Generic features of the neutron-proton interaction

P. Van Isacker, GANIL, France

The mother of all schematic interactions

A schematic neutron-proton interaction?

Aligned neutron-proton pairs

A comment on transfer reactions

NP pairing, ESNT, Saclay, September 2018

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Rapid Communications

Generic features of the neutron-proton interaction

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We show that fully aligned neutron-proton pairs play a crucial role in the low-energy spectroscopy of nuclei with valence nucleons in a high-j orbital. Their dominance is valid in nuclei with valence neutrons and protons in different high-j orbitals as well as in $N = Z$ nuclei, where all nucleons occupy the same orbital. We demonstrate analytically this generic feature of the neutron-proton interaction for a variety of systems with four valence nucleons interacting through realistic, effective forces. The dominance of fully aligned neutron-proton pairs results from the combined effect of (i) angular momentum coupling and (ii) basic properties of the neutron-proton interaction.

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Theory of complex spectra

In the 1940s Racah published a series of seminal papers on the application of group theory to atomic spectra. The third of the series (primarily concerned with coefficients of fractional parentage) contains the first mention of the pairing interaction and seniority.

PHYSICAL REVIEW VOLUME 63, NUMBERS 9 AND 10 MAY 1 AND 15, 1943

Theory of Complex Spectra. III

GIULIO RACAH
The Hebrew University, Jerusalem, Palestine
(Received February 8, 1943)

The consideration of the phases of the fractional-parentage coefficients allows the extension of the matrix methods to configurations with more than two equivalent electrons. Tables are given for the parentages of the terms of p^n and d^n. Applications are made to the spin-orbit interaction of the d^n terms and to the electrostatic interaction between the configurations d^n, $d^{n-1}s$, and $d^{n-2}s^2$. Errata in Part II are indicated.

Racah's "seniority number"

In this section we shall classify the terms of the configuration l^n according to the eigenvalues of

$$Q=\sum_{i<j} q_{ij}, \qquad (34)$$

where q_{ij} is a scalar operator which operates on the two equivalent electrons i and j and is defined by the relation

$$(l^2LM|q_{ij}|l^2LM)=(2l+1)\delta(L, 0). \qquad (35)$$

It will be shown that to every term of l^n with non-vanishing Q a term of the same kind corresponds in l^{n-2}, and this fact will allow us to assign to each term a "seniority number" according to the value of n for which the term appeared for the first time. Some useful relation between the fractional parentages of corresponding terms will be obtained and it will also be shown that the classification of the terms of l^{2l+1} according to the two possibilities of (76)II depends only on the seniority of the term.

We may thus assign to each term in the QSL scheme a "seniority number" v, which indicates the number of electrons of the first member of its chain; it follows immediately from (45) that Q depends only on n and v and that its values are given by

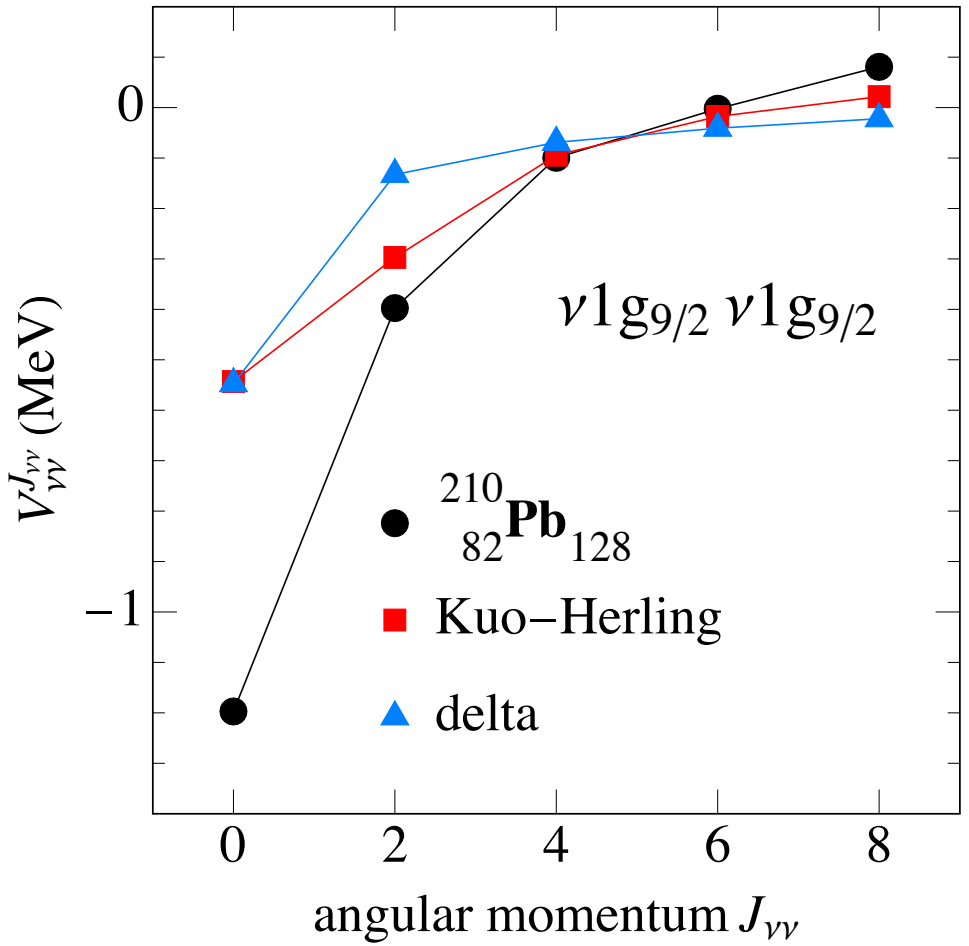
$$Q(n, v)=\tfrac{1}{4}(n-v)(4l+4-n-v). \qquad (50)$$

Confronting (41) and (50) we see that conjugate terms have the same seniority.

The seniority number suffices for distinguishing the different terms of the same kind in the configurations d^n but not in f^n, since there are in f^n terms of the same kind which have also the same seniority. For such configurations an unspecified parameter α must be maintained besides v; terms corresponding according to (49) will have the same values of v and of α.

G. Racah, Phys. Rev. **63** (1943) 367
I. Talmi, *Simple Models of Complex Nuclei*

The $\nu 1g_{9/2}$-$\nu 1g_{9/2}$ interaction



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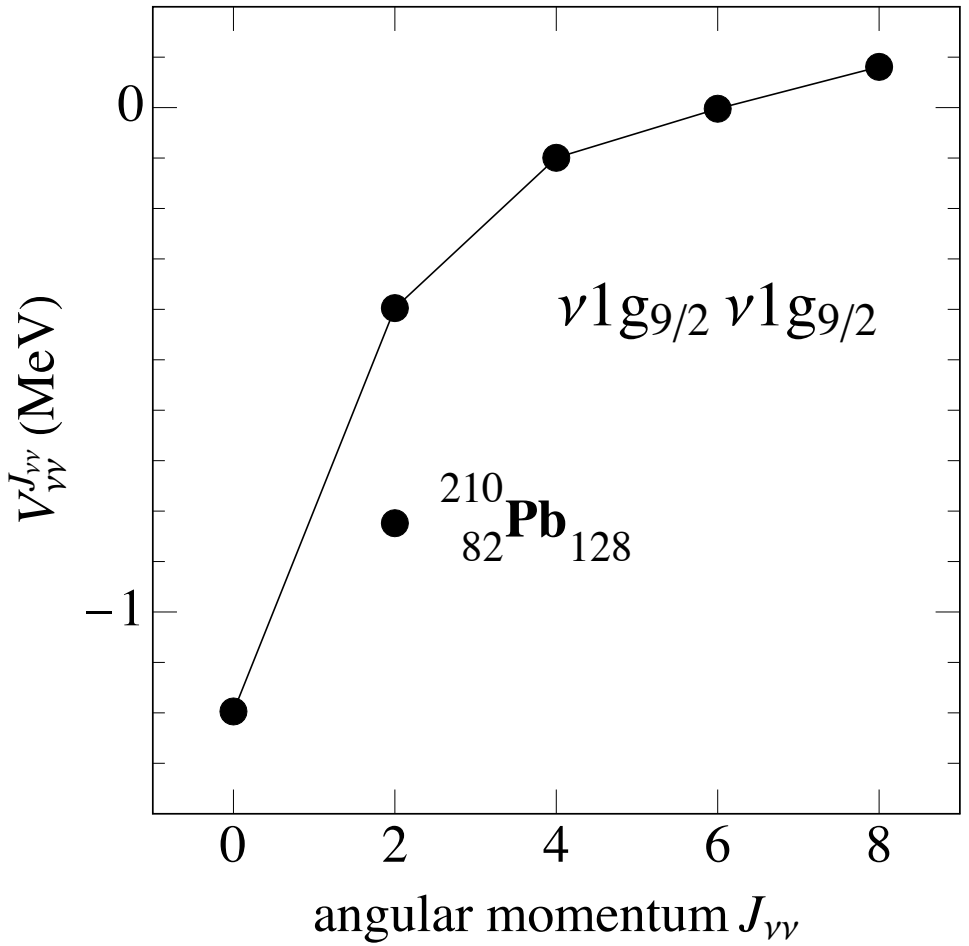

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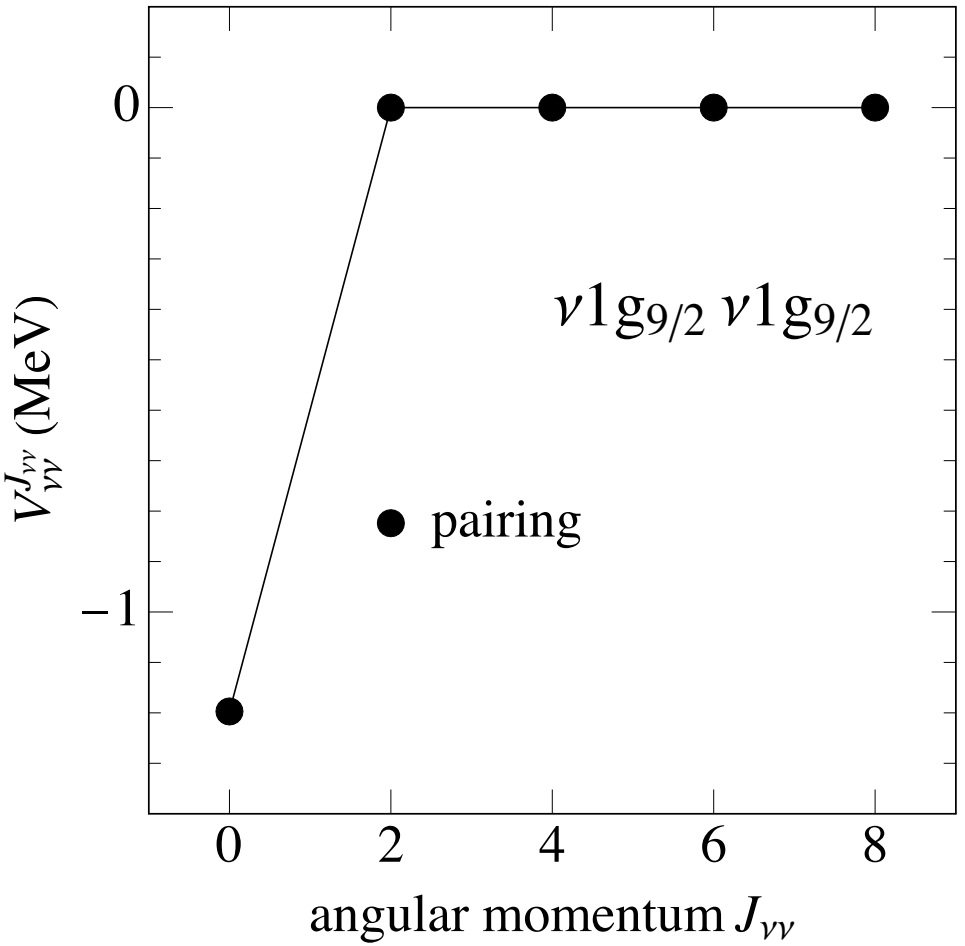


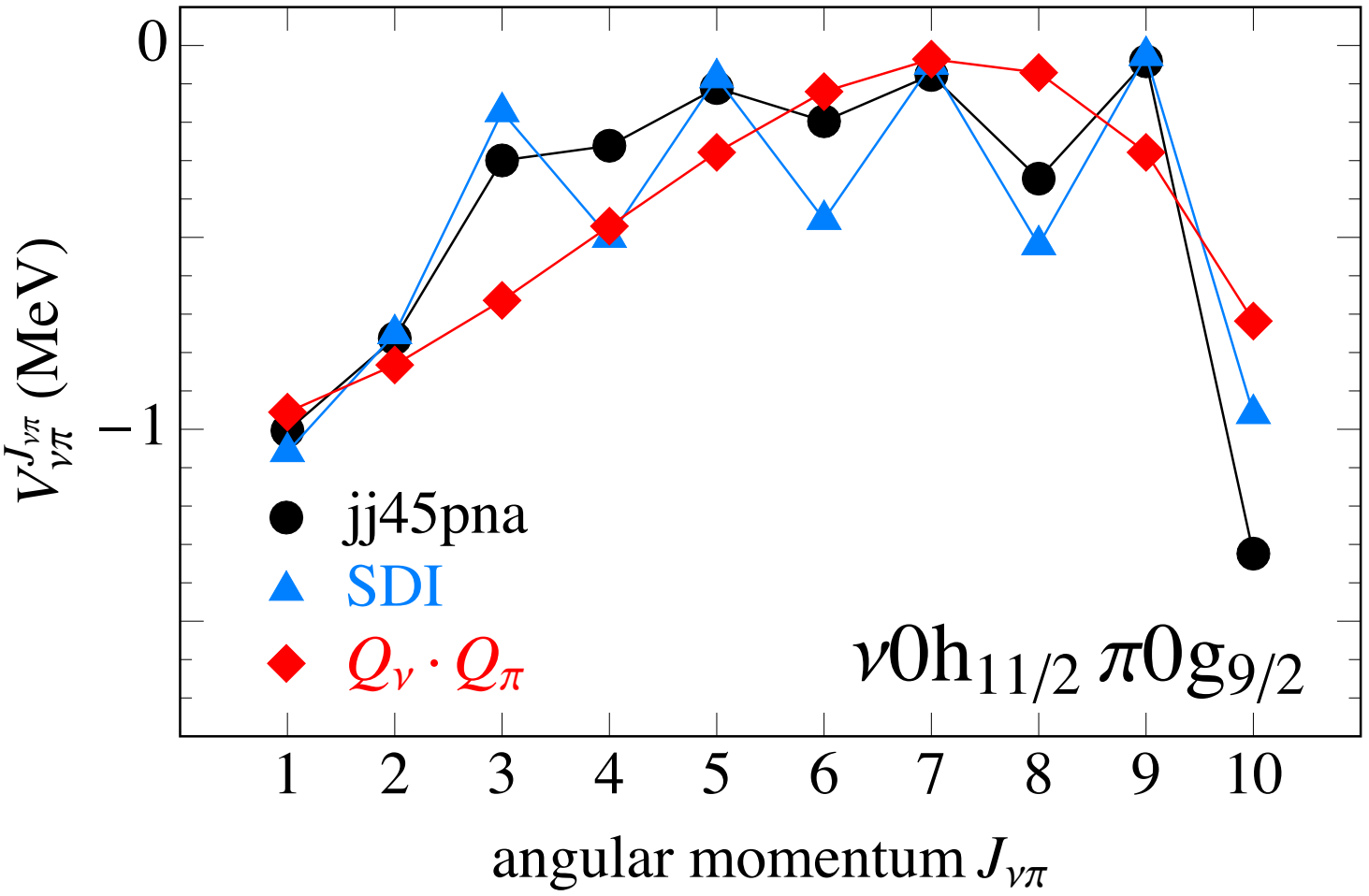
A schematic np interaction?

Can we similarly define a schematic neutron-proton interaction with a *single* non-zero component?

Study 2n-2p nuclei. Examples:

- ^{128}Cd with two neutron holes in $\nu 0h_{11/2}$ and two proton holes in $\pi 0g_{9/2}$
- ^{212}Po with two neutrons in $\nu 1g_{9/2}$ and two protons in $\pi 0h_{9/2}$
- ...

The $\nu 0h_{11/2}$-$\pi 0g_{9/2}$ interaction



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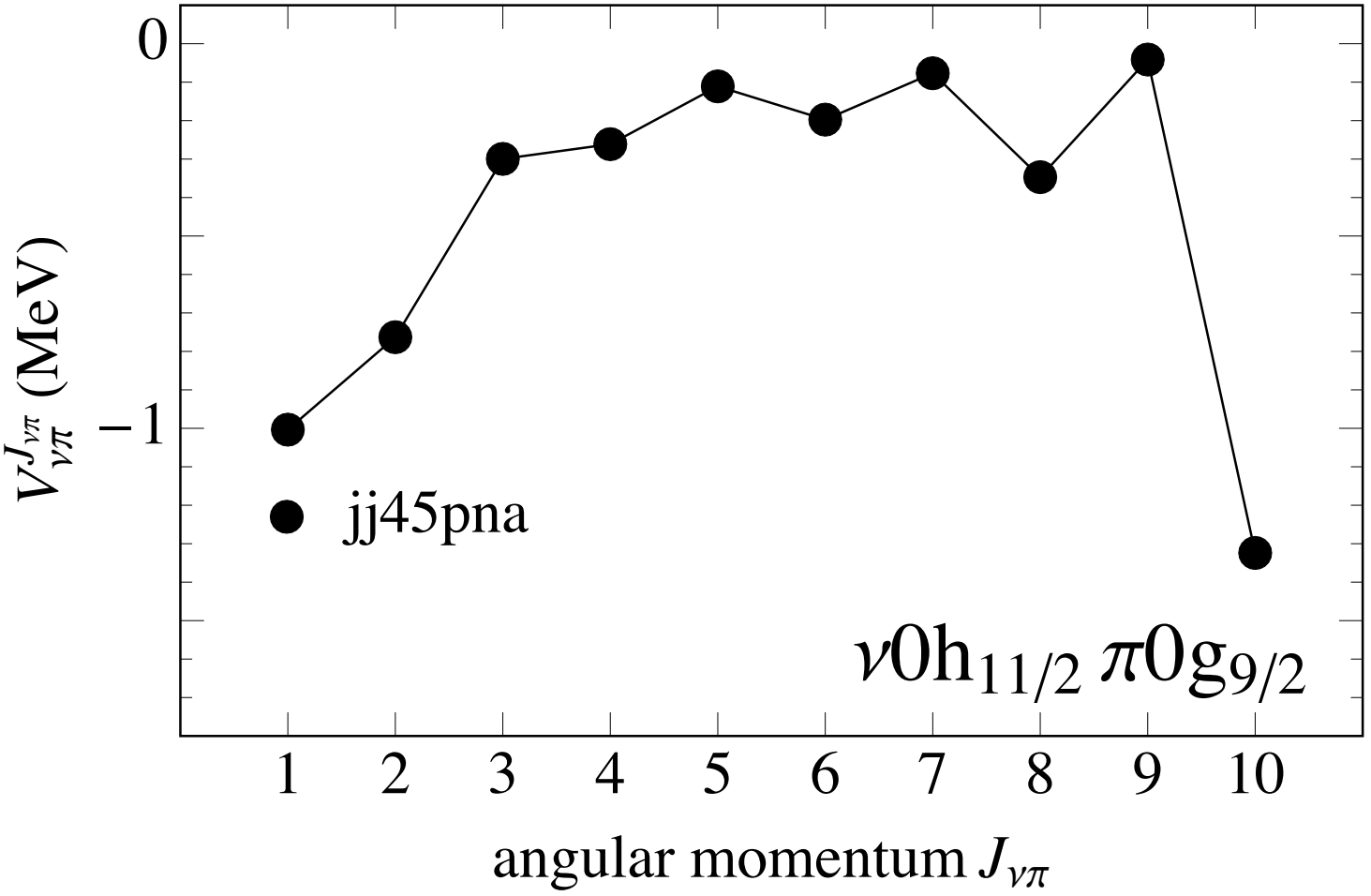

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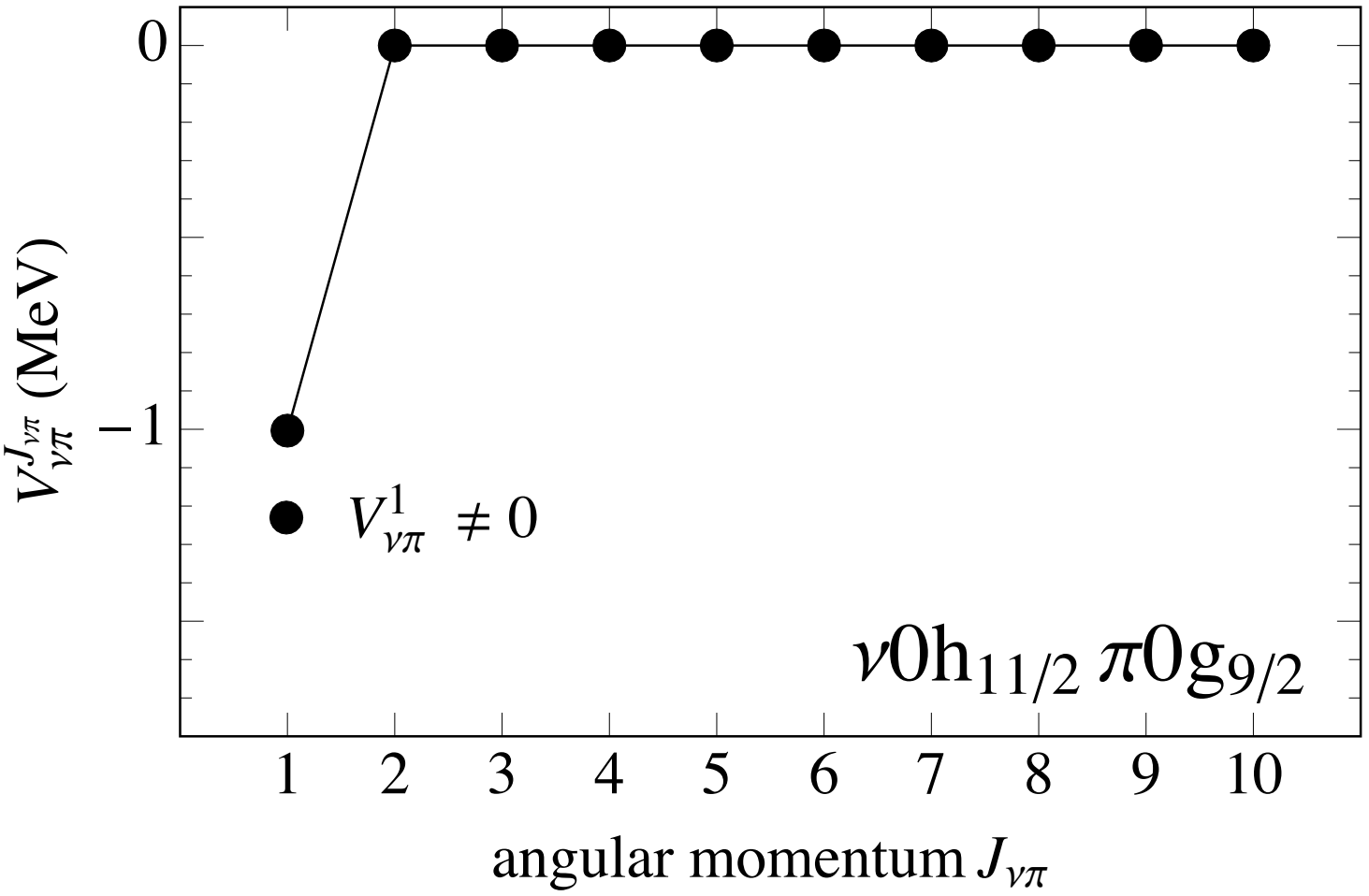

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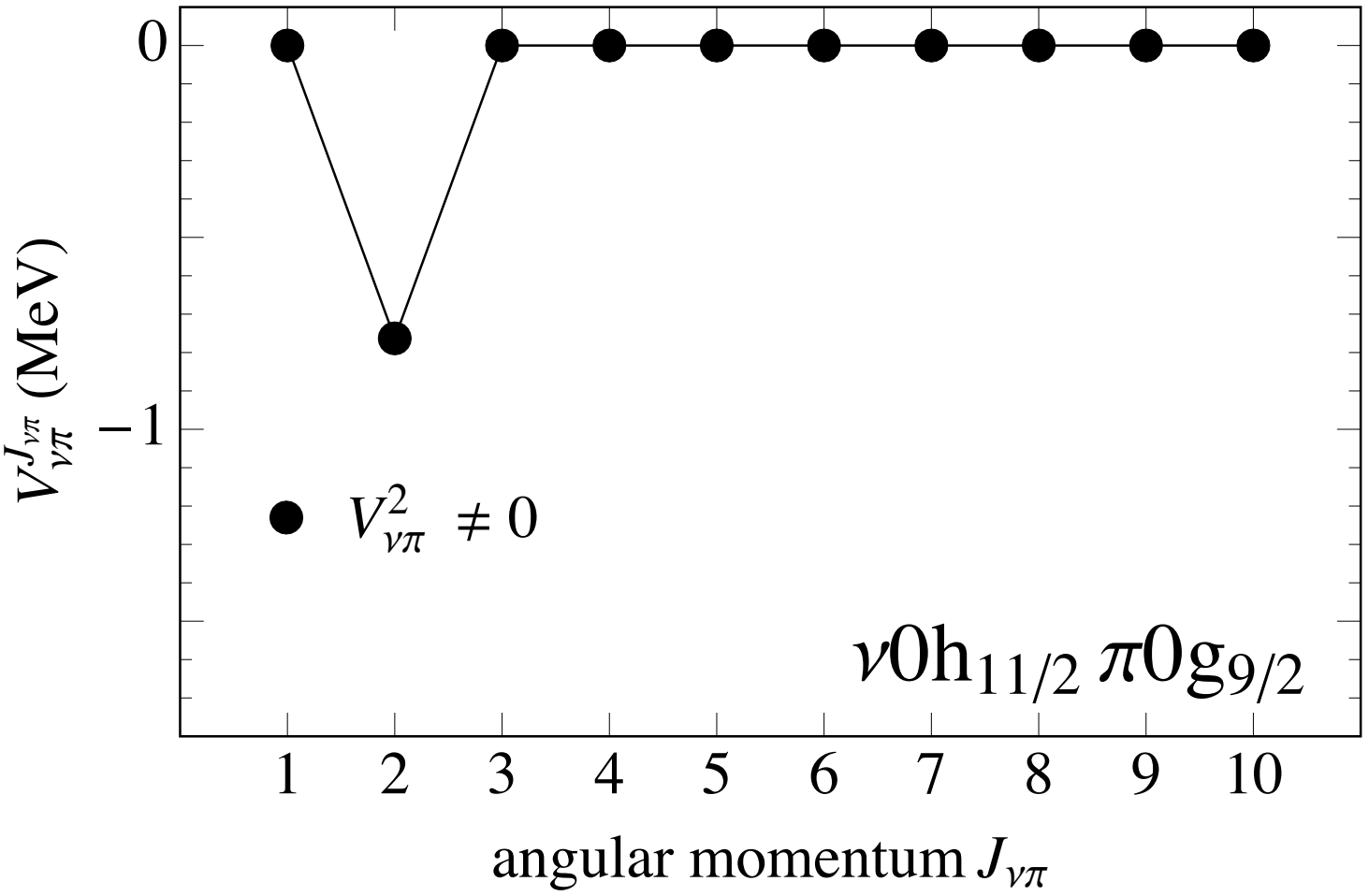

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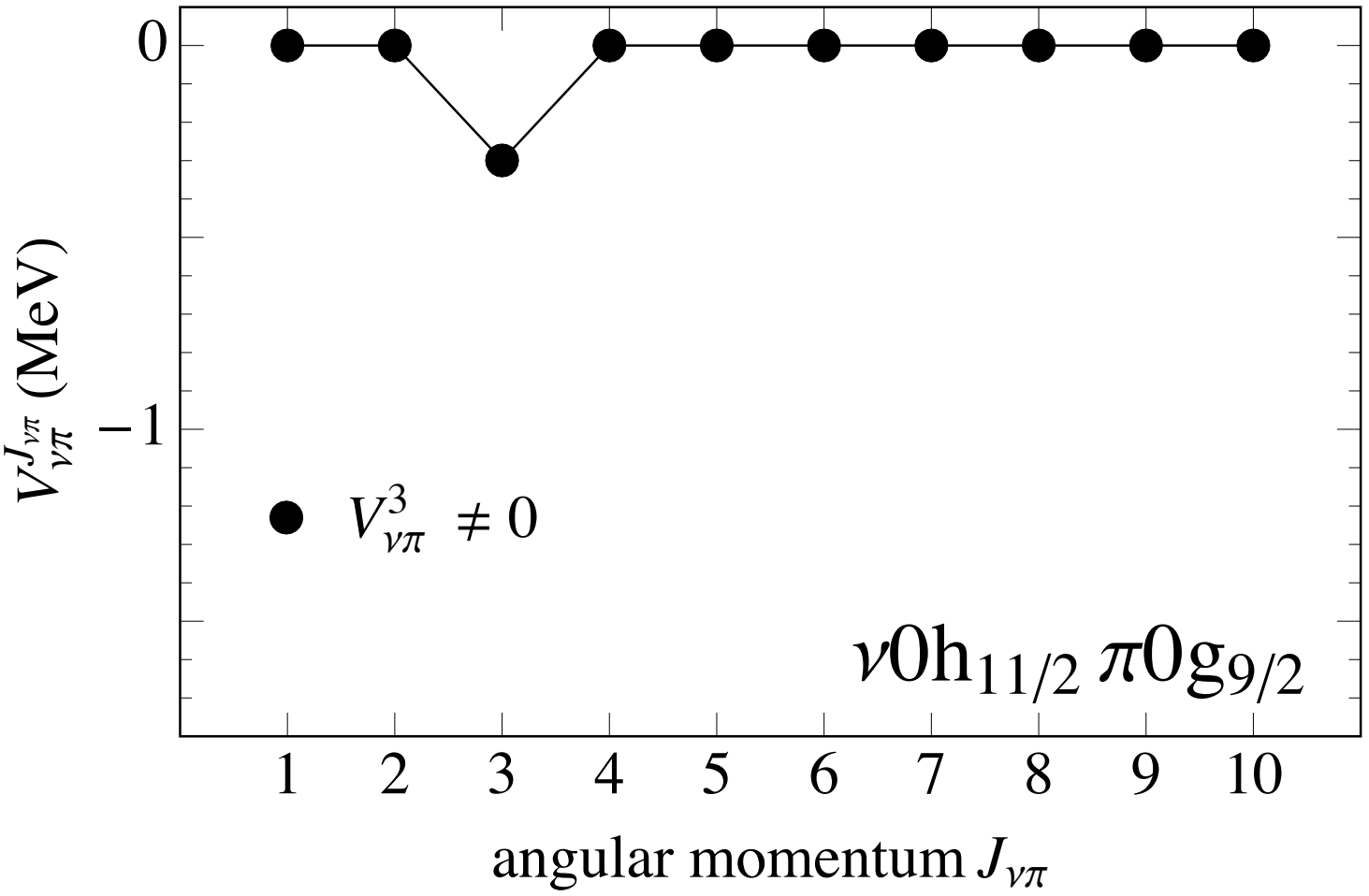

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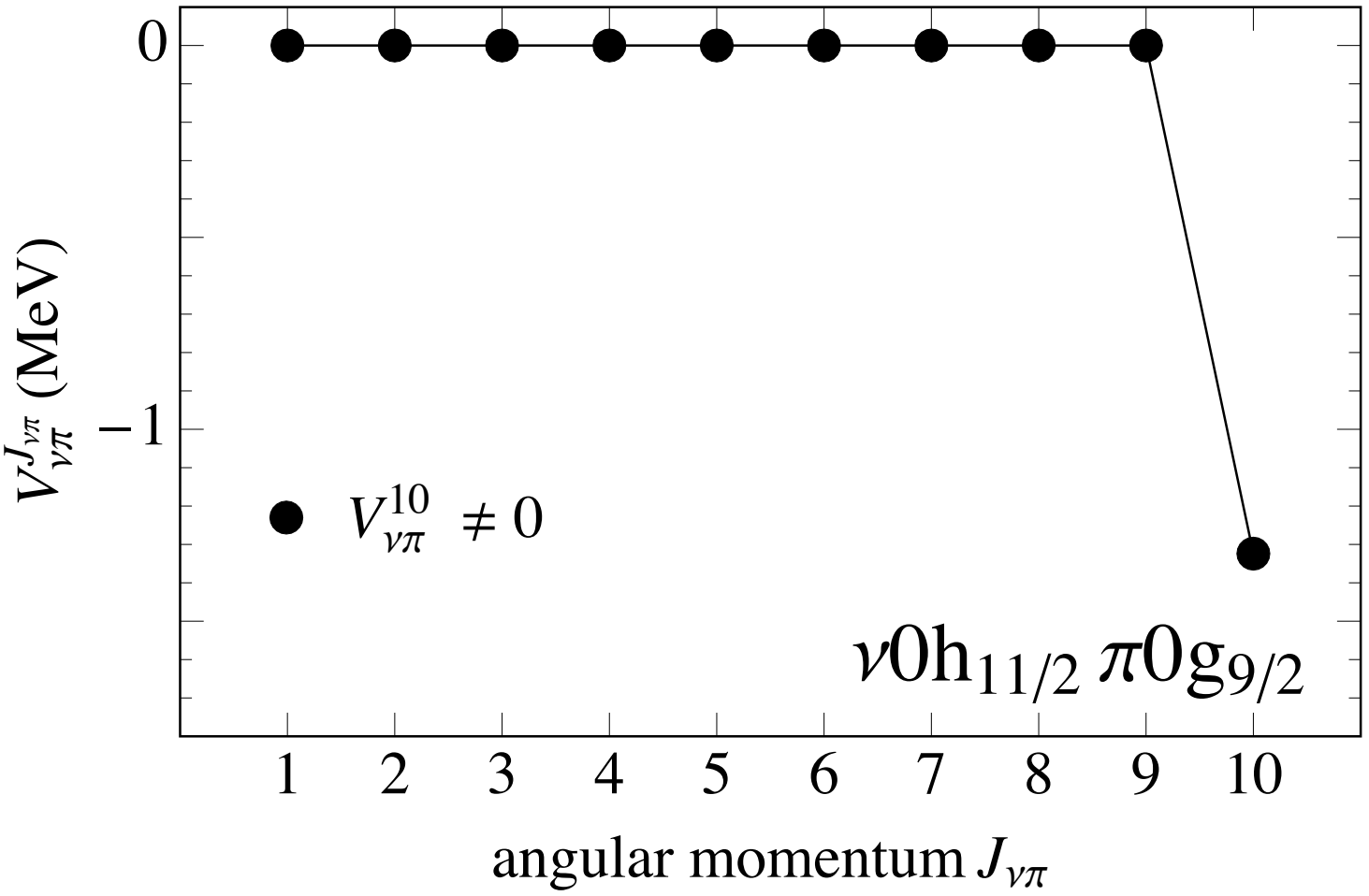
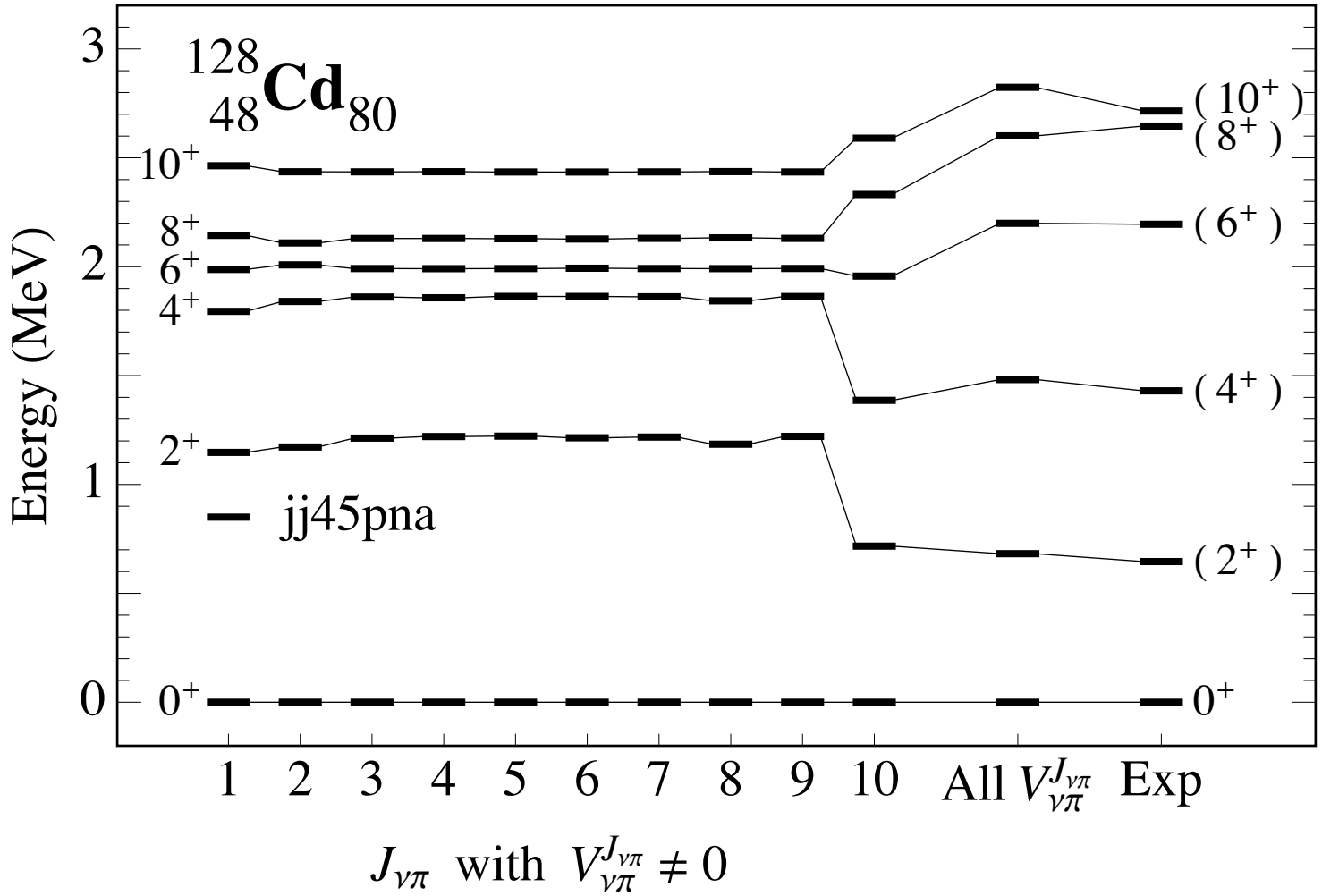


The 2n-2p spectrum: ^{128}Cd



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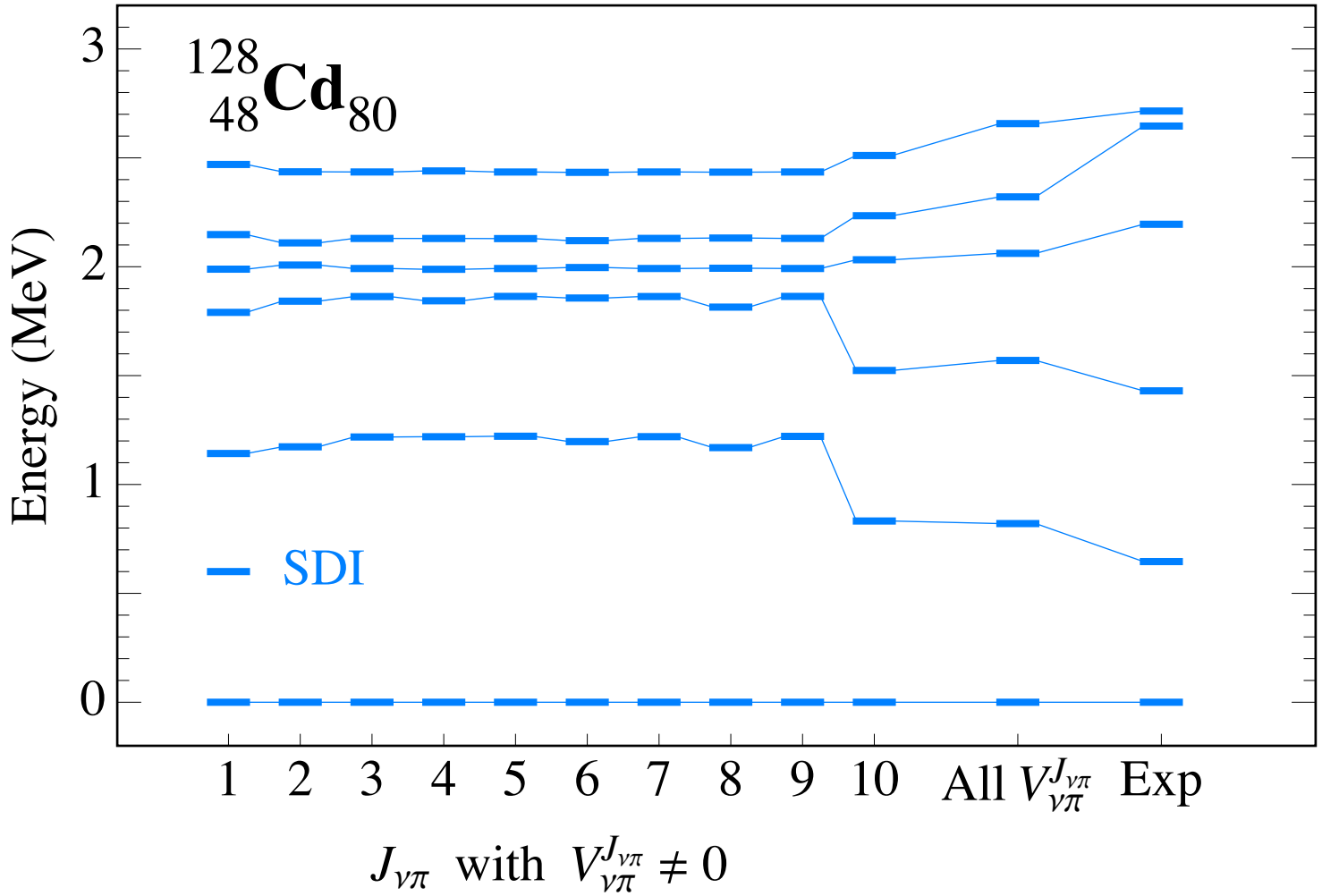

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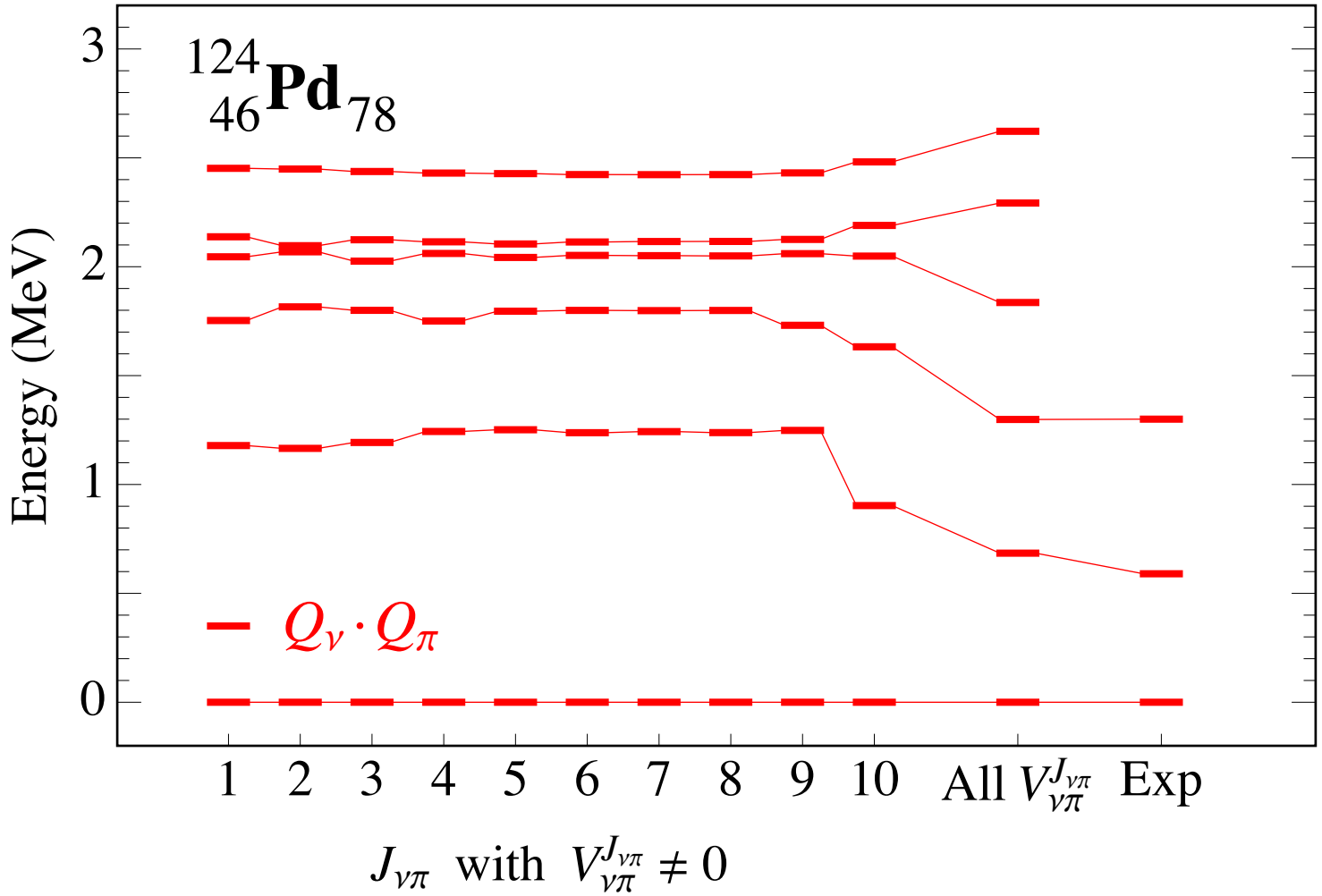

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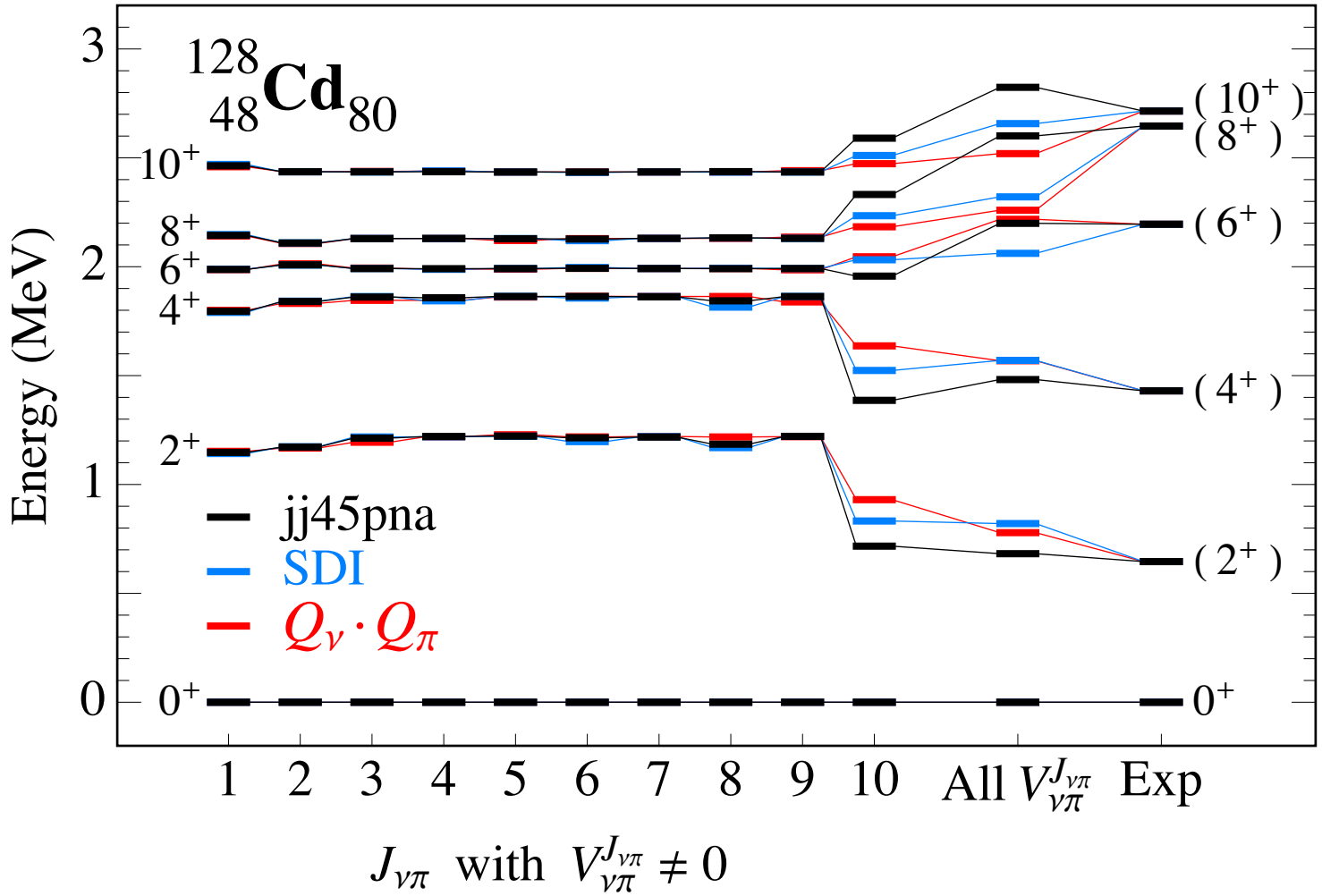


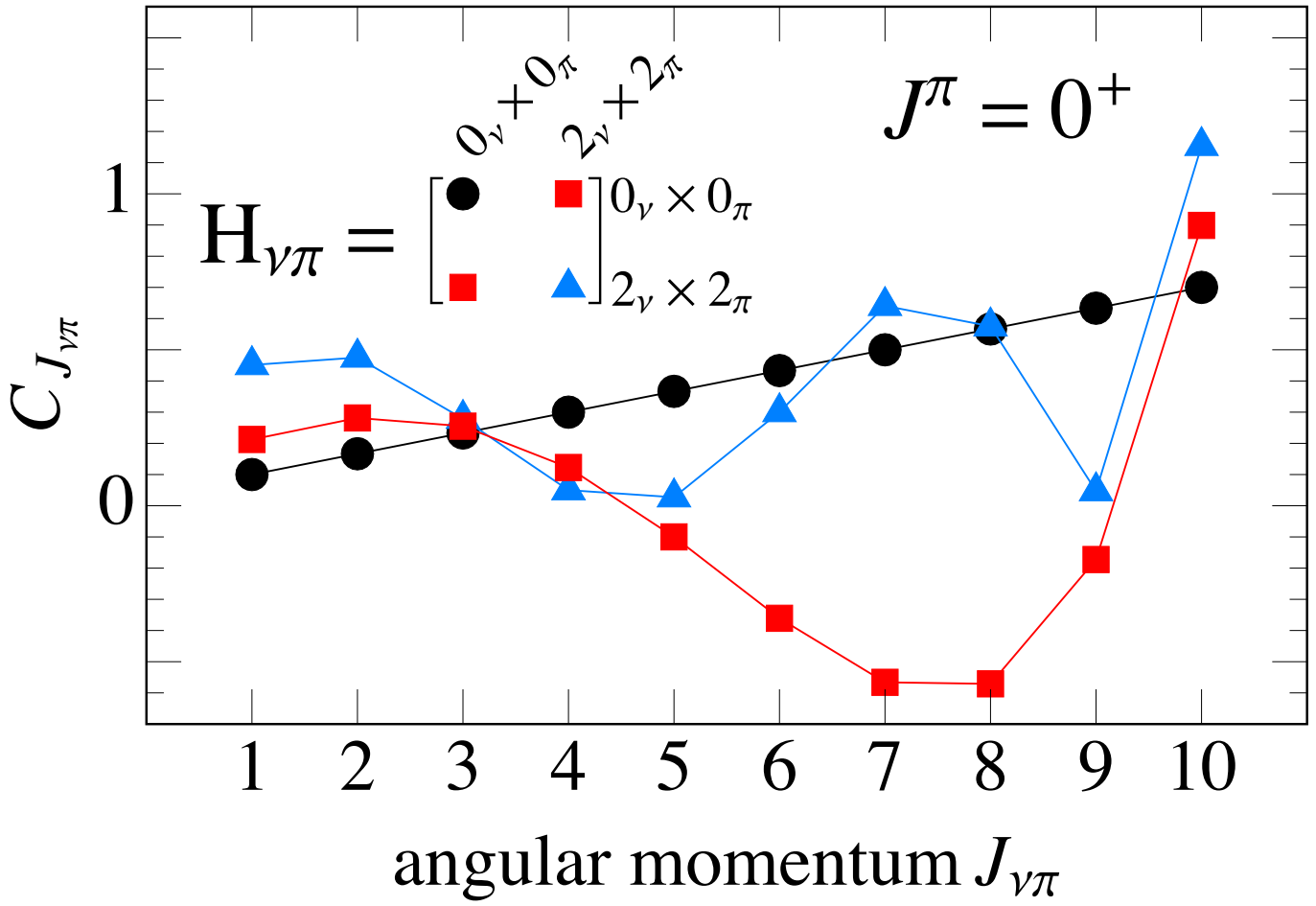
The 2n-2p matrix element

The 2n-2p matrix element of the np interaction

$$\left\langle J_\nu J_\pi ; J \left| \hat{V}_{\nu\pi} \right| J'_\nu J'_\pi ; J \right\rangle = \sum_{J_{\nu\pi}=|j_\nu - j_\pi|}^{j_\nu + j_\pi} C_{J_{\nu\pi}} \times V_{\nu\pi}^{J_{\nu\pi}}$$

$$C_{J_{\nu\pi}} \propto \begin{Bmatrix} j_\nu & j_\pi & J_\pi & J_\nu \\ J_{\nu\pi} & j_\pi & J & j_\nu \\ j_\nu & j_\pi & J'_\pi & J'_\nu \end{Bmatrix}$$

The 2n-2p matrix element



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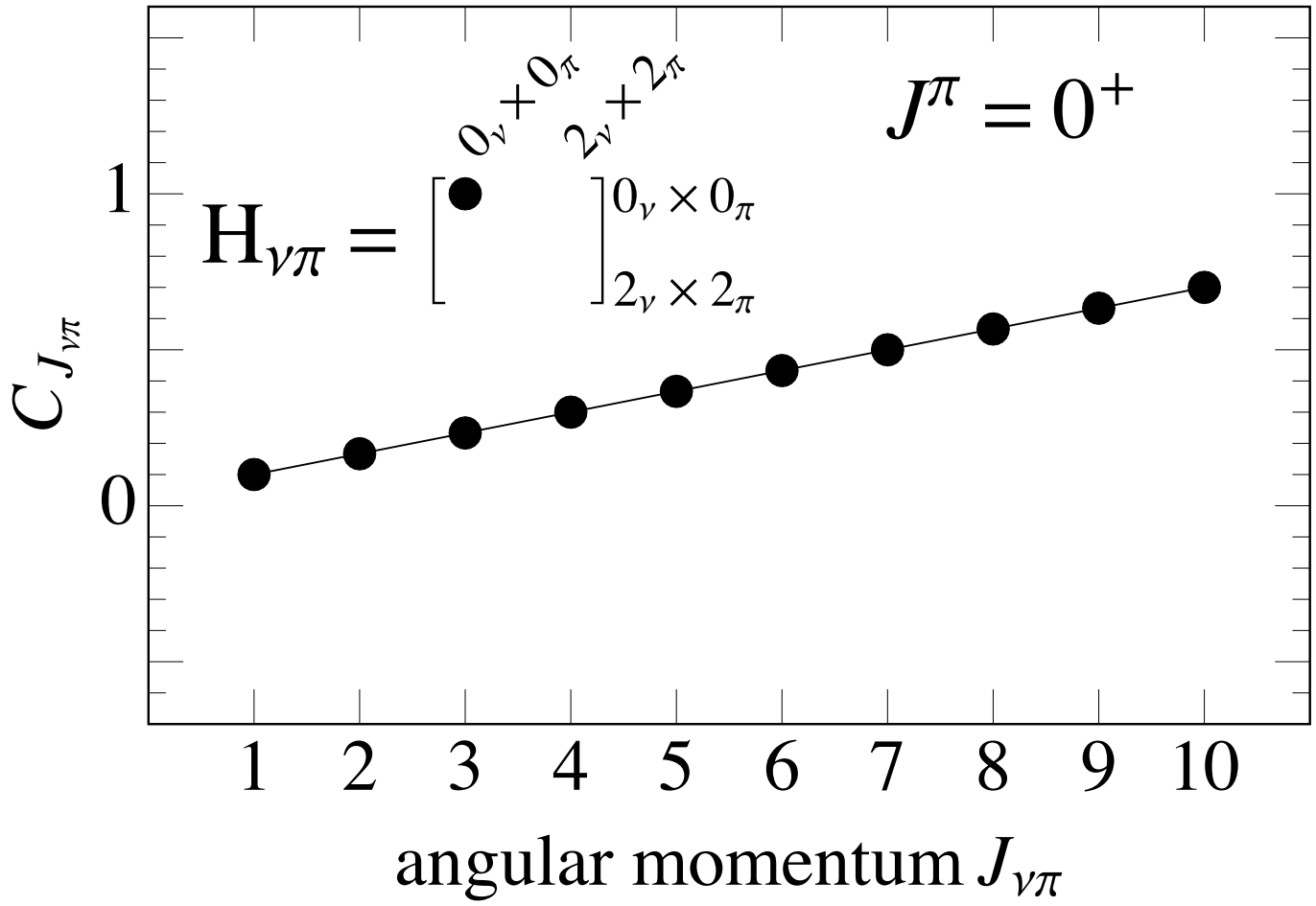
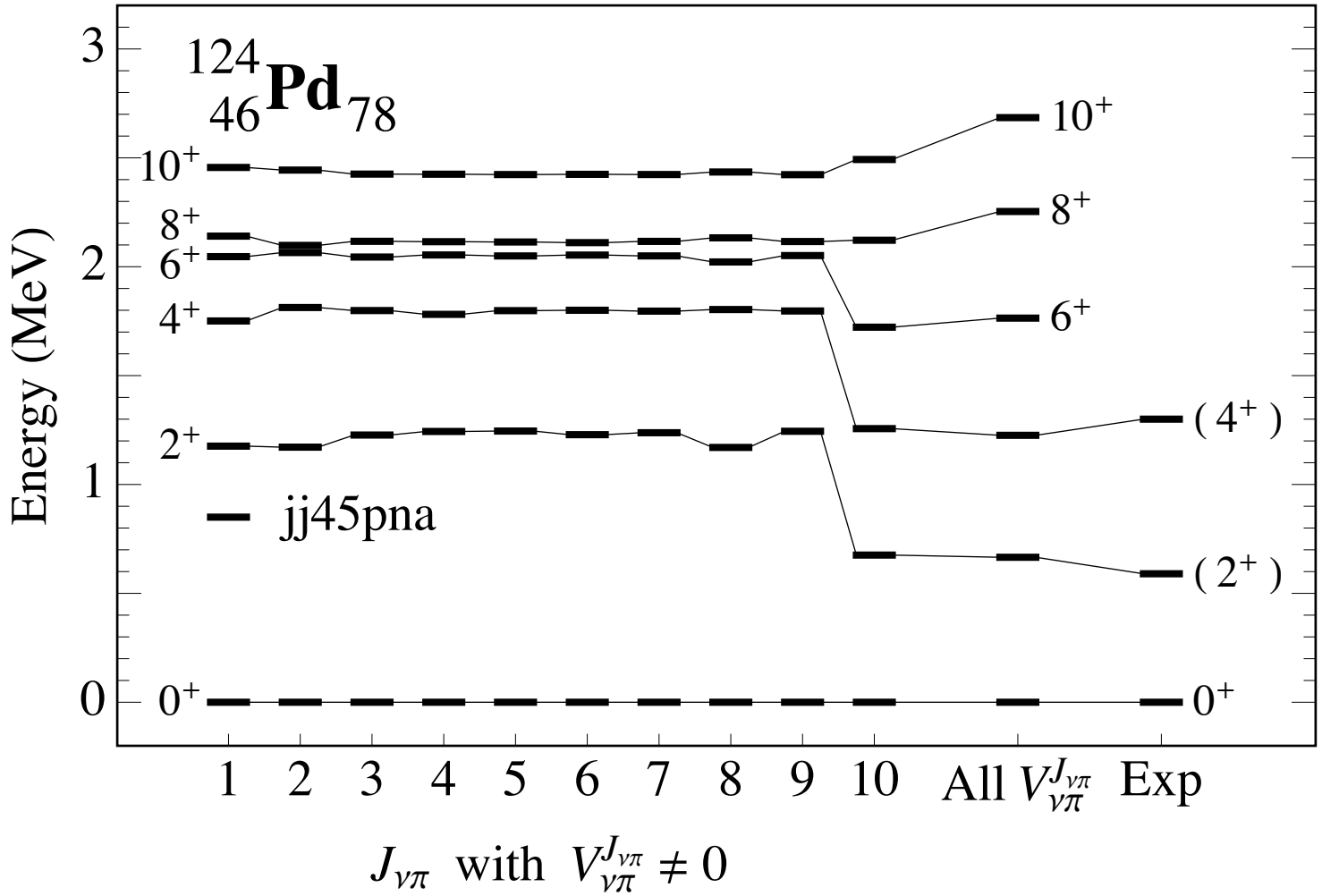
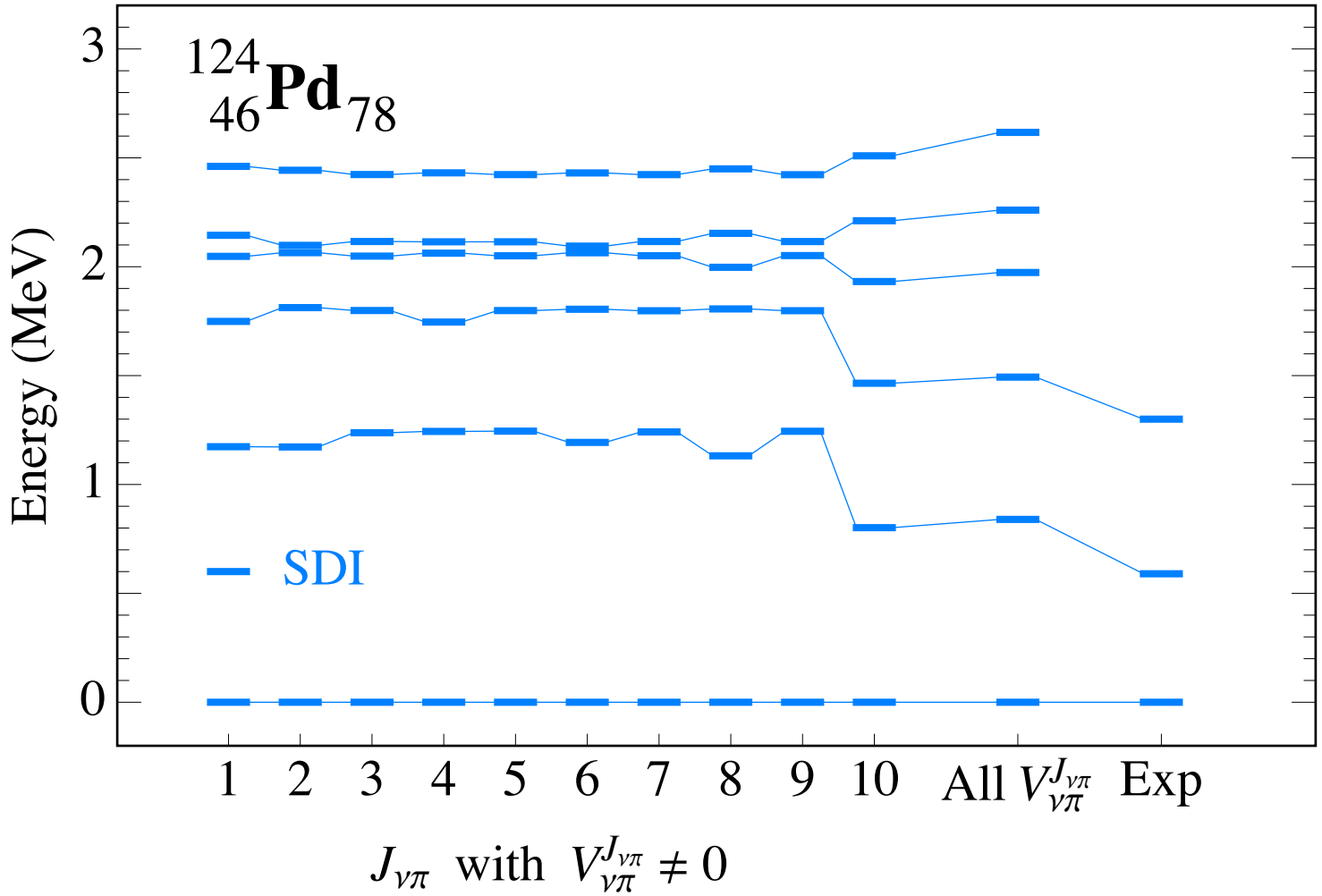


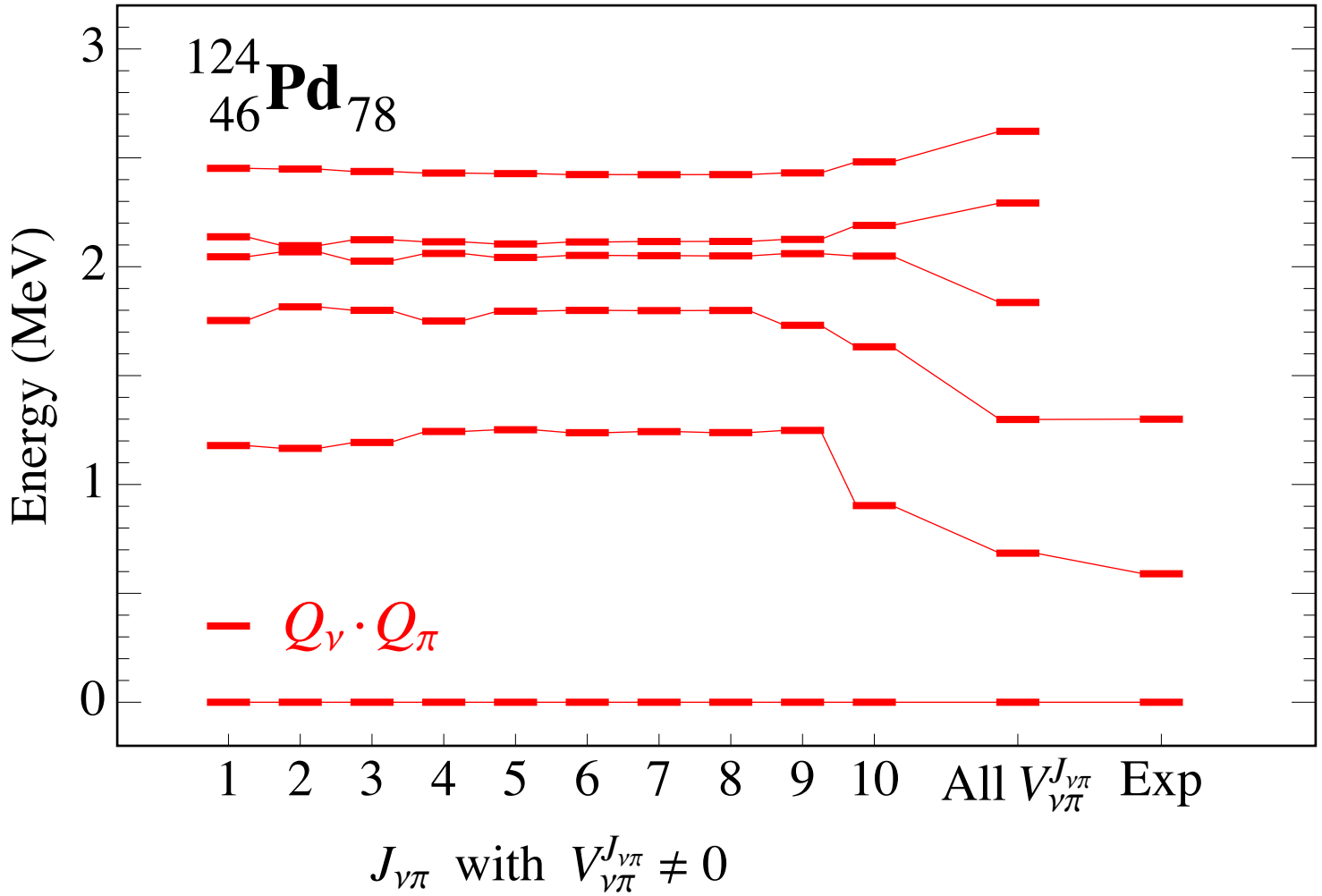
The 4n-4p spectrum: ^{124}Pd



The 4n-4p spectrum: ^{124}Pd



The 4n-4p spectrum: ^{124}Pd



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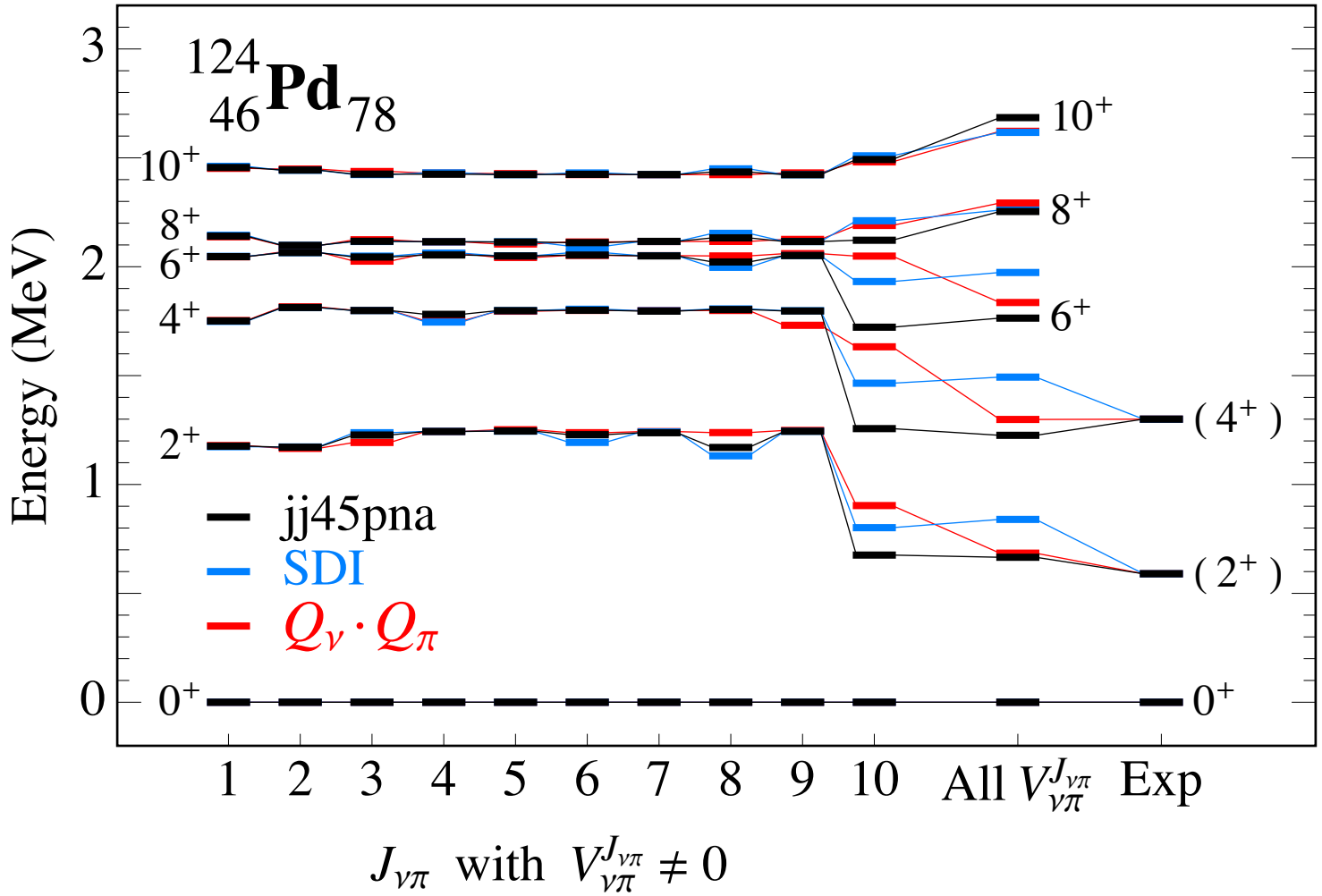
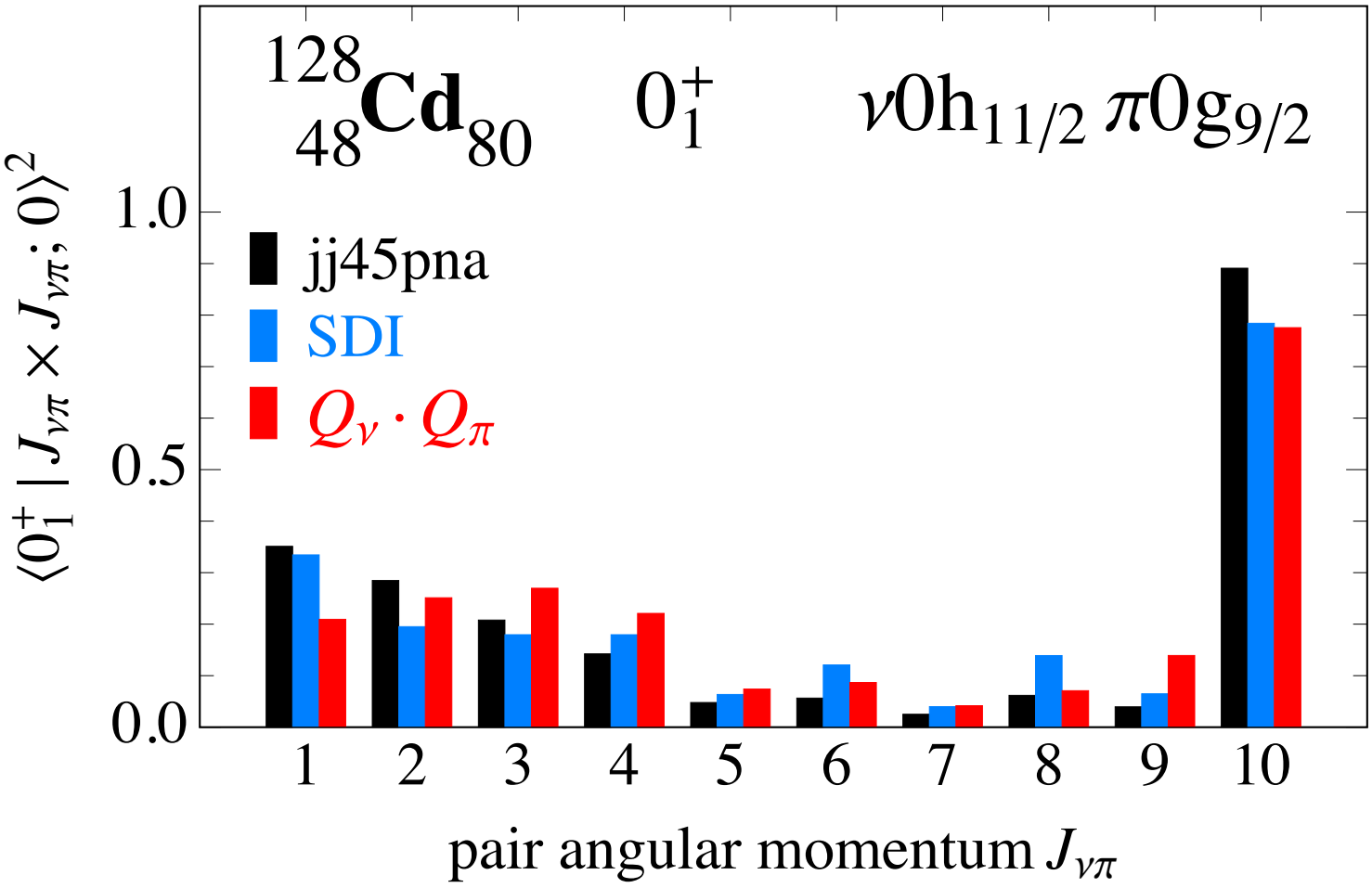


A schematic np interaction

If valence nucleons dominantly occupy high-j orbitals, the yrast spectroscopy is dominantly determined by a single matrix element, namely the one where neutron and proton are aligned in angular momentum.

Question: Can the wave functions be written dominantly in terms of aligned neutron-proton pairs?

Neutron-proton pair analysis



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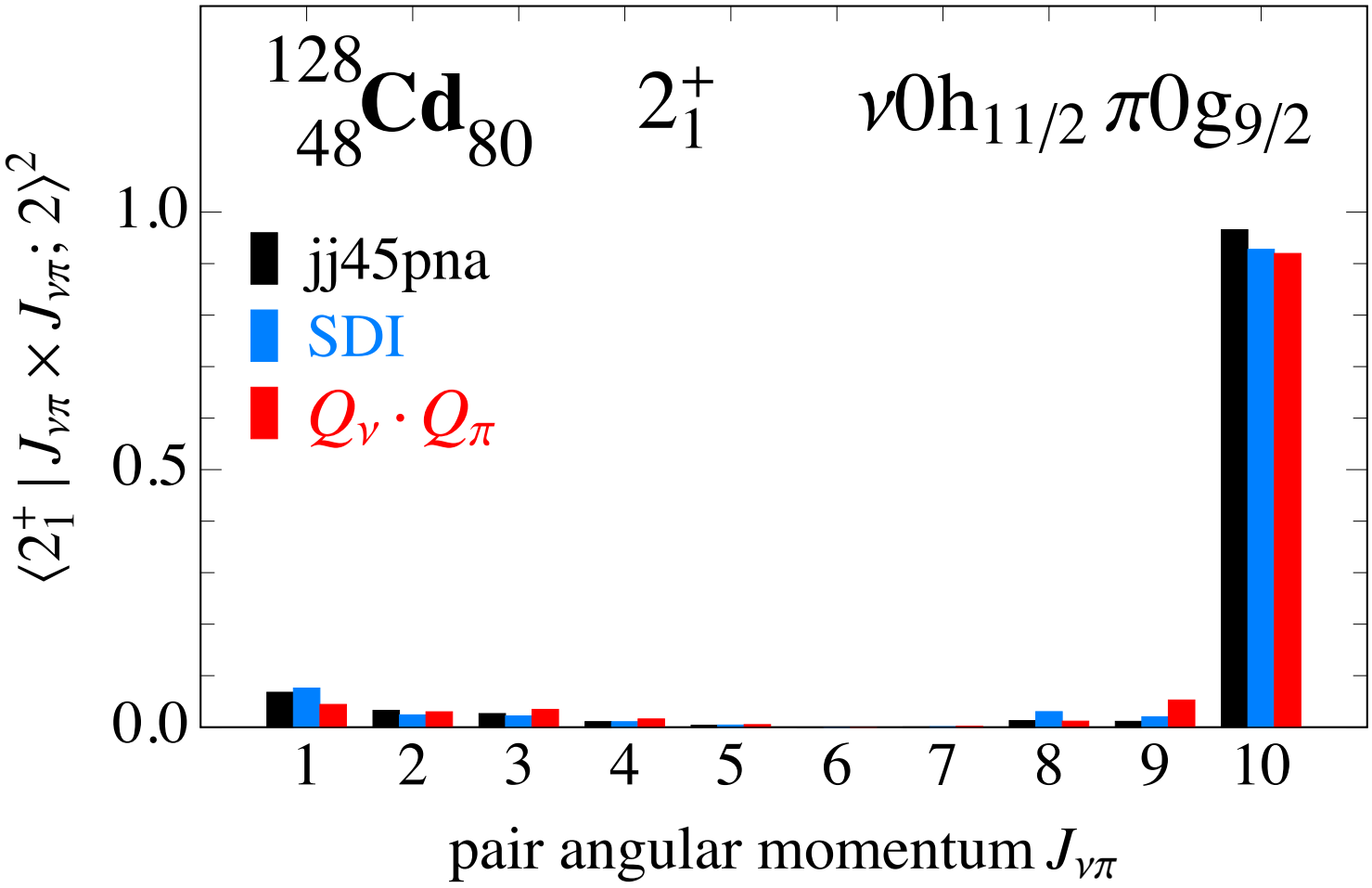

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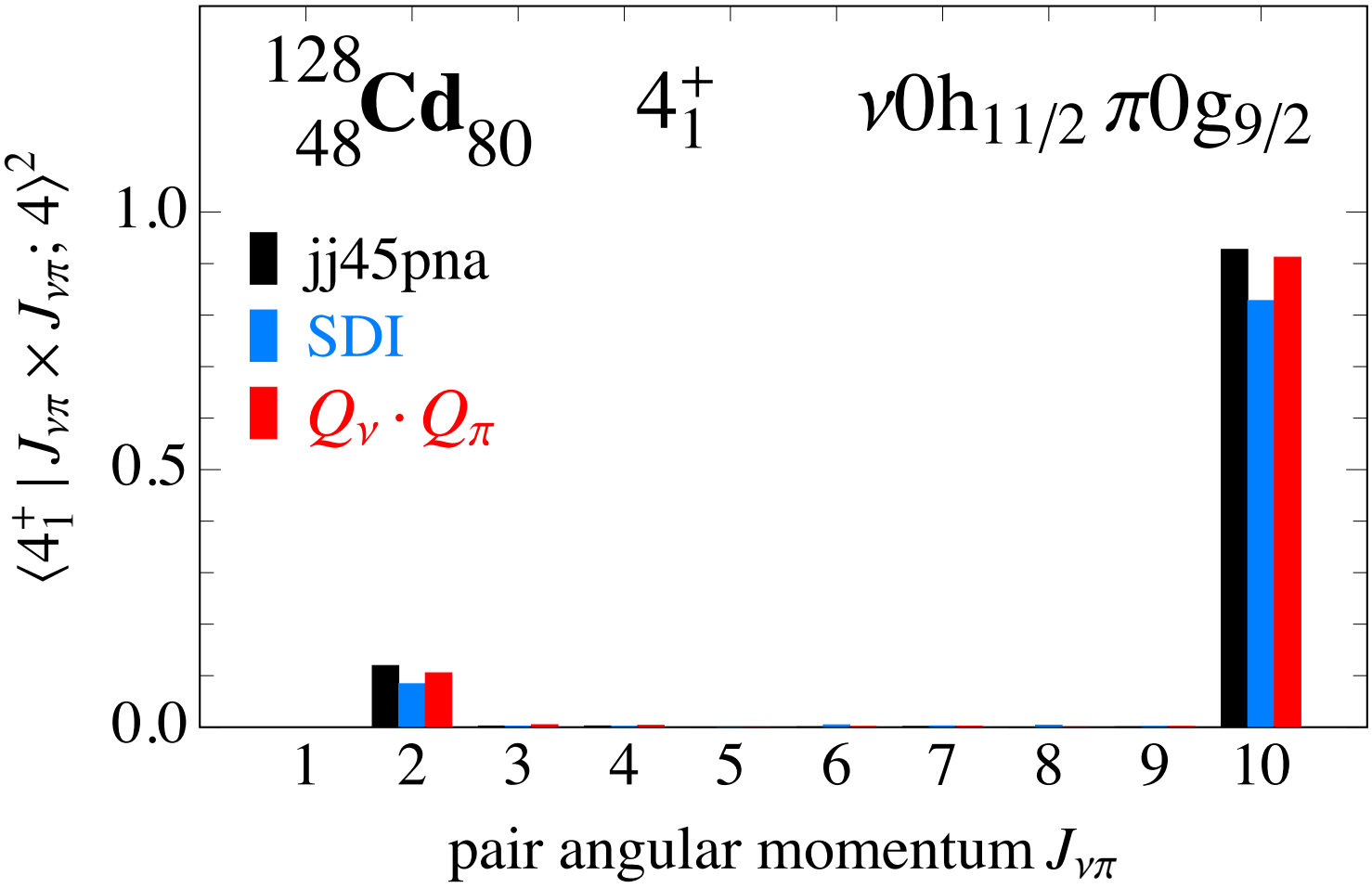

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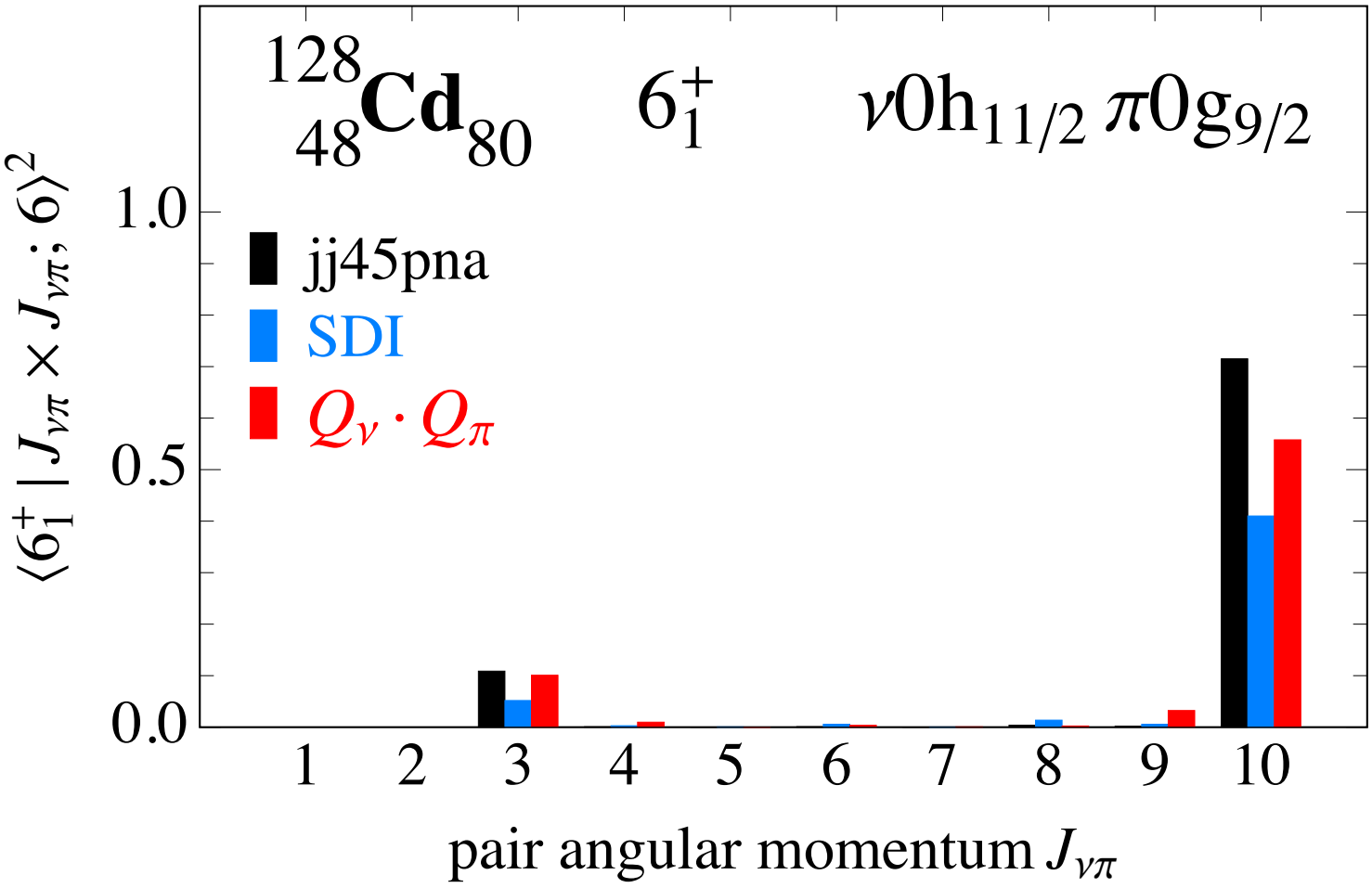

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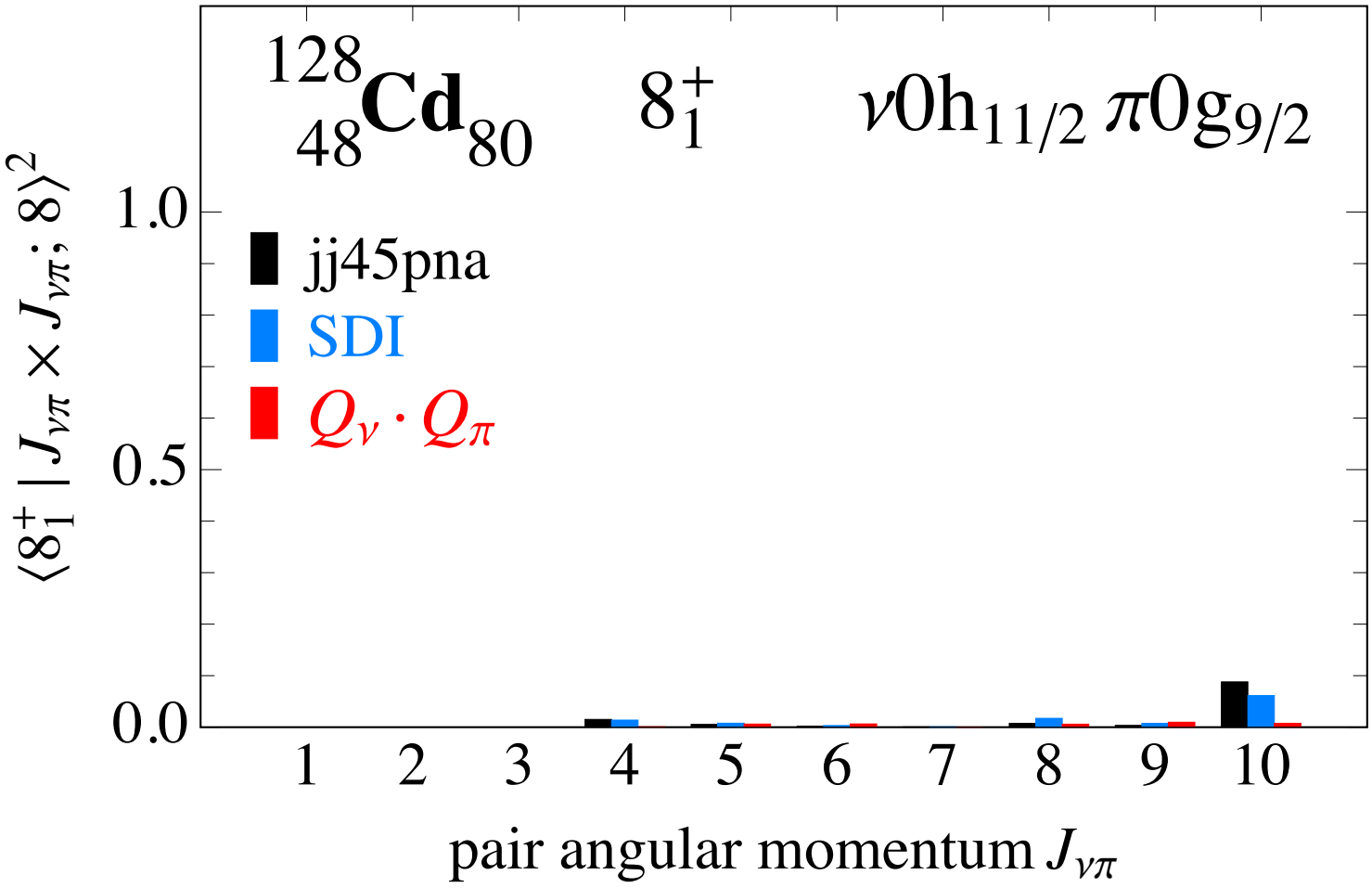

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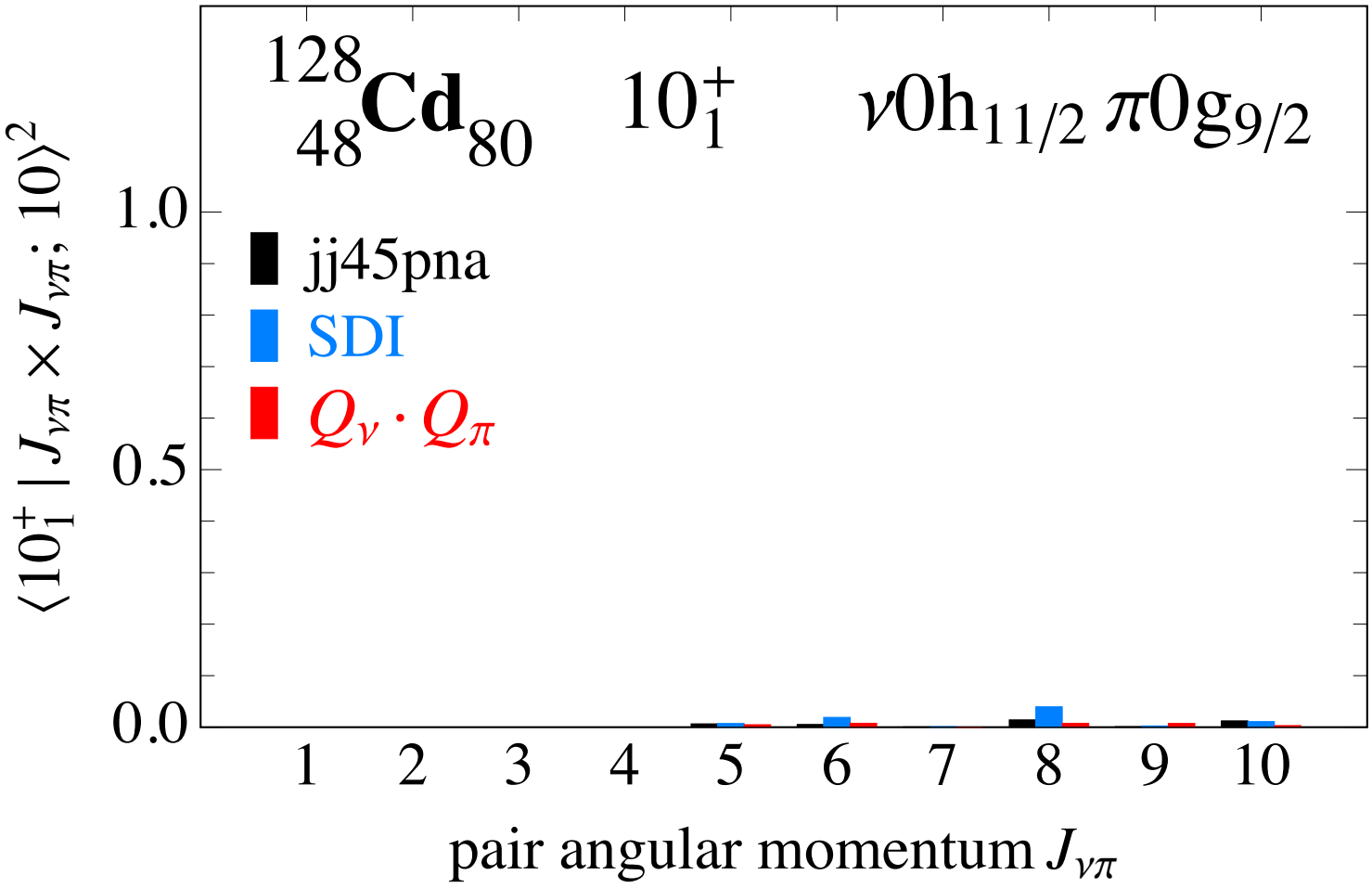

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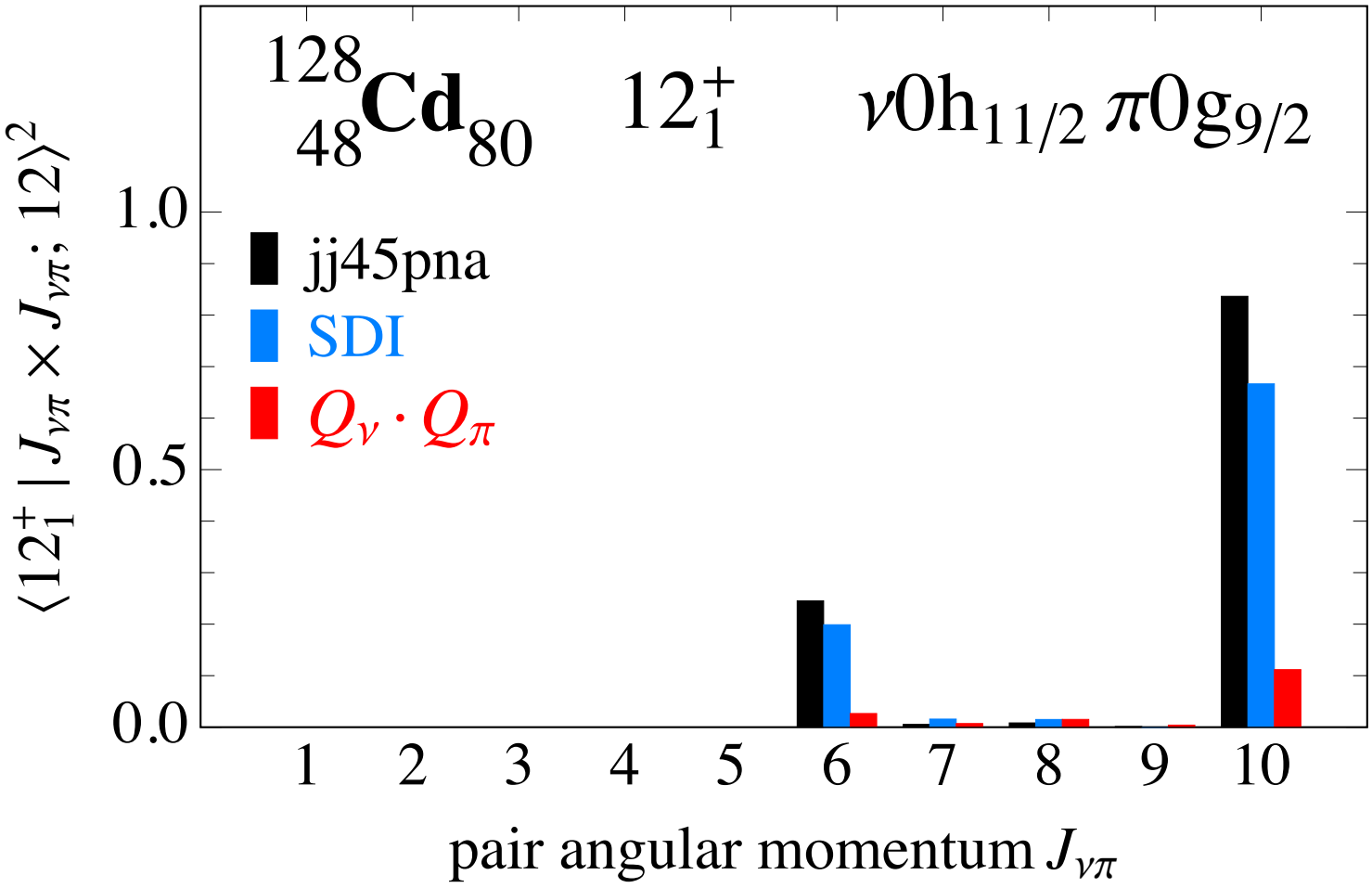

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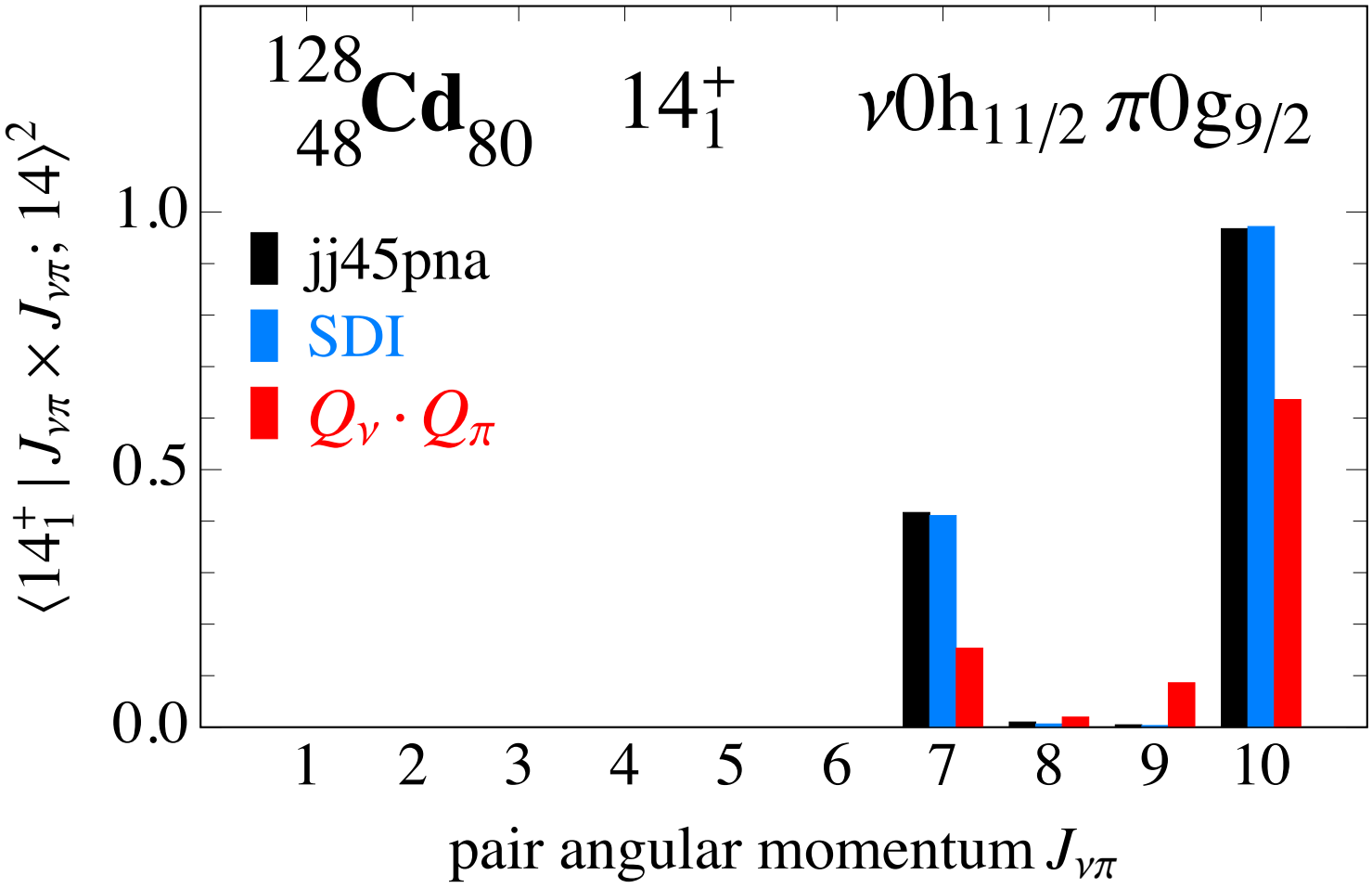

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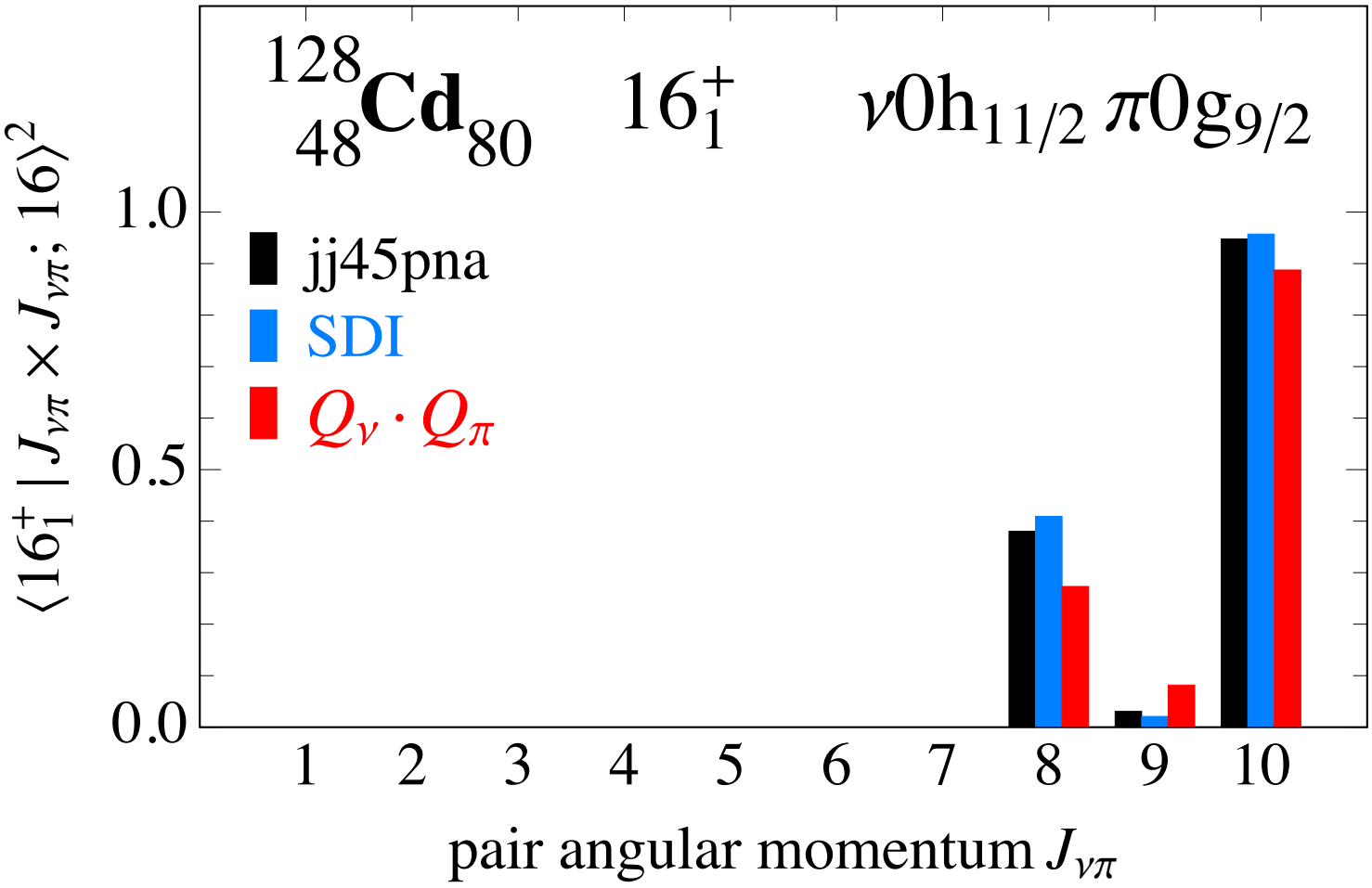

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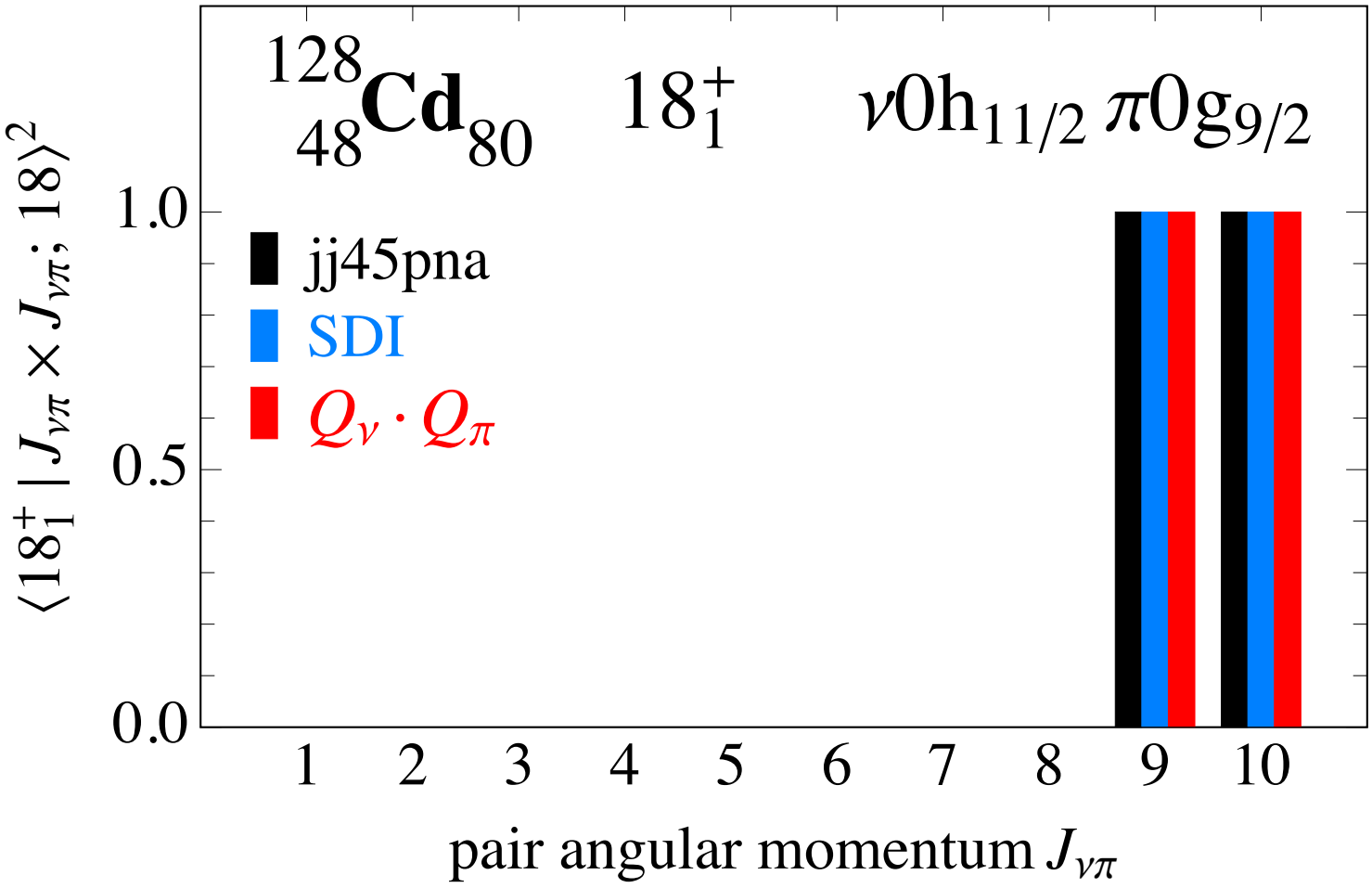
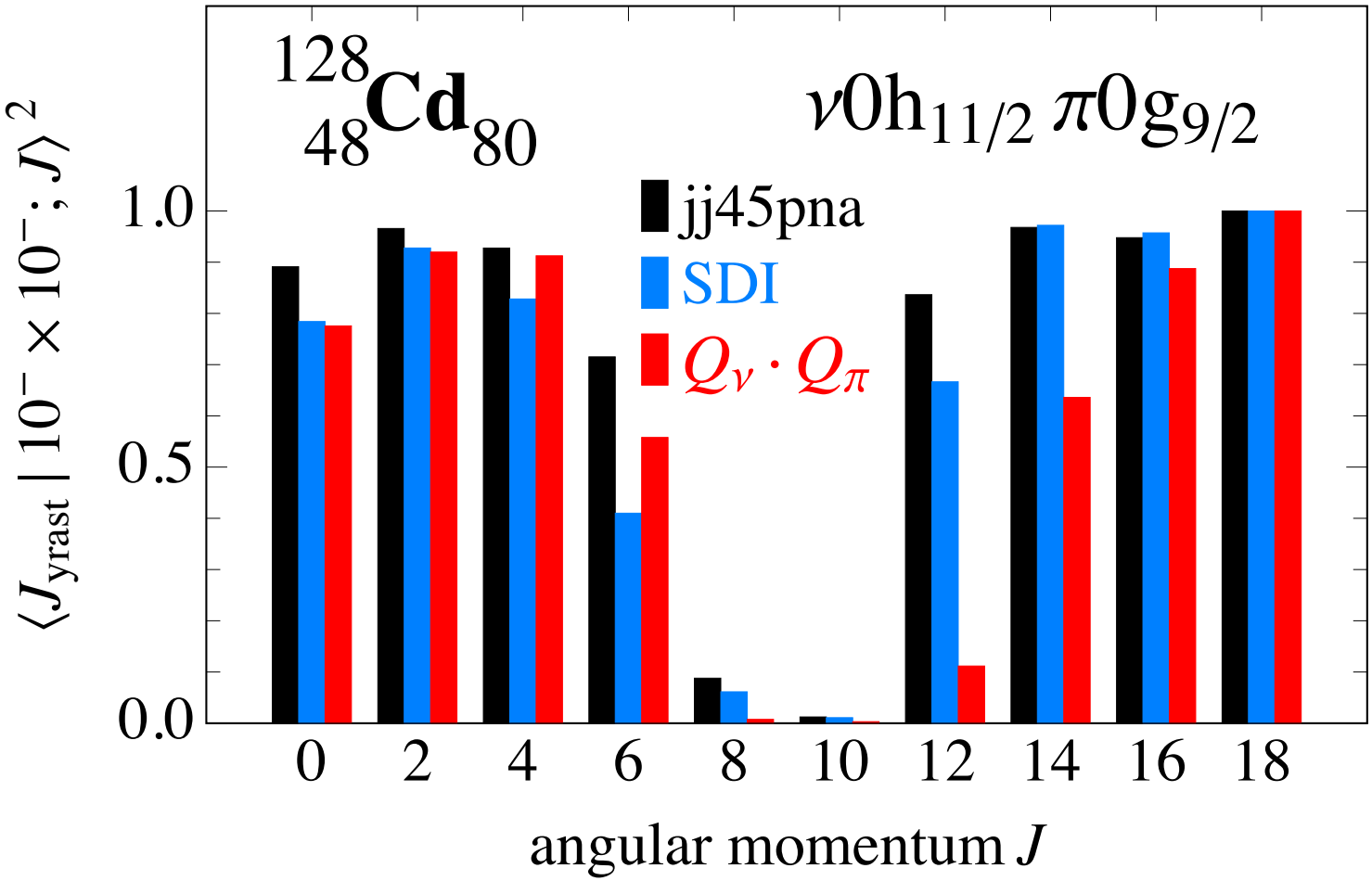


Aligned-pair analysis for ^{128}Cd



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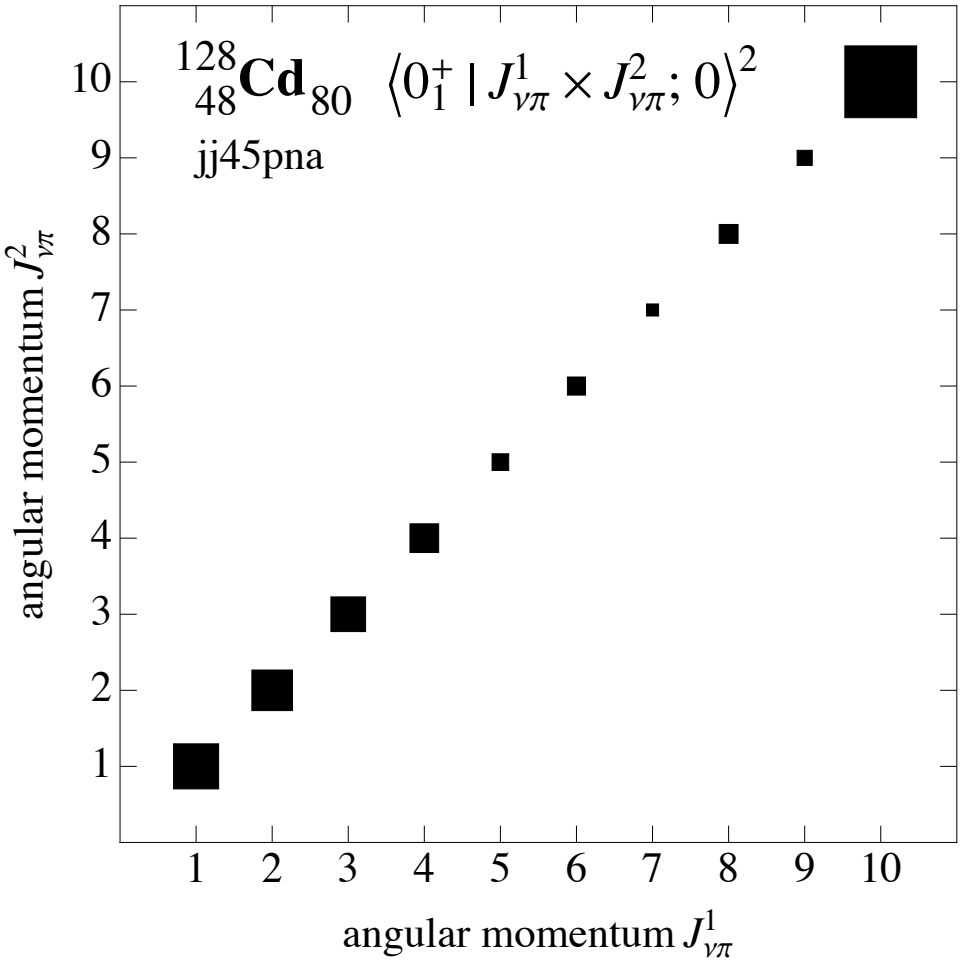

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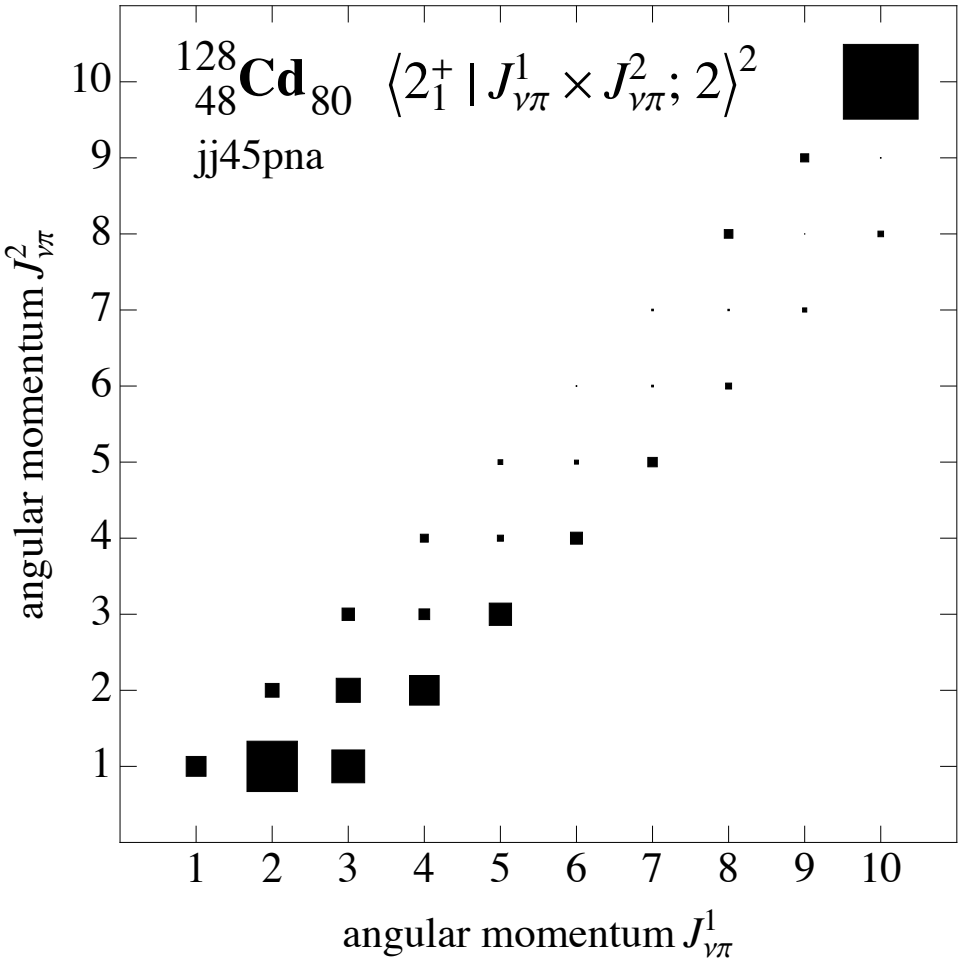

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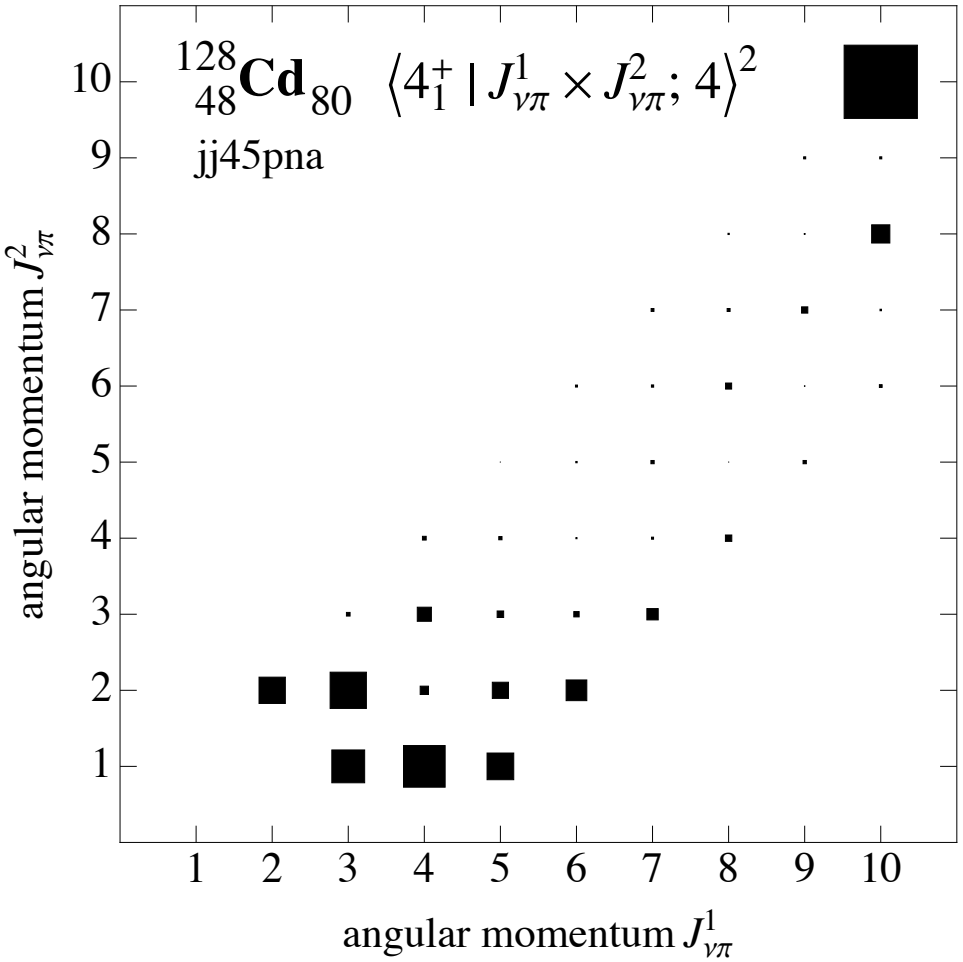

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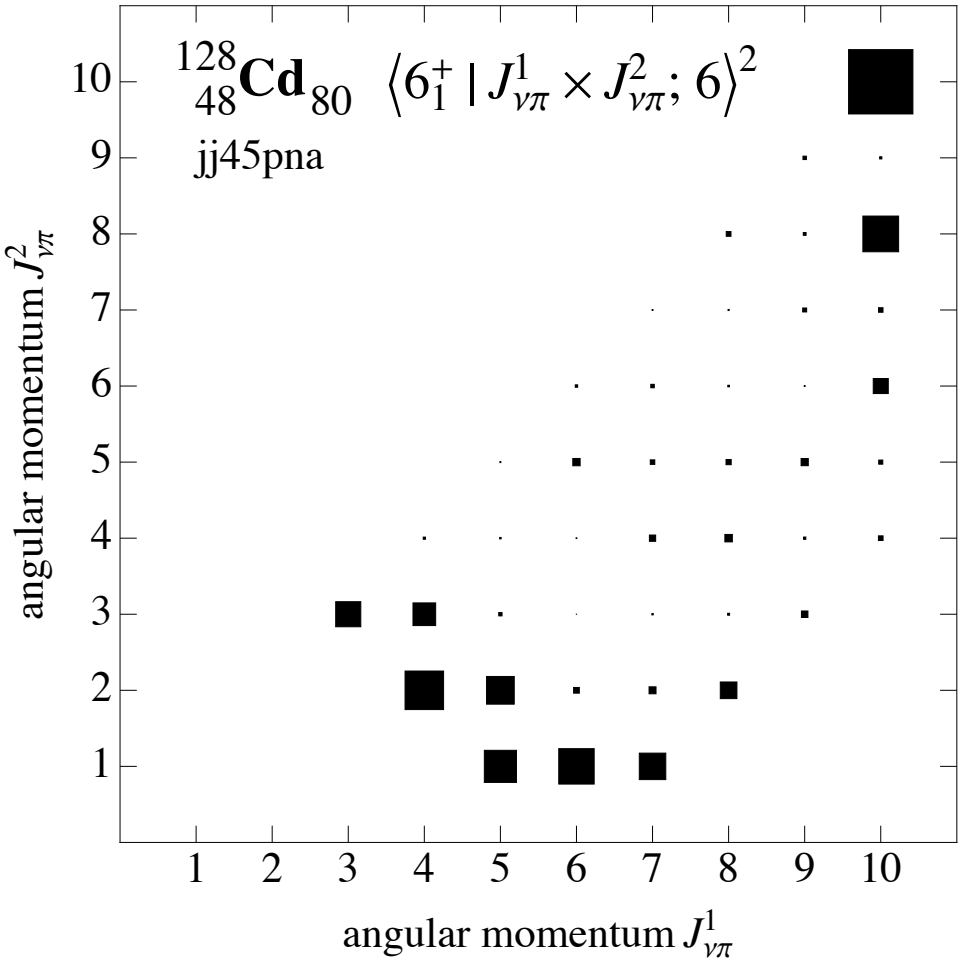

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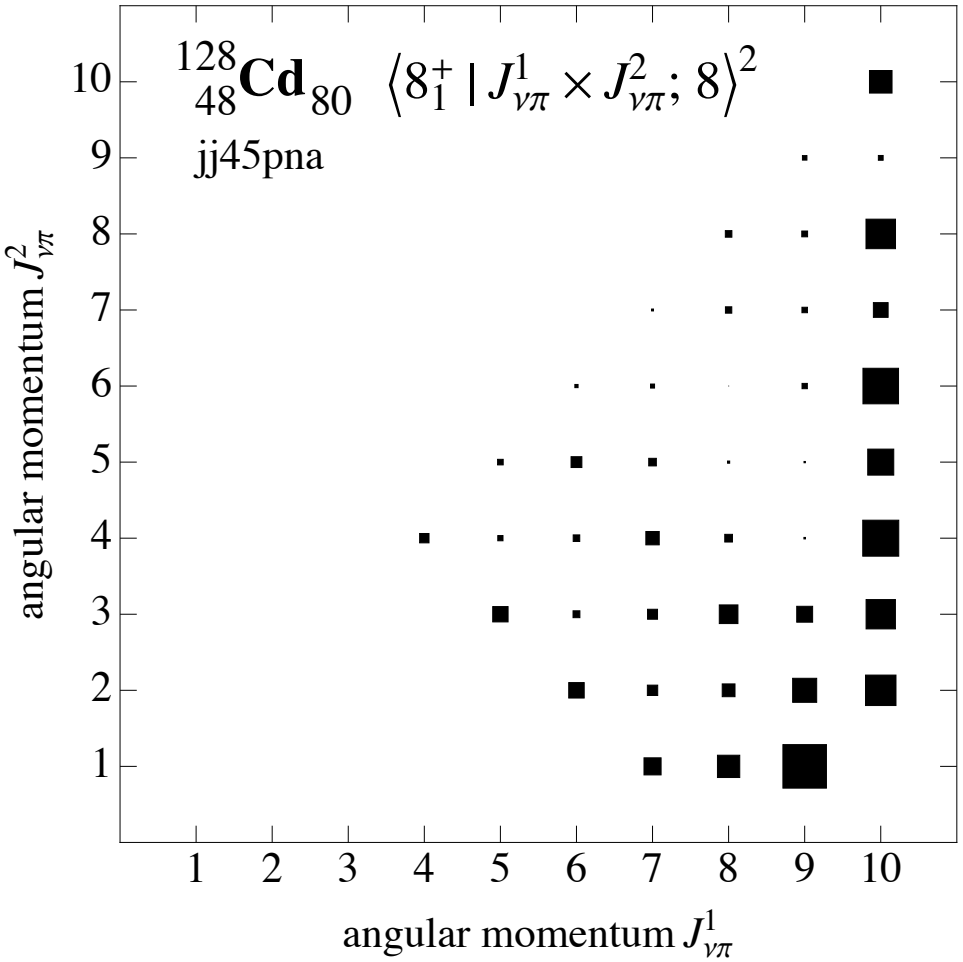

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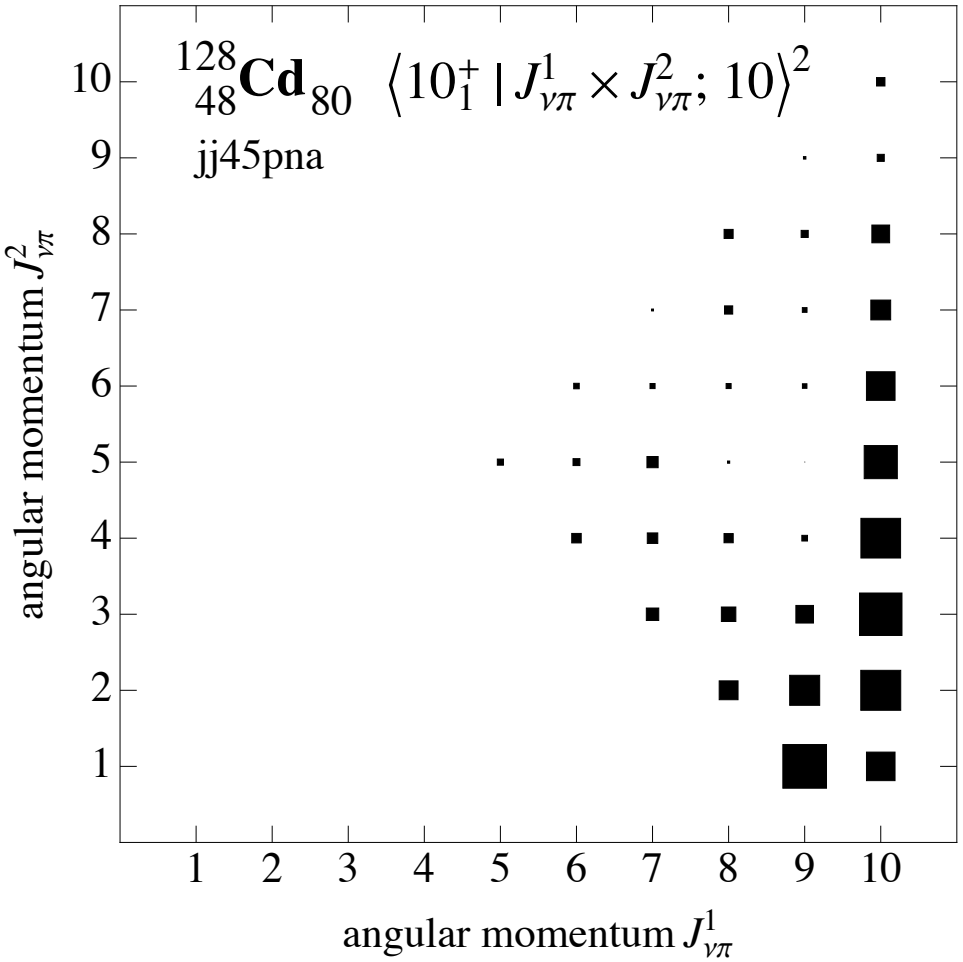

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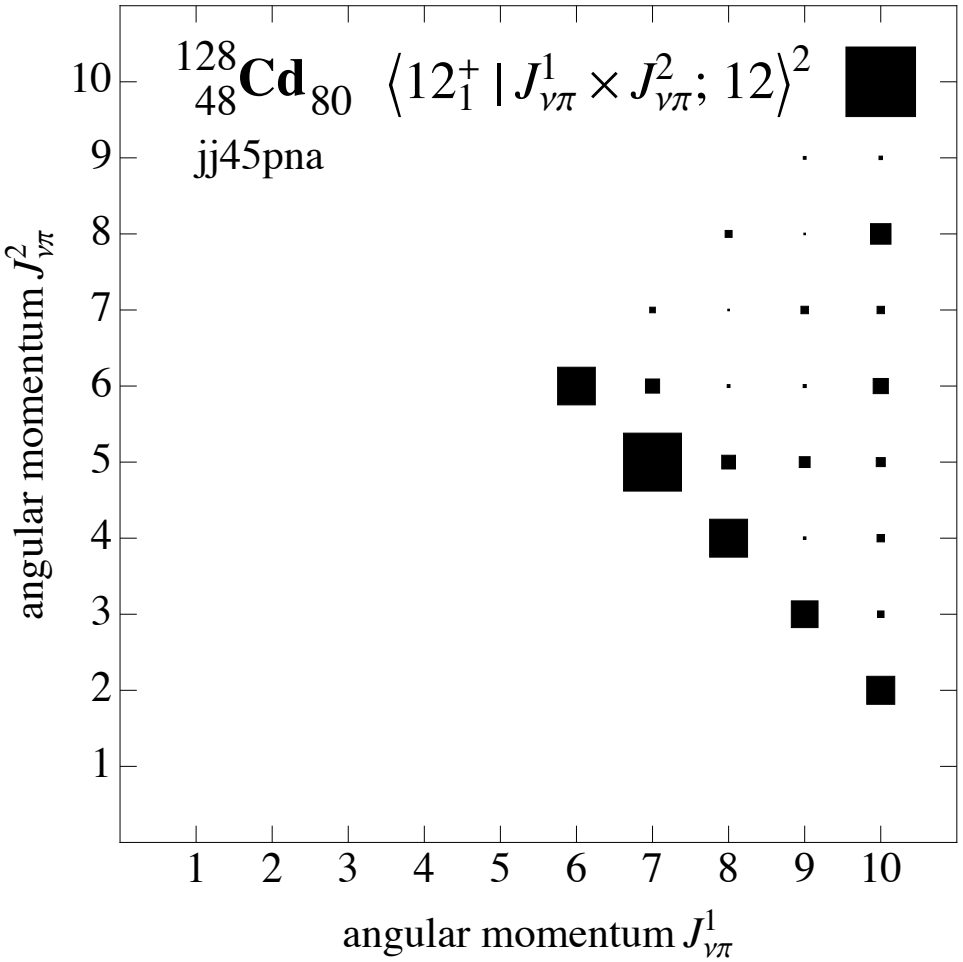

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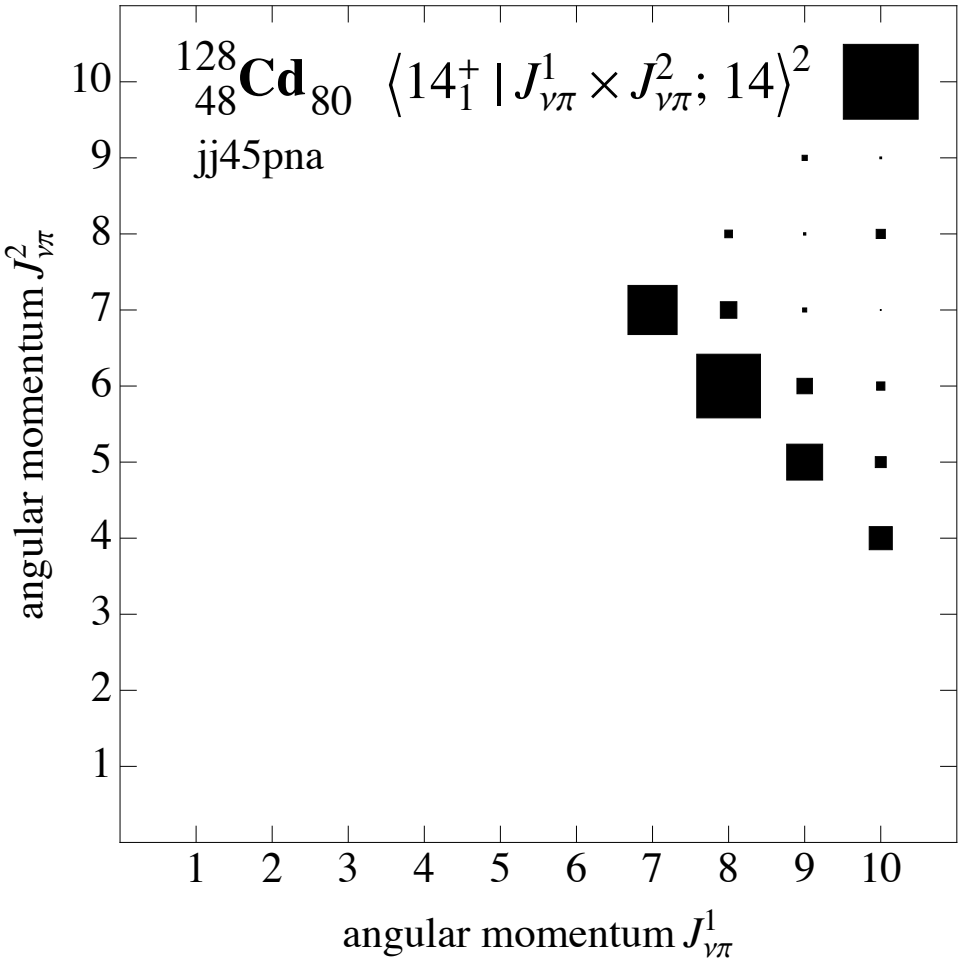

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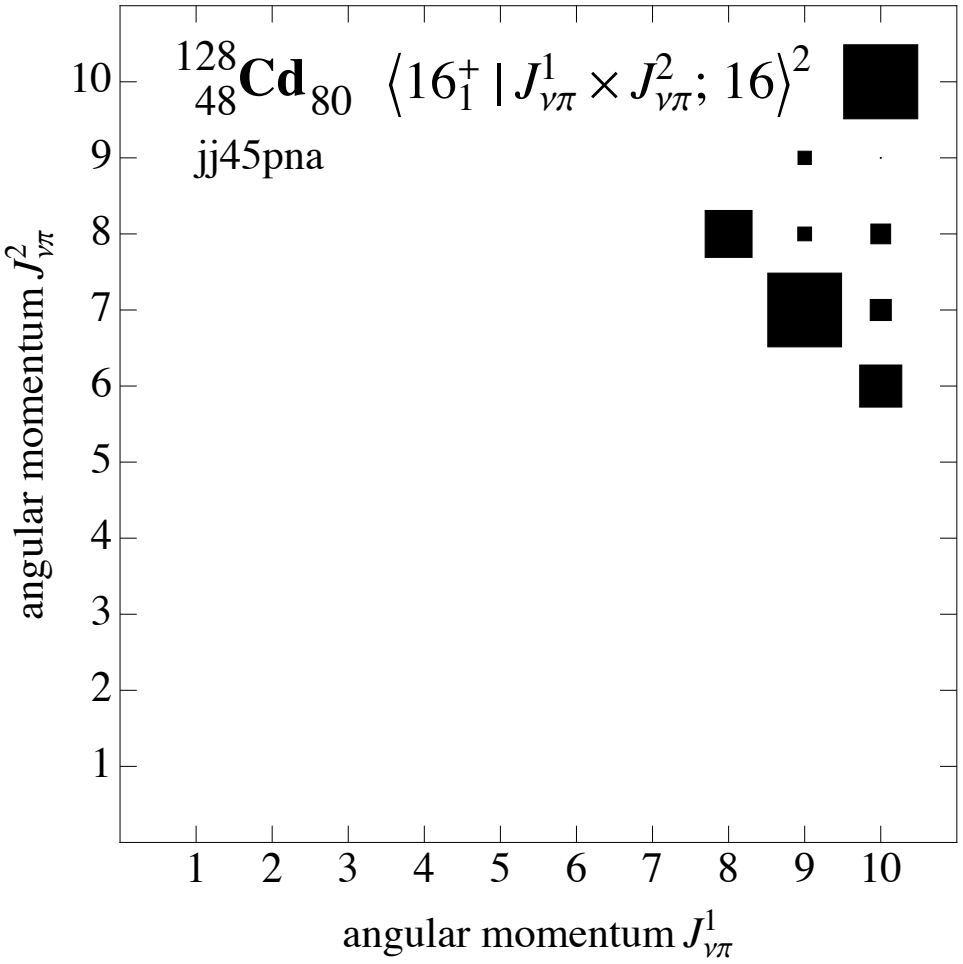

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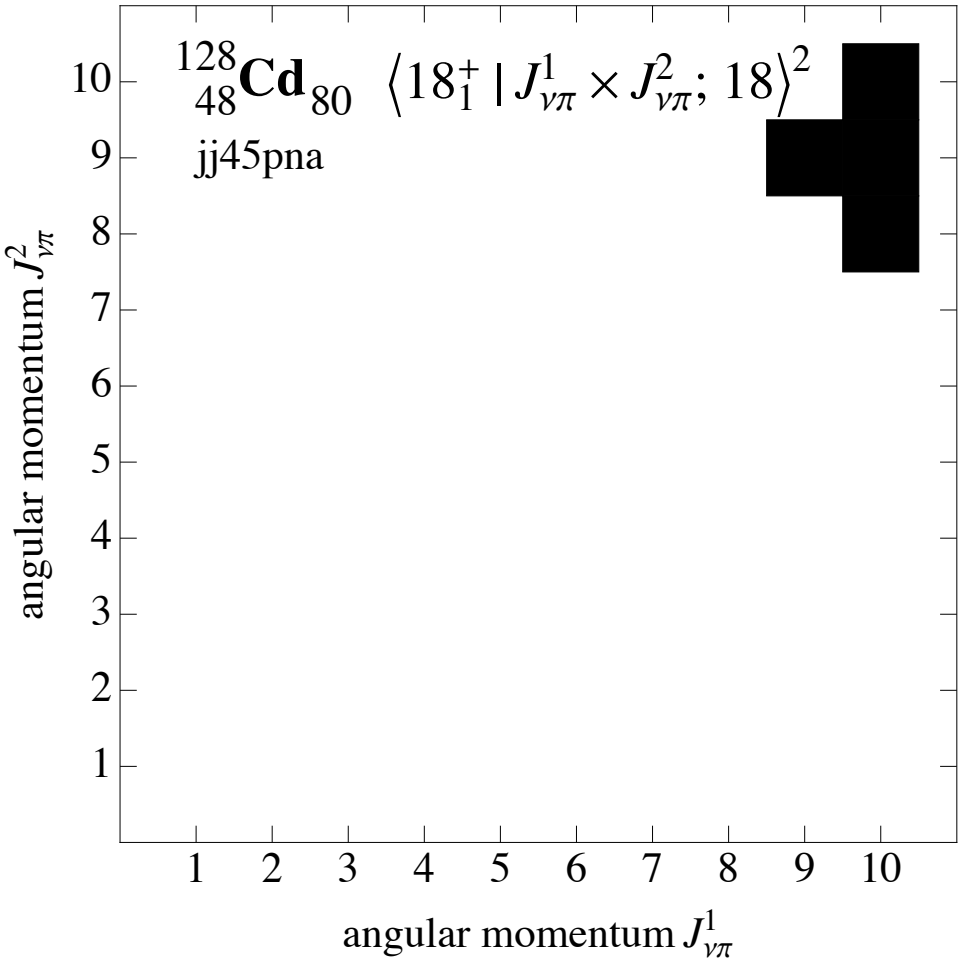
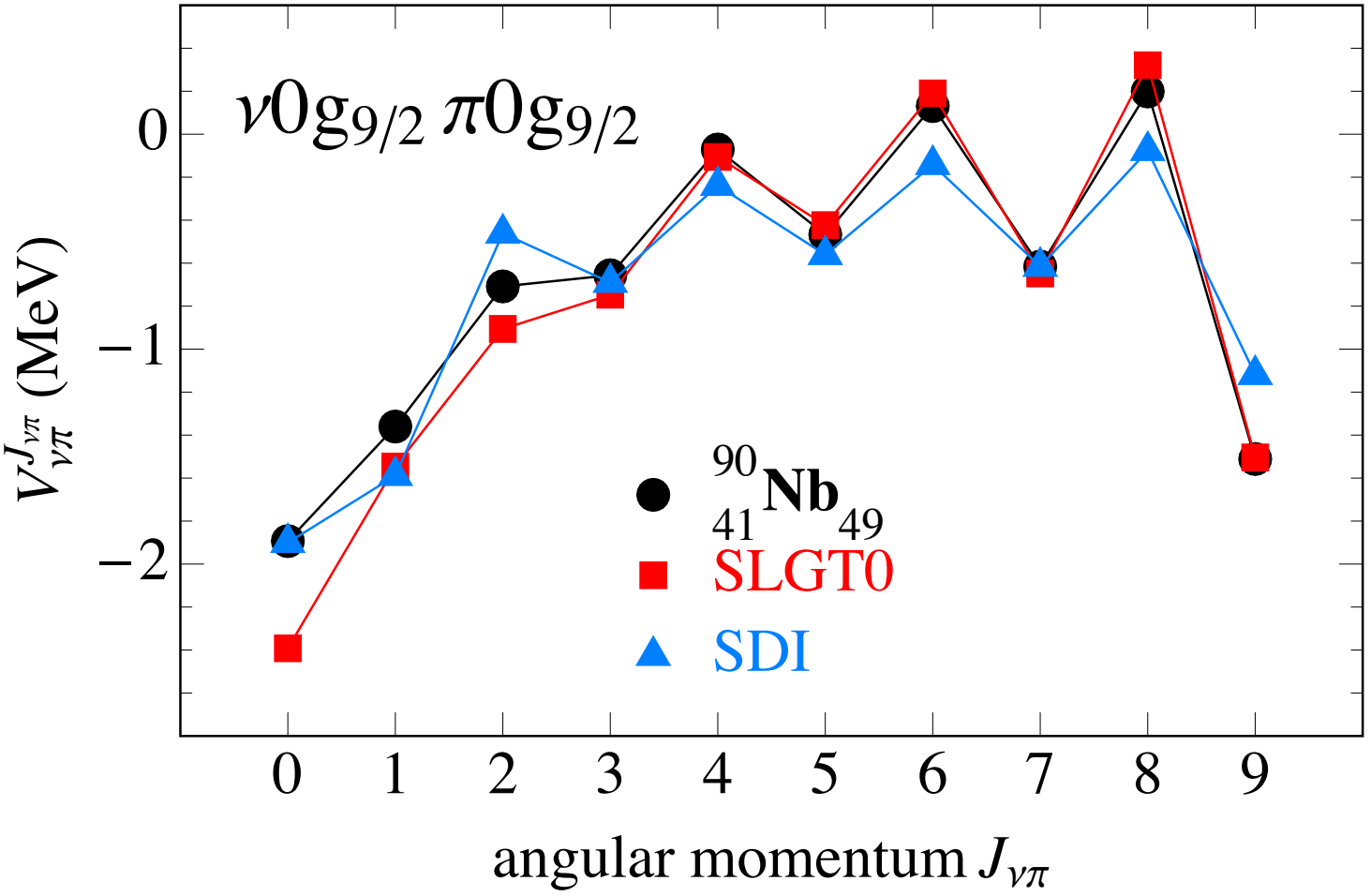
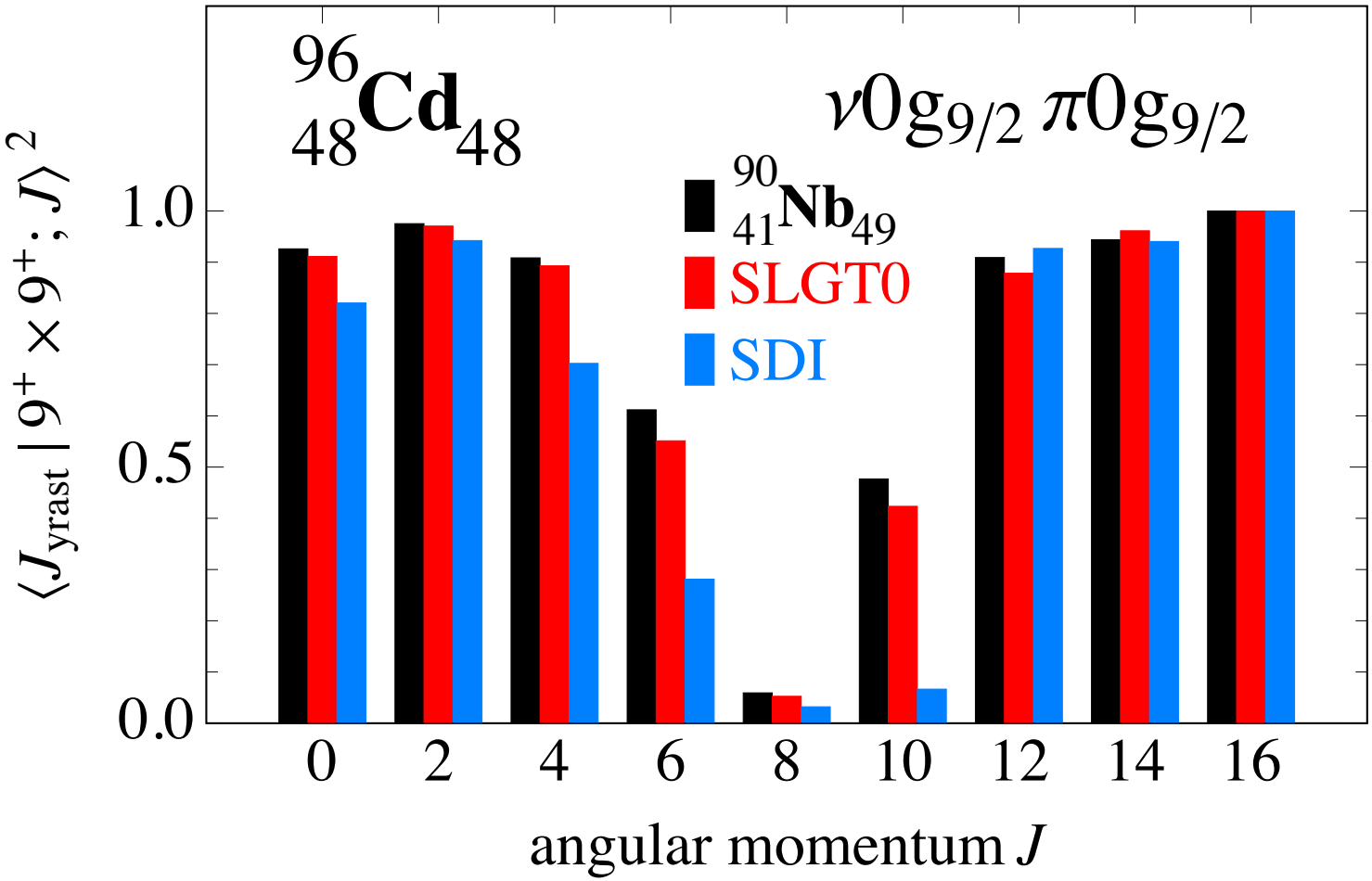


The $0g_{9/2}$-$0g_{9/2}$ interaction



Aligned-pair analysis for ^{96}Cd



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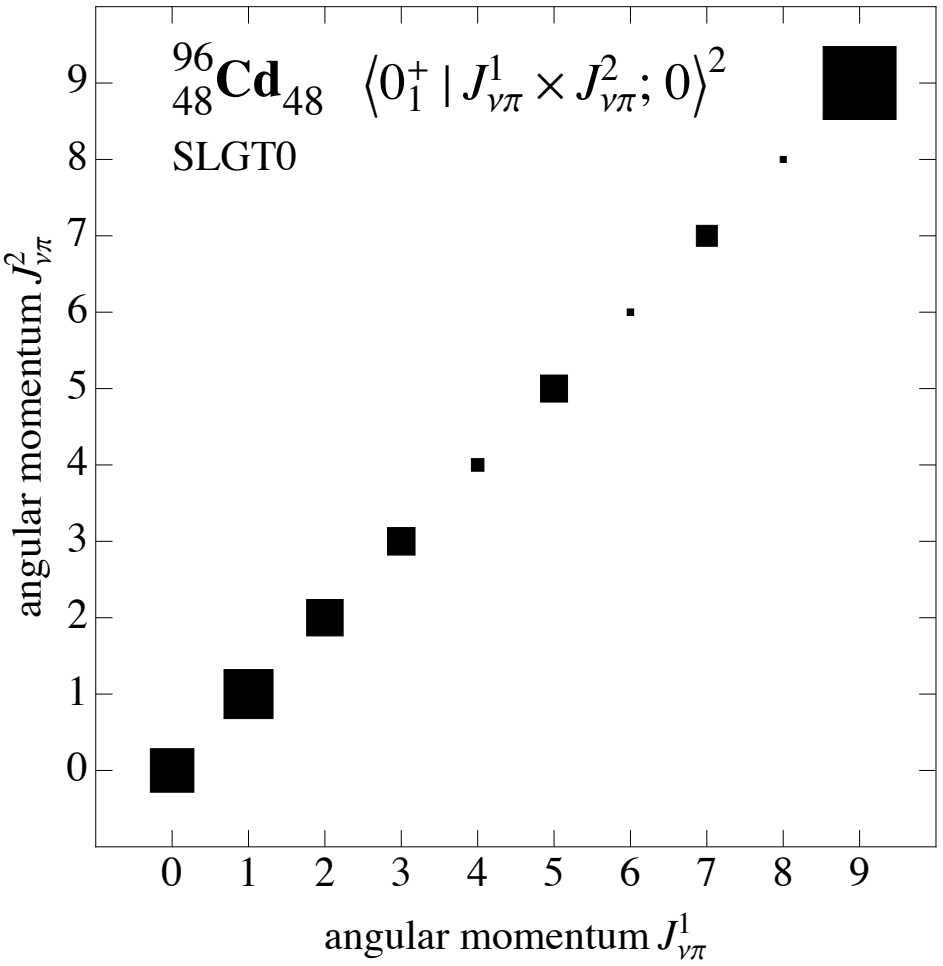

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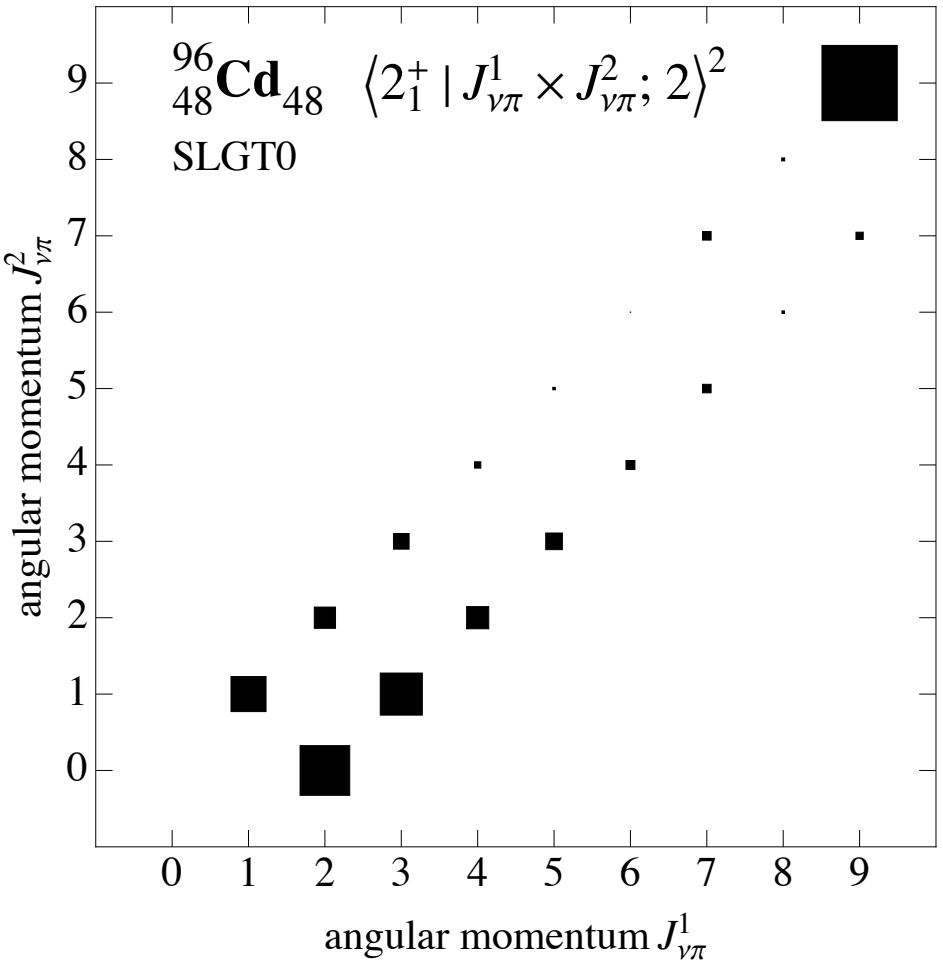

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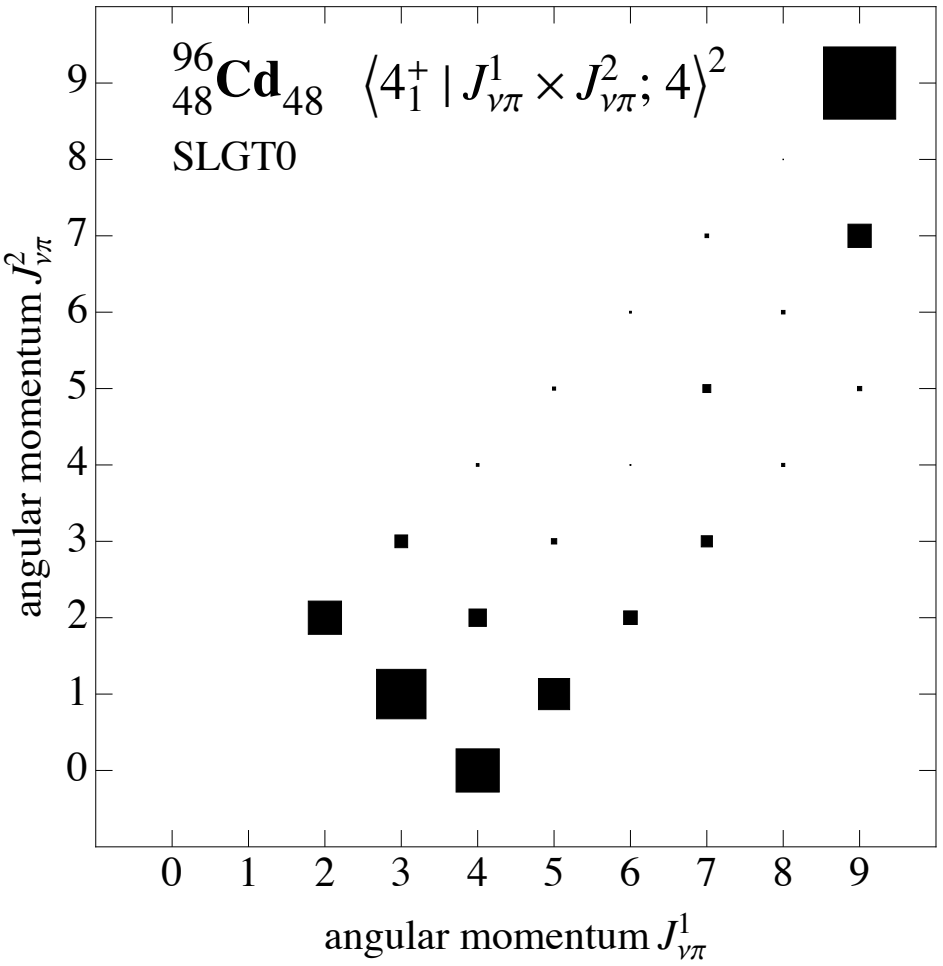

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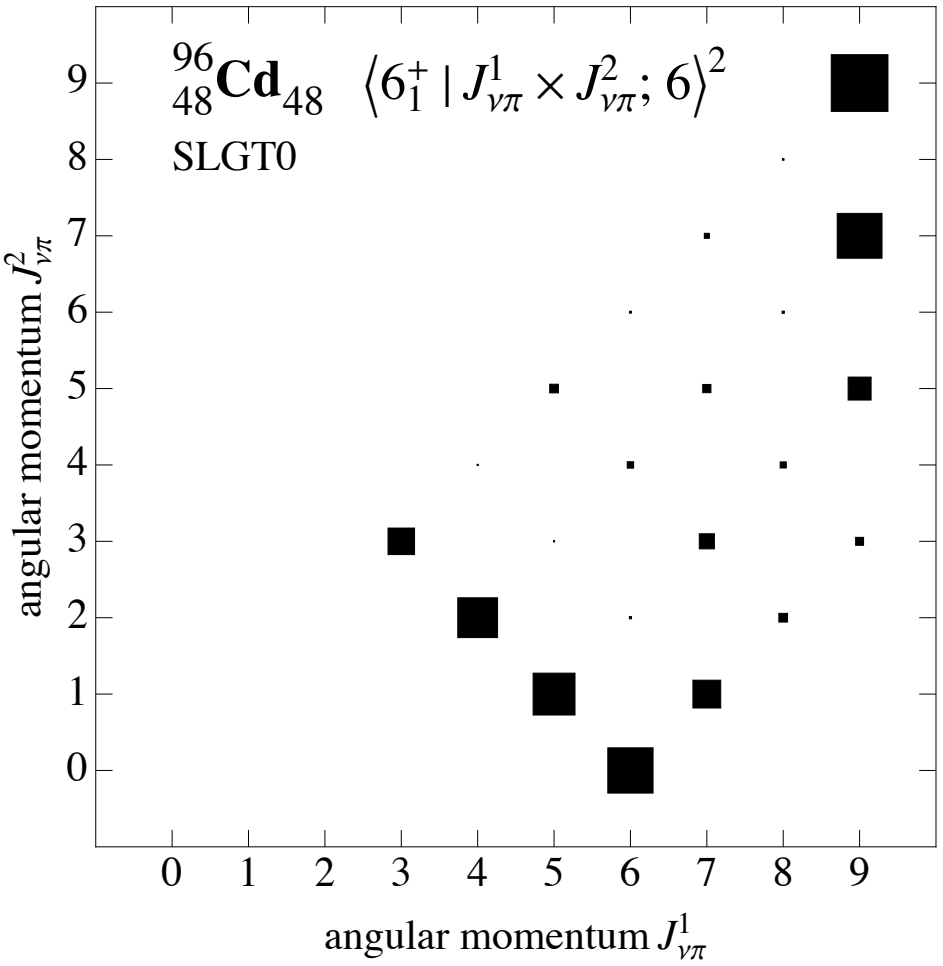

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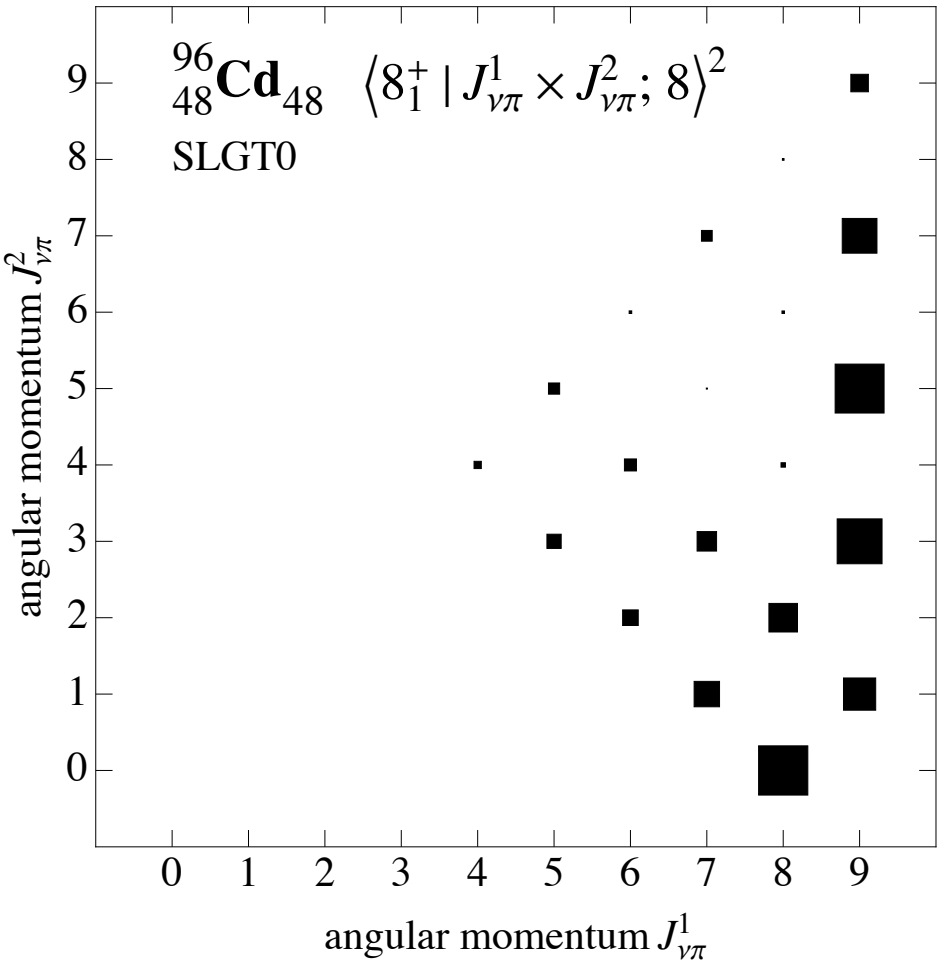
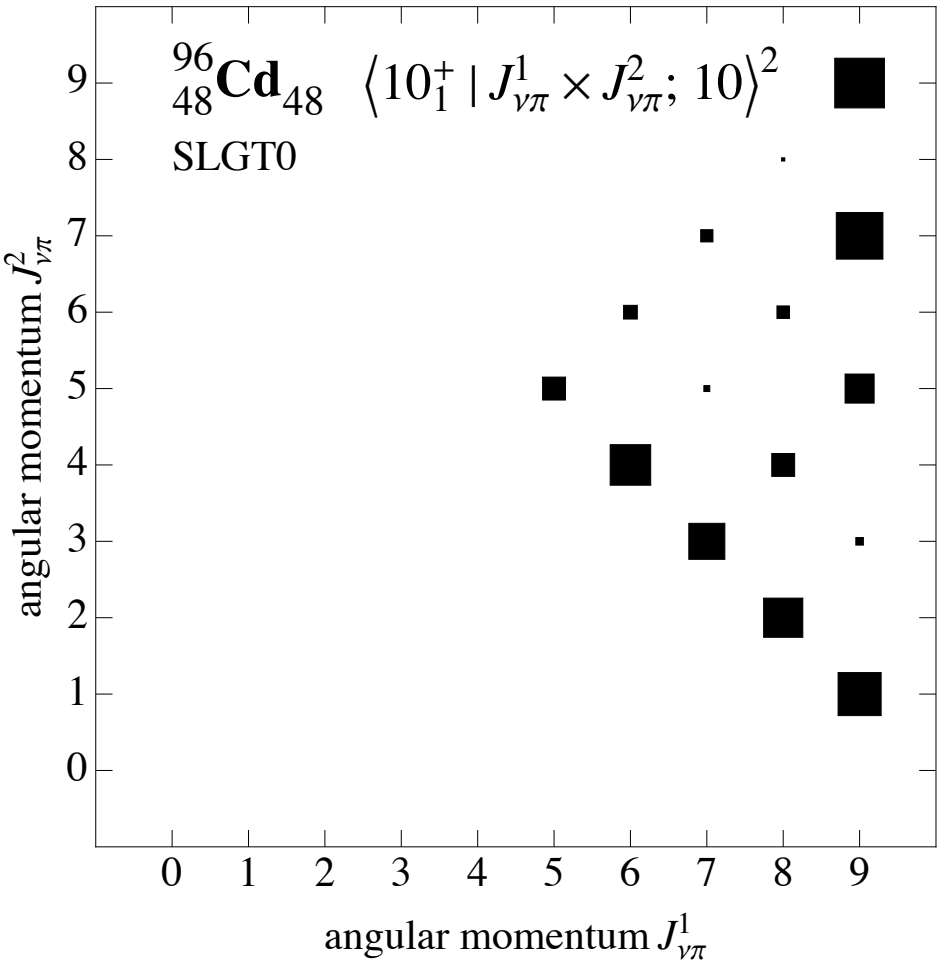


Neutron-proton pair analysis



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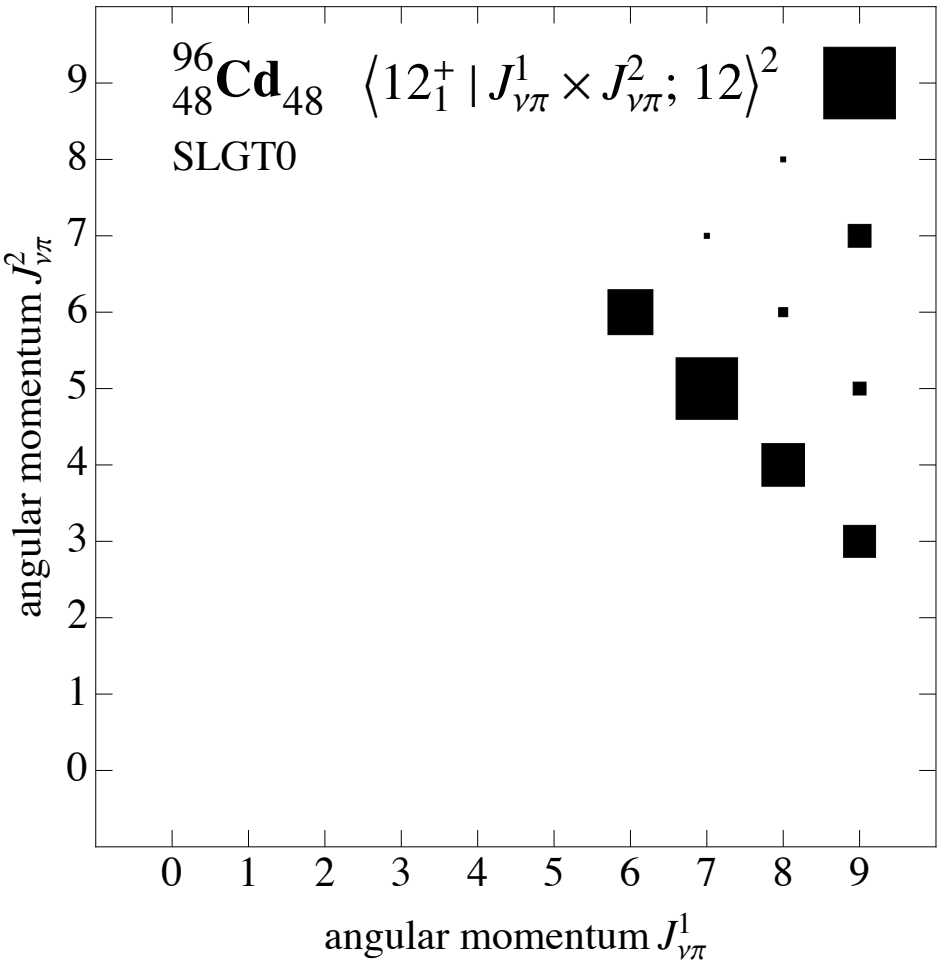

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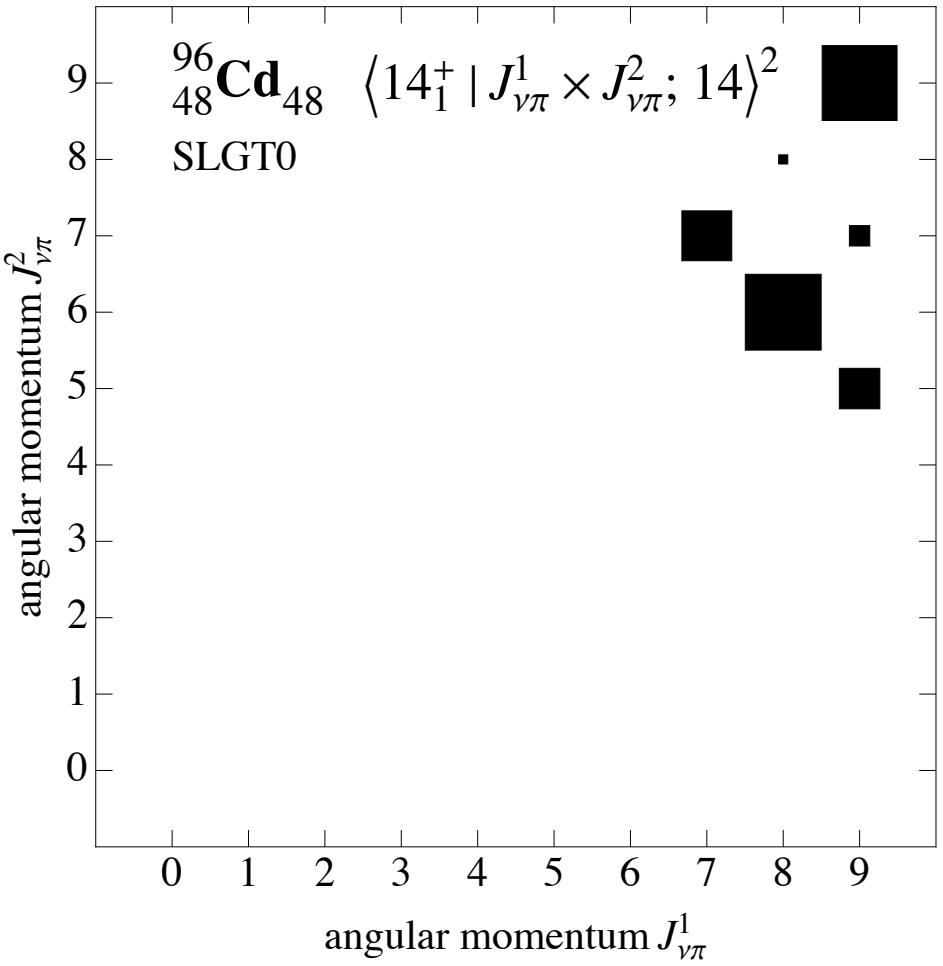

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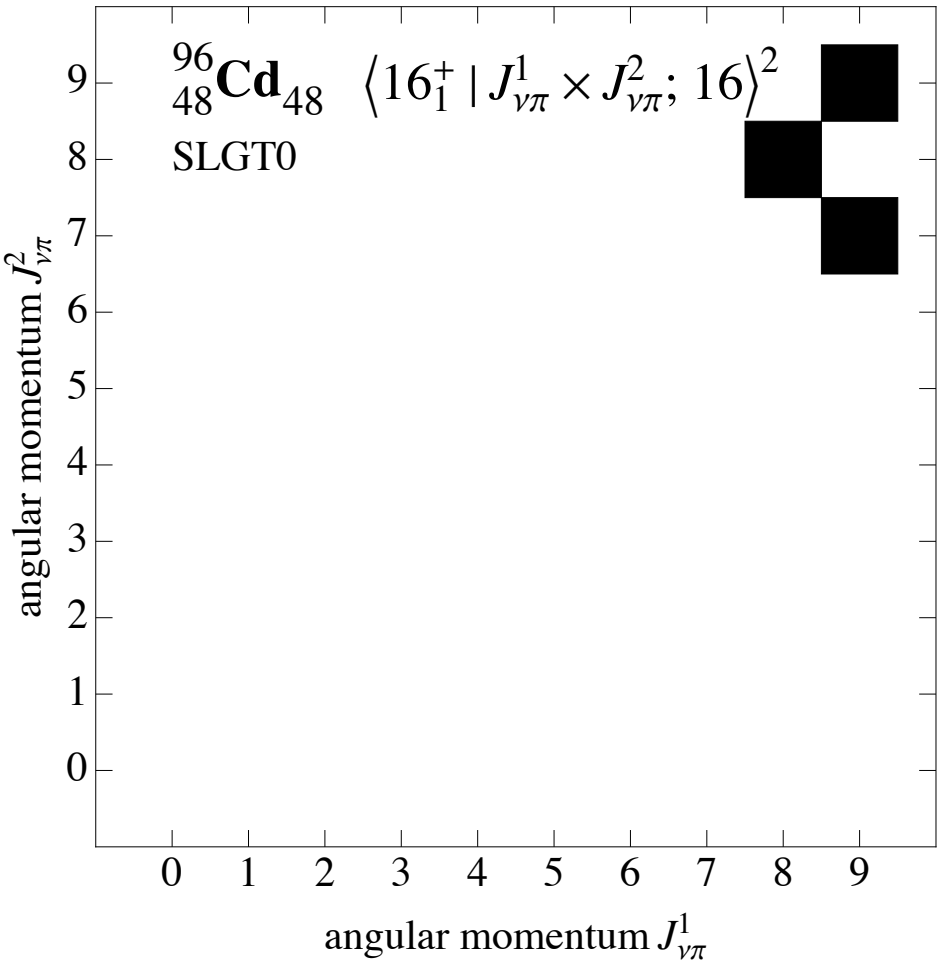
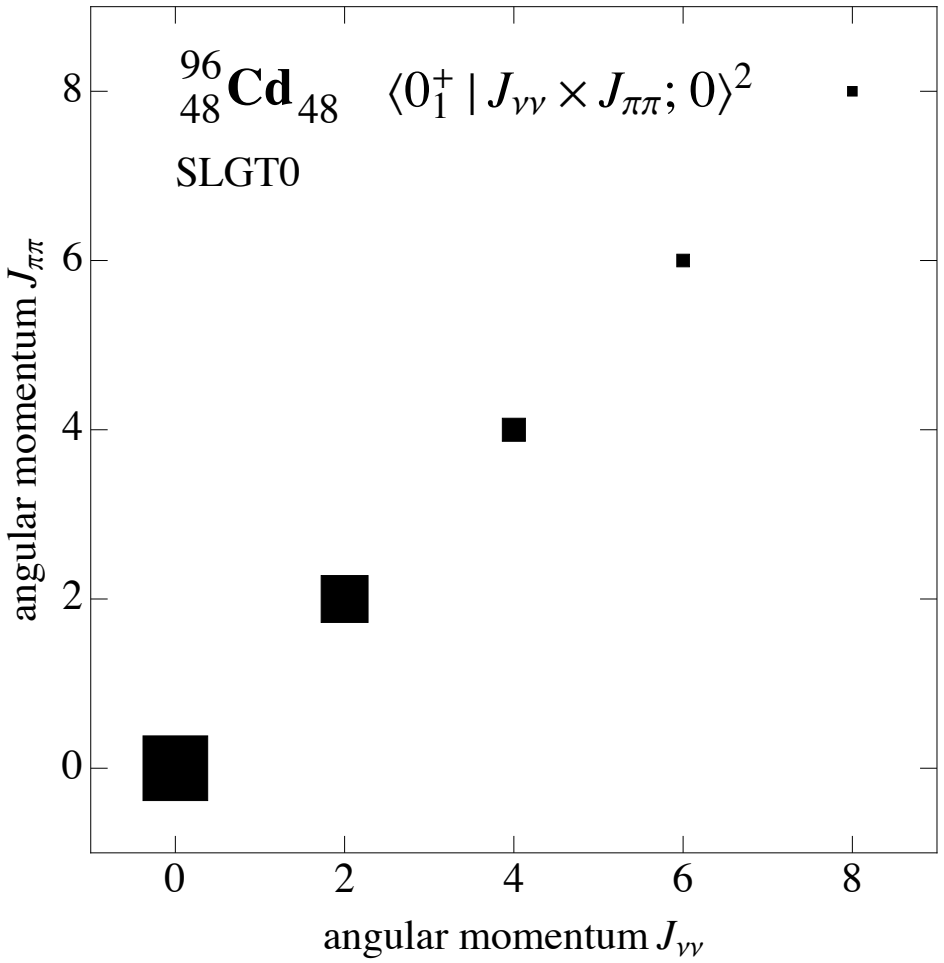


Like-pair analysis



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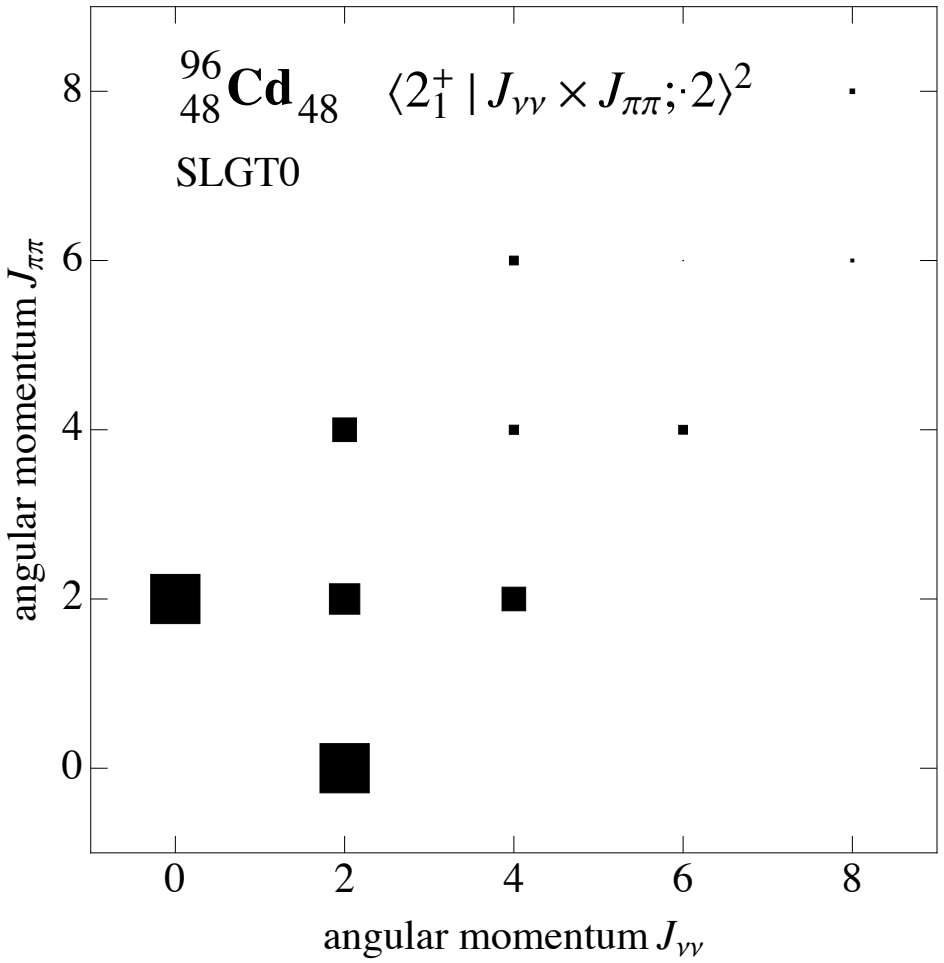

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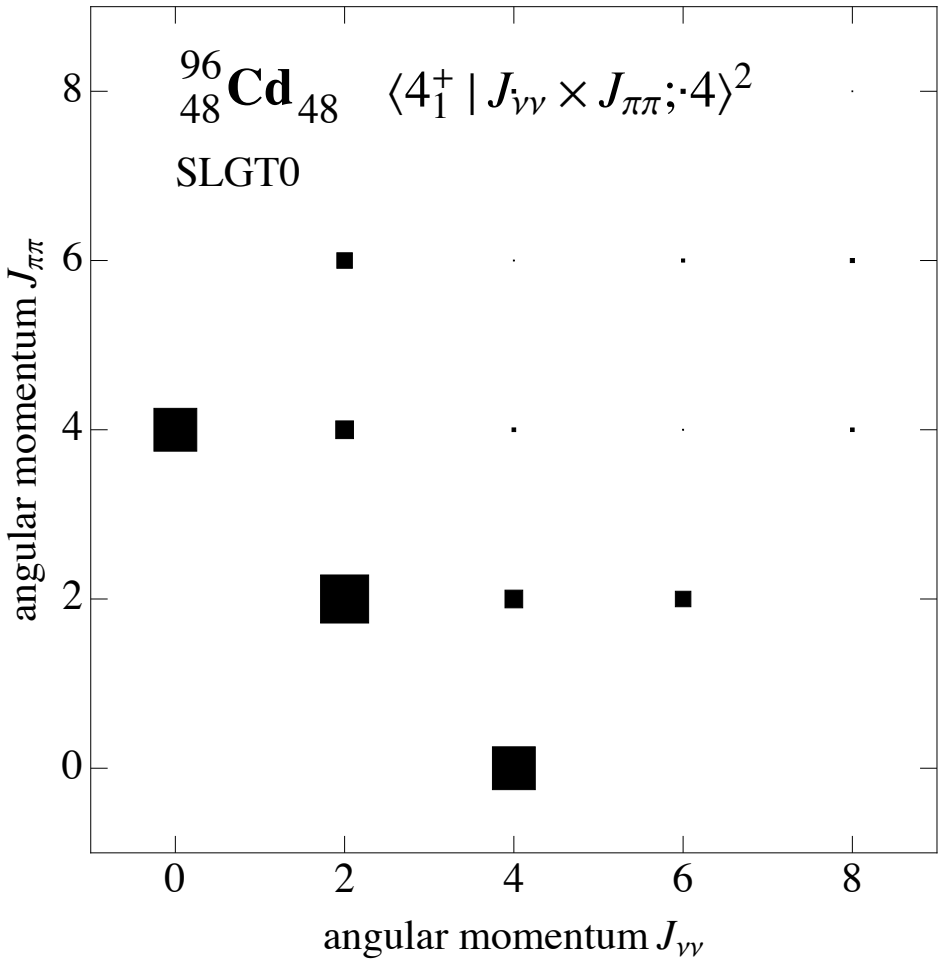

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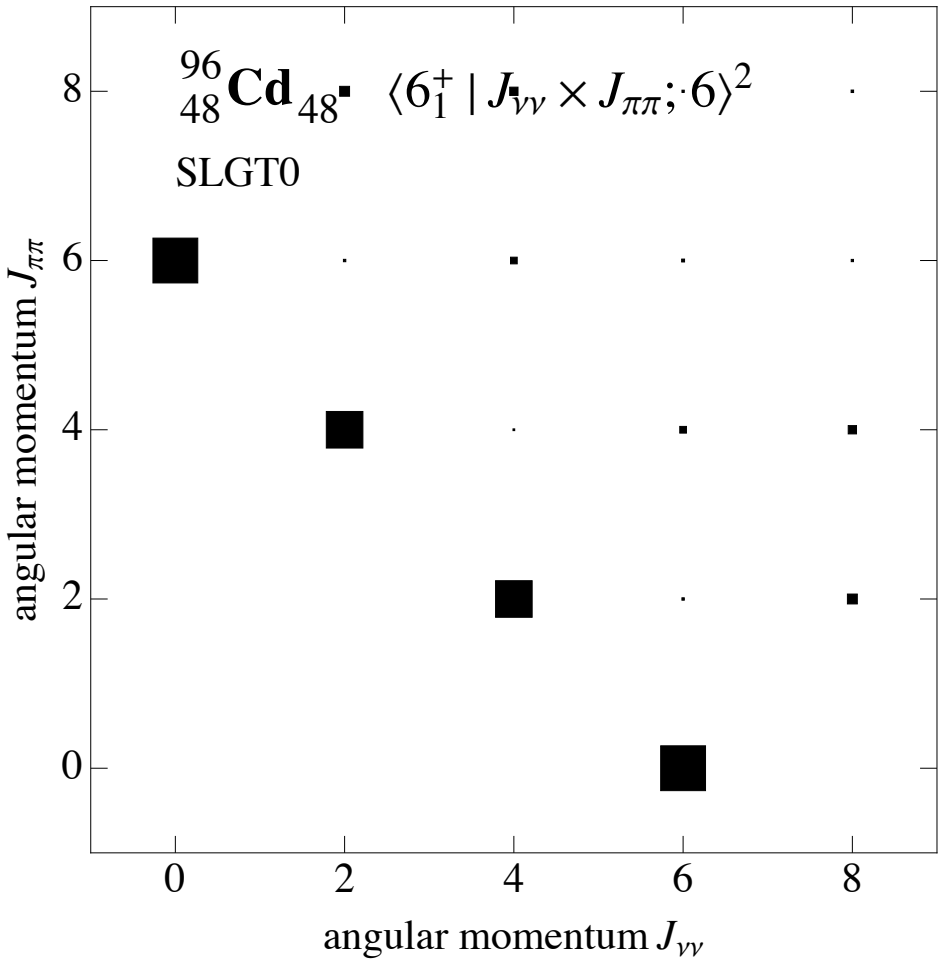

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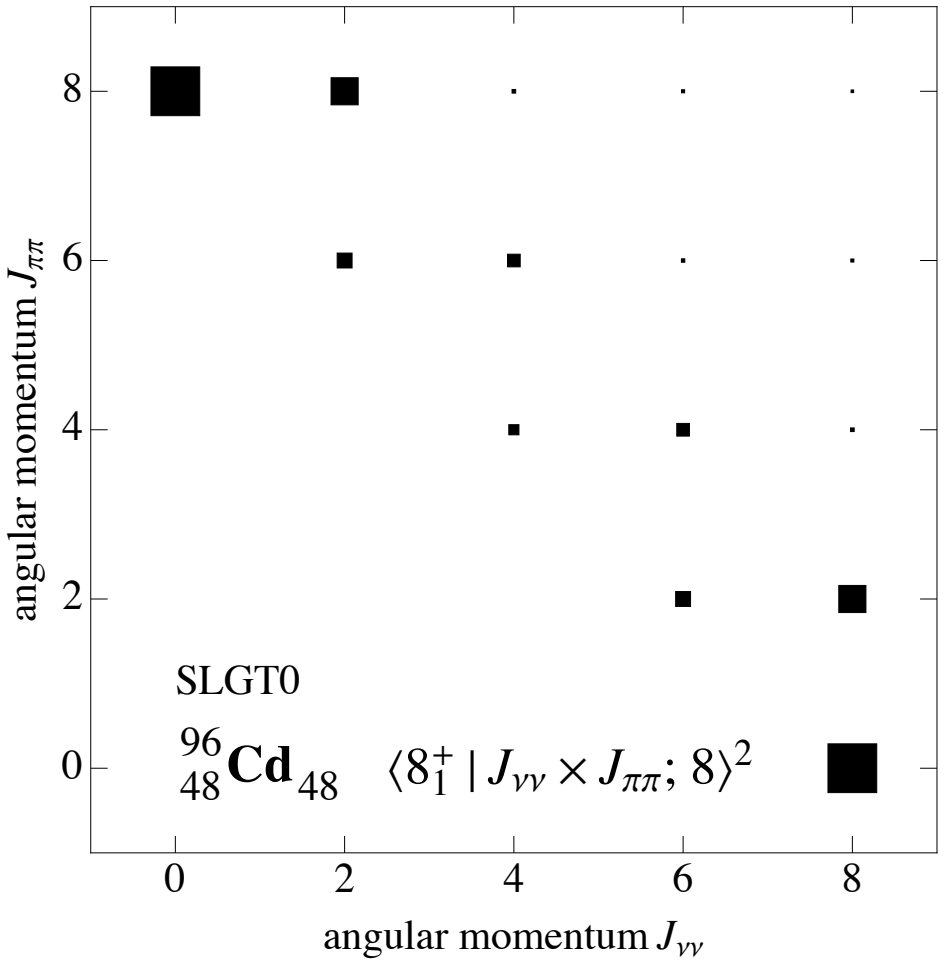

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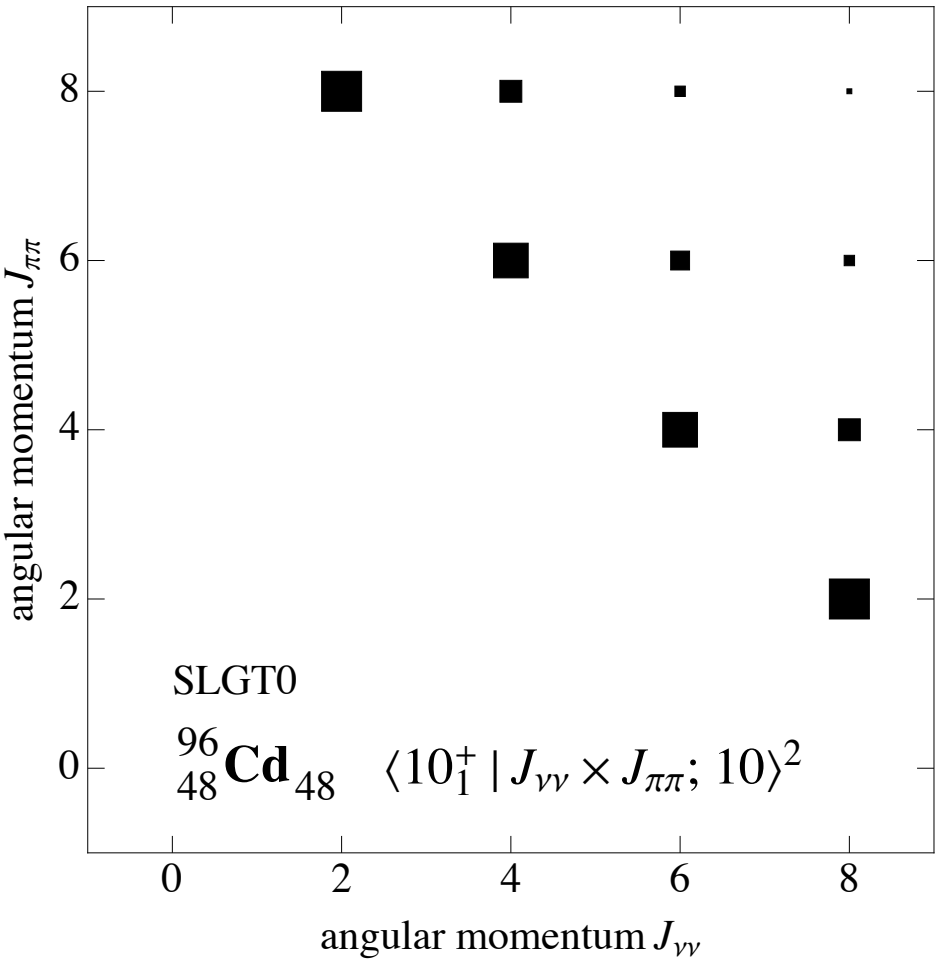

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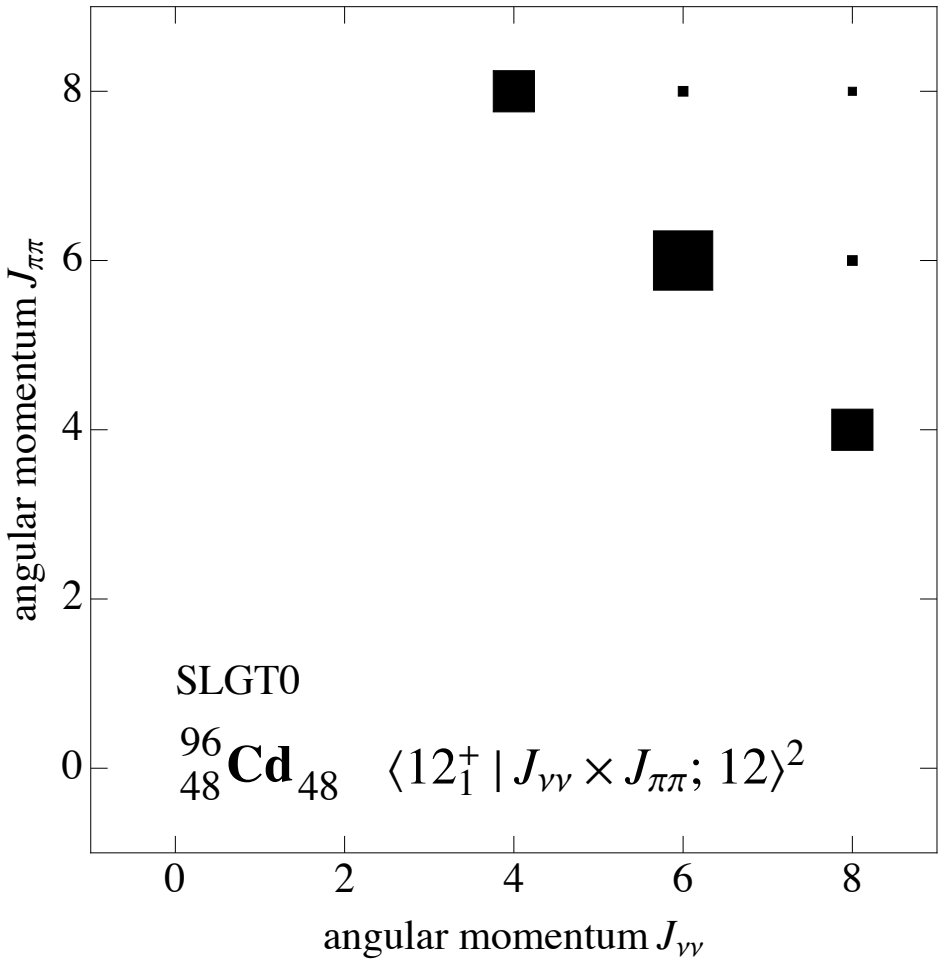

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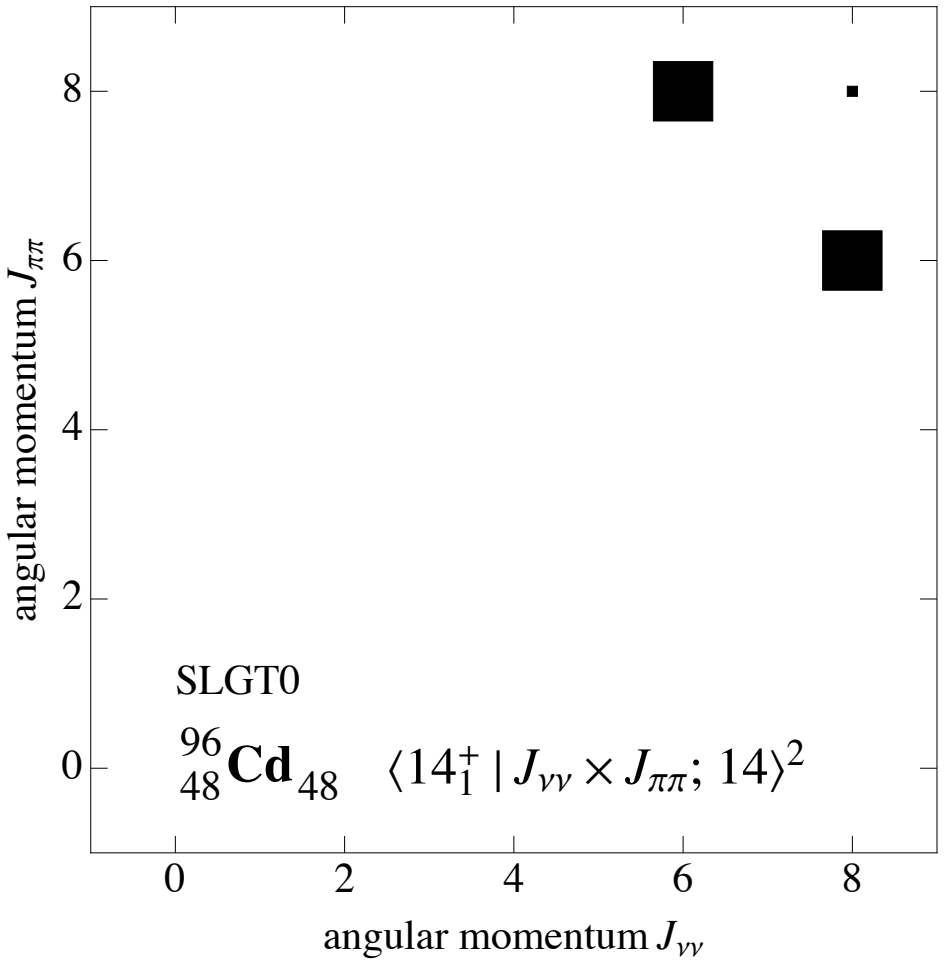

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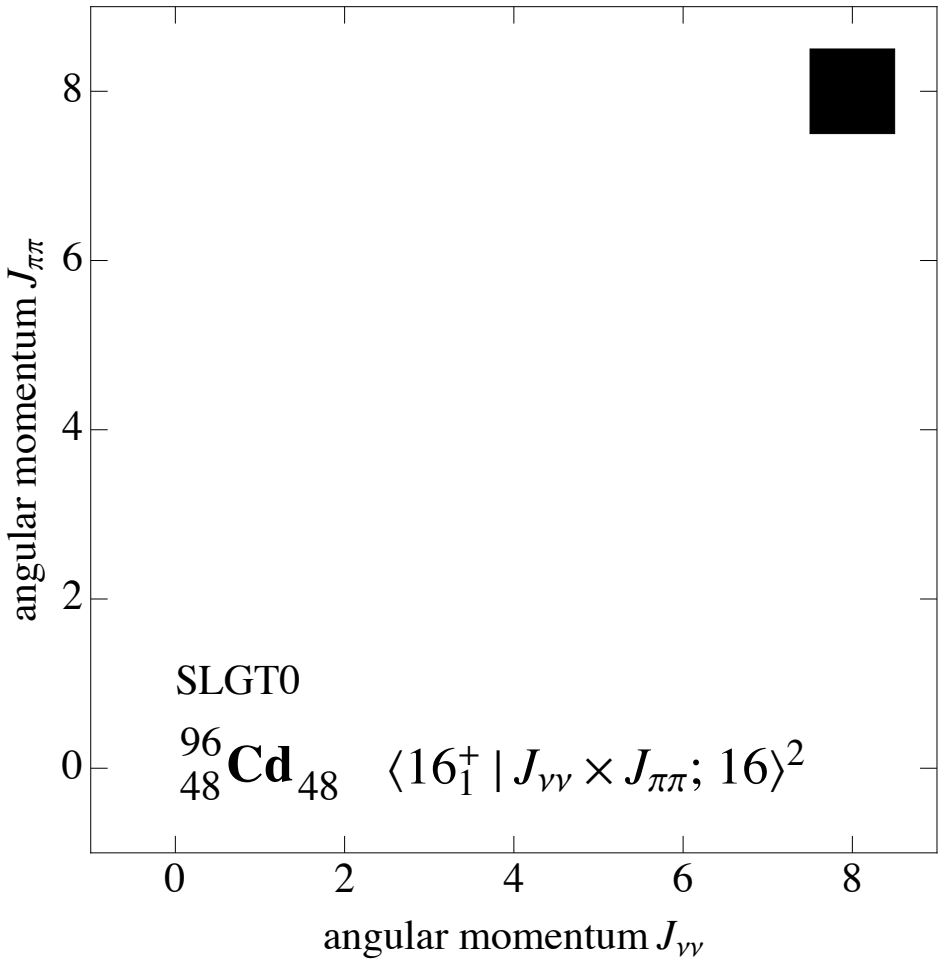
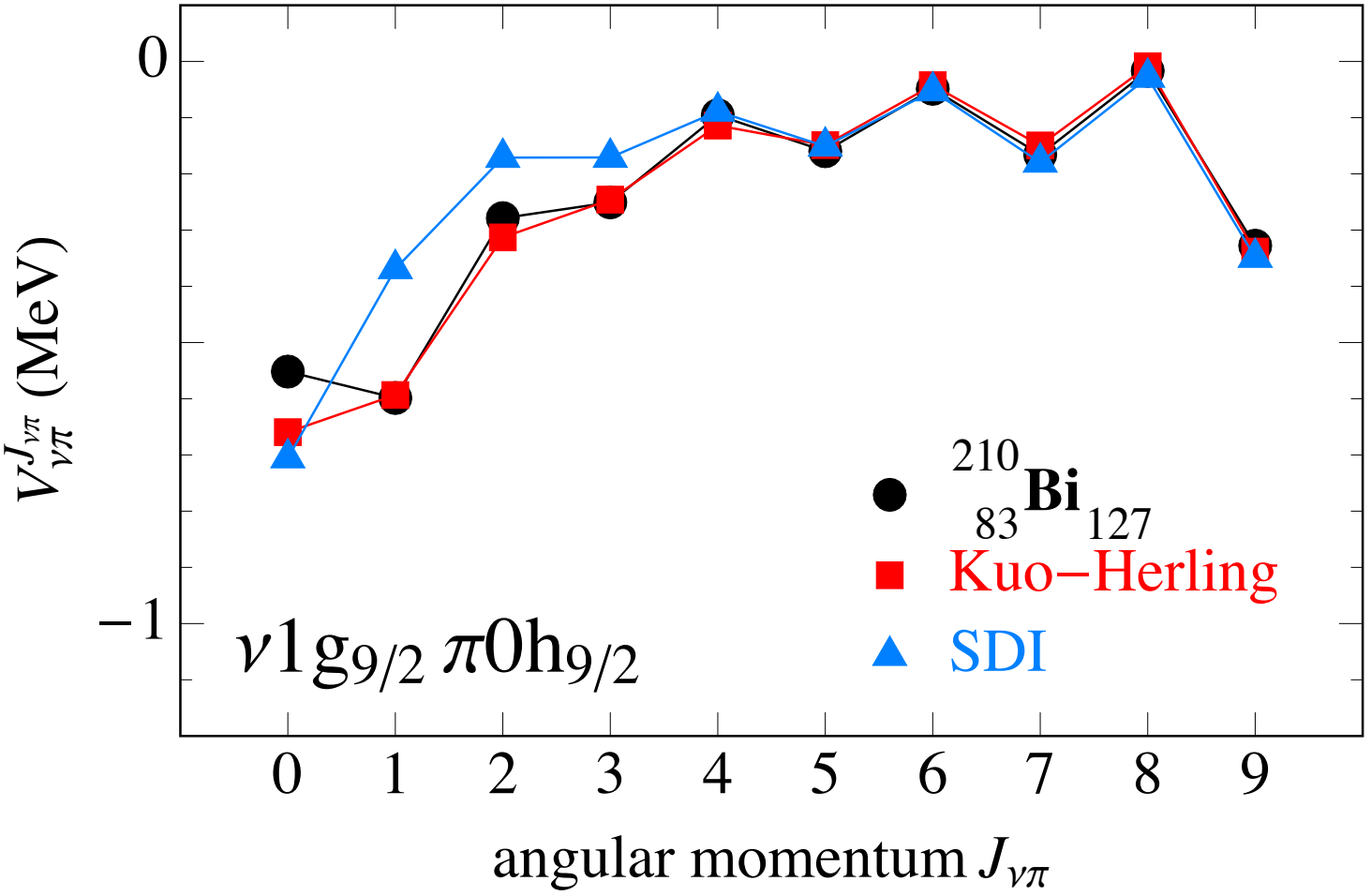
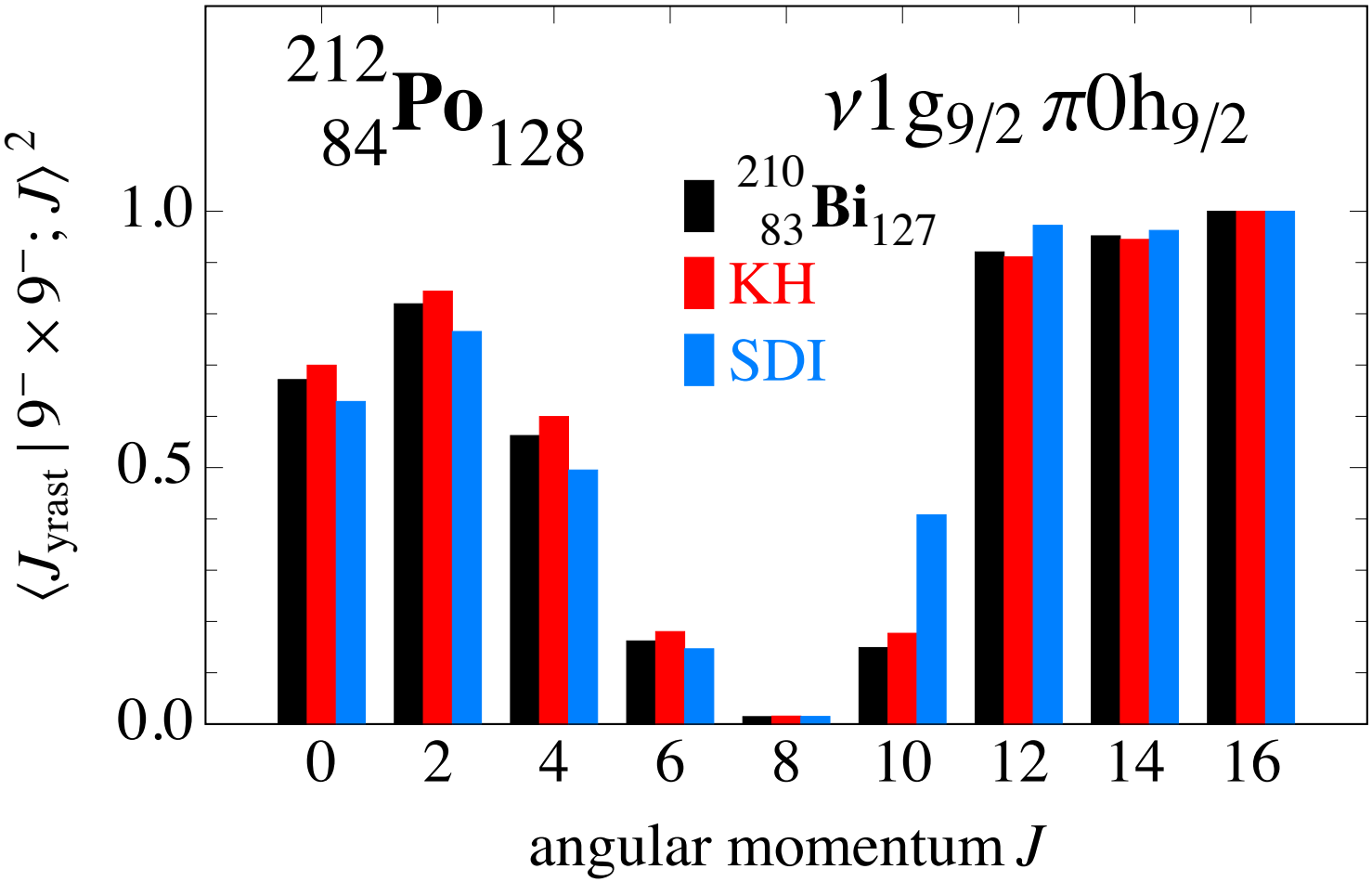


The $\nu 1g_{9/2}$-$\pi 0h_{9/2}$ interaction



Aligned-pair analysis for ^{212}Po



Conclusions

If valence nucleons dominantly occupy high-j orbitals, the yrast spectroscopy is essentially determined by a single matrix element, namely the one where neutron and proton are aligned in angular momentum.

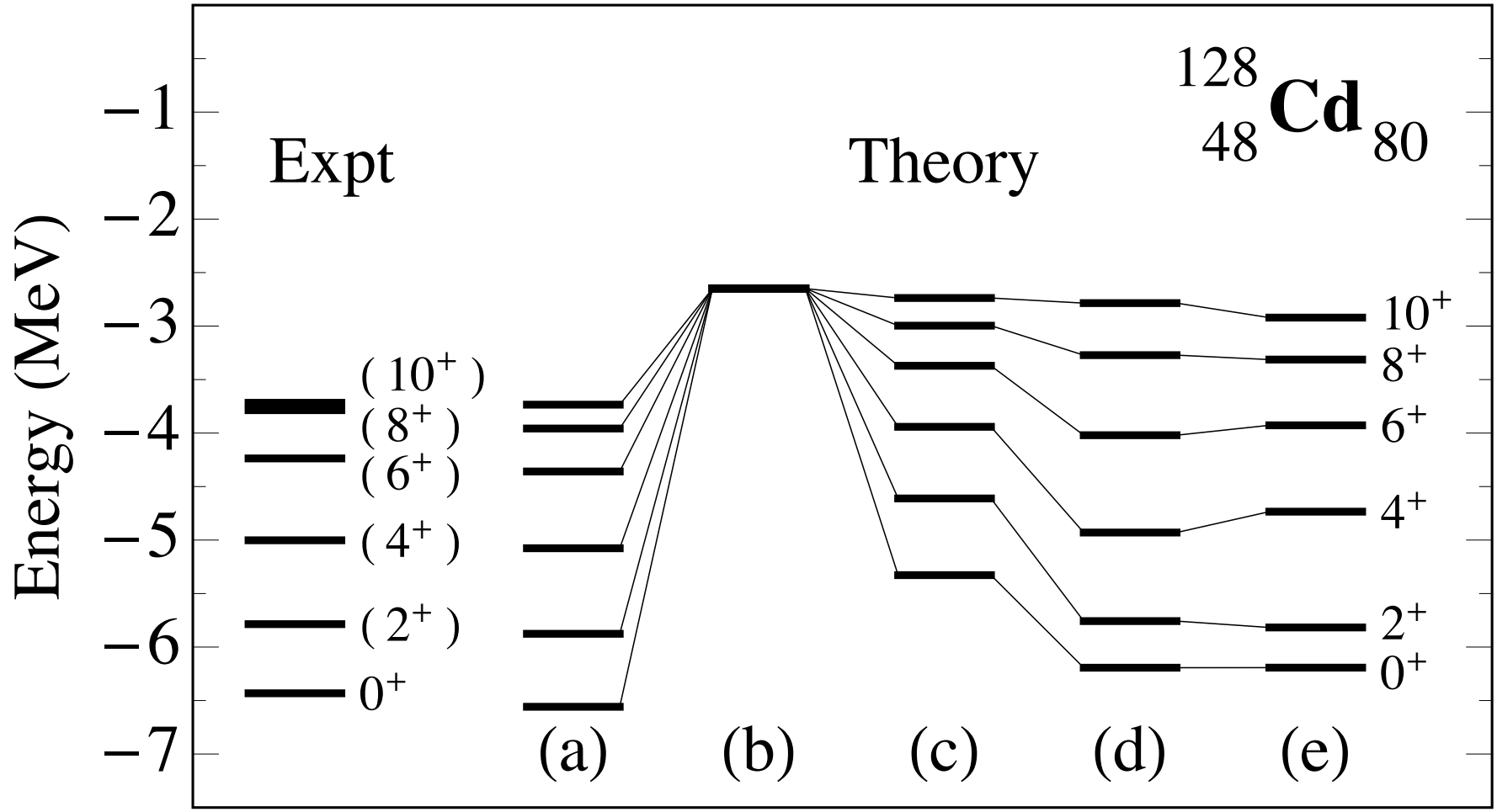
Under the same assumption, most (but not all) of the yrast states can be dominantly written in terms of aligned np-pairs. This dominance disappears in a multi-j scenario.

Outlook

Pairing + quadrupole is a popular schematic model, the friendly companion of the nuclear physicist.

Can it be replaced by pairing + aligned? A preliminary study shows that the 2n+2p system is solvable.

The 2n-2p spectrum: ^{128}Cd



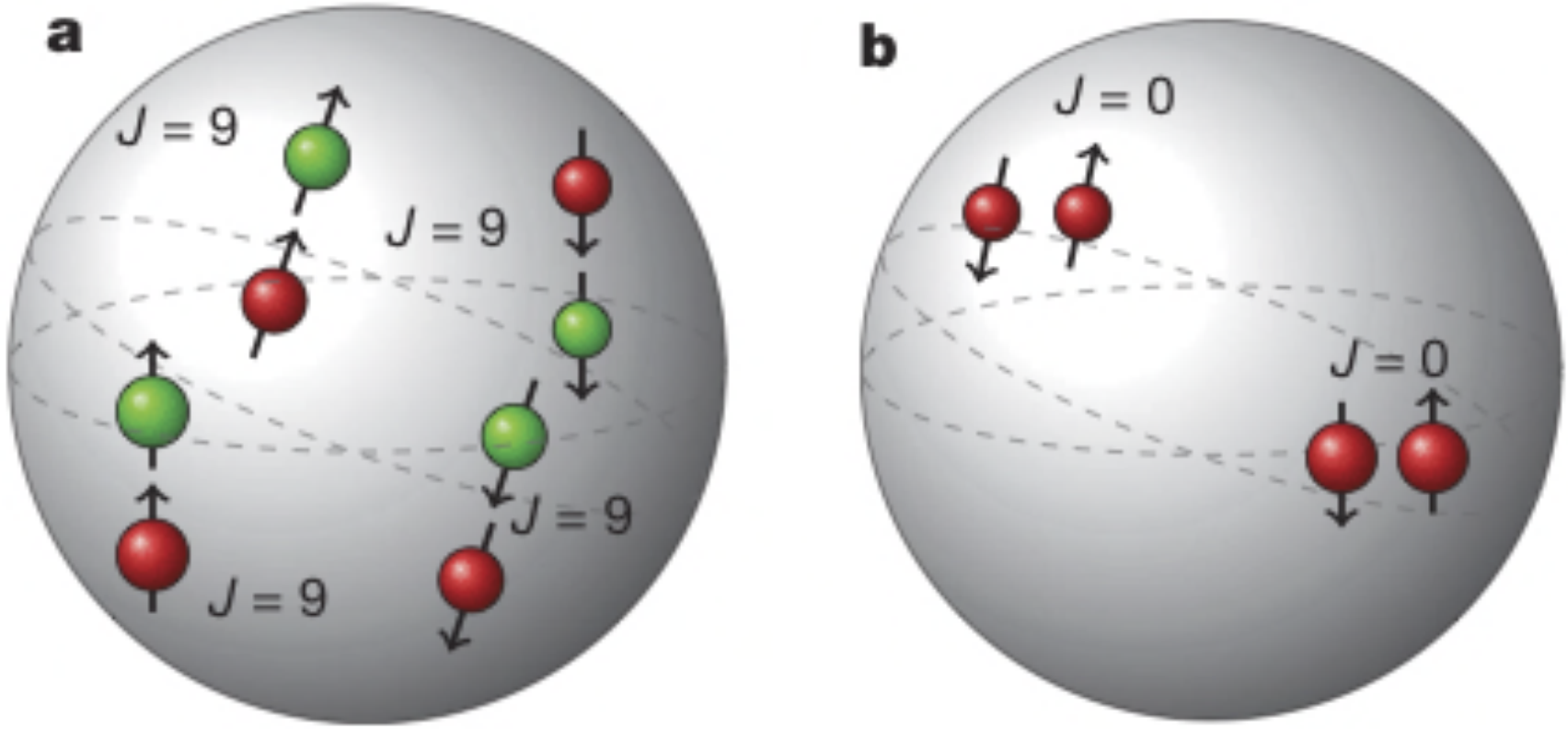
Spin-aligned $T=0$ np pairs

Motivation: A simple description of the $N=Z$ nuclei ^{98}In, ^{96}Cd, ^{94}Ag, ^{92}Pd, ^{90}Rh.

Starting point: Shell-model interpretation in terms of spin-aligned $T=0$ np pairs (Blomqvist).

Experiments have been proposed and carried out at GANIL (Cederwall, de France, Wadsworth...).

Nuclear belly dancer



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A new coupling scheme?

Our results reveal evidence for a spin-aligned, isoscalar neutron–proton coupling scheme.

[T]his coupling scheme replaces normal superfluidity (characterized by seniority coupling) in the ground and low-lying excited states of the heaviest $N=Z$ nuclei.

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