Transition to the Island of Inversion: Study of Excited States in $^{28-30}$Ne

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Abstract. An experiment was conducted at the National Superconducting Cyclotron Laboratory (MSU) to study N~20 Ne and Na nuclei. A 140 MeV/A $^{48}$Ca primary beam produced secondary-beam “cocktails” ($^{29}$Na/$^{30}$Mg/$^{32}$Al, $^{32}$Mg/$^{33}$Al/$^{35}$Si) which underwent secondary reactions to produce Ne and Na; $\gamma$-ray decays were detected by the segmented Ge array, SeGA. The data provide information on the transition to the island of inversion and a test of recent shell-model calculations.

1. Introduction
Neutron rich $sd$-$pf$ nuclei exhibit a rich variety of physics that includes modified shell structure, the onset of large collectivity, and increased binding of drip-line nuclei. One of the most studied phenomena in this region that touches on many of these aspects is the “island-of-inversion” – a region of deformed (2p2h) ground states that occurs around N=20 in Na, Mg, and Ne nuclei and corresponds to the promotion of a pair of neutrons across the N=20 shell from the d $3/2$ to f $7/2$ state. This intrusion of 2p2h states below the spherical (0p0h) states suggests a much reduced N=20 shell gap, compared to nuclei near beta-stability.

Recently, Monte Carlo Shell Model (MCSM) calculations, which have a sufficiently large valence space to allow mixing between $sd$-$pf$ states, have shown [1] a reduction in the N=20 shell gap from ~6 MeV in $^{40}$Ca (Z=20) to ~2 MeV in $^{30}$Ne (Z=10). The variation in the N=20 gap as a function of Z reflects the strong T=0 monopole interaction between valence d $3/2$ neutrons and d $5/2$ protons. As protons are removed from the d $5/2$ state, neutrons in the d $3/2$ state become “less-bound” and approach the f $7/2$ level causing the effective N=20 gap to shrink (and simultaneously the N=16 gap to enlarge).
Thus, cross-shell excitations from the $d_{3/2}$ to $f_{7/2}$ levels become energetically more favorable and due to the gain in deformation energy the $2p2h$ state can become the ground state. The reduced $N=20$ gap obtained by MCSM calculations for $Z \leq 12$ results in a broader range of nuclei having sizable ground-state $2p2h$ content and the switch to an intruder dominant ground state is predicted to occur around $N=18$ and not sharply at $N=20$. Mapping the border to the island of inversion and establishing the intruder content is a key test of modern shell model codes and nucleon interactions far from beta stability.

Here, we discuss new data on excited states in the neutron-rich nuclei $^{28,29,30}$Ne that span the transition to the island of inversion.

2. Experiment

The experiment was carried out at the National Superconducting Cyclotron Laboratory, Michigan State University. A 140 MeV/A $^{48}$Ca primary beam was used to produce a “cocktail” of secondary beams ($^{29}$Na/$^{30}$Mg/$^{32}$Al and $^{35}$Mg/$^{33}$Al/$^{35}$Si), which then underwent secondary knockout/fragmentation reactions to produce neutron-rich isotopes of Mg, Na, Ne and F. The segmented germanium detector array, SeGA [2], was used to measure the in-beam gamma-ray decays from excited states populated in the secondary reaction. Both the incoming secondary-beam and the final products were unambiguously identified on an event-by-event basis using the S800 spectrograph [3].

3. Results

3.1. $^{28}$Ne (N=18)

MCSM calculations predict the $N=18$ nuclei $^{29}$Na and $^{28}$Ne to have ~50% $2p2h$ admixtures in their ground states and, in that sense, define the transition to the region of intruder ground states. Data on $^{29}$Na [4] show a higher density of excited states compared with a USD [5] shell model calculation, which assumes a pure $sd$ configuration, and support the interpretation of a sizable $2p2h$ ground state component. Does $^{28}$Ne also display evidence for a reduced $N=20$ shell gap?

Figure 1 shows the Doppler-corrected prompt gamma-ray spectrum for $^{28}$Ne produced by one-proton knockout from $^{29}$Na, with a cross section of ~1.5 mb. The resulting decay scheme is also given in figure 1 together with USD [5] ($sd$ shell) and MCSM [6] (SDPF-M, both $sd$ and $pf$ shells with cross-shell mixing) calculations.

The low excitation energy of the $2_1^+$ state at ~1310 keV (observed in several experiments, [7,8]) and the relatively large $B(E2;2_1^+ \rightarrow 2_1^+)$ = 269(136) e²fm⁴ obtained from an early Coulex measurement [7] are in agreement with MCSM calculations [6] (also a $B(E2) = 269$ e²fm⁴) and support the idea of a reduced $N=20$ shell gap with large intruder admixtures into the ground state wavefunction at $N=18$. However, recent measurements [9,10] gave a smaller value of $B(E2;0^+_1 \rightarrow 2_1^+)$ = 132(23) e²fm⁴ and suggested that the proton and neutron matter distributions in $^{28}$Ne are far smaller than expected for an island of inversion nucleus and more consistent with a USD (0p0h) large shell gap interpretation. The story does not end there; by adopting smaller effective charges [10] the MCSM can also reproduce the $^{28}$Ne transition probabilities and we now have a situation where the $^{28}$Ne data can be interpreted within both an $sd$ and $sd$-$pf$ model space, depending on the choice of effective charges.

While it appears the transition matrix elements in $^{28}$Ne may be interpreted in either a large shell-gap (USD) or reduced shell-gap (MCSM) scenario, a reduced $N=20$ gap will naturally lead to low-lying intruder states, specifically an excited $0^+$ state, that are absent in large $N=20$ shell gap assumption (USD). In the MCSM calculation this second $0_2^+$ state occurs at ~2.2 MeV with a 50-50 mixture of 0p0h-2p2h configurations. The observation of a low-lying excited $0^+$ state would provide important confirmation of the validity of these MCSM calculations and a measure of the $N=20$ gap. A recent publication [11] reports a ~930 keV transition, which is assumed to directly feed the $2_1^+$ level (parallel to the 1720 keV gamma-ray). It is interpreted as the decay from the $0_2^+$ state to the $2_1^+$ in agreement with the MSCM calculation. However, from gamma-gamma coincidences we can
determine that the 1310, 1720, and 900 keV transitions form a cascade (figure 1), with relative intensities of 100, 25, and 15% respectively, and we can rule out the interpretation in ref [11]. The firm determination of the gamma-ray coincidence relationships in $^{28}\text{Ne}$ is an important result. It shows that the excitation energy of the $^2_2^+$ states has not been determined, and a large N=20 shell gap cannot be ruled out on this basis.

![Figure 1. Spectrum of gamma-rays from $^{28}\text{Ne}$. Experimental and calculated level schemes.](image)

$^{28}\text{Ne}$ does, however, contain one additional (and new) strong gamma-ray transition at 1130 keV, which is not in coincidence with any other transition. It is very unlikely that the 1130 keV gamma-ray directly feeds the ground-state, and it is placed “floating” to the left of the main cascade in figure 1. It is possible it feeds an isomeric state. One interpretation is that the 1130 keV gamma-ray corresponds to the transition from the $^2_{1^+} \rightarrow ^0_2^-$. If the $^0_2^-$ state is lower than predicted, even by a few hundred keV, it may well be isomeric. It is also possible that the energy of the $^0_2^+$ level is below the $^2_{1^+}$ level.

### 3.2. $^{29}\text{Ne}$ (N=19)

$^{29}\text{Ne}$ was produced by 2pn knockout from a $^{32}\text{Mg}$ secondary beam, with a cross section of ~0.14 mb. The gamma-ray spectrum is shown in figure 2 along with the decay scheme and SDPF-M and USD shell model predictions. MSCM calculations assign a ~100% 2p2h ground state to $^{29}\text{Ne}$, and it can be considered to be a neutron (K=3/2) hole in a deformed $^{30}\text{Ne}$ core.

The gamma-ray transitions at 626 and 472 keV are assumed to decay to the ground state. The peak at 626 keV is consistent with a recent fragmentation experiment [11] where only one transition was observed at 680 ± 80 keV. An earlier publication [12] reports a candidate gamma-ray at 472 keV in $^{29}\text{Ne}$. The present work, however, provides the first convincing data for two excited states in $^{29}\text{Ne}$.

The existence of two low-lying excited states is very well described within the framework of the MCSM calculations with a reduced N=20 shell gap, and it is then plausible to assign these gammas to the decay of the 7/2+, 1/2+ states in the 2p2h “K=3/2 band”, or one may involve the decay of the 1p1h 3/2 state to the ground state. A tentative third transition at 233 keV is also a candidate for the decay of the negative-parity 3/2 level to the 3/2+ ground state. It is interesting to note that the experimental
energies are lower than the SDPF-M shell model predictions, particularly if the decays correspond to the positive parity 2p2h states (a similar tendency is observed in 30Ne as discussed below). Moreover, all the experimental energies fall far below USD predictions, where the first excited state with positive parity (1/2+) lies at an energy of ~1700 keV (negative parity states would lie at 1 MeV and higher).

The observed 29Ne spectrum displays the expected characteristics of a strongly deformed 2p2h intruder configuration and is consistent with a reduced N=20 gap.

3.3. 30Ne (N=20)

The nucleus 30Ne is the least studied of the N=20 isotones that make-up the island of inversion, and the first excited state was only recently observed [12]. In the present experiment, 30Ne was produced by two-proton knockout from a 32Mg secondary beam with a cross section of ~0.15 mb, and the observed gamma-ray spectrum is shown in figure 3. The transition at 797 keV, associated with the decay of the deformed 2+ state, is consistent with the 791 keV gamma-ray from ref. [12] and provides important confirmation of this state. The SDPF-M calculations slightly overestimate the excitation energy of the 2+ state and the data indicate a larger moment of inertia than theory. It is interesting to note that the energy of the 2+ state in 30Ne is the lowest of all the 21+ energies levels in neighboring even-even N=20 isotones.

The spectrum in figure 3 also shows two new candidate transitions at 1090 and 1444 keV. It is intriguing to speculate that these transitions correspond to decays from the 4+ and 02+ states.

Finally, the experimental data cannot be described with the USD (sd shell only) framework, and it is an indication of deformed 2p2h ground state in 30Ne.

4. Summary

The excited states in neutron-rich neon isotopes have been studied using high-resolution in-beam gamma-ray spectroscopy following knockout reactions from fast (v/c ~ 0.42) secondary beams. The high-statistics 28Ne data yielded a cascade (determined from gamma-gamma coincidences) of three consecutive transitions decaying to the ground state, with energies of 900, 1720, and 1310 keV. These data show no definitive evidence for the predicted 02+ state at ~2.2 MeV, and the location of the intruder 02+ level in 28Ne remains undetermined. Overall, the spectrum and properties of states in 28Ne do not clearly discriminate between the presence of a large or reduced effective N=20 shell gap in this nucleus.
Two gamma-rays at 626 and 472 keV were observed in $^{29}$Ne. The measured excitation spectrum displays the expected characteristics of a nucleus with strongly deformed 2p2h ground state configuration and a reduced effective N=20 shell gap.

In $^{30}$Ne, the observed transition at 797 keV provides important confirmation of a recently reported low-energy $2_1^+$ state and is consistent with a large static ground state deformation. Two higher energy transitions are candidates for higher lying excited states.

References

[1] Utsuno Y, et al. 1999 Phys. Rev. C 60, 054315
[2] Mueller W F, et al. 2001 Nucl. Instrum. Methods Phys. Res. A 466, 492
[3] Bazin D, et al. Nucl. Instrum. Methods Phys. Res. B 204, 629
[4] Tripathi V, et al. 2005 Phys. Rev. Lett. 94, 162501
[5] Brown B A, http://www.nscl.msu.edu/~brown/resources/SDE.HTM
[6] Utsuno Y, private communication
[7] Pritychenko B V, et al., 1999 Phys. Lett. B 461, 322
[8] Belleguic M, et al. 2000 Phys. Scripta T 88, 122
   Azaiez F, et al. 2002 Nucl. Phys. A 704, 37c
   Guillemaud-Mueller D, et al., 2002 Eur. Phys. J. A 13, 63
[9] Iwasaki H, et al. 2005 Phys Lett B 620, 118
[10] Zs. Dombrádi Zs, et al. 2006 Phys. Rev. Lett. 96, 182501
[11] Belleguic M, et al. 2005 Phys. Rev. C 72, 054316
[12] Yanagisawa Y, et al. 2004 Nucl. Phys. A 734, 374
   Yaganisawa Y, et al, 2003 Phys. Lett. B 566, 84