Interaction cross sections for Ne isotopes towards the island of inversion and halo structures of $^{29}$Ne and $^{31}$Ne


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Abstract
Interaction cross sections ($\sigma_I$) for Ne isotopes from the stability line to the vicinity of the neutron drip line have been measured at around 240 MeV/nucleon using BigRIPS at RIBF, RIKEN. The $\sigma_I$ for $^{27-32}$Ne in every case exceed the systematic mass-number dependence of $\sigma_I$ for stable nuclei, which can be explained by considering the nuclear deformation. In particular the $\sigma_I$ for $^{29}$Ne and $^{31}$Ne are significantly greater than those of their neighboring nuclides. These enhancements of $\sigma_I$ for $^{29}$Ne and $^{31}$Ne cannot be explained by a single-particle model calculation under the assumption that the valence neutron of $^{29}$Ne ($^{31}$Ne) occupies the $0^d_3/2$ ($0^f_7/2$) orbital, as expected from the standard spherical shell ordering. The present data suggest an s dominant halo structure of $^{29}$Ne and s- or p-orbital halo in $^{31}$Ne.

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During the past few decades, structures of exotic nuclei have been extensively studied through a number of experiments using radioactive beams. In the 1980s, the nuclear halo structure of loosely-bound nuclei was first indicated through the measurements of interaction cross sections ($\sigma_I$) for light nuclei near the drip line [1]. This halo structure is one of the most interesting features of exotic nuclei, in which one (or two) weakly-bound valence nucleon(s) spatially extend(s) far beyond the nuclear core by means of the quantum tunneling effect. A further interesting point is that the formation of a halo structure often results from the breakdown of magic numbers and the collapse of the conventional shell structure in exotic nuclei. A large-halo formation can occur only when the valence nucleon occupies an orbital with a low orbital angular momentum ($\ell$), because when the orbital angular momentum of a valence nucleon is relatively large (e.g. $\ell \geq 2$) the quantum tunneling of a weakly-bound nucleon is impeded by the existence of the centrifugal barrier [2]. So far, several neutron halo nuclei have been found, and in many cases those halo structures originate from anomalous shell ordering and the valence halo nucleons in such halo nuclei unexpectedly occupy low-$\ell$ orbitals [3–6].

In the 1990s, strongly-deformed nuclei were found in the heavier neutron-rich region around $N = 20$ [7]. This is the so-called “island of inversion” region [8]. For nuclei in this region the vanishing of the $N = 20$ magic number for neutrons was reported [9] and the inversion of amplitudes between $sd$-normal and $pf$-intruder

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In the 1990s, strongly-deformed nuclei were found in the heavier neutron-rich region around $N = 20$ [7]. This is the so-called “island of inversion” region [8]. For nuclei in this region the vanishing of the $N = 20$ magic number for neutrons was reported [9] and the inversion of amplitudes between $sd$-normal and $pf$-intruder
shells has been considered along with nuclear deformation. The nature of the inversion mechanism has been extensively studied but remains unclear, and further experimental studies are needed.

An advanced radioactive-beam facility enables us to explore the weakly-bound nuclei near the drip line in this island of inversion, and we can investigate the single particle orbital of valence nucleons in those nuclei through a search for the possible low-\(\ell\) halo formation caused by the anomalous shell structures. The present Letter reports on the measurements of \(\sigma_t\) for 20–32Ne from the stability line to the vicinity of the neutron drip line. Among the neutron-rich Ne isotopes, 29Ne and 31Ne are particularly loosely-bound, with neutron separation energies of only 0.95 ± 0.15 and 0.29 ± 1.6 MeV [10], respectively. In the standard shell model, the 19th valence neutron in 29Ne and the 21st neutron in 31Ne are expected to occupy \(0d_{3/2}\) and \(0f_{7/2}\) orbitals, but when the lowering of the intruder \(fp\)-shell is taken into consideration, the valence nucleon could occupy a \(1p_{3/2}\)-orbital state and 29Ne and 31Ne could have \(p\)-orbital halo structures. Moreover, the nuclear deformation could produce an elevation of the \(1s_{1/2}\)-orbital component [11,12], which could even lead to the formation of \(s\)-orbital halo structures in 29Ne and 31Ne. In order to clarify the mechanism of the change of shell structure in nuclei in the island of inversion, experimental evidence for the existence of halo structures in those nuclei, including 29Ne and 31Ne, is essential.

Experiments were performed at the RIBF fragment separator [13,14] as a spectrometer to identify incoming and outgoing particles [15]. Fig. 1 is a schematic drawing of the experimental configuration using the second half of the BigRIPS. A carbon reaction target of 1.80 or 3.60 g/cm^2 thickness was located at the F5 dispersive focal plane of BigRIPS. Incoming particles were pre-separated and identified using the beam line between the F3 and F5 focal planes, and outgoing particles were identified between the F5 and F7 focal planes. For particle identification before and after the reaction target, magnetic rigidity, energy-loss, and time-of-flight information from ion chambers at F3 and F7 and plastic scintillation counters at F3, F5, and F7 were used. The position information from the PPACs at F3 was used to apply an appropriate emittance-cut for the incident beam so as to accurately count all of the noninteracting particles without missing them after the reaction target.

In Fig. 2, \(\sigma_t\) for Ne isotopes at 240 MeV/nucleon in the present work are plotted as a function of mass number (solid circles). The present mass-number dependence of \(\sigma_t\) for stable nuclei (solid curve with a shaded band) and a Glauber-type calculation with the deformation effect (open triangles and dashed lines) are also shown for comparison. The open circles indicate the data for stable nuclei [16–20]. The insert shows rms radii data for stable nuclei [21] and \(A^{1/3}\) dependence fitted to the data.

The beam energies of the Ne isotopes differ slightly from one another depending on the separator settings. The effects on the \(\sigma_t\) from these differences were corrected for by a Glauber calculation, which introduces a negligible increase in the error in \(\sigma_t\). For comparison, the systematic mass-number dependence of \(\sigma_t\) for stable nuclei is shown as a solid curve. The dependence was calculated by a Glauber-type calculation (MOF [20]), which gives the reaction cross section \(\sigma_{inel}\) = \(\sigma_t + \sigma_{inel}\) where \(\sigma_{inel}\) is the total inelastic scattering cross section) using proper nucleon density distributions as inputs. Note that at energies above a few hundred MeV/nucleon \(\sigma_{inel}\) can be assumed to be nearly equal to \(\sigma_t\) because the contribution of \(\sigma_{inel}\) would be very small [37]. In order to calculate the mass-number dependence of \(\sigma_t\) for stable nuclei in this mass region, the nucleon density distributions of stable nuclei are assumed to be Fermi distributions:

\[
\rho_{\text{Fermi}}(r) = \int \rho_0 \left(1 + \exp \left(\frac{r - R(\theta)}{c}\right)\right) d\Omega,
\]

Here, the quadrupole deformation parameter \(\beta_2\) is taken to be zero. The diffuseness parameter \(c\) and \(R_0\) are set so as to satisfy the condition that \(\rho_{\text{Fermi}}(0)\) should be the typical value of the nuclear saturation density (0.17 fm^{-1}), and the root-mean-square (rms) radius of the nucleon density distributions should follow the \(A^{1/3}\) mass number dependence of experimental rms radii data for stable nuclei shown in the insert of Fig. 2. The rms radii of point-nucleon distributions for stable nuclei, shown by the solid circles in the insert, were deduced from the experimentally determined charge radii [21] by unfolding them with the proton radius 0.85 fm assuming that the proton and neutron distributions in nuclei are the same. The solid curve in the insert shows the \(A^{1/3}\) dependence fitted to the data and the standard deviation of data from the solid curve is shown by the shaded area. Thus, the solid
curve in the main part of Fig. 2 is the calculation using the parameters $c$ and $R_0$ determined as described above and the shaded area is derived from the standard deviation of rms radii data shown in the insert.

In Fig. 2, existing experimental $\sigma_I$ for stable nuclei (from F to Mg) on a C target are shown with open circles [16–19] for comparison. It should be noted that the data for stable nuclei were measured at around 1 GeV/nucleon and have been corrected for the energy dependence of $\sigma_I$ using a Glauber-type calculation. The $\sigma_R$ data for $^{27}$Al [20] are plotted without correction for the very slight difference between $\sigma_L$ and $\sigma_R$ at 240 MeV/nucleon. It can be seen that the open circles and the present data for Ne isotopes up to mass number 24 closely follow the systematics for stable nuclei. However, starting at mass number 25 the present $\sigma_I$ data gradually deviate from the solid curve and the deviation increases with increasing mass number.

In order to study the origin of this deviation, we calculate the $\sigma_I$ using the finite values of the deformation parameter $\beta_2$. The $\beta_2 = 0.4–0.6$ of Ne isotopes have been deduced numerically from the intrinsic quadrupole moment obtained from the experimentally known $B(E2)$ values or from the spectroscopic quadrupole moments [22–24,27] assuming the rotation of a uniformly charged deformed nucleus. In Fig. 2 the $\sigma_I$ calculated with the same diffuseness parameters $c$ and $R_0$ used to obtain the systematic mass-number dependence of $\sigma_I$ for stable nuclei, but with each experimental $\beta_2$ for $^{20–24,26,28,30}$Ne are shown with open triangles connected and extrapolated to $^{32}$Ne by dashed lines. It can be seen that the trend of $\sigma_I$ for Ne isotopes is approximately reproduced by considering the experimentally measured quadrupole deformation of nuclei. Theory suggests that the nuclear deformation can enhance the rms matter radii which can increase the $\sigma_I$ in Ref. [28]. Here, the present experimental data for $^{20–32}$Ne clarify the enhancements of $\sigma_I$ for neutron rich Ne isotopes beyond $^{A1/2}$ systematics and it is shown that nuclear deformations in those nuclei account for most of the enhancement. However, for the loosely-bound nuclei $^{20}$Ne and $^{31}$Ne, the $\sigma_I$ show dramatic enhancements compared to what is expected from nuclear deformation. The one-neutron separation energies ($S_n$) for $^{29}$Ne and $^{31}$Ne ($0.95 \pm 0.15$ and $0.29 \pm 1.6$ MeV) [10] are as low as those for known one-neutron halo nuclei. Marked enhancements of $\sigma_I$ for such loosely-bound nuclei compared to those of neighboring nuclei are quite interesting, because such an enhancement often indicates the formation of halo structure, as can be seen in the data for light neutron-halo nuclei such as $^{11}$Li and $^{11}$Be [29, 30]. Moreover, the large difference of $86 \pm 28$ mb between the present $\sigma_I$ data for $^{31}$Ne and $^{30}$Ne ($\sigma_I(^{31}$Ne) = 1435 (22) mb, and $\sigma_I(^{30}$Ne) = 1349 (17) mb) is in good agreement with the recently measured one-neutron removal cross section ($\sigma_{-n}$) for $^{31}$Ne on a C target ($79 \pm 7$ mb [31]). This fact leads us to assume that $^{31}$Ne has a structure of $^{30}$Ne plus one loosely-bound valence neutron. The large difference also observed between the $\sigma_I$ for $^{29}$Ne and $^{28}$Ne is indicative of a similar structure.

In order to examine the mechanism of the change of shell structure in nuclei in the island of inversion, we quantitatively investigated the observed large enhancements of $\sigma_I$ for $^{29}$Ne and $^{31}$Ne based on the single-particle orbital of a valence neutron in a deformed nucleus. For this purpose the present $\sigma_I$ data for $^{28}$Ne and $^{31}$Ne were compared with $\sigma_I$ calculated using a Glauber-type calculation with model nucleon density distributions obtained by the simple deformed single-particle-model (DSPM) calculations. The density distributions for the valence neutron of $^{29}$Ne and $^{31}$Ne were deduced from wave functions obtained by solving the Schrödinger equation with axially-symmetric deformed Woods–Saxon potentials for given values of the one-neutron separation energy. For the $^{28}$Ne and $^{30}$Ne nuclear cores, Fermi-type density distributions were used, with parameters determined so as to fit the present $\sigma_I$ data under the constraint of $\rho_{\text{Fermi}}(0) = 0.17$ fm$^{-3}$.

Fig. 3 shows the Nilsson diagram for the $^{28}$Ne $+$ n system calculated using Woods–Saxon potentials, with the diffuseness parameter $c$ and the radius parameter $R_0$ taken from Ref. [32], of 0.67 fm and 1.27 A$^{1/3}$ fm, respectively. The potential depth (V) is taken to be 42 MeV [32]. Colors indicate the expectation values of orbital angular momentum which show the changes in composition in each Nilsson orbital. The spherical $s_1/2$, $d_3/2$, $d_5/2$, $g_7/2$, and $g_9/2$ channels are included in the calculation of positive-parity orbitals, while the $p_{1/2}$, $p_{3/2}$, $f_5/2$, and $f_7/2$ channels are included for negative-parity orbitals. The $\beta_2$ for the $^{28}$Ne core nucleus is deduced from the experimental $B(E2)$ value as $\beta_2 = 0.36(3)$ [23] and $\beta_2 = 0.49(10)$ [24]. The region from $\beta_2 = 0.33$ to 0.59 is shown by the shaded area in Fig. 3. From these experimental values of $\beta_2$, possible orbitals which the 19th neutron in $^{29}$Ne can occupy are limited to the ($330 1/2$) and ($200 1/2$) orbitals in the regions denoted by (1) and (2), respectively. (The ground-state spin-parity for $^{29}$Ne has not yet been determined, although there are some spectroscopic data on $^{29}$Ne [33,34].) In the insert of Fig. 4(a), the corresponding density distributions for $^{29}$Ne are shown with the core density indicated as the shaded area. Those valence density distributions are deduced from the wave functions obtained with the experimental $S_n$ value of 0.95 MeV, where the potential depth was adjusted to reproduce the experimental $S_n$ value. The main spherical-base components calculated for the wave function (1) are $1p_{1/2}$ (59%) and $0f_{7/2}$ (37%), while those for (2) are $1s_{1/2}$ (74%) and $0d_{3/2}$ (16%). As a reference, the spherical $0d_{3/2}$ orbital is also plotted by the dotted curve. The angular momentum composition of the Nilsson orbital can also vary as the $S_n$ changes. Therefore, for closer comparison with the experimental data the $\sigma_I$ for $^{28}$Ne on a C target are calculated as a function of $S_n$ with a Glauber-type calculation using nucleon density distributions as inputs. Here we used the MOL[FM] calculation [20,26] which gives essentially the same result as the optical-limit approximation of the Glauber theory, but also includes an approximation of the higher-order multiple-scattering effect which is important for halo nuclei (partially equivalent to the few-body effect [25]). The results assuming the Nilsson orbitals (1) and (2) and $0d_{3/2}$ orbital for the valence neutron are compared with the present experimental value in Fig. 4(a). The experimental value is shown by a
suggestions that both $^{31}\text{Mg}$ and $^{20}\text{Ne}$ carry an $s$-dominant structure for the valence neutron due to the nuclear deformation.

A similar analysis has been carried out for $^{31}\text{Ne}$. The experimental $\beta_2$ for the core nucleus $^{30}\text{Ne}$ is deduced from the experimental $B(E2)$ data [27] as $\beta_2 = 0.6 \pm 0.2$, which is shown by the hashed area in Fig. 3. Therefore, candidates for the possible Nilsson orbitals for the 21st neutron in $^{31}\text{Ne}$ are the $[321 3/2]$ and $[200 1/2]$ orbitals denoted by (1) and (2) in Fig. 3, respectively. (The difference between the calculated results for Nilsson orbitals of $A = 30$ and $A = 28$ is small and Fig. 3 is still helpful for considering the single particle level of the valence neutron in $^{31}\text{Ne}$.) The main spherical-base components calculated with the DSPM using the value $S_n = 0.29$ MeV for (1) are $0f_{7/2}$ (70%) and $1p_{3/2}$ (22%), while those for (2) are $1s_{1/2}$ (82%), $0d_{3/2}$ (9%) and $0d_{5/2}$ (6%). The corresponding density distributions are plotted in the insert of Fig. 4(b). As a reference, the spherical $0f_{7/2}$ orbital is also plotted by the dotted curve. Using the DSPM densities, the $\sigma_1$ for $^{31}\text{Ne}$ on a C target are calculated as a function of $S_n$. Similar to the case of $^{29}\text{Ne}$, a calculation using the spherical $0f_{7/2}$ density cannot reproduce the data at all, even considering the large experimental error in the $S_n$ for $^{31}\text{Ne}$. Here, Nilsson orbital $[200 1/2]$, denoted by (2), contains a dominant s-wave component originating from the $1s_{1/2}$ orbital and (1) contains a certain amount of $p$-wave component contributed by the $1p_{3/2}$ orbital in the spherical limit. Either (1) or (2) can reproduce the present $\sigma_1$ data due to the large $S_n$ error. The present data support both possibilities that $^{31}\text{Ne}$ has a $p$-orbital halo component or a $s$-dominant halo structure. This result is consistent with a recent Coulomb-breakup experiment [31].

In this analysis, only the $[200 1/2]$ and $[321 3/2]$ orbitals are considered, given the restriction of the experimental $\beta_2$ value, but as in Ref. [36], there is another possibility for the valence neutron to occupy $[330 1/2]$ orbital with much smaller $\beta_2$ and have a dominating $p$-wave halo component. This possibility is not inconsistent with the present $\sigma_1$ data. In either case, the present data indicate the existence of a long tail in the neutron density distribution of $^{31}\text{Ne}$ as shown by the solid curve in the insert of Fig. 4(b).

In summary, $\sigma_1$ for Ne isotopes from the stability line to the vicinity of neutron-drip line have been very precisely measured using BigRIPS at RIBF. The $\sigma_1$ for neutron-rich Ne isotopes are generally and in some cases greatly enhanced compared to the mass-number dependence of $\sigma_1$ for stable nuclei. The general tendency of $\sigma_1$ to gradually increase in neutron-rich Ne isotopes is in good agreement with a Glauber-type calculation with the deformation effect taking into account the experimental deformation parameters. Besides the gradual increase of $\sigma_1$ for neutron-rich Ne isotopes, marked enhancements of $\sigma_1$ compared to their neighboring nuclei can be seen for the weakly-bound nuclei $^{29}\text{Ne}$ and $^{31}\text{Ne}$. Such sudden increases of $\sigma_1$ cannot be explained by the assumption that the valence neutrons of those nuclei should occupy orbitals with $d$- or $f$-orbital angular momentum as expected from the standard spherical shell ordering. It is shown that the $\sigma_1$ for $^{29}\text{Ne}$ can be best reproduced by the Nilsson orbital $[200 1/2]$ for the valence neutron which contains a dominating $s$-orbital component. Thus, this work is a first experimental indication of a halo structure with most probably a dominating $\ell = 0$ component in $^{29}\text{Ne}$. In addition, the sudden increase of $\sigma_1$ for $^{31}\text{Ne}$ can be explained by Nilsson orbitals $[321 3/2]$ or $[200 1/2]$, depending on $S_n$. This represents a low-$\ell$ ($\ell = 0$ or $1$) orbital halo structure in $^{31}\text{Ne}$, which is consistent with the results from a recent Coulomb breakup experiment [31]. Further experimental studies of the nuclei $^{29}\text{Ne}$ and $^{31}\text{Ne}$, e.g. a precise mass measurement of $^{31}\text{Ne}$, should yield a better understanding of the anomalous structure of nuclei in the island of inversion.
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