FOUR-NEUTRON DECAY CORRELATIONS*

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The mechanism of simultaneous non-sequential four-neutron emission (or "true" four-neutron decay) has been considered in the phenomenological five-body approach. It is demonstrated that four-neutron decay fragments should have specific energy and angular correlations reflecting strong spatial correlations of "valence" nucleons orbiting in their four-neutron precursors. Due to the Pauli exclusion principle, the valence neutrons are pushed to the symmetry-allowed configurations in the four-neutron precursor structure, which causes a "Pauli focusing" effect. Prospects of the observation of the Pauli focusing have been considered for the hydrogen-7 nucleus. Fingerprints of its nuclear structure or/and decay dynamics are predicted.

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1. Introduction

In the last decade, there was great progress in the studies of three-body decays (*e.g.* two-proton radioactivity) [1]. In contrast to "conventional" two-body decays, three-body decays encrypt a lot of additional information in the momentum (energy and angular) correlations of the decay products. Theoretical studies indicate that both effects of the initial nuclear structure and the decay mechanism may show up in the core$+n+n$ and core$+p+p$ fragment correlation patterns in various ways [2–13].

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With the development of experimental techniques, more and more "complicated" nuclear systems become available for studies. One of such complicated cases are isotonic neighbors of the $4n$-halo systems located beyond the neutron dripline, which are expected to have a narrow resonance ground state decaying via $4n$-emission. The examples of such systems, which are now actively studied by experiment, are ^{7}H and ^{28}O. The $4n$-emission phenomenon is known to be widespread beyond the neutron dripline, and other possible candidates for such a decay mode, *e.g.* ^{18}Be, can be mentioned. Their ground states are expected to be unbound with $E_{\mathrm{T}} \lesssim 2$ MeV (E_{T} is energy above the $4n$-decay threshold), and the decay mechanism can be assumed as "true" $4n$-emission: there are no sequential neutron emissions, which means that all neutrons are emitted simultaneously.

In the $4n$-emission (core+$4n$ decay), the five-body correlations encrypt enormously more information compared to the three-body decay. In five-body case, the complete correlation pattern is described by 8-dimensional space compared to the 2-dimensional space in the three-body decay. The core+$4n$ system permutation symmetries should decrease the effective dimension of the correlation space, but there should be still a lot left. The question can be asked here "How we should look for physically meaningful signals in this wealth of information?"

2. Pauli focusing

The concept of "Pauli focusing" was proposed in [14] and further discussed *e.g.* in [15, 16] for the bound state structure of three-body core+n+n systems. It was demonstrated that due to the Pauli exclusion principle, the population of orbital configurations $[l_{j_1} \otimes l_{j_2}]_J$ for the valence nucleons may induce strong spatial correlations depending on the specific values of j_1, j_2, and J. Various forms of such correlations were actively discussed as an integral part of the two-nucleon halo phenomenon.

For bound states, the predicted Pauli focusing correlations are "hidden" in the nuclear interior and can be accessed experimentally only in some indirect way. In contrast, in the three-body decay process, these internal correlations may directly exhibit themselves in the momentum distributions of the decay products. The fingerprints of Pauli focusing can be illustrated by examples of well-studied core$+p+p$ three-body decays of ^{6}Be and ^{45}Fe ground states [1, 7, 9, 17].

Pauli focusing for 5-body systems was discussed in Ref. [18] by the example of ^{8}He nucleus described by the α+$4n$ model. The complicated spatial correlation patterns were predicted. The same case was considered in more detail in Ref. [19]. In analogy with the three-body case, we may expect that

Pauli focusing correlations found in the bound five-body systems should exhibit themselves in decays if such systems are located above the five-body breakup threshold.

3. Theoretical model

The theoretical model we develop in this work for dynamics of 5-body decay is a generalization of the *improved direct* $2p$*-decay* model [20] to the $4n$ emission case. In direct decay models, it is assumed that emitted particles are propagating to asymptotics in fixed quantum states, while the total decay energy is shared among single-particle configurations described by R-matrix-type amplitudes.

Following the improved direct $2p$-decay model approach, the differential decay probability of the 5-body decay for core $+ n_1 + n_2 + n_3 + n_4$ system is

$$\begin{aligned} \mathrm{d}W &\sim |T|^2 \, \mathrm{d}V_4 \prod_{k=1\ldots4} \mathrm{d}\Omega_k \, , \\ \mathrm{d}V_4 &\sim \delta\left(E_{\mathrm{T}} - \sum_i \varepsilon_i E_{\mathrm{T}}\right) \sqrt{\varepsilon_1\varepsilon_2\varepsilon_3\varepsilon_4}\, \mathrm{d}\varepsilon_1 \mathrm{d}\varepsilon_2 \mathrm{d}\varepsilon_3 \mathrm{d}\varepsilon_4 \, , \\ T &= \mathcal{A}\left[\prod_{k=1\ldots4} A_{cn_k}\left(l_k, j_k, \boldsymbol{p}_{cn_k}\right)\right]_J \, . \end{aligned} \tag{1}$$

The amplitude T has defined total spin J and is antisymmetrized for permutation of four valence nucleons.

4. Discussion

Now we can demonstrate that for true five-body decays of core+$4n$ systems, the *Pauli focusing* — the cumulative effects of antisymmetrization and population of definite orbital configurations — may lead to distinctive correlation patterns.

These patterns are presented in Fig. 1 for one-dimensional energy and angular distributions. Here, they can also be masked by other dynamical effects. However, we have found a way to reliably extract the information on internal structure from correlations.

In addition to the one-dimensional distributions, the *correlated two-dimensional energy* $\{\varepsilon_{ik}, \varepsilon_{nm}\}$ and *angular* $\{\theta_{ik}, \theta_{nm}\}$ $(i \neq k,\ n \neq m)$ *distributions* may be constructed, see Fig. 2. For core+$4n$ decays, in total five topologically nonequivalent two-dimensional distributions exist. Two topological types "*nnn*" and "*cn–nn*" are illustrated in Fig. 2. Similarly, the types "*ncn*", "*cnn*" and "*nn–nn*" can be introduced. The reconstruction of all these distributions requires a complete kinematical characterization of the core+$4n$ decay, which is within the reach of the modern experiment.

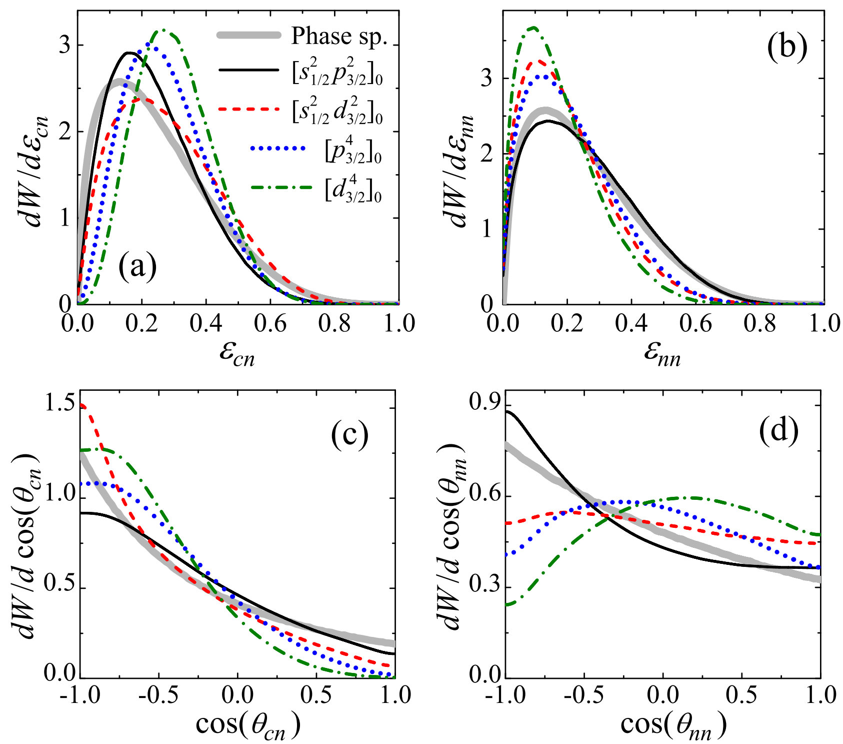

Fig. 1. The normalized energy (a), (b) and angular (c), (d) distributions in the core–n (a), (c) and n–n (b), (d) channels of $4n$-decay for all different pure $4n$ configurations. The decay energy is $E_{\mathrm{T}} = 500$ keV. The reference phase-space distributions are shown by the thick gray lines.

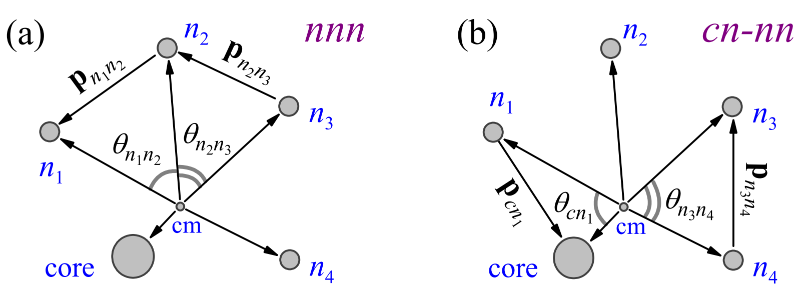

Fig. 2. Schemes of kinematical variables describing 5-body decays, which are used in constructing correlated two-dimensional energy $\{\varepsilon_{ik}, \varepsilon_{nm}\}$ and angular $\{\theta_{ik}, \theta_{nm}\}$ distributions of fragments. Examples (a) of "connected" nnn and (b) of "disconnected" cn–nn topologies.

We propose to study the *full set of the two-dimensional correlated energy or/and angular distributions* for the derivation of the information concerning the quantum-mechanical $4n$-decay configuration. We predict that, taken together, these distributions form a unique "fingerprint" of the decaying quantum state.

5. Summary

Our theoretical studies of the correlations in emission of four nucleons in the nuclear five-body decay show that such kind of correlation can provide information on nuclear system internal structure. The paper [21] provides a discussion about kinematics and dynamics of the nuclear five-body decay and possible kinematical variables for correlations studies. The problem of the n–n interaction in the nuclear five-body decay is also discussed in [21]. The paper [22] provides an example of the correlation analysis, based on the approach developed in [21].

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