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Observation of a two-proton halo in ^{17}Ne

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Abstract. The measurement of longitudinal momentum distribution for two-proton removal from the proton-drip line nucleus ^{17}Ne with a Be target at 64 A MeV is reported. The observed narrow momentum distribution and the large interaction cross-section suggests the formation of a two-proton halo. The data analyzed within the Few-body Glauber model suggests a significant probability of the two valence protons to abnormally occupy the $2s_{1/2}$ orbit, indicating its lowering in proton-rich nuclei.

PACS. 25.60.Dz Interaction and reaction cross-sections – 25.60.Gc Breakup and momentum distributions

1 Introduction

The first observations on neutron halos were for Borromean nuclei (^{6}He, ^{11}Li) [1] which have a two-neutron halo structure. A two-proton halo has however not been observed so far. It is thus interesting to search for their possible existence which is reported in this article.

The investigation involved a simultaneous study of the longitudinal momentum distribution ($P_{||}$) from two-proton removal and the interaction cross-section (σ_I). A possible candidate seemed to be ^{17}Ne, the lightest borromean nucleus at the proton drip-line. It has a small two-proton separation energy (S_{2p} = 0.96 MeV). A normal shell model places the valence protons in the $d_{5/2}$ orbital giving rise to a wide momentum distribution and a small two-proton removal cross-section. An abnormal occupancy of the protons in the $2s_{1/2}$ orbital will lead to a narrow momentum distribution with a large cross-section.

The earliest studies on the nucleus observed a large asymmetry in the beta decay strength of ^{17}Ne and its mirror partner ^{17}N [2]. This asymmetry could be explained [3] through an enhanced s-wave component in the ground state of ^{17}Ne compared to ^{17}N. The amount of enhancement was however not significantly large and the ground state wave function of ^{17}Ne was considered to be dominated by the normal d-wave nature. The work on Coulomb energy [4] also reached similar conclusions. Some other recent theoretical investigation [5] however suggests a larger s-wave probability of the valence protons. A large s-wave strength is also expected from the observed large interaction cross-section [6] which requires detailed interpretation. The situation is thus unclear and new experimental information may help to shed more light on it.

2 Experiment and analysis

The experiment for $P_{||}$ was performed using the new direct time-of-flight (TOF) technique [7]. The secondary beam of ^{17}Ne interacted with a secondary Be target, with an energy of 60 A MeV. The fragment ^{15}O after two-proton

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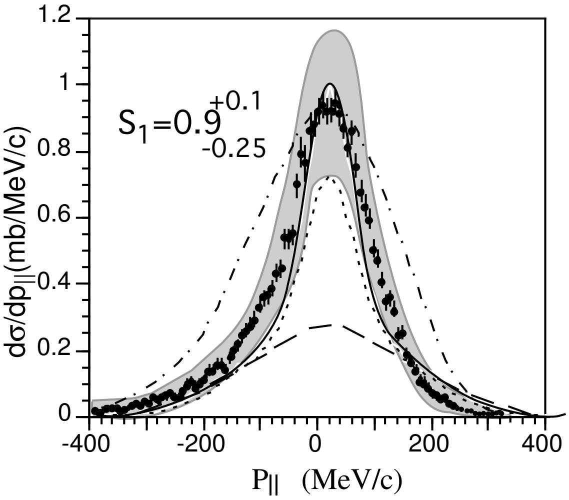

Fig. 1. Longitudinal momentum distribution data of ^{15}O fragments from ^{17}Ne. The curves are Glauber model calculations for model-1 as explained in the text. The dash-dotted line is the data for $^{15}\mathrm{O} \rightarrow {}^{13}\mathrm{O}$ normalized to the peak of $^{17}\mathrm{Ne} \rightarrow {}^{15}\mathrm{O}$ data. The shaded region is the uncertainity from the two-proton removal cross-section.

removal was detected and its $P_{||}$ distribution was measured converting to the projectile rest frame. The experimental details are described in ref. [8].

The $P_{||}$ distribution of $^{17}\mathrm{Ne} \rightarrow {}^{15}\mathrm{O}$ shown in fig. 1 (black points) is found to have a very narrow width of 168 ± 17 MeV/c (FWHM) compared to the Goldhaber estimate of ~ 290 MeV/c. A large two-proton removal cross-section of 191±48 mb is also observed. In comparison, the two-proton removal cross-section of ^{15}O is 54 ± 14 mb [9]. For a comparison on the change of valence proton $P_{||}$ distribution we also measured the $P_{||}$ distribution for two-proton removal from the core nucleus, *i.e.* $^{15}\mathrm{O} \rightarrow {}^{13}\mathrm{O}$. The data (dash-dotted line in fig. 1) shows nearly two times wider distribution than ^{17}Ne [9]. This suggests a halo formation ^{17}Ne, showing the two valence protons in ^{17}Ne to have a significant probability of being outside the ^{15}O core.

The data is analysed in the framework of the few-body Glauber model, considering two possibilities for fragmentation. In the first approach (model-1) we consider the fragmentation process to arise from the emission of two uncorrelated protons. ^{17}Ne has a model of ^{15}O core + two uncorrelated protons. The solid curve here shows the momentum distribution from such a fragmentation process considering the two valence protons to occupy only the $2s_{1/2}$ orbital. It agrees with the data within the error bars. The dashed line shows the distribution for condition where the two valence protons occupy the $d_{5/2}$ orbital. This is both small in magnitude and wider than the data. We have considered the mixing of these s and d configurations where S_1 is the probability of finding two protons in the s-orbital. $S_1 = 1$ denotes a pure s-wave configuration while $S_1 = 0$ denotes a pure d-wave configuration. The dotted line represents $S_1 = 0.65$. It is seen that the data can be explained by a 65%–100% s-wave probability of the valence protons. This is favorable for a halo formation in ^{17}Ne.

In the second approach (model-2), we consider the possibility of proton evaporation from ^{17}Ne. In this process, first one proton is knocked out from the ^{17}Ne nucleus and this leads to a resonance in the unbound ^{16}F. It then decays to ^{15}O by another proton emission. In the first knockout step, the valence proton from the s or d orbitals can be removed. Besides, there exists some probability of proton removal from the deeply bound p orbitals populating much higher resonance states in ^{16}F. The individual contributions for proton removal from the s, p, d, orbitals are shown in fig. 2a by solid, dotted and dashed lines, respectively. They do not agree with the measured distribution.

Next we consider a mixed probability of proton removal for the proton evaporation process. Here we have an additional spectroscopic factor S_3 for the p-wave proton knockout. It assumes values from zero to 3 independent of S_1 (because this is only the probability of knockout and not a part of the ^{17}Ne wave function description). $S_3 = 3$ represents the conditions where a total of 6 p-wave protons can contribute to the two-proton knockout. Figure 2b summarizes the result of a mixed emission probability which can explain simultaneously the $P_{||}$ width and the cross-section for two-neutron removal. The shaded region in fig. 2b shows the S_1 and S_3 values which are in agreement with these data. It is seen that $S_3 > 1.0$ is needed for ovelap with the data, showing that emission of more than 2 protons is necessary. This means, that emission from the $p_{3/2}$ orbital is needed. Thus, within this framework a 20%–50% s-wave probability of valence protons in ^{17}Ne is suggested. A 50% s-wave probability is suggestive of a moderate halo formation.

To confirm on the structure of ^{17}Ne we need to now interpret the measured σ_I for this nucleus. Weighted average of data from ref. [6] when analysed in a Glauber model framework considering core + two-uncorrelated-proton structure for ^{17}Ne, suggest $S_1 = 0.75$–1.0 [8]. The shaded band in fig. 3 shows that $S_1 = 0.7$–1.0 is the region of s-wave which consistently explains both the $P_{||}$ and σ_I data.

3 Discussion

The narrow $P_{||}$ distribution data from two-proton removal and the large interaction cross-section taken together are suggestive of a two-proton halo formation. A consistent description of these data in a core + p + p Glauber model requires a large s-wave probability of the protons.

The extent of the two-proton halo is shown in fig. 4, which demonstrates the percentage of the two-proton density outside the distance "r" measured from the center of the nucleus. The boundary of the core is defined as the radial distance beyond which only 10% of the core density exists. The vertical shaded line shows this distance. The two-proton density is shown by dashed (solid) line for $S_1 = 0.0$ (1.0). From the above analysis the s-wave probability in ^{17}Ne is $S_1 \sim 0.7$. It is then found that the valence protons have around 60% probability of residing outside

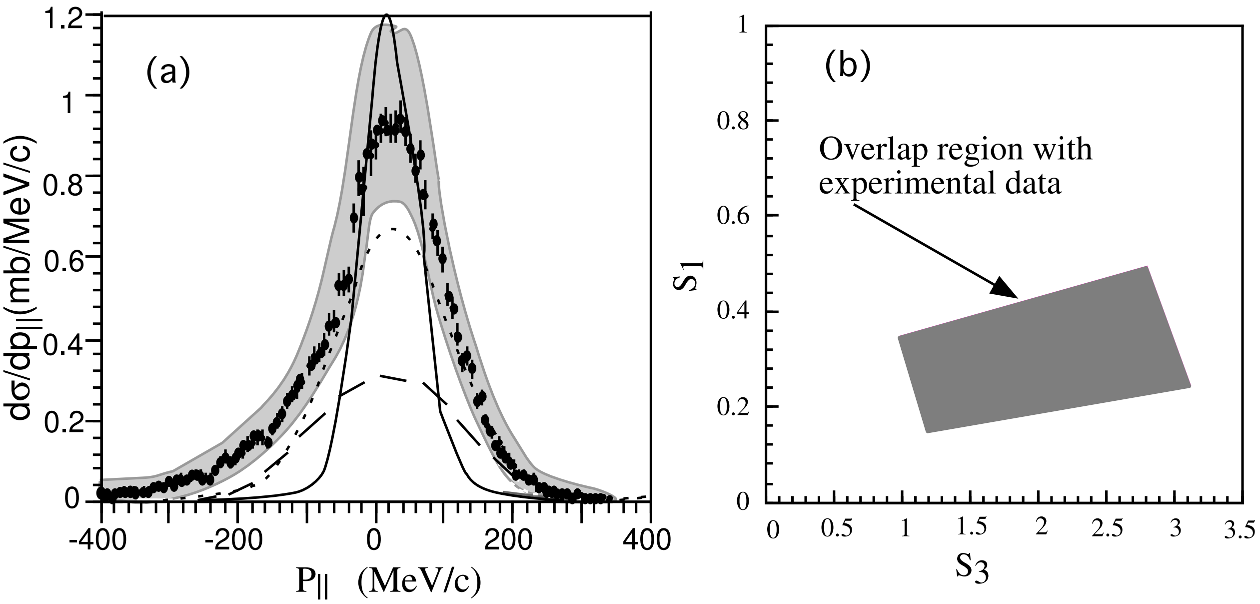

Fig. 2. (a) The longitudinal momentum distribution of ^{15}O fragments from ^{17}Ne. The curves are results of proton evaporation as explained in the text. (b) The range of S_1 and S_3 which overlaps with both the $P_{||}$ and σ_{-2p} data.

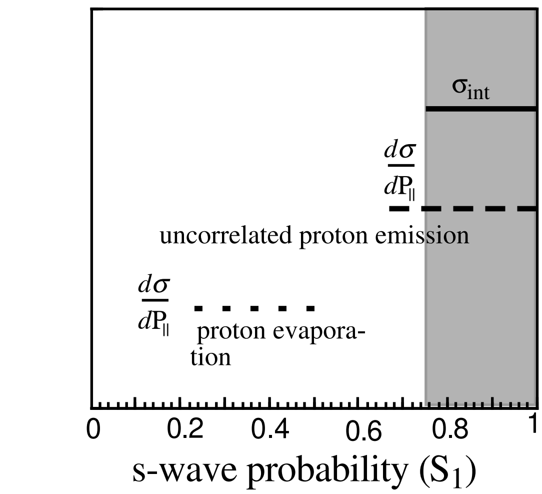

Fig. 3. Summary of s-wave probability of the two valence protons from the different analysis. The shaded vertical band shows the region of consistency between interaction cross-section and momentum distribution.

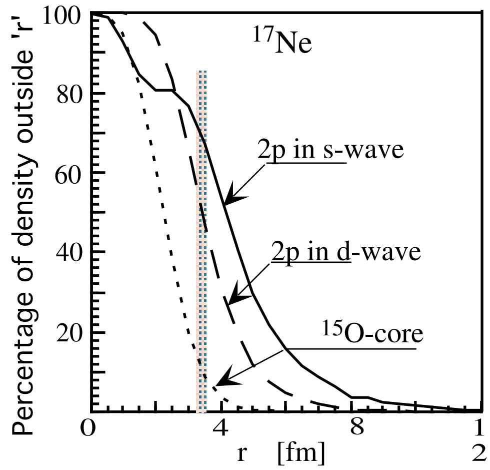

Fig. 4. The probability of the two valence protons to be outside the ^{15}O core for ^{17}Ne. The dotted line shows the percentage of density of ^{15}O outside "r". The dashed/solid line shows the percentage of two-proton density for protons in the $d_{5/2}/2s_{1/2}$ orbit.

the core. A similar analysis for the two-neutron halo nucleus ^{11}Li [10] shows 73% of the two-neutrons being outside the ^{9}Li core (considering the ^{11}Li ground state to have an equal mixture of s and p wave configurations). In contrast, well-bound nuclei like ^{15}O or ^{17}N, show only 38% of the valence nucleon to be outside the core (the "core" nuclei here are ^{13}O and ^{15}N, respectively). It is certainly true that proton halos are far less pronounced than neutron halos. Nevertheless, that fact that despite the Coulomb barrier, the s-orbit is lowered even in proton-rich drip-line nuclei, causes them to have spatial extension compared to well-bound normal nuclei. Evidence for the lowering of the $2s_{1/2}$ orbit can also be noted in neighbouring nucleus ^{16}F.

It may be mentioned here that further interpretation with a microscopic correlated wave function for ^{17}Ne maybe useful for obtaining deeper insights. In addition, some alternative experimental investigation would help to put further constraint on the s-wave probability.

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