

# Nuclear shell structure from ab initio perspectives

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## Introduction

- Maria Goeppert Mayer and J. Hans D. Jensen received the 1963 Nobel Prize for introducing strong spin-orbit (SO) coupling, which explained magic numbers beyond 20 and established the nuclear shell model. However, the microscopic origin of the strong SO potential is not fully understood.
- Since the 1969 discovery of pseudospin symmetry in nuclear shells, many studies using phenomenological models have explored it, but its first-principles origin is still unresolved.
- In this work, we address both questions by showing that strong SO coupling and pseudospin symmetry **emerge naturally** in low-energy nuclear structure. Using similarity renormalization group (SRG) methods applied to chiral effective field theory forces, **we reveal a universal transition from spin to pseudospin symmetry as the resolution scale decreases**, offering a unified explanation.

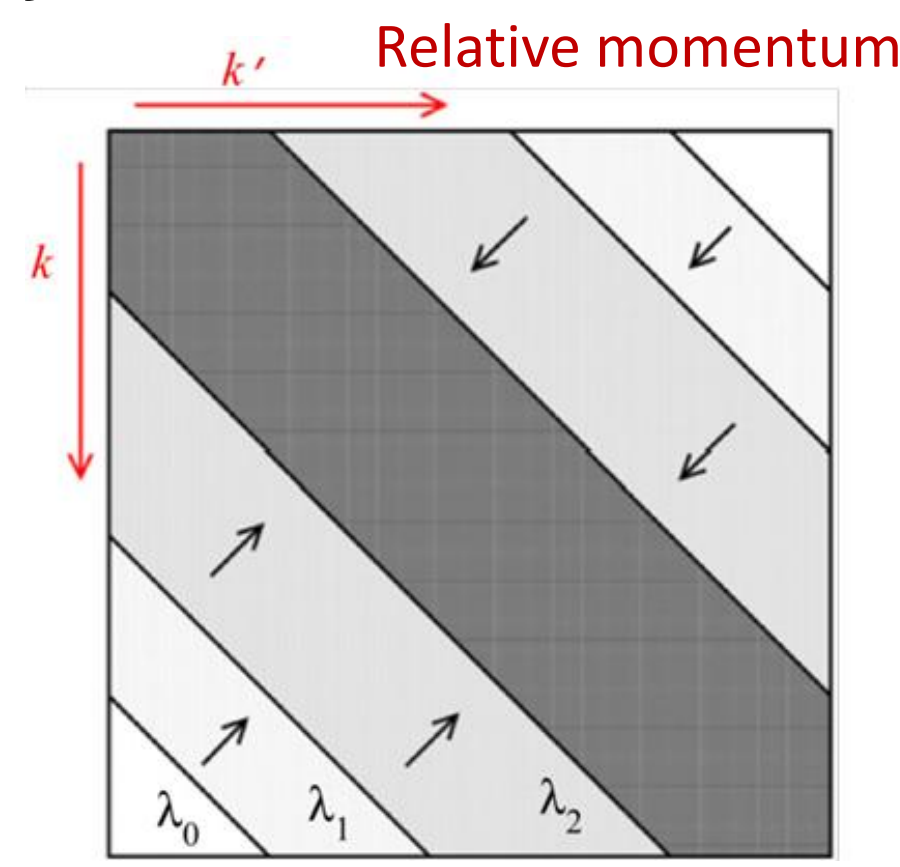
## Chiral interactions with different energy scales

- The intrinsic nuclear Hamiltonian containing both two-body (NN) and three-body (3N) interactions derived from chiral effective field theory can be written as:

$$\hat{H}_0 = \sum_{i<j} \frac{(\mathbf{p}_i - \mathbf{p}_j)^2}{2MA} + \sum_{i<j} V_{ij}^{(NN)} + \sum_{i<j<k} W_{ijk}^{(3N)}.$$

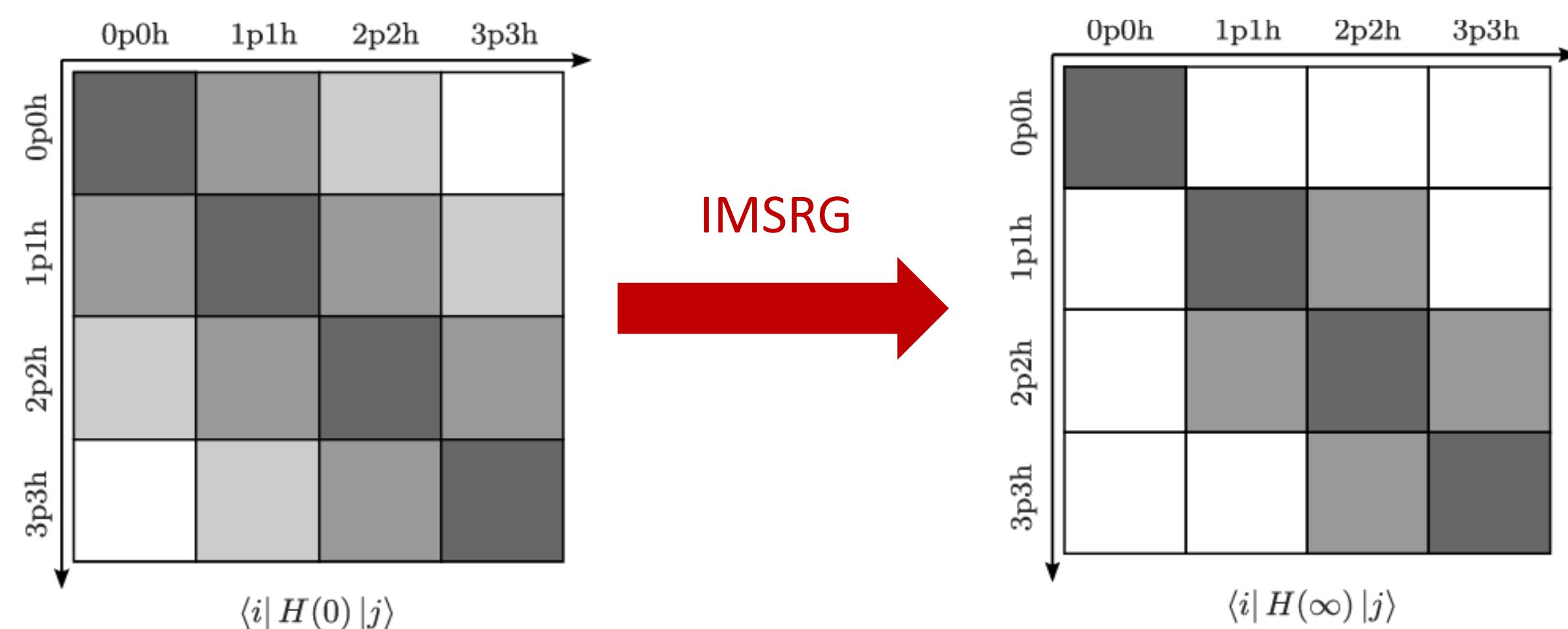
- The above Hamiltonian is evolved to different energy scales  $\lambda$  with the free-space similarity renormalization group (SRG) technique:

$$\frac{dH_\lambda}{d\lambda} = -\frac{4}{\lambda^5} [T_{rel}, H_\lambda], H_\lambda].$$

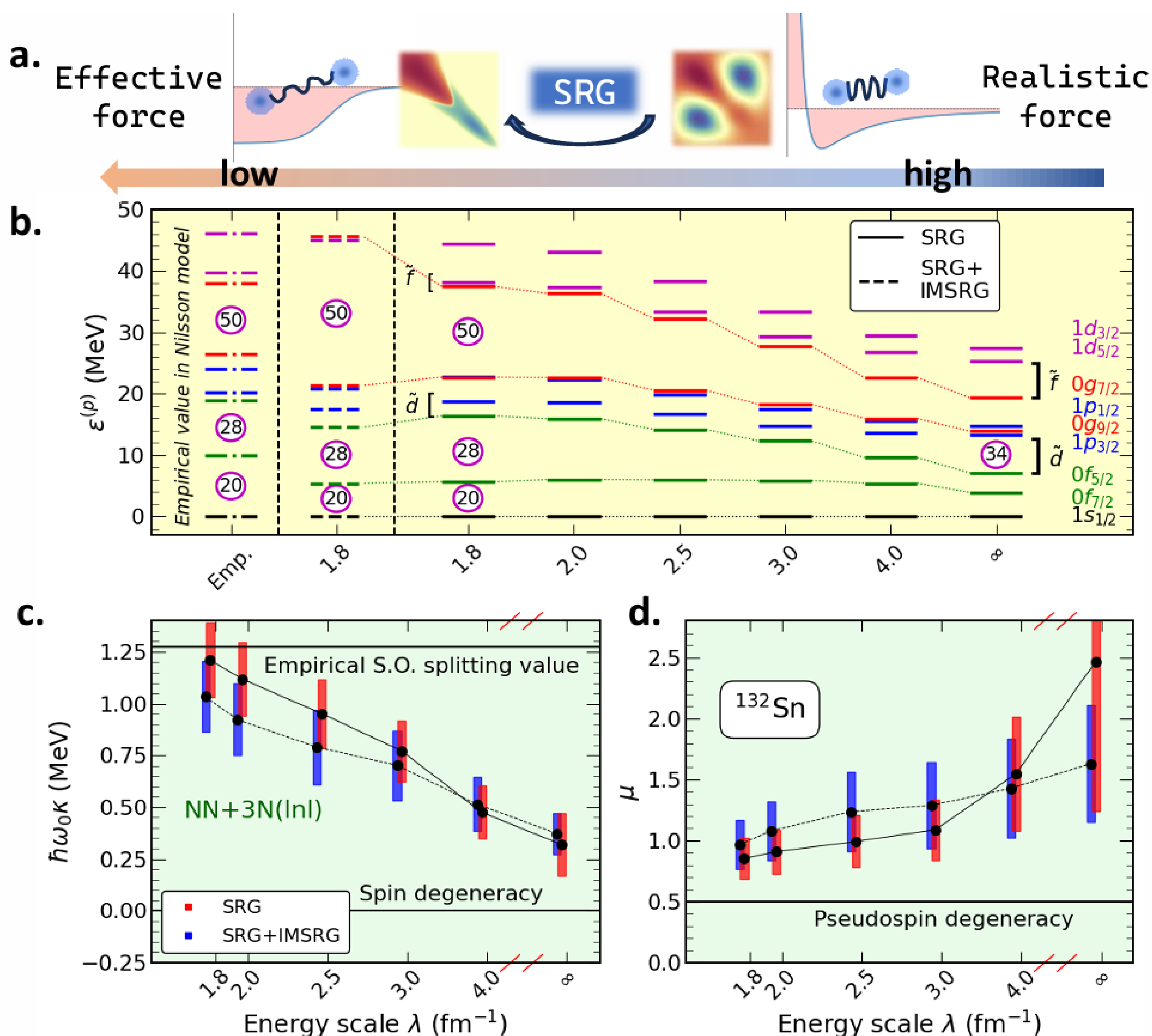


- The in-medium effect is also embedded into the Hamiltonian by using the in-medium SRG, the basic idea of which is to use a flow equation to decouple the reference state  $|\Phi\rangle$  from all other states

$$H_\lambda(s) = U(s)H_\lambda(0)U^\dagger(s), \quad \frac{dH_\lambda(s)}{ds} = [\eta(s), H_\lambda(s)].$$

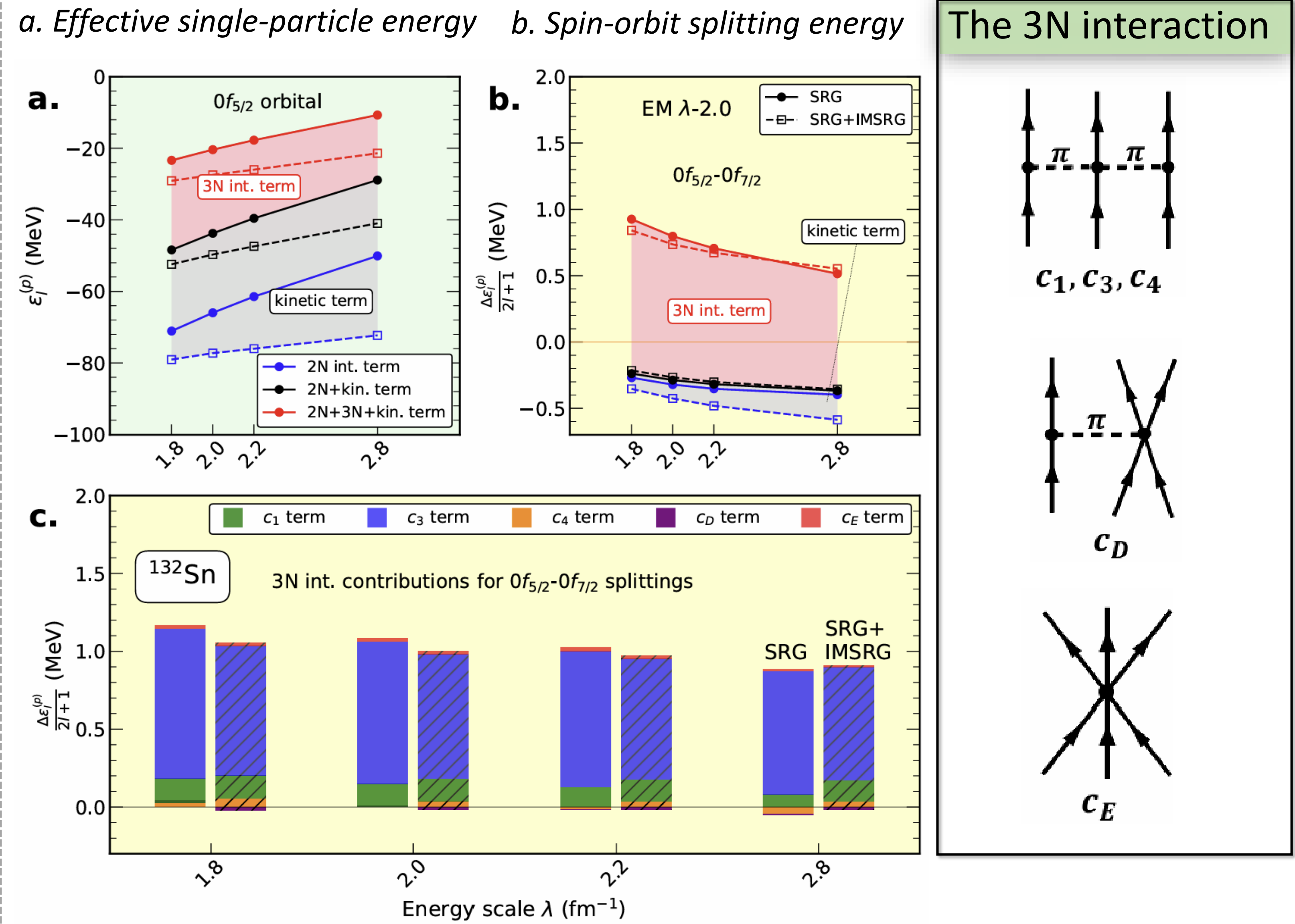


## From spin to pseudospin symmetries



- Spin-orbit splitting increases
- Pseudospin splitting decreases
- The magic numbers emerge with the decrease of the energy scale

## Connection between interactions and SO splitting



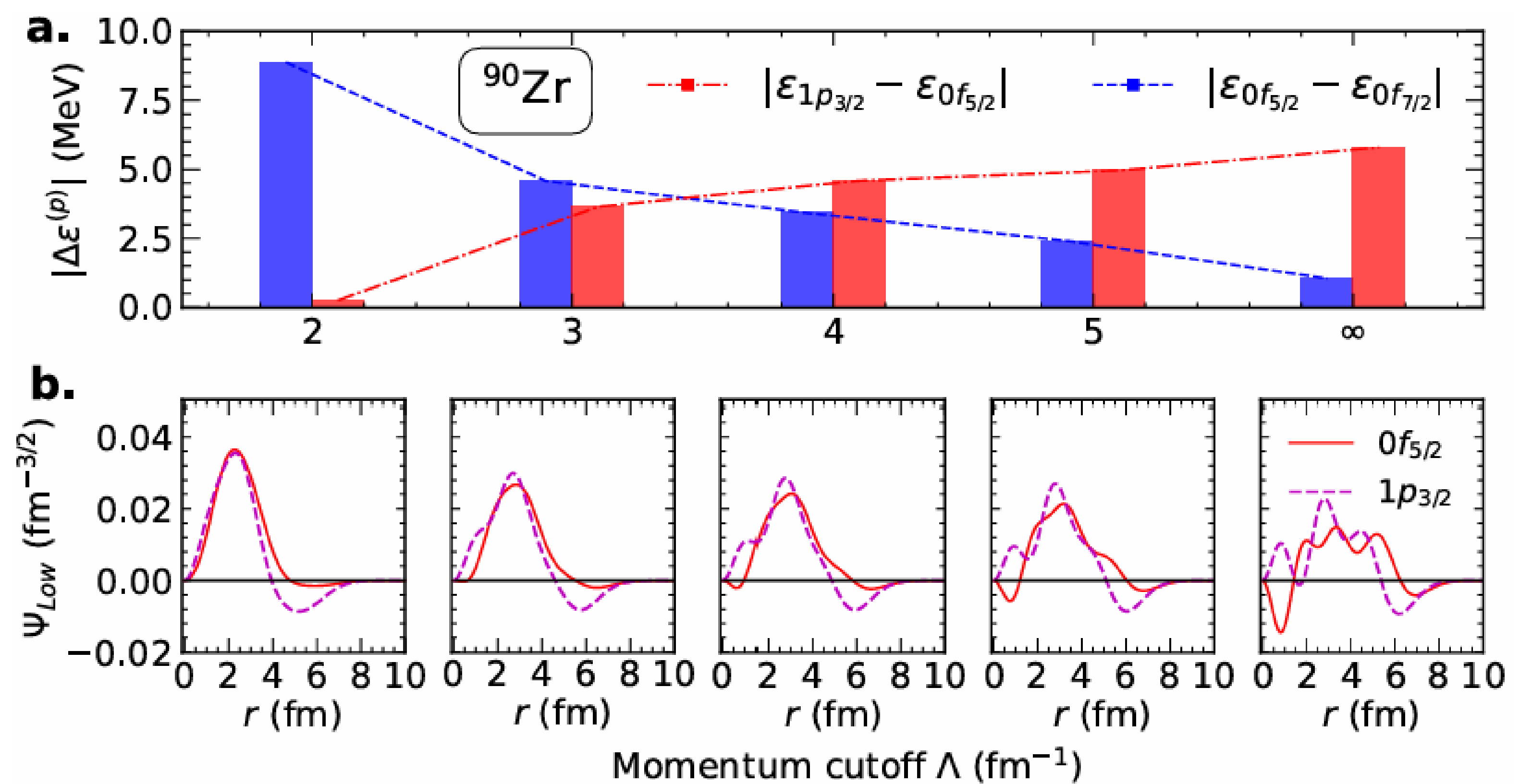
- The 3N force plays an essential role in enhancing spin-orbit splitting during the evolution.
- The  $c_3$  term dominates the 3N contribution to spin-orbit splitting.

## Nuclear shell structure from relativistic studies

- The relativistic NN force is defined as the one-boson-exchange potential (OBEP), which is constructed with non-local regulators as:

$$V_\Lambda(q', q) = R(q')V(q', q)R(q), \quad R(q) = \exp[-(q^{2n}/\Lambda^{2n})].$$

Fit the partial-wave phase shifts for different cutoffs  $\Lambda$ , and obtain the potentials with different energy scales.



With the decrease of energy scale:

- The wave functions of the lower components in Dirac spinors exhibit convergent behavior between pseudospin partners, demonstrating the phenomenon of pseudospin degeneracy.
- A transition from spin symmetry to pseudospin symmetry is observed.

## Conclusions

- We uncover a universal transition from spin symmetry to pseudospin symmetry as the resolution scale decreases, during which magic numbers emerge naturally.
- A similar pattern is found in calculations using relativistic one-boson-exchange potentials, underscoring the robustness of the phenomenon.
- This work establishes a direct connection between realistic nuclear forces with a high-resolution scale and effective nuclear forces at coarse-grained scales, offering a first-principles explanation for the origin of magic numbers and pseudospin symmetry in nuclear shell structure, and new insights into the shell structure far from stability.

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