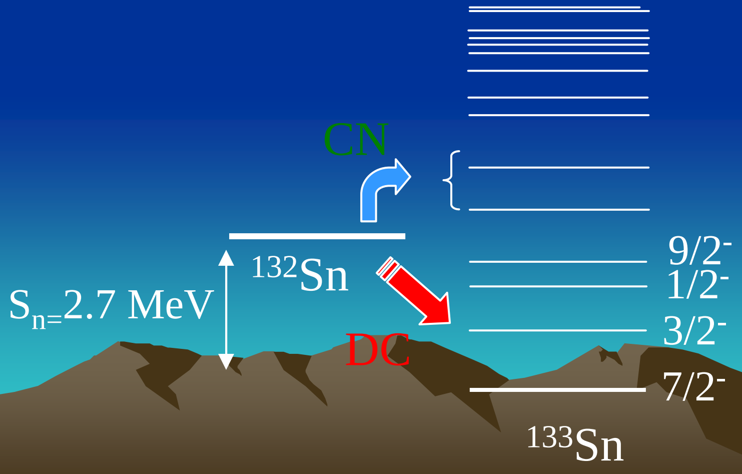
Estimated difference in neutron and proton root-mean-square radii of the Sn isotopes (H.Lenske).



Neutron Transfer on ^{132}Sn

A jump !!
Physics with 10^9 pps
To day 100 to 10000 pps





Determine neutron-captures at stellar temperatures
Spectroscopic factors

Statistical models not valid at magic shells
- **Direct capture component**
- **Compound nucleus component**

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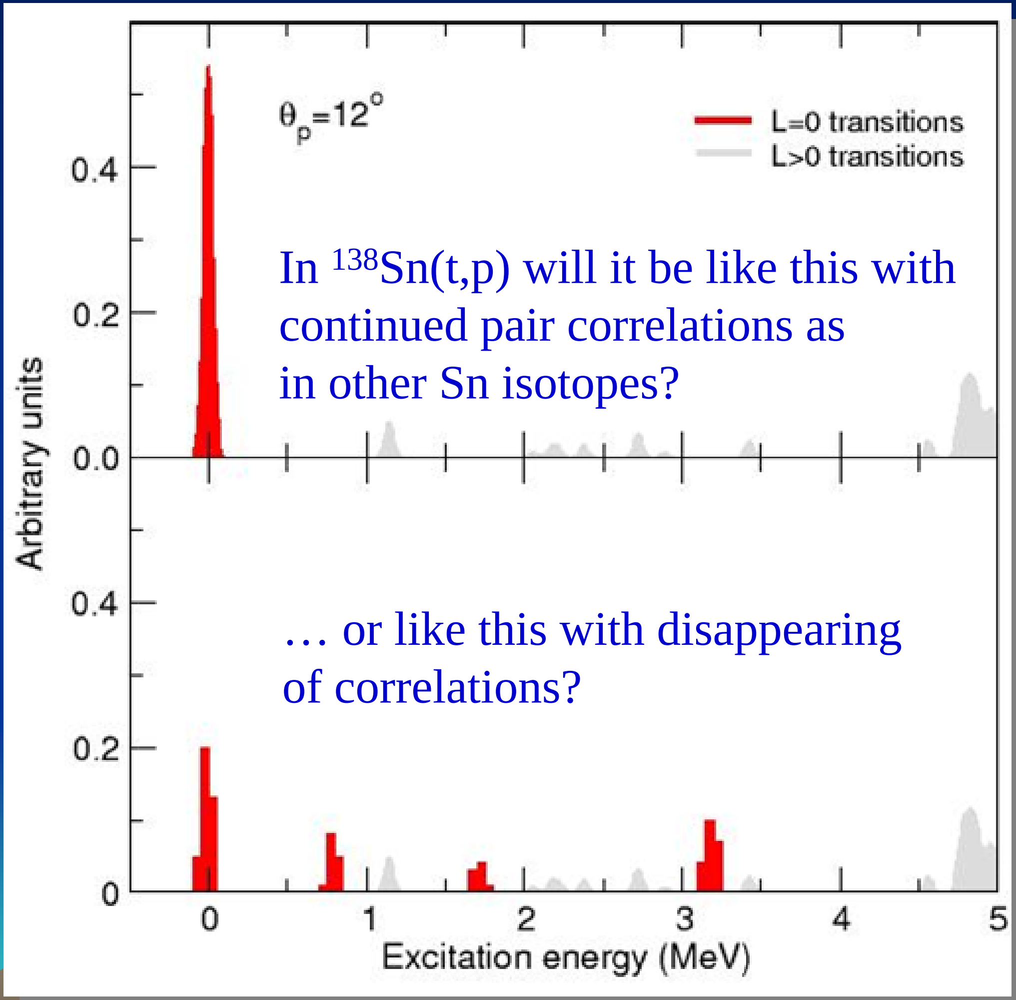

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Hot Topic :Pygmy resonances

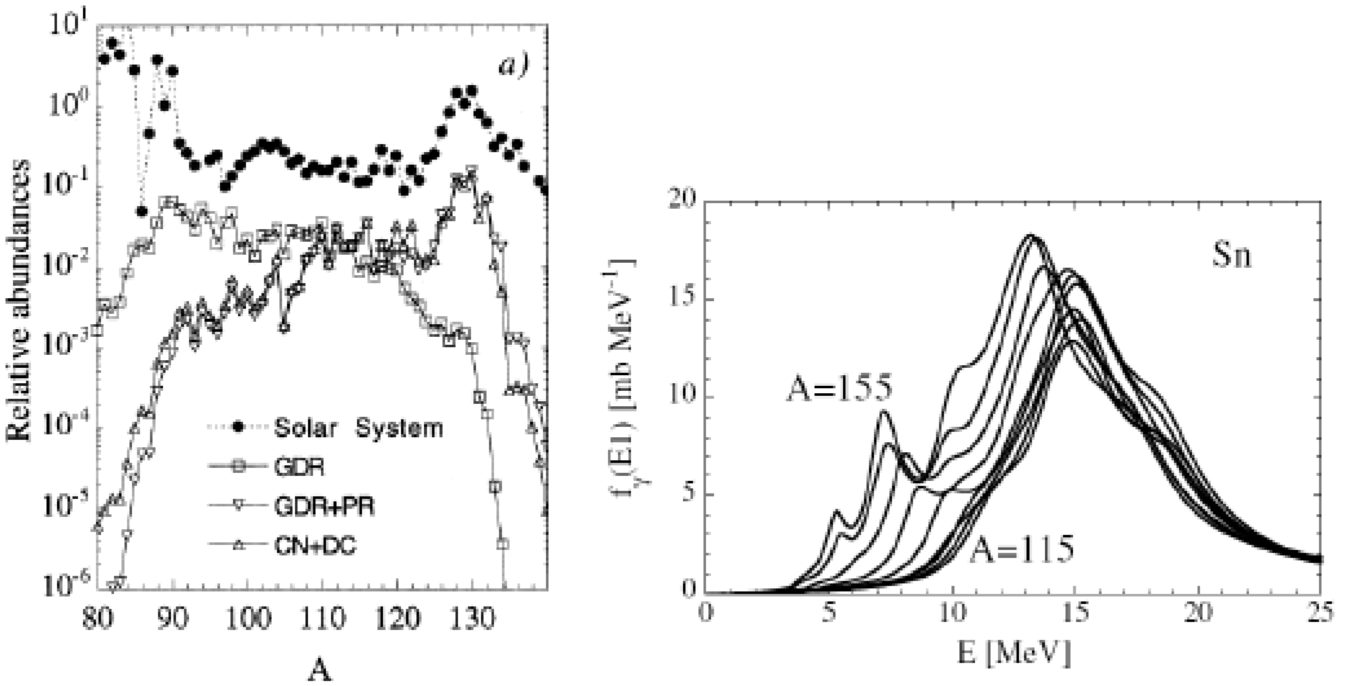
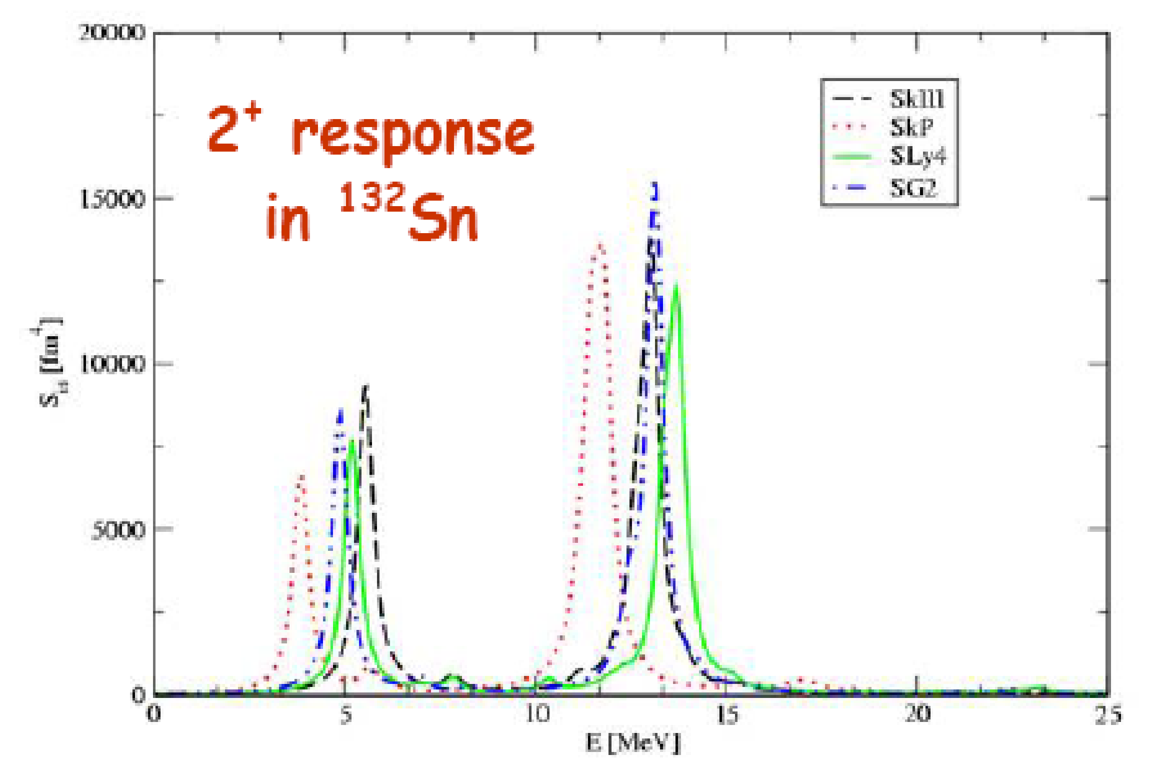


Figure 28 : à gauche : prédiction des abondances du processus-r avec un modèle phénoménologique ne tenant pas compte des résonances pygmées (carrés), et un modèle phénoménologique en tenant compte (triangles vers le bas). Les abondances expérimentales (ronds noirs) sont normalisées arbitrairement (Tiré de S. Goriely, Phys. Lett. B436(1998)10). A droite : distribution de force E1 pour la chaîne isotopique de S_n obtenue avec HFB+QRPA.

QRPA Response for « exotic nuclei »



**Conclusions

- Absolute spectroscopic factors for strong s-p bound valence states with are within reach ,combining careful analysis from nucleon transfer and electron knock-out with an accuracy of (10% at best)
- But s-p have partial occupation ,rest of the strength at very high(Ex>100 MeV)
- outside shell model space
- SM describes only 70% of nucleons due to SRC (15%) and LRC (15%)

- Highly fragmented sp strengths, in particular for unbound resonances embedde in the continuum suffer greatly from the use of inadequate « standard » parameters (E dependence of form factors , continuum) .

Form factors from HF-RPA or QPM models may improve the accuracy.

For exotic nuclei coupling to continuum occurs even more rapidly as a functio of Ex . Careful analysis of deduced SF needed to establish for exemple

SPIN-ORBIT SPLITTING

Nuclear Knock-out is promising, in particular for "exotic" nuclei,careful evaluation of the reaction model parameters and various kinematics ,and target conditions are certainly needed to assess the potential of this approach.

With new heavy "exotic beams" shells above N=50 ,pairing and pygmy,GMR ,GTR resonances may play important roles in Nuclear astrophysics and are exciting avenues for the future