Possibility to study a two-proton halo in $^{17}\text{Ne}$.

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The nuclide $^{17}\text{Ne}$ is studied theoretically in a three-body $^{15}\text{O}+p+p$ model. We demonstrate that the experimental conditions for existence of a proton halo in $^{17}\text{Ne}$ can be reasonably quantified in terms of $s/d$ configuration mixing. We discuss experimental evidences for a proton halo in $^{17}\text{Ne}$. We define which kind of experimental data could elucidate this issue.

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The $^{17}\text{Ne}$ nucleus is an interesting and relatively poorly studied system. It is a Borromean nucleus, since none of the binary subsystems ($^{15}\text{O}-p$ and $p-p$) are bound. It seems to be the only realistic candidate to possess a two-proton halo $^{15}\text{O}$-$^{17}\text{Ne}$. The level scheme was established not so long ago $^{2}$ in multinucleon transfer reactions. Available experimental data include Coulomb excitation $^{3,4}$ and low energy nuclear fragmentation $^{3,5}$ measurements. The $^{17}\text{Ne}$ nucleus has attracted attention also due to the possibility of two-proton emission from the excited states $^{6,7}$. Another interesting issue in comparison with $^{17}\text{N}$ is a $\beta$-decay asymmetry for decays to the first excited $1/2^+$ states in daughter nuclei $^{8}$.

The results of theoretical studies of $^{17}\text{Ne}$ are controversial. In papers $^{2,10,11}$ the structure of $^{17}\text{Ne}$ was studied with emphasis on the Coulomb displacement energy (CDE) derivation. In papers $^{10,12,13}$ the $s^2$ configuration is predicted to dominate, while in paper $^{11}$ the dominating configuration is predicted to be $d^2$. In paper $^{12}$ effects of the “halo” kind (connected with larger radial extension of WF on the proton side) were considered being irrelevant for the $\beta$-decay asymmetry problem $^{9}$. However, in paper $^{14}$ the $\beta$-decay asymmetry was successfully explained in these terms. It seems that theoretical agreement about the basic properties of $^{17}\text{Ne}$ is still missing at the moment.

In papers $^{6,15}$ the comparatively narrow core momentum distribution was interpreted as possible evidence for proton halo in $^{17}\text{Ne}$. This is a reasonable approach to the problem, as among typical experimental evidences for halo (e.g. large interaction, electromagnetic dissociation, and nucleon removal cross sections), the momentum distributions should give most expressed signal for this system. The aim of this paper is to test three-body WFs, obtained in $^{2}$, against the most recent experimental data $^{6,7}$. We demonstrate that the experimental question of the proton halo existence in $^{17}\text{Ne}$ formulated as in $^{6,15}$ is largely defined by $s/d$ configuration mixing. As we have already mentioned, the exact $s/d$ ratio in $^{17}\text{Ne}$ is difficult to obtain unambiguously by theoretical calculations. To derive it from experimental data it is necessary to know the sensitivity of various observables to this aspect of the dynamics. We show that currently available experimental data are insufficient to determine reliably the structure (and possible halo properties) of $^{17}\text{Ne}$. We can, however, confidently define which kind of experimental data is required to resolve the puzzling issues of the $^{17}\text{Ne}$ structure.

Structure model. — Studies in this paper are based on the $^{17}\text{Ne}$ WF obtained in a three-body model $^{2}$. The model predicts about 50% $s/d$ mixing for the ground state of $^{17}\text{Ne}$. Recently this nucleus has been studied in a three-body model $^{10}$, providing results very close to those in Ref. $^{2}$. Beside the WF from $^{2}$, which we refer to here as GMZ, we have also generated two WFs with high $|W(s^2)| \sim 70\%$ and low $|W(s^2)| \sim 7\%$ weights of $s^2$ components. Note that this required unrealistic modifications of the $^{15}\text{F}$ spectra. Thus, these WFs should not be regarded as variants of a theoretical prediction. They are used in this paper only to estimate a scale of the sensitivity of different observables to variations in $^{17}\text{Ne}$ structure. Table 1 and Fig. 1 show various properties of the three lowest states in $^{17}\text{N}$ and $^{17}\text{Ne}$ calculated with realistic GMZ, “high s” and “low s” WFs.

Studies of the $^{17}\text{N}$-$^{17}\text{Ne}$ pair as core+$N+N$ systems are reasonably well motivated. The nuclei $^{15}\text{N}$ and $^{15}\text{O}$ are well suited for the role of cores in a cluster model. Their lowest excitations are located at about 5.2 MeV and the lowest particle decay thresholds are at 10.2 and 7.3 MeV respectively. Also, in shell model studies of $^{17}\text{N}$ $^{13}$ and $^{17}\text{Ne}$ $^{14}$ the admixture of excited core configurations was found to be below 5%, which is not enough to change “bulk” properties of these nuclei significantly. The core matter radius enters the definition of the composite system radius, the core charge radius is used to define a Coulomb interaction (if needed). For $^{15}\text{N}$ the charge radius is known from electron scattering $r_{ch}(^{15}\text{N}) = 2.615 \text{ fm}$ $^{15}$. The corresponding matter radius is $r_{mat}(^{15}\text{N}) = 2.49 \text{ fm}$. We estimated the matter radius of $^{15}\text{O}$ in two ways (from known experimental charge radii $r_{ch}(^{14}\text{N}) = 2.57 \text{ fm}$ and $r_{ch}(^{16}\text{O}) = 2.71 \text{ fm}$), providing the same result: $r_{mat}(^{15}\text{O}) = 2.53 \text{ fm}$.

CDE. — This is the only observable, for which a sensitivity to $^{17}\text{Ne}$ structure far exceeds an experimental uncertainty. Calculations $^{2}$ provide the WF with about 50% $s/d$ mixing (GMZ case) reproducing experimental
CDE very well. We rely much on this fact, as a correct CDE should guarantee very reasonable radial characteristics of the WF. However, there is no agreement among theorists on this issue and other checks are also necessary.

**E2 transitions.** — Experimental derivation of $B(E2)$ values for the first excited states of $^{17}$Ne is a significant advance in studies of this system: $B(E2, 1/2^+ \rightarrow 3/2^-) = 66.2 \pm 1.8 \text{e}^2\text{fm}^4$ [4] and $B(E2, 1/2^+ \rightarrow 5/2^-) = 124(18) \text{e}^2\text{fm}^4$ [5]. If we consider the $^{15}$O core as a rigid charged body, its contribution to $B(E2)$ of $^{17}$Ne in a three-body model is small due to large core mass. The $B(E2)$ values are underestimated by $30 - 50\%$ in such calculations. To improve the model, we extract $E2$ matrix element $M(E2)_{\text{core}}$ for the core from experimental value $B(E2, 1/2^+ \rightarrow 5/2^-) = 6.7(1.2) \text{e}^2\text{fm}^4$ for $^{17}$Ne [12]. It is possible, because here valence neutrons do not contribute the $B(E2)$ value. The resulting calculated $B(E2)$ values for different versions of $^{17}$Ne WF are given in Table I (see also Fig. 1). One can see that only in the case of a significant configuration mixing a good agreement with experimental values can be achieved.

Large, compared to ours, theoretical $B(E2)$ values were obtained in shell model calculations with effective charges [6]: 105 and 155 $\text{e}^2\text{fm}^4$ for transitions to $3/2^-$ and $5/2^-$ states. Note that in our calculations there are no effective charges. If we recalibrate our $B(E2)$ values using effective charges from [6], we get a good agreement with these calculations for GMZ WF.

**Momentum distributions.** — The first step in studies of momentum distributions from fragmentation reactions is to study the momentum distribution in the nucleus itself.

![Image](https://via.placeholder.com/150)

**FIG. 1:** Dependence of observables for $^{17}$Ne on the structure. (a) Difference of experimental and theoretical CDEs for $^{17}$Ne–$^{15}$Ne pair. (b) Matter radius. (c) $B(E2)$ probabilities for transitions between g.s. and first excited states. The vertical dotted line corresponds to $W(s^2)$ of the GMZ WF.
where $\Psi_2^{JM}(p_x, X)$ are the WFs of $^{16}$F resonance states with different $j^\pi$, $\chi_p$ is a spin function of a removed proton and $\sigma$ stands for summation over spin variables. The Jacobi coordinates $X$, $Y$ and the conjugated momenta $p_x$, $p_y$ are in the “Y” coordinate system ($X$ is a distance between the core and a valence proton). This mechanism is dominating e.g. in fragmentation of $^6$He and $^{11}$Li [22].

Four low-lying single-particle states in $^{16}$F are taken into account: $0^−$, $1^−$, $2^−$, and $3^−$ with energies 0.535, 0.728, 0.959, and 1.256 MeV above the $^{15}$O+p threshold. The calculated distributions [17], shown in Fig. 3b, well agree with “no FSI” approximation Fig. 3a, for “high s” and GMZ WFs. In the “low s” case the shapes of the distributions are different (due to strong correlations in the $d^2$ WF) but the rms longitudinal momenta $(p_{l\perp}^2)^{1/2}$ for these distributions are reasonably close (they are 150 and 113 MeV/c for Figs. 3a and 3b, respectively). It is known [23, 24, 25] that the core “shadowing” effect will lead to realistic momentum distributions which are only narrower than those obtained in the sudden removal approximation. Thus, looking in these Figures one could conclude that experimental data [6] giving FWHM 168(17) MeV/c for LMD of the $^{15}$O core support case of $d^2$ domination in the structure of $^{17}$Ne [W$(s^2)$ < 25%]. There is, however, an obstacle which makes the analysis of the situation more complicated.

Interaction cross sections. — Interaction and proton removal cross sections are calculated in the eikonal approximation of the Glauber model [27] for three-body $^{17}$Ne nucleus. In this model breakup cross sections are related to interaction cross sections of the fragments as

$$\sigma^{1p}_{str} + \sigma^{2p}_{str} + \sigma_{diff} = \sigma_{-2p} = \sigma(I^{17}\text{Ne}) - \sigma(I^{15}\text{O}).$$

In our calculations the cross sections are determined by the interaction potential [28] generated from the free NN-interaction [27] and nuclear fragment densities.

The $^9$Be density $\rho$ is parameterized by the modified harmonic oscillator expression [29] with $\hbar \omega = 1.791$ fm

$$\rho(r) = \rho_0[1 + \alpha(r/a)^2]\exp[-(r/a)^2],$$

which gives the $^9$Be charge radius 2.52 fm. The $^{12}$C and $^{16}$O density distributions are different (due to strong correlations in the $d^2$ WF) but the rms longitudinal momenta $(p_{l\perp}^2)^{1/2}$ for these distributions are reasonably close (they are 150 and 113 MeV/c for Figs. 3a and 3b, respectively). It is known [23, 24, 25] that the core “shadowing” effect will lead to realistic momentum distributions which are only narrower than those obtained in the sudden removal approximation. Thus, looking in these Figures one could conclude that experimental data [6] giving FWHM 168(17) MeV/c for LMD of the $^{15}$O core support case of $d^2$ domination in the structure of $^{17}$Ne [W$(s^2)$ < 25%]. There is, however, an obstacle which makes the analysis of the situation more complicated.

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### TABLE II: Experimental [6] and theoretical interaction cross sections $\sigma_I$ for the $^{15}$O+$^9$Be reaction (in mb).

| $E_{beam}$ (MeV/amu) | $\sigma_I$(exp)  | $\sigma_I$(th) |
|---------------------|-----------------|----------------|
| 22.00               | 1740(40)        | 1860           |
| 30.80               | 1790(40)        | 1780           |
| 38.00               | 1680(40)        | 1725           |

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28Si densities are approximated by the sum of Gaussians with parameters from Ref. [28].

The $^{15}$O density distribution is not known; we approximate it by the two-parameter Fermi expression [28]

$$\rho(r) = \rho_0/(1 + \exp[(r-c)/z]),$$

(4)

Parameters $c = 3.266$ fm and $z = 0.1$ fm are chosen to reproduce both the $^{15}$O matter radius and interaction cross sections for reactions $^{15}$O+$^{28}$Si at energies 22 – 44 MeV/amu [6] (Table II) and $^{15}$O+$^9$Be, $^{15}$O+$^{12}$C at the energy 710 MeV/amu [28] (Table III).

The above choice of core and target densities allows us to reproduce the experimental data on the $p+^{28}$Si [30] and $^{15}$Ne+$^{28}$Si [6] interaction cross sections at energies 20 – 50 MeV/amu [6] (Table IV). The agreement with experiment for $p$, $^{15}$O, $^{17}$Ne interaction cross sections on $^{9}$Be and $^{12}$C targets is also very good for two available experimental energies (Table III). All results for $^{17}$Ne in Tables III and IV are calculated with the GMZ WF. The matter radius for our WF (Table I) is also in an agreement with effective $r_{max}$ = 2.75(7) fm extracted in [31] using Glauber model with harmonic-oscillator densities.

Proton removal from halo in $^{17}$Ne. — Contrary to the total interaction cross sections, the $2p$ removal cross sections are 30 – 40% underestimated in our calculations (see Tables III and IV). To check the sensitivity of the cross sections to variations of the $^{17}$Ne structure we have calculated the $2p$ removal cross sections for $^{17}$Ne on Be target at 66 MeV/amu with different $^{17}$Ne WFs. The corresponding $\sigma_{-2p}$ are 120 mb, 109 mb and 82 mb for “high s”, GMZ and “low s” WFs. These results show that this variation of the $^{17}$Ne structure is not sufficient to compensate for the discrepancy with experiment.
TABLE III: Experimental and theoretical cross sections (in mb) for \( ^{15}O \) and \( ^{17}Ne \) on different targets at 710 and 66 MeV/amu. The experimental values for \( ^{17}Ne \) from [29], measured at the energy 680 MeV/amu, are scaled according to the energy dependence of the interaction cross section.

| Target (amu) | \( \sigma_I(p) \) | \( \sigma_I(\frac{1}{2}) \) | \( \sigma_I(\frac{3}{2}) \) | \( \sigma_{-2p}(\frac{3}{2}) \) |
|-------------|-----------------|-----------------|-----------------|-----------------|
| \( ^{15}O \) | 30               | 92(23)          | 972(45)         | 73              |
| \( ^{17}Ne \) | 210              | 914             | 987             | 80              |
| \( ^{17}O \) | 232(14)          | 922(49)         | 1094(76)        | 80              |

To overcome this problem, it was suggested in Ref. [7] that (i) the halo is very large (\( \langle r_p \rangle \approx 4.5 \) and 3.8 fm for pure \( s^2 \) and \( d^2 \) configurations compared to \( \langle r_p \rangle \approx 3.7, 3.5 \) and 3.3 fm given by “high s”, GMZ and “low s” WFs) and (ii) the matter radius of the \( ^{15}O \) core is small (\( r_{mat} = 2.42 \) fm compared to 2.53 fm in this work). Only these (too strong, in our opinion) assumptions provided \( \sigma_{-2p}(th) \approx 168 \) mb for pure \( s^2 \) configuration in an agreement with experiment. In our model, the halo size is fixed by CDE and a reduction of the core size leads to a deterioration of the agreement for multiple calculated reaction cross sections. We do not feel there is a freedom in that direction and other explanations are required.

The calculated \( \sigma_{-2p} \) values (see Table III) for 710 MeV/amu on C target of about 40 mb “per proton” (for proton removal from the halo) are in a qualitative agreement with theoretical proton knockout cross section from \( ^{8}B \) (about 80 mb [32]) which are also in a good agreement with experimental data. It is expected that in \( ^{8}B \) the halo feature is more expressed than in \( ^{17}Ne \) due to smaller Coulomb interaction and smaller binding energy. Also, the \( ^7Be \) core in \( ^{8}B \) is smaller than the \( ^{15}O \) core in \( ^{17}Ne \) increasing the probability of the \( ^7Be \) core survival. Otherwise, if we explain the whole two-proton removal cross section in \( ^{17}Ne \) as a removal from halo we come to a contradiction. From this cross section it should then be concluded that in \( ^{17}Ne \) the halo is much more pronounced than in \( ^{8}B \) (which is not in accord with general expectations) whereas from momentum distribution [7] (which is relatively broad) a pronounced halo in \( ^{17}Ne \) should not be expected.

Proton removal from the \( ^{15}O \) core. — The possible solution of the above problem is incorporates processes which are beyond a simple valence nucleon removal. For the case of \( ^{11}Be \) (one neutron halo nucleus) it was shown in papers [33, 34, 35] that beside the valence nucleon removal, the removal of a tightly bound core nucleon leading to low-lying excited states of a fragment can also give an important contribution to the cross section. For the \( ^{17}Ne \) case it means that a process of \( p \)-wave proton removal from \( ^{15}O \) core has to be considered (see also [7], “model-3’’). The simplest possible mechanism is schematically illustrated in Fig. 4. A \( p \)-wave proton knockout from the \( ^{15}O \) (1/2\(^-\)) core leads to \( ^{14}N \) in \( \bar{l} \) states. These states together with the valence protons (which are predominantly in the 0\(^+\) relative motion state in \( ^{17}Ne \)) could populate \( ^{1+} \) states in \( ^{16}F \) located below the \( ^{14}N+2p \) threshold. These states decay only via \( ^{16}O+p \) channel and thus contribute the two-proton removal cross section for \( ^{17}Ne \).

The calculated cross section of the \( p_{1/2} \) proton removal from the \( ^{15}O \) nucleus with the proton separation energy \( S_p = 7.279 \) MeV and \( \sigma_p = 19.4 \) mb and the FWHM of the LMD is 177 MeV/c. The removal cross section of the \( p_{3/2} \) proton with \( S_p = 11.247 \) MeV is \( \sigma_{p_{3/2}} = 15.3 \) mb and FWHM=200 MeV/c. Taking into account two protons in the \( p_{1/2} \) state and four protons in the \( p_{3/2} \) state, we get an assessment of the proton removal cross section 100 mb and FWHM=190 MeV/c, that is in a good agree-

![FIG. 4: Dominating reaction mechanisms for one-proton knockout from \( ^{17}Ne \). (a) \( s/d \)-wave proton knockout from halo, populating negative parity states in \( ^{16}F \). (b) \( p \)-wave proton knockout from \( ^{15}O \) core, populating 1\(^+\) states in \( ^{16}F \).]

![FIG. 5: Momentum distribution of \( ^{16}F \) cm for proton knock-out from \( ^{17}Ne \) gated on the energy ranges with \( s \)-wave (a) and \( d \)-wave (b) negative parity states in \( ^{16}F \).]
ment with the experimental data 80(10) mb and 190(10) MeV/c from for the beam energy 56 MeV/amu. The cross section of the proton removal from the $^{16}$O core is obtained in the three-body model similarly to $^{17}$Ne: $\sigma_{\rightarrow p} = 53$ mb. Together with the $2p$ removal from halo (Table III), this provides the total $2p$ removal cross section of 162 mb, which is in agreement with the results from $^{17}$Ne. Thus, broad momentum distribution [168(17) MeV/c] found in [7] cannot be a proof of $d^2$ domination in the $^{17}$Ne halo as these data are presumably strongly influenced by the processes on the core.

Invariant mass measurement of $^{16}$F. — It is easy to disentangle halo and core contributions to the two-proton removal cross section in an exclusive experiment. The invariant mass measurement of $^{15}$O and proton should allow to distinguish the processes of proton knock out from halo (which should mainly proceed through low-lying negative parity states in $^{16}$F) and proton knock out from the core (which involves $1^-$ states of $^{16}$F). From simple spectroscopic considerations the populations of the energy ranges for relative motion of $p$ and $^{15}$O corresponding to $0^-, 1^-, 2^-$, and $3^-$ states in $^{16}$F are proportional to $\frac{1}{2}W(s^2)$, $\frac{1}{2}W(s^3)$, $\frac{1}{2}W(d^2)$, and $\frac{1}{2}W(d^3)$ in the first approximation. Real situation could be more complicated and exclusive momentum distributions can help to improve the understanding. The momentum distributions of $^{16}$F cm calculated in the same model as Eq. (1) and gated on different ranges of excitation energy in $^{16}$F (where there are only negative parity states) are shown in Fig. 5. If the reaction mechanism of the model Eq. (1) prevails, such experimental distributions should be free from the core contributions. Moreover, the ratio and shapes of the corresponding distributions in Figs. 5a and 5b are strongly sensitive to the structure of halo in $^{17}$Ne. So, comparison of such distributions could make it possible to obtain conclusive information on this issue.

Conclusion. — The question of an existence of a proton halo in $^{17}$Ne, as it is approached from experimental side, can be quantified as the question of $s/d$ configuration mixing. In case of significant (say, $\geq 50\%$) $s$-wave component in the $^{17}$Ne WF the “classical” fingerprints of the halo should exist, e.g. narrow core momentum distributions for valence proton knock out. These distributions should have comparable width to the corresponding distributions in $^6$He case, which is a recognized example of halo nucleus. There is considerable experimental evidence [CDE, B(E2)] that the halo part of $^{17}$Ne WF is a significant mixture of $s^2$ and $d^2$ configurations.

The proton removal from halo is likely to be responsible only for $60 - 70\%$ of the two-proton removal cross section from $^{17}$Ne. The rest is possibly connected with the proton removal from the core. Thus consideration of inclusive LMD of the core is insufficient to draw conclusions about the halo property of $^{17}$Ne as this characteristic possibly has large contribution from processes on core. The question about configuration mixing in $^{17}$Ne can be resolved by invariant mass measurement of $^{16}$O and $p$ after proton knockout.

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