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Microscopic self-consistent study of neon halos with resonant contributions

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ABSTRACT

Recent reaction measurements have been interpreted as evidence of a halo structure in the exotic neutron-rich isotopes ^{29,31}Ne. While theoretical studies of ^{31}Ne generally agree on its halo nature, they differ significantly in their predictions of its properties and underlying cause (*e.g.*, that ^{31}Ne has an inverted ordering of p–f orbitals). We have made a systematic theoretical analysis of possible Neon halo signatures – the first using a fully microscopic, relativistic mean field approach that properly treats positive energy orbitals (such as the valence neutron in ^{31}Ne) self-consistently with bound levels, as well as the pairing effect that keeps the nucleus loosely bound with negative Fermi energy. Our model is the analytical continuation of the coupling constant (ACCC) method based on a relativistic mean field (RMF) theory with Bardeen–Cooper–Schrieffer (BCS) pairing approximation. We calculate neutron- and matter-radii, one-neutron separation energies, p- and f-orbital energies and occupation probabilities, and neutron densities for single-particle resonant orbitals in $^{27-31}$Ne. We analyze these results for evidence of neutron halo formation in ^{29,31}Ne. Our model predicts a p-orbit $1n$ halo structure for ^{31}Ne, based on a radius increase from ^{30}Ne that is 7–8 times larger than the increase from ^{29}Ne to ^{30}Ne, as well as a decrease in the neutron separation energy by a factor of ~ 10 compared to that of $^{27-30}$Ne. In contrast to some other studies, our inclusion of resonances yields an inverted ordering of p and f orbitals for spherical and slightly deformed nuclei. Furthermore, we find no evidence of an s-orbit $1n$ halo in ^{29}Ne as recently claimed in the literature.

1. Introduction

The search for exotic nuclei with greatly extended valence nucleon density distributions – "halo" structures – is at the forefront of nuclear structure physics. Tightly coupled with halo searches are studies to understand the underlying causes of these unusual configurations. A number of criteria have been developed to collectively diagnose nuclear halos, including large radii, small separation energies, and high occupation probabilities of low-l valence orbitals. In the search for the heaviest halo systems, attention has recently been focused on neutron-rich Neon isotopes right above and below the closed $N = 20$ neutron shell at ^{30}Ne. The first indication of a halo in ^{31}Ne came from a measurement [1] of its large Coulomb breakup cross section on Pb and C targets at the RIBF facility at RIKEN. This large soft $E1$ excitation for the ground state was theoretically interpreted as the first case of a p-wave single neutron halo, making ^{31}Ne the heaviest halo candidate [1]. A subsequent systematic measurement of Neon interaction cross sections at RIBF [2] found 10% (12%) enhancement for ^{29}Ne (^{31}Ne) above systematics of nearby stable nuclei. This was interpreted as an s-dominant halo structure in ^{29}Ne – the first (and unconfirmed) indication of a halo in this isotope – and an s- or p-orbital halo in ^{31}Ne [2]. A direct time-of-flight technique was recently used to determine the mass of ^{31}Ne and found a very weak binding $S_n = -0.06(41)$ MeV [3], consistent with a halo. They also deduced a matter radius R_m of 3.27(14) fm, a surprisingly small value, comparable to the 3.3 fm expected for a non-halo nucleus from simple $r_0A^{1/3}$ mass scaling law (see, *e.g.*, Ref. [4]). Here, we use an r_0 value of 1.05 fm, which is taken from Penning trap mass spectrometry and collinear laser spectroscopy measurements of $^{17-22}$Ne combined with Fermionic Molecular Dynamics theory [5]. In Ref. [6], the $2p_{3/2}$ configuration can explain the measured ^{31}Ne interaction cross section enhancement, and they ruled out an s-wave orbital for the ^{31}Ne valence neutron.

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Table 1
Root-mean-square matter radii R_m in fm, one neutron separation energies S_n in MeV, and deformations β_2 for ^{29}Ne and ^{31}Ne from available theoretical calculations, ordered by decreasing value of R_m for ^{31}Ne. The current experimental constraints [7] on S_n are 0.95 ± 0.1 MeV for ^{29}Ne and 0.29 ± 1.62 MeV for ^{31}Ne, respectively. Using simple $r_0 A^{1/3}$ scaling, the matter radius expected for a non-halo ^{29}Ne (^{31}Ne) is 3.23 fm (3.30 fm). "This work" denotes our calculations with a spherical model; results with deformation are given in Section 4.

Models	^{29}Ne			^{31}Ne		
	R_m	S_n	β_2	R_m	S_n	β_2
This work	3.22	2.9	0.00	3.58	0.1	0.00
PRM [6]				3.53	0.1	0.20
AMD [8]	3.30	1.3	0.44	3.47	0.25	0.42
DWS [9]	3.33	0.8	0.44	3.43	1.0	0.42
SkM* [10]	3.26	3.3	0.26	3.39	2.7	0.38
DRMF [11]	3.20	2.7	0.08	3.34	−1.1	0.20
SLy4 [10]	3.22	2.8	−0.1	3.34	1.3	0.16
GCM [12]				2.96	−0.5	

Much is still unknown about the ground states of ^{29}Ne and ^{31}Ne – including their deformations β_2, the spin and parities of the valence neutron I^π, and the energy ordering and occupation probabilities of their p and f orbitals. Their neutron separation energies S_n also need tighter constraints. For these reasons, and because of the conflicting (^{31}Ne) and unconfirmed (^{29}Ne) evidence mentioned above, assessing the halo nature of these nuclei necessitates the use of nuclear models.

2. Previous theoretical studies

A number of theoretical approaches have been used to study ^{29,31}Ne and their neighboring isotopes, with a range of predictions for matter radii – and wide ranges for separation energies and deformations – as summarized in Table 1. Some of these studies (*e.g.*, Refs. [6,8–10]) include reaction cross section calculations to check consistency with the measured cross section enhancements.

The predictions of almost all of these studies are consistent with ^{29}Ne having an S_n value well over 1 MeV and an R_m comparable to the 3.2 fm value expected for a non-halo nucleus via $r_0 A^{1/3}$ scaling; this suggests that ^{29}Ne is *not* a halo nucleus, despite the measured enhancement of its interaction cross section. While there is no consensus for ^{31}Ne, numerous studies do predict R_m values well above that from $r_0 A^{1/3}$ scaling, along with low to moderate values of S_n – both indicative of a halo nature.

There is also no consensus on the underlying cause(s) of the halo. Numerous studies of neutron-rich Ne, Na, and Mg nuclei near the $N = 20$ magic number have been made. This is due to the proximity of the dripline, and to the likelihood [13] that the $N = 20$ shell gap (between orbitals in the *sd* and *pf* shells) disappears (so called "island of inversion" [14]) and is replaced by a new magic number at $N = 16$ [15]. Nuclei in this region are thought to be well deformed [16] so that the energy of the p orbital lies below that of the f orbital, inverted from the standard spherical shell ordering. This may allow a valence nucleon to have higher occupation probabilities for a low-l p orbital, one of the criteria for halo nuclei. This was, for example, suggested by particle-rotor model (PRM) in Ref. [6] where a valence neutron configuration from a $p_{3/2}$ component with $\beta_2 = 0.2$ was found to be a very promising candidate for the ground state of the deformed halo nucleus ^{31}Ne.

However, as seen from Table 1, the deformations of ^{29,31}Ne are quite uncertain, and there are no direct experimental constraints (*i.e.*, no $B(E2)$ measurements) and the indirect evidence is ambiguous. For example, the enhanced cross sections in ^{31}Ne have been shown to be consistent with deformations ranging from ~ 0.2 to ~ 0.4 [8,9] on the assumption of small binding energy $S_n = 0.2$ MeV [6]. Using non-relativistic Skyrme interactions, the deformation of ^{31}Ne was found to be 0.16 for SLy4 interaction, but 0.38 for SkM* interaction. Additionally, the shape of ^{30}Ne for these two interactions are totally opposite, even if the total reaction cross sections of Ne isotopes in Glauber model seem to reproduce the data with the density distributions in the Skyrme–Hartree–Fock calculation [10]. Furthermore, models with similar deformations can yield very different occupation probabilities. For example, in the deformed Woods–Saxon (DWS) potential of Ref. [9], p orbitals have higher energy than f orbitals at $\beta_2 = 0.2$, with *lower* occupation probabilities, so the valence neutron is not in a low-l p orbital, as needed to satisfy the criteria for a halo nucleus.

3. Approach

Since the pf orbitals discussed above have *positive* energy, proper treatment of such resonant orbitals must be included when calculating the structure of these exotic Neon isotopes. This is especially crucial because previous relativistic mean field studies [17–21] and non-relativistic mean field studies [22,23] have demonstrated that resonant orbitals with low angular momentum close to Fermi surface are a primary mechanism to form halo nuclei. In our studies, the analytical continuation of the coupling constant (ACCC) method [24] was used to determine structure information on resonant orbitals. In the ACCC method, the attractive potential is temporarily increased so that a resonant state becomes "bound"; this enables the energy, width, and wave function for the orbital neutron to be determined by an analytic continuation carried out via a Padé approximant from the bound-state solutions [24]. It can be easily implemented in conjunction with a variety of bound-state techniques to provide single-particle resonant orbitals with positive energies. When coupled to the RMF model, this approach has been demonstrated to work with narrow resonances as well as with broad resonances in which the phase shift $\delta(\mathrm{E})$ smoothly passes through $\pi/2$ [25]. This fully microscopic RMF-ACCC approach has been successfully used to describe the single-particle resonant states in ^{120}Sn [26] and Zr isotopes [25].

An extension of this technique was recently developed to include pairing correlations in the BCS approximation with contributions from resonant orbitals. This resonant-BCS model differs from the conventional BCS model in that resonant states $1\hbar\omega$ shell above the Fermi surface (*e.g.*, p–f shell for Ne isotopes) are included along with the bound states, and spurious states are naturally kicked off the continuum [22,27]. The BCS approximation uses a pairing strength $G = C/A$ in which A refers to the nuclear mass and C is a constant determined by fitting the odd–even mass difference by three-point formula [28],

$$\Delta_n = \frac{1}{2}\big[B(Z, N-1) - 2B(Z, N) + B(Z, N+1)\big] \tag{1}$$

extracted from the binding energies of neighboring nuclei $B(Z, N)$ from Ref. [7]. In this approach, the microscopic potential, resonant continuum, and pairing correlations are all calculated in a self-consistent manner. The RMF + ACCC + BCS approach was recently used to well describe the properties of bound orbitals and single-particle resonant orbitals in stable and unstable Ni, Zr, and Sn isotopes [20,29,30].

We use the RMF + ACC + BCS approach to quantitatively explore the role of resonant orbitals in the possible formation of halos in ^{29,31}Ne. Since halo criteria are often more effectively evaluated through comparisons of neighboring isotopes – *e.g.*, large increases in radius or decreases in separation energy as neutron number varies – we have made a systematic investigation of exotic neutron-rich $^{27-31}$Ne with this model. Our study is the first using a fully microscopic, self-consistent approach that includes pairing