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Three-body decays of light nuclei: ^{6}Be, ^{8}Li, ^{9}Be, ^{12}O, ^{16}Ne, and ^{17}Ne

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Abstract. The theoretical approach to the two-proton radioactivity and three-body decays developed in (L.V. Grigorenko, R.C. Johnson, I.G. Mukha, I.J. Thompson, M.V. Zhukov, Phys. Rev. Lett. **85**, 22 (2000) and to be published in Phys. Rev. C) is applied to the range of light nuclear systems. We study nuclear structures, widths, and momentum correlations for the decay fragments. Strong contradictions with experiment, as well as effects of special interest, are found in ^{12}O and ^{16}Ne nuclei.

PACS. 21.60.Gx Cluster models – 21.45.+v Few-body systems – 23.50.+z Decay by proton emission

1 Introduction

The experimental studies of the two-proton radioactivity were very active in the recent years. However, it is still a complicated and controversial field. From the methodological point of view the process of "true" two-proton radioactivity is of a special importance. The term was proposed by Goldansky [1] for states where the two-proton emission is the only decay channel. Originally it was discussed for the *medium mass* ($A = 20$–70) proton-rich nuclei. While for these nuclei the clear identification of the true two-proton emission is still questionable, a wider class of processes (including three-body decays) is reasonably well studied in *light* nuclei. For example, in the following cases three-body breakup has been directly observed: ^{6}Be 0^+ g.s. and 2^+ states $\rightarrow \alpha + p + p$ [2], ^{8}Li 4^+ state $\rightarrow \alpha + T + n$ [3], ^{9}Be $5/2^-$ state $\rightarrow \alpha + \alpha + n$ [4], ^{12}O 0^+g.s. $\rightarrow {}^{10}$C $+ p + p$ [5]. We do not mention here other cases of interest, where either theoretical or experimental interpretations are not that straightforward. The states with dominating three-body decay mode have unexpectedly low widths, broad distributions and complicated correlations of the emitted particles.

A theoretical model (the source function model or SF) has been developed in [6] for the heavier two-proton emitters. Some of them can be extremely narrow states. So narrow, actually, that two-proton emission becomes hindered by weak transitions. In this model we first find a "box" WF for a finite domain and then use it as a source, to construct a decaying WF with outgoing asymptotic. The approximate boundary conditions for the long-range three-body Coulomb interaction employed in the model allow us to achieve sufficient precision and stability for observables. The model is specially suited for extremely narrow states, but we found it also applicable and useful even for comparatively wide states (up to hundreds of keV) in the light nuclei.

The results obtained in [6] are the first actual calculations of the two-proton radioactivity. In this paper we demonstrated the robustness of the method for some anticipated cases of two-proton radioactivity. More detailed and systematic studies and careful comparison with experiment (whether it is accessible) are the logical continuation of this work. Here we present the results of studies of the following nuclear states: ^{6}Be 0^+ g.s, ^{8}Li 4^+ $E^* = 6.53$ MeV, ^{9}Be $5/2^-$ $E^* = 2.43$ MeV, ^{9}B $5/2^-$ $E^* = 2.36$ MeV, ^{12}O g.s., ^{16}Ne g.s., ^{17}Ne $3/2^-$, $1/2^+, 5/2^-$ at $E^* = 1.288, 1.850, 1.910$ MeV. For the well-studied cases in $A = 6$–9 nuclei the calculated widths of the states are in a good agreement with experiment. For ^{12}O g.s. and ^{16}Ne g.s. the calculated widths $\Gamma \sim 66$ keV and $\Gamma \sim 0.8$ keV are much less than the experimental values 578(205) keV [5] and 122 keV [7], respectively. The controversy between theory and experiment for ^{12}O g.s. is well known and widely discussed (see [8] and references therein). Our results in [9] support the conclusion of [8] that the width of ^{12}O g.s. should be much lower than the observed width. The problem with ^{16}Ne is not that well studied (it is only discussed in [10]), and we feel that it is somehow forgotten by the community. Both the theoretical and experimental situations in ^{16}Ne are very similar to the ^{12}O case and deserve more attention.

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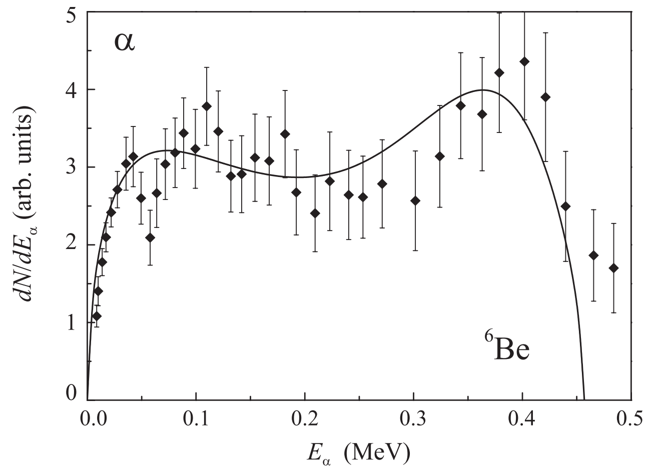

Fig. 1. Spectrum of α-particles from the decay of the ^{6}Be 0^+ state.

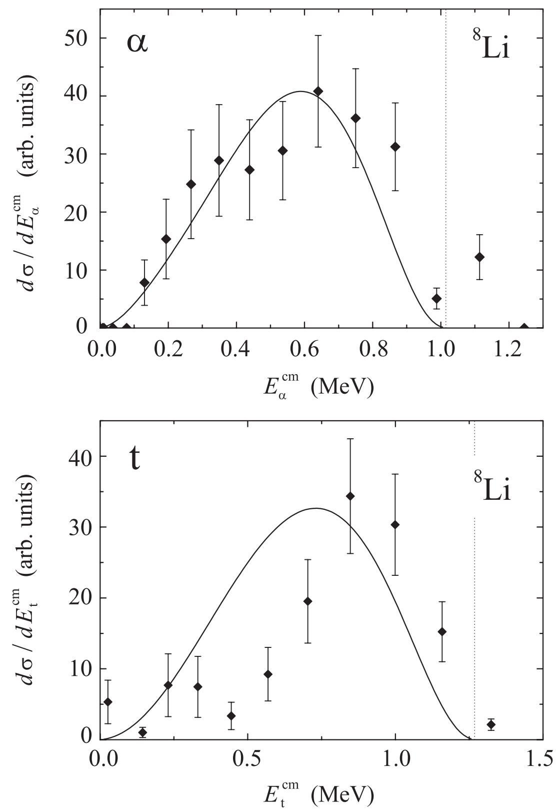

Fig. 2. Spectra of α-particles and tritons from the decay of the ^{8}Li 4^+ state.

We also have found that the structure of the ground states in ^{12}O and ^{16}Ne differs significantly from the mirror isobaric analogue states (a breaking of isobaric symmetry at the level of tens of percents). Together with the corresponding decrease of the Coulomb energy, this effect can be interpreted as a three-body mechanism of the Thomas-Ehrman shift.

We use the realistic intercluster potentials based on experimental data wherever possible. However, the decay characteristics are very sensitive to the energy of state. For that reason in our calculations it is always adjusted to exactly the experimental one using a simple three-body potential [11].

2 ^{6}Be 0^+ state

Both the bound states and the continuum of the ^{6}He nucleus are well studied in a three-body $\alpha + n + n$ model. The situation is less developed with ^{6}Be as all its states are situated in the continuum and some way of taking into account the three-body Coulomb interaction is essential for their description. There are actually very few papers, where these states are treated as continuum ones.

Our calculated widths of the states in ^{6}Be are in good agreement with experiment. With our model we can also calculate the momentum distributions of the decay fragments. For example, the spectrum of α-particles from the decay of the ^{6}Be 0^+ state is shown in fig. 1 (experimental data is from [2]). The only work where this kind of data has been considered so far is the phenomenological analysis in [12]. At the moment our results for distributions are preliminary and should be more carefully discussed.

3 ^{8}Li 4^+ state

The narrow width of the 4^+ state in ^{8}Li ($\Gamma_{\rm exp}$ = 35(15) keV) is easily explained if we assume the decay into ^{7}Li(g.s.) and a neutron in the relative f-wave. The width we estimate in a two-body potential model gives $\Gamma = 27$ keV. However, it was shown in experiment [3] that the branching of the decay into ^{7}Li(g.s.)$\,+\,n$ does not exceed 10% and the $\alpha + T + n$ channel is dominating. It was considered as an evidence for the cluster structure of the 4^+ state.

The three-cluster ground and excited states of ^{8}Li, ^{8}B have been studied theoretically in a three-body model in [13]. In this model various properties of the lowest 2^+, 1^+ states are reproduced well with the potentials fitted to the experimental phase shifts for the subsystems. The energy of the 4^+ state practically coincides with the experimental value $E = 2.03$ MeV, and the obtained width $\Gamma = 31$ keV is also in good agreement with experiment. The dominating component of the WF can be interpreted as ^{7}Li$^*(7/2^-)$ and a neutron in the relative p-wave. The calculations predict a low weight for the component with quantum numbers of ^{7}Li(g.s.)$\,+\,n$ (less than 14%), which is consistent with low branching ratio to this channel observed in [3].

Figure 2 shows the experimental spectra of the α-particle and triton [3] compared with calculations. The possible binary decay channel ^{7}Li(g.s.)$\,+\,p$ is not taken into account in our calculations, but we do not think it can influence the results strongly, as it is known from experiment to be small.

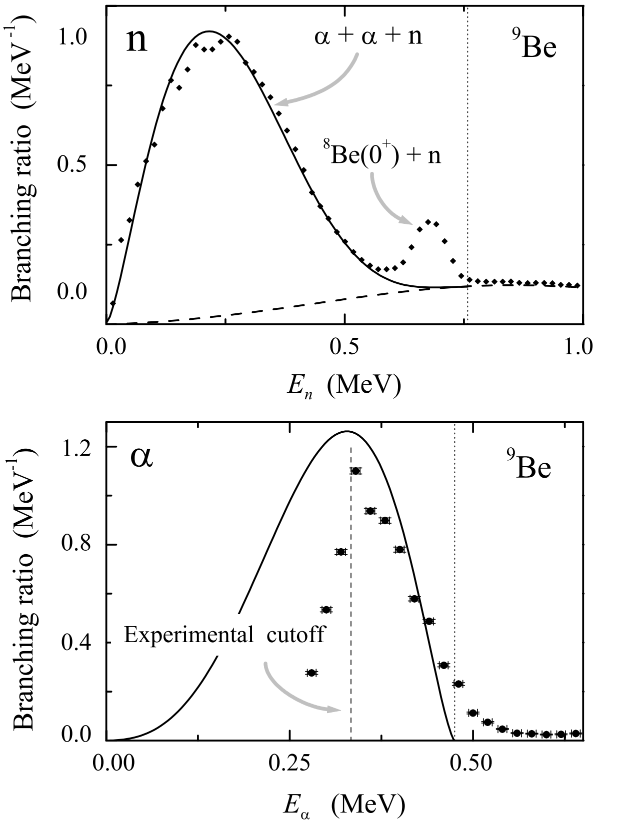

Fig. 3. Spectra of α-particles and neutrons from the β-delayed decays of states in ^{9}Be. Vertical dotted lines show the maximal energies for particles from the decay of the $5/2^-$ state. Spectra are in units of the branching ratio to the total decay rate. Contribution from higher states for neutrons is shown by the dashed curve. The spectrum of α-particles has a detector cutoff at low energy.

4 ^{9}Be, ^{9}B $5/2^-$ states

The $5/2^-$ state in ^{9}Be is strongly populated in the β-decay of ^{9}Li. In [4] the β-delayed particle spectra from this decay have been studied and it was shown that the decay of this state is predominantly three body (the two-body $^8\mathrm{Be}+n$ branch is only about 7%).

The calculated widths of the ^{9}Be ($\Gamma = 0.13$ keV) and ^{9}B ($\Gamma = 55$ keV) $5/2^-$ states reasonably agree with the experimental values $\Gamma_{\rm exp} = 0.77(15)$ keV and $\Gamma_{\rm exp} = 81(5)$ keV. The spectra of α-particles and neutrons [4] from the β-delayed decays of states in ^{9}Be are compared with theoretical calculations in fig. 3. The low-energy parts of the spectra are dominated by the wide structures from the “democratic” decay of the $5/2^-$ state, which itself has a very narrow width. The description of experimental spectra is very good for neutrons and at least consistent for α-particles, where the data is not that good. It should be noted that theoretical spectra in fig. 3 show the same distribution plotted for different particles.

Both the structure and widths of the $5/2^-$ states are governed by the component which can be described as ^{8}Be(2^+) and a neutron in the $p_{3/2}$ orbital, in agreement with qualitative ideas about the structure of these states.

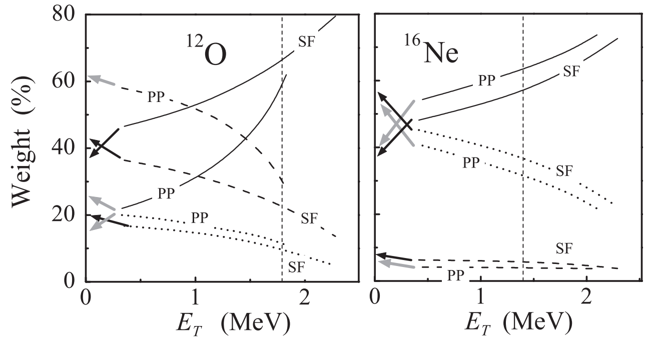

Fig. 4. The weights of single-particle configurations for valence protons if the binding is artificially changed. Solid, dashed, and dotted curves stand for s-, p-, and d-waves. Arrows show the weights of corresponding components in the mirror IAS g.s. WFs at the correct binding energies. Vertical dashed lines show the experimental energies above the two-proton threshold. The PP model (Pauli projection) differs from the SF model in the way the Pauli principle is treated.

5 ^{12}O and ^{16}Ne: widths, isobaric symmetry breaking, and Thomas-Ehrman shift

The ^{12}O and ^{16}Ne nuclei are very good examples of systems where we can expect true two-proton decay mode: the one-proton separation energy is approximately the same as the two-proton separation energy, but the lowest states on the core$+p$ subsystems are very wide s-wave resonances, which cannot form strong two-body correlations. Studies of ^{12}O and ^{16}Ne ground states [9] have shown a range of interesting issues.

i) There are large discrepancies between the calculated and experimental widths, which are too serious to be attributed to uncertainties of the theoretical models. The results of different model approaches are quite close to each other and all far from experiment. We expect the width for ^{12}O to be about 60 keV, and for ^{16}Ne about 1 keV. For a specified resonance energy the obtained limits on the widths are reliable and should not be ignored when interpreting the experimental results. This issue is of considerable methodological importance for the theory of two-proton radioactivity in general.

ii) We have found a three-body mechanism of the isobaric symmetry breaking and relate it to the Thomas-Ehrman shift. The structures of ^{12}O and ^{16}Ne differ considerably from those of their mirror isobaric partners ^{12}Be and ^{16}C. The effect is large (tens of percents) and should be experimentally observable. To have an insight into the dynamics, we investigated the energy dependence of the effect. Figure 4 shows what happens with the structure, if we artificially change the resonance energy. The isobaric symmetry is clearly recovering when the state moves to the sub-barrier region. In the phenomenological shell model analysis [14] it was suggested that a modification of the residual nuclear interaction is required to describe the Thomas-Ehrman shift in nuclei around ^{16}O. In our

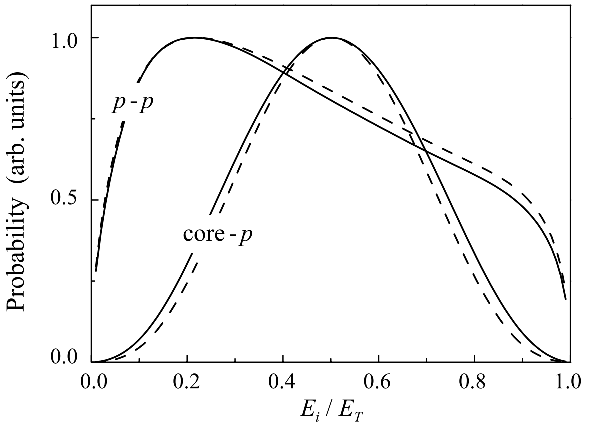

Fig. 5. Energy distributions for *p-p* and core-*p* subsystems for ^{12}O (solid line) and ^{16}Ne (dashed line). The energy between two particles is scaled to the two-proton threshold energy E_T.

three-body model we describe well the Coulomb shifts for the ^{12}Be-^{12}O and ^{16}C-^{16}Ne pairs. However, we find that responsible for this is a peculiar three-body effect (the increase of the s^2 component in the ^{12}O and ^{16}Ne WFs compared to that of their mirror partners).

iii) In paper [5] measured correlation spectra are presented. Unfortunately the authors have chosen to show the spectra which are quite featureless from the theoretical point of view. A better insight into dynamics could be obtained by studying, for example, energy correlations among the decay fragments. The predicted correlation spectra for ^{12}O and ^{16}Ne are given in fig. 5.

iv) In paper [15] the first excited state in ^{16}Ne, found at an excitation energy of 2.1 MeV, was identified as second 0^+ rather than 2^+. In our calculations the 0^+ and 2^+ states have practically the same energy (see also the analysis in [14]) but their widths differ by two orders of magnitude. The width of the state could be a good indicator of whether it is a 2^+ or a second 0^+ state.

6 Excited states in ^{17}Ne

The first time ^{17}Ne was considered as a candidate for two-proton radioactivity was by Goldansky and Goldberg in [16]. They predicted that the threshold for two-proton decay should be the lowest one in ^{17}Ne, and at least two excited states ($3/2^-$ and $5/2^-$) at 1.3 and 1.8 MeV could be good candidates to investigate the phenomenon. Recently these two levels were found at excitation energies 1.29 MeV and 1.76 MeV and more precise data on the mass defect of ^{17}Ne was obtained in [17]. Some interest in ^{17}Ne was also caused by the possible halo structure of its ground state [18].

The decay of the first excited state has been studied in [19], where the total width was found to be 1.3×10^{-5} keV. The results were interpreted in [19] as giving some evidence for the two-proton decay branch. However, calculations in [6] have shown that the two-proton partial width of the state should be negligible. In this context it could be interesting to see if the other excited states in ^{17}Ne have substantial two-proton branches.

Table 1. Characteristics of the ^{17}Ne states. All energies are in keV. The column Γ_3 gives the calculated three-body widths of the states. The column Γ_2 gives potential model estimates of the width for sequential decay via 0^-, 1^- states.

J^π	E	E_T	S_p	Γ_3	Γ_2
$1/2^-$	0	−944	1480		
$3/2^-$	1288	344	191	4.1×10^{-16}	
$5/2^-$	1850	906	−371	1.2×10^{-8}	5×10^{-6}
$1/2^+$	1910	966	−431	2.1×10^{-6}	3.5×10^{-4}

Table 1 shows the decay characteristics of states in ^{17}Ne. The results for the three-body widths of $5/2^-$ and $1/2^+$ states should be considered as estimates, because we do not take into account the strong binary channel ^{16}F$(0^-) + p$ properly. The estimates for the partial width connected with this channel are given in column "Γ_2". From this estimates we can expect a branching ratio for the two-proton decay of about 1%.

7 Conclusion

In this paper we report the results of studies of the two-proton (three-body) decays of light nuclei. A very reasonable description for the well-studied cases of $A = 6$–9 nuclei has been obtained. For heavier nuclei we are coming to much poorer exploited studies and we find several interesting problems there. Further studies are required to clarify those problems.

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