Weisskopf units for neutron-proton pair transfers

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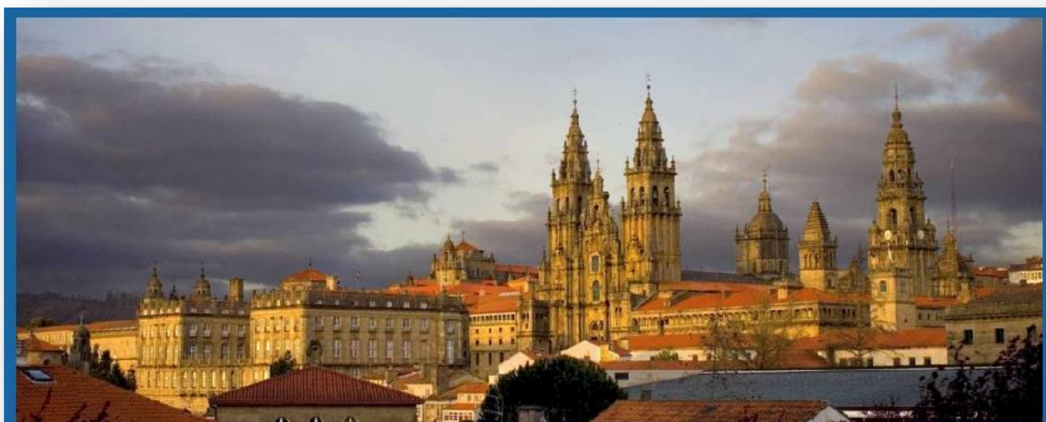
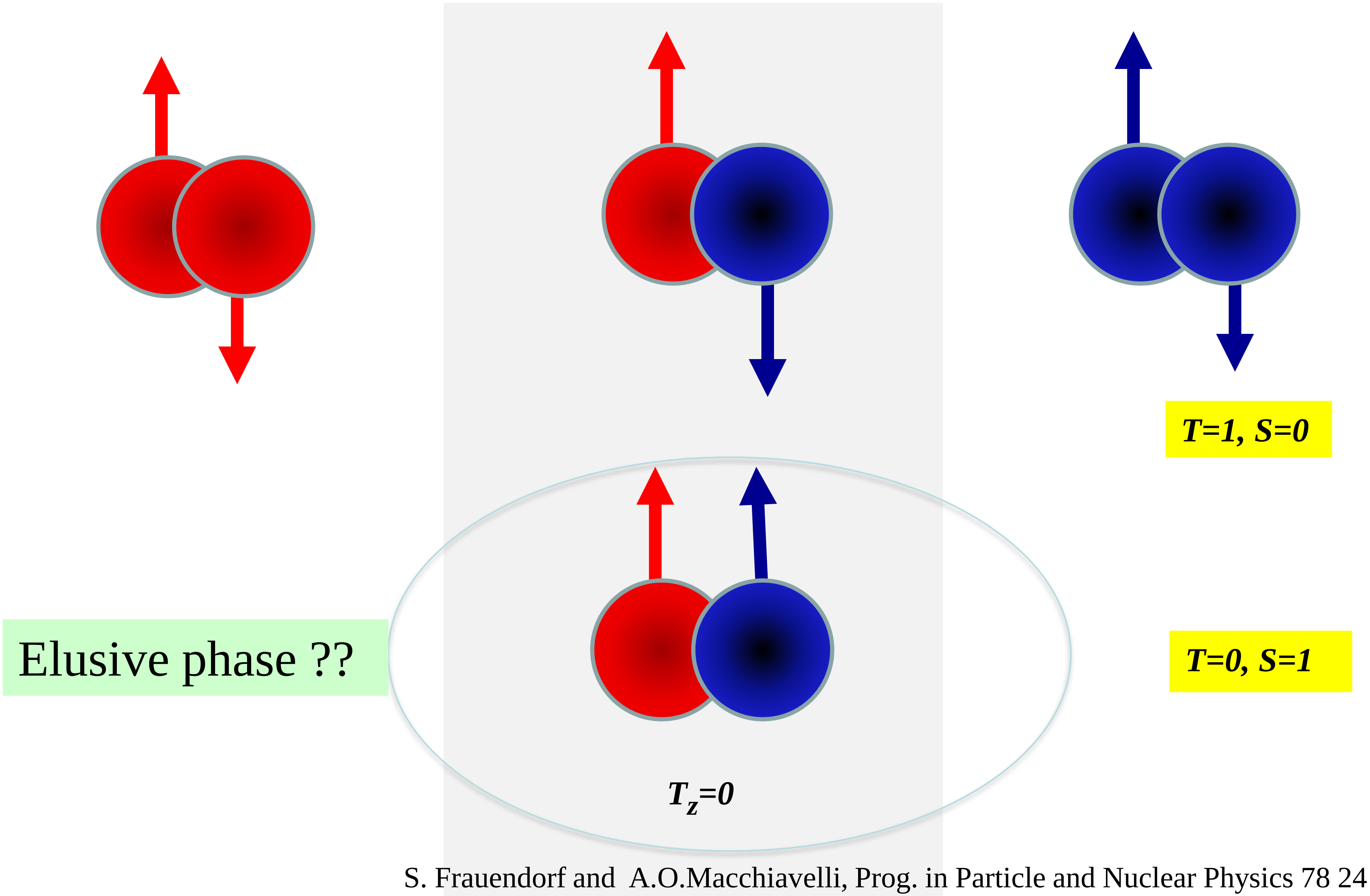


DREB2022 - Direct Reactions with Exotic Beams

26 June 2022 to 1 July 2022
University of Santiago de Compostela

Neutron-Proton Pairing



S. Frauendorf and A.O.Macchiavelli, Prog. in Particle and Nuclear Physics 78 24 (2014)

N=Z nuclei, unique systems to study *np* correlations

- **As you move out of N=Z, T=1 *nn* and *pp* pairs will start to dominate. T=0 excited states.**

Role of isoscalar (T=0) and isovector (T=1) pairing

- **Large spatial overlap of *n* and *p***
- **Pairing vibrations (normal system)**
- **Pairing rotations (superfluid system)**

Does isoscalar pairing give rise to collective modes?

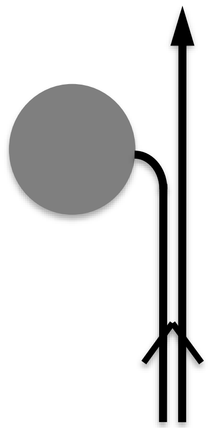
Possible signals

- **Binding energy differences**
- **Low-lying states of odd-odd self-conjugate nuclei**
- **Rotational properties: moments of inertia, alignments**
- **Alpha decay, Beta decay, Gamow-Teller**
- **Radii, Electromagnetic properties**
- **Direct reactions** ⟵

Direct Reactions

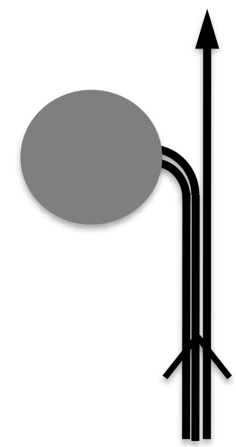
The smoking gun ?

Direct Reactions



$$< A+1 \,|\, a^{+} \,|\, A >$$

Spectroscopic (*u*, *v*) Factors



$$< A+2 \,|\, a^{+} a^{+} \,|\, A >$$

Constructive interference

Two particle transfer reactions like (t,p) or (p,t), where 2 nucleons are deposited or picked up at the same point in space provide an specific tool to probe the amplitude of this collective motion.

The transition operators <f|a⁺a⁺|i>, <f|aa|i> are the analogous to the transition probabilities BE2's on the quadrupole case.

R.A. Broglia, O. Hansen and C. Riedel, Adv. Nucl. Phys. Vol 6 (1973) 287

D. M. Brink and R.A. Broglia, Nuclear Superfluidity, Cambridge Monographs.

A brief reminder

In superfluid nuclei, where the BCS theory provides a good representation of the ground states, the cross-section for two-neutron transfers from the nucleus A_0 to $A_0 \pm 2$ is given approximately by

$$d\sigma / d\Omega \approx |\sum_j U_j V_j|^2 (d\sigma / d\Omega)_{2sp} = (\frac{\Delta}{G})^2 (d\sigma / d\Omega)_{2sp}$$

Collective enhancement over *sp* cross-section due to coherent contributions of correlated *nn* pairs

where U_j and V_j are the probability amplitudes for the orbit j to be empty and occupied respectively, Δ is the pairing gap and G is the strength of the pairing interaction.

With typical values of $\sim 12/\sqrt{A}$ MeV and $G \sim 20/A$ MeV, the enhancement factor is $\sim A/4$, increasing with A as expected from the larger number of available orbits for the pairs to scatter into

S. Yoshida, Nucl. Phys. 33 (1962) 685.

In analogy to (t,p) and (p,t) transfer reactions:

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ENHANCEMENT OF DEUTERON TRANSFER REACTIONS BY NEUTRON-PROTON PAIRING CORRELATIONS*

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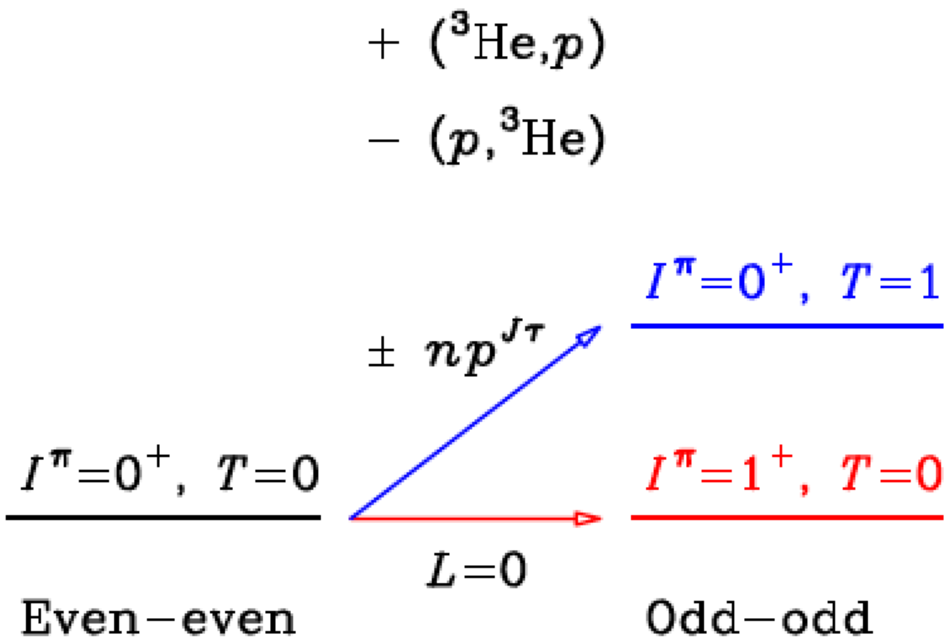
(p, ^{3}He), (^{3}He,p)	ΔT=0,1
(d,α), (α,d)	ΔT=0
(α, ^{6}Li), (^{6}Li,α)	ΔT=0

Cf. Marlène ASSIE talk. Thursday 11:20

(^{3}He,p) and (p,^{3}He) Transfer Reactions



Measure the *np* transfer cross section to T=1 and T=0 states

Both absolute σ(T=0) and σ(T=1) <u>and</u> relative σ(T=0) / σ(T=1) tell us about the character and strength of the correlations

How to assess collective *np* pairing effects ?

Quadrupole collectivity –> *B(E2)* in Weisskopf units

V.F. Weisskopf, Phys. Rev. 83 (1951) 1073.

Two-particle units in the analysis of two-neutron transfer reactions

R.A. Broglia, C. Riedel and T. Udagawa, Nuclear Physics A184 (1972) 23.

How to assess collective *np* pairing effects ?

Thus:

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Neutron-proton pair transfer reactions and corresponding Weisskopf-type units

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The *np* Weisskopf units

For the case at hand, we look at the experimental ratio in terms of two-particle units:

$$\frac{\mathcal{R}_{01}}{\mathcal{R}_{01,2sp}} = \frac{d\sigma^{01}/d\sigma^{01}_{2sp}}{d\sigma^{10}/d\sigma^{10}_{2sp}}$$

For a single *np* pair transfer, the cross-section factorizes in a structure part, *S*, and a DWBA reaction part, usually calculated with codes such as DWUCK or FRESCO

$$d\sigma/d\Omega_{2sp} = \mathcal{S}\sigma_{DW}$$

The *np* Weisskopf units

Let us assume that the $np\tau J$ pairs are constructed from a given single-particle orbit with (nj) orbit quantum numbers, appropriate for the case under study, and that A and B are respectively the initial and final nuclei.

Since we start from an even-even nucleus with I_A=0and T_A=0, it follows from the selection rules that I_B=J and T_B=τ, then the structure factors are:

$$\mathcal{S}^{\pm}(I) = (C^{J\tau}_{^3He,p})^2 S^{J\tau}_{^3He,p} (C^{J\tau}_{A,B})^2 S^{J\tau}_{A,B}$$

Reaction	(I,T)	$(C^{J\tau}_{^3He,p})^2$	$S^{J\tau}_{^3He,p}$	$(C^{J\tau}_{A,B})^2$
$(^3\mathrm{He},p)$	(0,1)	$\frac{1}{3}$	$\frac{3}{2}$	1
	(1,0)	1	$\frac{3}{2}$	1
$(p,^3\mathrm{He})$	(0,1)	$\frac{1}{3}$	$\frac{3}{2}$	$\frac{1}{3}$
	(1,0)	1	$\frac{3}{2}$	1

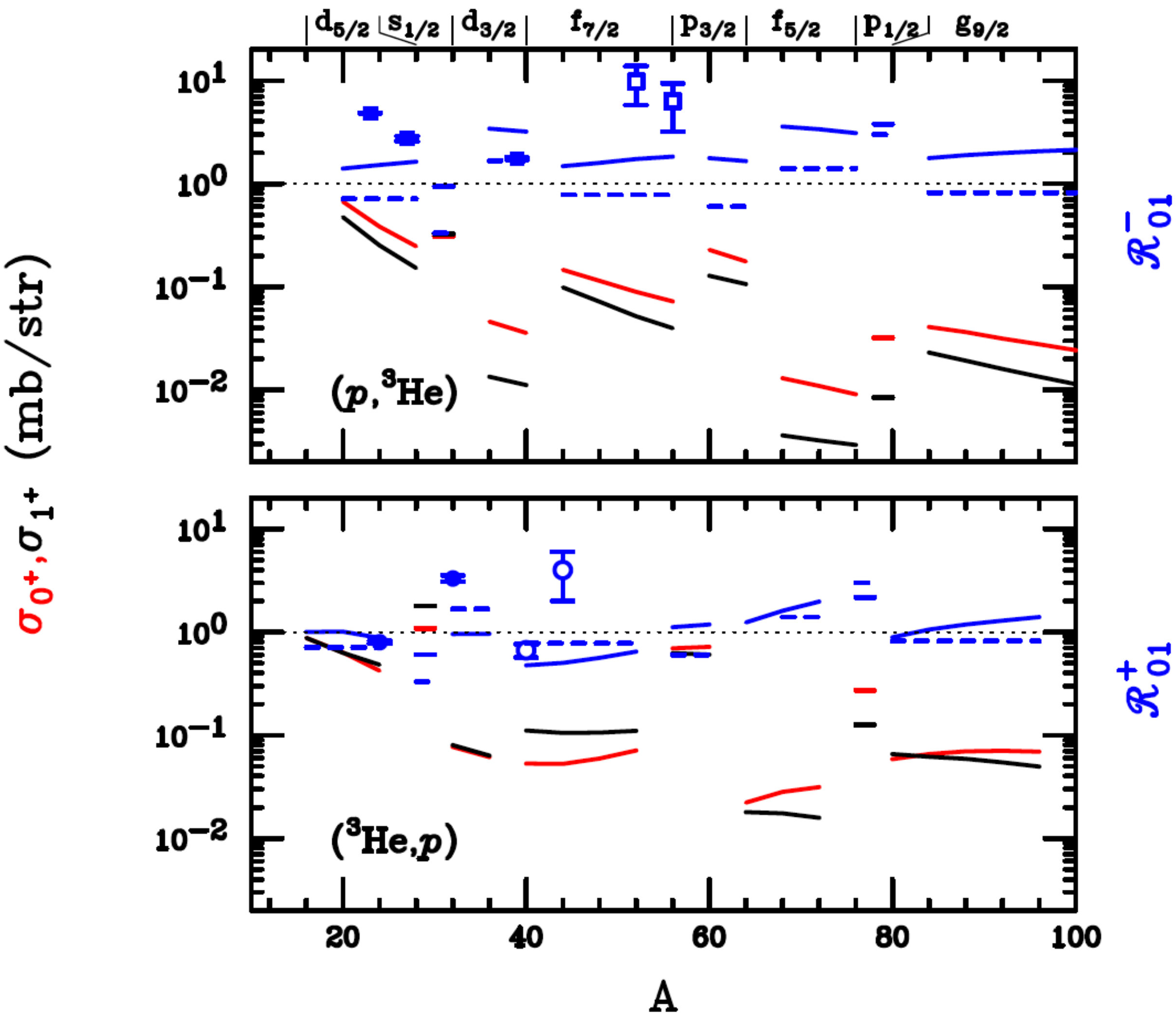
The *np* Weisskopf units

Being interested only in L =0 transfers, we consider the limit $\theta \rightarrow 0$ for the DW cross-sections:

$$\boxed{\mathcal{R}^{\pm}_{01,2sp}} = \frac{\mathcal{S}^{\pm}(0^{+})}{\mathcal{S}^{\pm}(1^{+})}\frac{\sigma_{DW}^{n\ell j,01}}{\sigma_{DW}^{n\ell j,10}}$$

which we introduce as the *np*-Weisskopf units.

The *np* Weisskopf units



65 MeV

25 MeV

Second-order DWBA calculations with the code FRESCO, with conditions relevant to the filling of the different *(n, l, j)* orbits at the *N*=*Z* line, from ^{16}O to ^{100}Sn.

A simple expression

Since the energy difference of the T=0 and T=1 low-lying states in the odd-odd final nucleus is small compared to the reaction and binding energy scales, it is expected that the reaction kinematics part will cancel out, leaving only the different probabilities of finding in the *(nlj)*^{2} configuration, an *np* pair in relative $^3S_1$ or $^1S_0$ states entering in the pair form factor.

The cross sections for stripping (^{3}He,p) or pick-up (p,^{3}He) depend on:

$$\left.\frac{d\sigma}{d\Omega}\right|_0 = \frac{\mu_p \mu_{^3\mathrm{He}}}{(2\pi\hbar^2)^2} \sum_{LSJ\tau} (C^{J\tau}_{A,B})^2 b^2_{S\tau} \sum_M \left| \sum_N G^{NLS}_{J\tau} B^M_{NL} \right|^2$$

structure information from the heavy ion

N.K. Glendenning, Phys. Rev. 137 (1965) B102.

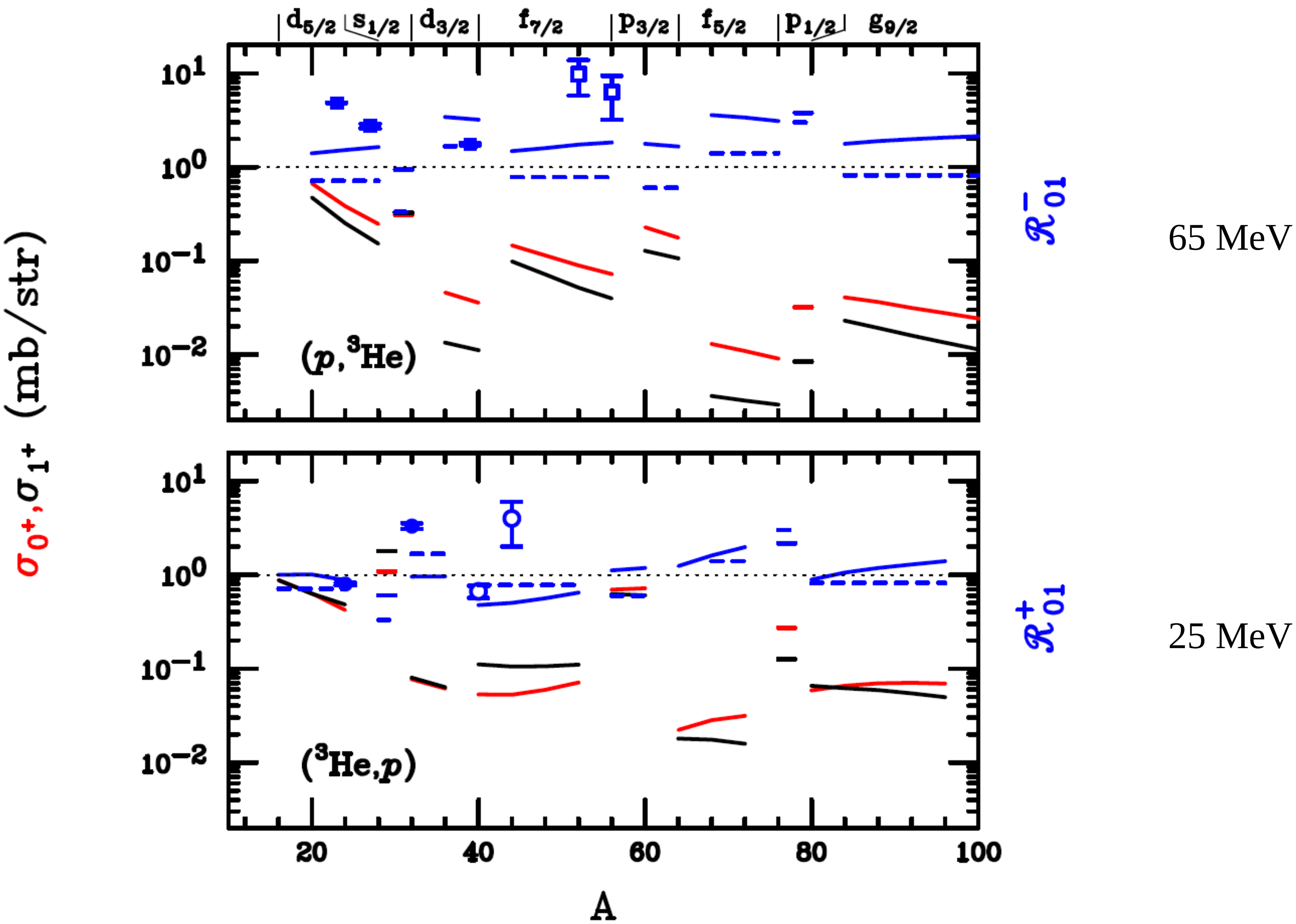
A simple expression

For a single j^2 configuration, this factor is proportional to:

$$G_{J\tau}^{N0S} \propto (2j+1)\sqrt{2S+1}\begin{Bmatrix} \ell & \frac{1}{2} & j \\ \ell & \frac{1}{2} & j \\ 0 & S & J \end{Bmatrix} \langle 10N0;0|n\ell n\ell;0\rangle$$

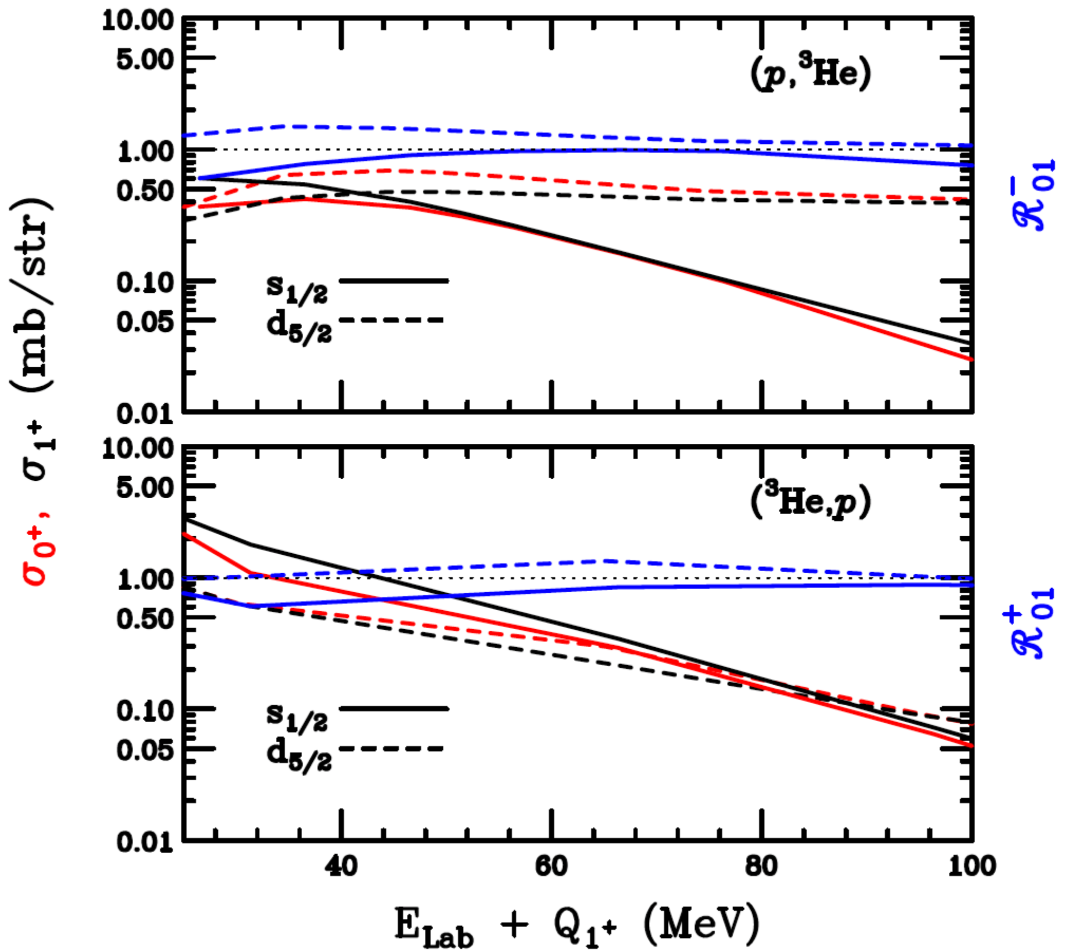
$$\mathcal{R}^{+}_{01,2sp} \approx \mathcal{R}^{-}_{01,2sp} \approx \frac{1}{9}\frac{\begin{Bmatrix} \ell & 1/2 & j \\ \ell & 1/2 & j \\ 0 & 0 & 0 \end{Bmatrix}^2}{\begin{Bmatrix} \ell & 1/2 & j \\ \ell & 1/2 & j \\ 0 & 1 & 1 \end{Bmatrix}^2}$$

A simple expression (----)



Second-order DWBA calculations with the code FRESCO, with conditions relevant to the filling of the different *(n, j, l)* orbits at the N=Z line, from ^{16}O to ^{100}Sn.

Energy dependence



np WU's as a function of the bombarding energy plus the Q-value to the 1^+state, for the representative cases of the $s_{1/2}$ and $d_{5/2}$orbits.

Note that the ratios are stable even when the cross-sections change by factors of 10-100, and thus reflect a robust measure of the structural properties

Summary

Understanding the role of *np* pairing on the structure of $N=Z$ nuclei is a topic of much interest, which will be featured prominently in studies with radioactive beams

The transfer of *np* pairs, in particular the (^{3}He, *p*) and (*p*, ^{3}He) reactions, stand as a unique tool to probe these correlations and the competition between the isoscalar and isovector channels

We have introduced the concept of *np*-Weisskopf units to provide a simple and robust measure of *np* pairing collectivity from experimental cross-sections and/or ratios, much in the same way as the Weisskopf units are used for electromagnetic transitions

A related aspect is the well-known strong manifestation of alpha clustering competing with pairing close to ^{100}Sn. A comparison between *np*-pair and α-transfer reactions along the lines discussed in this paper will be of interest