Spectroscopy of $^{32}$Ne and the “Island of Inversion”

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Abstract

We report on the first spectroscopic study of the $N = 22$ nucleus $^{32}$Ne at the newly completed RIKEN Radioactive Ion Beam Factory. A single $\gamma$-ray line with an energy of 722(9) keV was observed in both inelastic scattering of a 226 MeV/u $^{32}$Ne beam on a Carbon target and proton removal from $^{33}$Na at 245 MeV/u. This transition is assigned to the de-excitation of the first $J^\pi = 2^+$ state in $^{32}$Ne to the $0^+$ ground state. Interpreted through comparison with state-of-the-art shell model calculations, the low excitation energy demonstrates that the “Island of Inversion” extends to at least $N = 22$ for the Ne isotopes.

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One of the most fundamental concepts in nuclear structure, as first introduced by Mayer and Jensen [1, 2], is the notion of “magic numbers”. A nucleus with a certain number of protons and neutrons is said to be “magic” when large gaps occur in the single-particle (SP) energy spectra near the Fermi energy. In this case residual interactions, which are weaker than the energy gap in the SP spectrum, can only induce weak correlations and the nucleus exhibits typical SP properties. On the other hand, for smaller gaps or partially filled orbitals the residual interactions can easily promote nucleons to SP states with a higher energy, giving rise to large correlations that are manifested in various collective phenomena.

While in the past magic neutron and proton numbers were considered static, i.e. independent of the region in the nuclear chart being considered, it has become clear that this is not the case and modifications of the standard shell ordering occur in nuclei far from stability. Currently considerable experimental and theoretical effort is being expended to uncover the mechanisms driving these changes in shell structure [3].

Beyond ground-state binding energies, a variety of signatures exist to identify magic numbers. One of the most direct is the reduced transition probability \( B(E2; 0^+_\text{gs} \rightarrow 2^+_1) \) for even-even nuclei, which provides a measure of the correlations present in the wave functions. Another key signature is the ratio of the energies of the first \( J^\pi = 4^+ \) and \( 2^+ \) states. For the most exotic nuclei such information is often unavailable. However, it has been shown that the energy of the first \( 2^+ \) state, \( E(2^+_1) \), is a very good indicator of changes in nuclear structure [4, Sec. 2-2b]. More recently, and with a much larger data-set, Cakirli and Casten [5] have demonstrated that the \( E(2^+_1) \) alone provides a very strong signature of shell evolution.

The archetypical example of very rapid changes in nuclear structure is the vanishing of the \( N = 20 \) shell gap for the very neutron-rich Ne, Na and Mg isotopes, a region which is now known as the “Island of Inversion” [6]. Soon after the pioneering work of Klapisch and Thibault [7, 8] revealing anomalies in the binding energies of the neutron-rich Na isotopes it was suggested that the \( \nu f_{7/2} \) orbitals actually intrude into the \( sd \) shell at \( N = 20 \), leading to a vanishing of the \( N = 20 \) shell gap [9]. In a later seminal shell-model study of this region by Warburton et al. [6] a true inversion of the orbitals was not found. However, \( \nu(sd)^{-2}(fp)^2 (2\hbar\omega) \) intruder configurations were predicted to become so low in energy that they form the ground states for \( Z = 10–12 \) and \( N = 20–22 \), as subsequently confirmed by mass measurements for neutron numbers \( N \leq 20, 21 \) and 22 for the Ne, Na and Mg isotopes, respectively [10]. More recently, this behavior has been found to be a general phenomenon.
that should occur for most standard shell closures far from stability and the mechanism behind this effect has been traced back to the nucleon-nucleon tensor interaction by Otsuka and collaborators [11].

The borders delineating the “Island of Inversion” are by now rather well established on the high-\(Z\) and low-\(N\) sides [3, 12]. For the Mg isotopes experiment confirms the dominance of the intruder configurations for \(^{31-34,36}\text{Mg}\), placing them inside the “Island of Inversion” [13, 14, 15, 16, 17] with a sharp transition from \(^{30}\text{Mg}\), which is dominated by normal configurations [18]. For the Ne isotopes data are much more scarce but evidence available places \(^{30}\text{Ne}\) squarely inside the “Island of Inversion” with \(^{28,29}\text{Ne}\) at the boundary [10, 19, 20, 21]. Until now no spectroscopic data exists for the Ne isotopes with \(N > 20\).

Here, we report on the first spectroscopic study of the \(N = 22\) nucleus \(^{32}\text{Ne}\). The experiment was carried out at the recently commissioned Radioactive Ion Beam Factory (RIBF) [22] operated by the RIKEN Nishina Center and the Center for Nuclear Study, University of Tokyo. The secondary beams were produced by bombarding a 20 mm thick rotating Be target [23] with a \(^{48}\text{Ca}\) beam at 345 MeV/\(u\) with an average intensity of \(\sim 120\) pnA. The projectile fragmentation products were analyzed and selected using the standard magnetic rigidity, \(B\rho\), selection method employing an achromatic Aluminum energy degrader of 15 mm median thickness located at the dispersive focus F1 [38] of the first stage of the BigRIPS fragment separator [24, 25] (F0 to F2). The momentum acceptance was \(\pm 3\%\). The second stage of BigRIPS (F3 to F7) was used to identify the transmitted fragmentation products using the \(\Delta E-B\rho\)-velocity method, where the energy loss \(\Delta E\) of the ions was measured in an ion chamber located at F7, the \(B\rho\) was determined from a position measurement (PPAC [25]) at the dispersive focus F5 and the time-of-flight (TOF) was measured between two thin plastic scintillators at F3 and F7 separated by a flight path of 47 m. The resulting particle identification (PID) is shown in Fig. 1 where all isotopes are well separated—the resolution in \(Z\) is 0.5 (FWHM) and the resolution in \(A\) for the Ne isotopes is 0.06 (FWHM). The average secondary beam intensities were \(6 \ \text{^{32}Ne s}^{-1}\) and \(27 \ \text{^{33}Na s}^{-1}\) in approximate agreement with the EPAX2 predictions [26]. It should be noted that this corresponds to a gain in intensity of over two orders of magnitude in comparison to the older RIPS facility.

The secondary beams were transported to the F8 focus where a 2.54 g/cm\(^2\) thick (natural) carbon target was mounted. The mid-target energy of the \(^{32}\text{Ne}\) and \(^{33}\text{Na}\) beams was 226 MeV/\(u\) and 245 MeV/\(u\), respectively. The energy loss in the target amounted to \(\sim 13\%\) of
FIG. 1: (color online) Particle identification before the secondary target.

the incident beam energy in both cases.

The secondary target was surrounded by the DALI2 NaI(Tl) based γ-ray spectrometer \[27\] consisting of 180 detectors covering laboratory angles from 11° to 147°. The measured full energy peak efficiency was 15 % at 1.3 MeV, in agreement with GEANT4 simulations, and the resolution was 6% (FWHM).

After the secondary reaction target the beam and reaction products entered the Zero Degree Spectrometer (ZDS) \[24, 28\] with angular and momentum acceptances of $\sim 80 \times 60$ mrad$^2$ and ±4%, respectively. The ZDS provided the PID and the $B\rho$ was set to that of elastically scattered $^{32}$Ne. The overall transmission for elastically scattered $^{32}$Ne was > 90%. Owing to the high acceptance of the ZDS the single-proton removal channel from $^{33}$Na to $^{32}$Ne was observed simultaneously, albeit with a much lower transmission. As before, the $\Delta E$–$B\rho$–TOF method was applied to identify the particles event-by-event, with a $B\rho$ measurement (PPAC) at the dispersive foci F9 and F10, a $\Delta E$ measurement at the final focus F11 (ion chamber) and a TOF measurement between plastic scintillators mounted at F8 and F11 with a flight path of 37 m. The resolutions in Z and A (for Ne) were 0.32 and 0.09 (FWHM), respectively.

After a total measuring time of 8 hours a γ-ray transition, which we assign to the $2^+_1 \rightarrow 0^+_gs$ transition in $^{32}$Ne, could be clearly identified not only after inelastic excitation, but also after single-proton removal from $^{33}$Na. The Doppler corrected γ-ray energy spectra are shown in Fig. 2 where the new transition can be clearly seen. Fitting the sum spectrum with a Gaussian peak and an exponential background a transition energy of 722(9) keV was
FIG. 2: Doppler corrected $\gamma$-ray energy spectra in coincidence ($\pm$ 5 ns) with $^{32}$Ne (a,b) and $^{30}$Ne (c,d). Panel a) shows the results for inelastic scattering of $^{32}$Ne and b) the result for proton removal from $^{33}$Na. The outcomes of the fitting procedure are shown by the solid (total) and dashed (background) curves. Here, both spectra were fitted simultaneously with the same peak position and peak width, but different peak areas and background parameters. The inset panels c) and d) show the results for inelastic scattering of $^{30}$Ne and for $p2n$ removal from $^{33}$Na, respectively, populating the first $2^+$ state in $^{30}$Ne.

derived, whereby the quoted uncertainty includes statistical (7 keV) and systematic (6 keV) contributions. The latter are dominated by the unknown lifetime of the $2^+$ state resulting in an uncertainty in the position and velocity of the $\gamma$-ray emitting particle. The observed resolution is 15% (FWHM). Assuming no feeding transition (there is no evidence in either spectrum) the cross section for inelastic excitation on C of the first $2^+$ state was deduced to be 13(3) mb. Owing to the large uncertainty in the cross section and in the unknown optical model parameters at this beam energy, no meaningful deformation parameter could be extracted from the cross section.

In order to study the effect of the lifetime of the excited state on the deduced $\gamma$-ray energy
a GEANT4 simulation was developed. In addition to the full detector, target and beam line geometries, the simulation (as well as the data analysis) took into account the lifetime of the excited state, which is the principal contribution to the systematic uncertainty. The assumed lifetimes were varied in an interval from \(0.5 \cdot \tau_R = 31\) ps to \(2.0 \cdot \tau_R = 123\) ps, where \(\tau_R = 61\) ps was given by Raman’s global systematics \([29, \text{Eq. (11)}]\).

As a check of our method we determined the \(E(2_1^+\!\!\!\!\!\!\!\!\!\!\!\rangle\) of \(^{30}\text{Ne}\) produced after \(p2n\) removal from \(^{33}\text{Na}\) and after inelastic scattering of \(^{30}\text{Ne}\)—another BigRIPS setting was used for this measurement. Our result of 801(7) keV agrees well with the literature value of 791(26) keV \([20]\). The corresponding spectra are displayed in the insets of Fig. 2.

We now turn to the interpretation of our results. In Fig. 3, the experimental \(E(2_1^+\!\!\!\!\!\!\!\!\!\!\!\rangle\) values are shown as a function of neutron number. The very low \(E(2_1^+\!\!\!\!\!\!\!\!\!\!\!\rangle\) at \(N = 20\) and 22 strongly suggest that there is no \(N = 20\) shell gap and that \(^{32}\text{Ne}\) as well as \(^{30}\text{Ne}\) belong to the “Island of Inversion”. A very different behavior would be expected if \(N = 20\) was a good magic number. For instance, the \(E(2_1^+\!\!\!\!\!\!\!\!\!\!\!\rangle\) as a function of neutron number for \(14 \leq Z \leq 20\) exhibit a sharp peak at \(N = 20\) and where \(E(2_1^+\!\!\!\!\!\!\!\!\!\!\!\rangle\) in excess of 2 MeV are observed. Also, according to the \(“N_pN_n”\) scheme \([30]\), in which the \(E(2_1^+\!\!\!\!\!\!\!\!\!\!\!\rangle\) is correlated with the inverse of the product of the number of valence neutrons \(N_n\) and protons \(N_p\), a very different trend to that observed would be expected if \(N = 20\) were a good magic number. Clearly this is not the case.

As long ago as 1990 Warburton et al. \([6]\) predicted \(^{32}\text{Ne}\) to lie inside the “Island of Inversion”, with essentially degenerate intruder \((2\hbar\omega)\) and normal \((0\hbar\omega)\) configurations. Unfortunately no attempt was made to calculate the \(E(2_1^+\!\!\!\!\!\!\!\!\!\!\!\rangle\). Even now only a few predictions for the \(E(2_1^+\!\!\!\!\!\!\!\!\!\!\!\rangle\) of \(^{32}\text{Ne}\) exist \([31, 32, 33, 34, 35]\). Of particular interest are those of Utsuno et al. \([31]\) and Caurier et al. \([34]\) as they exhibit the best agreement with experimental data. This is shown in Fig. 3, where for completeness, the predictions and experimental data for the Mg isotopes are also displayed.

The Monte Carlo shell model (MCSM) with the SDPF-M interaction of Utsuno et al. allows for a comprehensive theoretical exploration of nuclei in and around the “Island of Inversion” with unrestricted mixing of the \(sd\) and \(pf\) configurations \([31, 36]\). It provides an almost perfect description of all \(E(2_1^+\!\!\!\!\!\!\!\!\!\!\!\rangle\) in Fig. 3, including that of \(^{32}\text{Ne}\)—the largest discrepancy occurs for \(^{30}\text{Ne}\), but is less than 200 keV. The MCSM calculations predict that the Ne and Mg isotopes with \(N = 20\) and 22 are strongly deformed and dominated by intruder configurations \([31]\). Employing mean field calculations with the separable monopole
FIG. 3: Comparison of experimental $E(2^+_1)$ in neutron-rich Ne and Mg isotopes [15, 17, 20, 29], indicated by horizontal lines (the present work is shown in bold), with the shell model results of Utsuno et al. [31] (+), and Caurier et al. [33, 34] for the normal ($N$, dashed) and intruder ($I$, dash-dotted) configurations, respectively. Their prediction for the configuration ($N$ or $I$) with the lowest energy $0^+$ state, i.e. the ground state, is marked by a circle. The $E(2^+_1)$ are given relative to the $0^+_1$ state of the same configuration.

interaction, a similar conclusion with regard to the deformation was reached by Stevenson et al. [37] for $^{32,34}$Mg and $^{32}$Ne, but not $^{30}$Ne. Utsuno et al. also predict the number of additional neutrons in the pf shell with respect to normal filling. Their result for the Ne and Mg isotopes with $N = 20$ and 22, of $\langle n_{pf} \rangle \approx n_{pf}^{\text{norm}} + 2$, agrees very well with the original predictions of Warburton et al. Deviations only occur for $N = 18$ and $N = 24$, where Utsuno et al. still anticipate sizable intruder components in the ground-state wave functions, especially for the Ne isotopes, while Warburton et al. do not.

Caurier et al. [34] performed separate large-scale shell-model calculations for the normal ($0h\omega$) and intruder ($2h\omega$) configurations, but did not allow mixing of the two. The results of the calculations are shown in Fig. 3. Contrary to Warburton et al. and Utsuno et al. they predict that only the $N = 20$ isotones have intruder ground states and reproduce the $E(2^+_1)$ in these cases. While the intruder configuration result for $^{32}$Ne reproduces the experimental value very well, the normal configuration $0^+_1$ state is actually predicted to be the ground
state with the intruder $0^+_1$ state lying 1.5 MeV above it [34]. The normal configuration $2^+_1$ state is predicted at 1 MeV at variance with our observation.

Besides the expectation from the systematic trend of the $E(2^+_1)$ energies, where decreasing values with larger $N$ suggest increased collectivity for $^{32}$Ne, all model predictions consistent with the experimental $E(2^+_1)$—i.e. the predictions of Utsuno et al. [31] and the intruder results of Caurier et al. [34]—show $^{32}$Ne to be highly collective and therefore inside the “Island of Inversion” with the ground state dominated by $2\hbar\omega$ intruder configurations.

In summary, we have reported on the first observation of a $\gamma$-ray line ($E_\gamma = 722(9)$ keV) in in-beam $\gamma$-ray spectroscopy of $^{32}$Ne, which we assign to the $2^+_1 \rightarrow 0^+_gs$ transition. This measurement demonstrates that the “Island of Inversion” extends to neutron number $N = 22$ for the Ne isotopic chain.

It is interesting to note that thirty years after the first observation of an excited state in $^{32}$Mg [13] experiment has progressed such that we can now report on the same observation in the much more neutron-rich isobar $^{32}$Ne from the first in-beam $\gamma$-ray spectroscopy experiment at the newly commissioned RIBF. Developments in the near future should permit similar measurements to be extended to other “Island of Inversion” nuclei as well as Coulomb excitation studies.

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[38] See [24, Fig. 2] for the location of the focal points.