Spectroscopy in and around the Island of Inversion

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Abstract. The magic neutron number \( N = 20 \) arises after 2 quanta of the harmonic oscillator and persists, albeit weakened, after considering a more realistic potential including the spin-orbit interaction. The \( N = 20 \) shell gap can be found between the \( 0d_{3/2} \) and \( 0f_{7/2} \) orbitals.

It has become clear that magic numbers are not a fixed property throughout the nuclear chart, but can evolve as a function of \( Z \) and \( N \) due to (residual) proton-neutron interactions, which can lead to a quenching of certain magic numbers and the appearance of others. The archetypical example of these very rapid changes in nuclear structure is the so-called 'island of inversion', comprising the very neutron-rich nuclei near \( N \sim 21 \) and \( Z \sim 11 \).

Historically it was found that these nuclei are more bound than expected and subsequent experimental observations pointed toward an abrupt onset of collectivity with deformed ground states. The most striking observations are highly collective E2 transitions between low-lying states, in particular the low energy of the first \( J^\pi = 2^+ \) state of \(^{32}\text{Mg}\) and the very large \( B(E2; 0^+_gs \rightarrow 2^+_1) \). These properties can best be explained by the dominance of intruder configurations, i.e. configurations outside the sd-shell.

The interest in this region of the nuclear chart has grown enormously over time, due to the ever better accessibility of these nuclei at RNB facilities. I will review the current experimental understanding of these nuclei on a few selected examples and will give an outlook on the experimental progress to be expected in the near future.

Furthermore an outlook and future plans concerning in-beam \( \gamma \)-ray spectroscopy at RIKEN is given.

1. Introduction

One of the most fundamental concepts in nuclear structure is the notion of “magic numbers”. A nucleus with a certain number of protons and neutrons is considered “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 [1].

Beyond ground-state binding energies, a variety of signatures exist to identify magic numbers. One of the most direct is the reduced transition probability \( B(E2; 0^+_gs \rightarrow 2^+_1) \) for even-even
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” [4]. The enormous interest in this region of the nuclear chart is illustrated in figure 1, which shows the number of publications per year concerning this subject. Positive values are mainly experimental works and negative mainly theoretical. Soon after the pioneering work of Klapisch and Thibault [5, 6] 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 [7]. In a later seminal shell-model study of this region by Warburton et al.[4] a true inversion of the orbitals was not found. However, $\nu (sd)^{-2} (fp)^{2} \langle 2h\omega \rangle$ 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 [8]. 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 [9, 10, 11].

The borders delineating the “Island of Inversion” are by now rather well established on the high-$Z$ and low-$N$ sides [1, 12]. For the Mg isotopes experiment confirms the dominance of the intruder configurations for $^{31-34,36}$Mg, placing them inside the “Island of Inversion” [13, 14, 15, 16, 17] with a sharp transition from $^{30}$Mg, which is dominated by normal configurations [18]. For the Ne isotopes data are much more scarce but evidence available

Figure 1. Number of publications per year concerning the “Island of Inversion”. Positive values: mainly experimental publications. Negative values: theoretical publications. An enormous increase in interest is evident after 1995 largely driven by the availability of radioactive nuclear beams.
places $^{30}$Ne squarely inside the “Island of Inversion” with $^{28,29}$Ne at the boundary \cite{8, 19, 20, 21}. Until recently no spectroscopic data existed for the Ne isotopes with $N > 20$ and the Mg isotopes with $N > 22$.

2. Experimental Methods

Besides standard experimental methods such as low-energy “safe” Coulomb excitation or low-energy transfer reactions, various experimental methods have been developed specifically for the use with low-intensity (and often high-energy) radioactive nuclear beams. In particular most methods employed with fast beams are characterized by the possibility to use thick targets compensating the usually low beam intensities, for an introduction to some of the techniques see e.g. \cite{12} and references therein.

In the following a short overview of the experimental techniques to study (mainly) excited states is given with the accessible observables.

- $\beta$-decay: level scheme, $t_{1/2}$, $(J^\pi)$
- $\beta$-NMR (+ opt. pumping): $g$-factors, $\mu$ moment, $Q$ moment, $J^\pi$ (gs)
- TDPAD, LEMS, TF: $g$-factors, $\mu$ moment (non-gs)
- Coulomb excitation
  - slow beams: transition and static $(E2)$ moments ($B(E2\uparrow)$, $Q(2^+)$)
  - fast beams: transition moments (mainly $B(E2\uparrow)$) (lowest states only)
- other reactions:
  - secondary fragmentation: level scheme, $J^\pi = 2^+, 4^+$ from systematics
  - $(p, p')$: level scheme, $l$-values, $M_n$, $M_p$
  - $(d, p)$: level scheme, $l$-values, spectroscopic factors (SF) (empty orbitals)
  - $(t, p)$: level scheme, $l$-values, pairing correlations, shape co-existence
  - $1N$ knockout: level scheme, $l$-values, SF (filled orbitals)
  - $2N$ knockout: level scheme, wave function overlap, $J$

3. Recent Results

In the following recent experimental progress is illustrated by discussing a few examples.

3.1. The $J^\pi = 4_1^+$ state in $^{32}$Mg

While the $J^\pi = 2_1^+$ state in $^{32}$Mg was already observed in 1979 \cite{13} the nature of other excited states has remained largely uncertain. In particular the spin and parity of the 2321 keV state has long been debated. For instance an intermediate energy Coulomb excitation study suggested the $J^\pi$ values of $1^−, 1^+$ or $2^+$ \cite{22}, while the results of $\beta$-decay studies are more consistent with a $4^+$ assignment \cite{23}. Only recently proton inelastic scattering on the neutron-rich nucleus $^{32}$Mg has been studied at 46.5 MeV/nucleon in inverse kinematics proving that it is indeed a $4^+$ state by analyzing the angular differential cross sections via coupled-channel calculations \cite{24}.

3.2. Intruder components in the first excited state of $^{36}$Mg

Recently Gade et al. reported on the first spectroscopy study of the very neutron-rich nucleus $^{36}$Mg using the direct 2-proton knockout from $^{38}$Si on a thick $^9$Be target at a beam energy of 83 MeV/u \cite{17}. Not only could the energy of the first excited $2^+$ state of $^{36}$Mg, of 660(6) keV, be established, but also the magnitude of the partial cross sections to the ground and the $2^+_1$ state. These cross sections were interpreted with the help of a reaction theory based on eikonal dynamics and microscopic, correlated two-nucleon transition densities from shell-model calculations, which carry the nuclear structure information and show that the $0\hbar\omega$ component of the wave functions of both the $0^+_gs$ and the $2^+_1$ states is only about 35%. This is in agreement
Figure 2. Doppler corrected γ-ray energy spectra in coincidence with $^{32}\text{Ne}$. Panel a) shows the results for inelastic scattering of $^{32}\text{Ne}$ and b) the result for proton removal from $^{33}\text{Na}$.

Figure 3. Comparison of experimental $E(2^+)$ in neutron-rich Ne isotopes [26, 20], indicated by horizontal lines, with the shell model results of Utsuno et al.[27] (+), and Caurier et al.[28, 29] for the normal ($N$, dashed) and intruder ($I$, dash-dotted) configurations, respectively.

with MCSM calculations, which predict the main component of the wave function to be $2\hbar\omega$ placing $^{36}\text{Mg}$ inside the “Island of Inversion”.

3.3. First excited state of $^{32}\text{Ne}$
In [25] a first spectroscopic study of the $N = 22$ nucleus $^{32}\text{Ne}$ at the newly completed RIKEN Radioactive Ion Beam Factory is reported. A single γ-ray line with an energy of 722(9) keV was observed in both inelastic scattering of a 226 MeV/u $^{32}\text{Ne}$ beam on a Carbon target and proton removal from $^{33}\text{Na}$ at 245 MeV/u. This transition is assigned to the de-excitation of the first $J^\pi = 2^+$ state in $^{32}\text{Ne}$ 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. Figure 2 shows the observed spectra and Figure 3 shows a comparison to model calculations.

3.4. Spectroscopy of neutron-rich Na isotopes $^{31,32,33}\text{Na}$
Recently the structure of the neutron-rich sodium isotopes $^{31,32,33}\text{Na}$ was investigated by means of in-beam γ-ray spectroscopy following one-neutron knockout and inelastic scattering
Figure 4. The top panel displays the Doppler corrected $\gamma$-ray energy spectrum in coincidence with the one-neutron removal from $^{32}$Na. In the bottom panel, a $\gamma$-ray energy cut between 325 and 425 keV on the $(5/2^+ + 1) \rightarrow 3/2^+_{g.s.}$ transition in $^{31}$Na was applied.

of radioactive beams provided by the RIKEN Radioactive Ion Beam Factory [30]. The secondary beams were selected and separated by the fragment separator BigRIPS and incident at $\approx 240$ MeV/u on a natural carbon (secondary) target, which was surrounded by the DALI2 array to detect coincident de-excitation $\gamma$ rays. Scattered particles were identified by the spectrometer ZeroDegree. In $^{31}$Na, a new decay $\gamma$ ray was observed in coincidence with the known $(5/2^+ + 1) \rightarrow 3/2^+_{g.s.}$ transition, while for $^{32,33}$Na excited states are reported. From a comparison to state-of-the-art shell-model calculations it is concluded that the newly observed excited state in $^{31}$Na belongs to a rotational band formed by a $2p2h$ intruder configuration within the “Island of Inversion.”

Figure 4 displays the Doppler corrected $\gamma$-ray energy spectra for the one-neutron removal reactions from $^{32}$Na. Two distinct transitions are visible at 376(4) keV and at 787(8) keV. The former is in agreement with previous observations of 350(20) keV [31] and 370(12) keV [32] and is generally interpreted to be the $(5/2^+_1 \rightarrow 3/2^+_{g.s.})$ transition. Applying a gate ranging from 325 to 425 keV on this transition shows that both observed decays are in coincidence, as illustrated in the lower panel of Fig. 4. From the observed coincidence and from the later discussed comparison to shell-model calculations, we concluded that the observed transition at 787(8) keV is the $(7/2^+_1 \rightarrow 5/2^+_1)$ decay. No indication for a direct transition from the $(7/2^+_1)$ state to the ground state was found. This is consistent with the shell-model prediction of Ref. [31] for a strong $B(M1; 7/2^+_1 \rightarrow 5/2^+_1)$ causing the $(7/2^+_1)$ state to decay with an intensity of 95% into the $(5/2^+_1)$ state. From the intensity ratio of the two transitions it follows that...
4. Summary

We have seen considerable progress in the understanding the rapid changes in nuclear structure in and near the “Island of Inversion”. An overview of the current status with respect to E2 properties is shown in figure 5. To a very large extent this is due to the ever increasing accessibility of these nuclei at radioactive nuclear beam facilities, in particular with the commissioning of the RIBF facility at RIKEN much new data can be expected in the near future.
Table 1. Summary of basic properties of LaBr₃(Ce) with a comparison to other scintillators

|                              | NaI(Tl) | BaF₂ | LaBr₃(Ce) |
|------------------------------|---------|------|-----------|
| Light Output (1/keV)        | 38      | 2    | > 71      |
| Decay Time (ns)             | 250     | .7   | 630       |
| Density (g/cm³)             | 3.67    | 4.88 | 5.1       |
| Temp. Coef. (%/K)           | -0.3    | 0    | 1.1       |
| Max. Sc. Wavel. (nm)        | 415     | 220  | 310       |
| Energy Res. (%)             | 7       | 12   | 2.5       |
| Time Res. (ns)              | 2.5     | 0.2  | 0.2       |
| Linearity                   | low     | low  | very high |
| Hygroscopic                 | yes     | no   | yes       |

The outstanding properties of LaBr₃(Ce) in nearly all categories are evident.

5. A next generation γ-ray spectrometer for in-beam experiments with fast beams: The SHOGUN array

Before concluding this article a possible future detector for in-beam γ-ray spectroscopy with fast beams at the RIBF facility will be introduced. So far, when doing in-beam γ-ray spectroscopy with fast beams one has to choose between high-efficiency or good resolution.

5.1. Introduction: typical energy resolution in fast-beam experiments

To reconstruct the γ-ray energy in fast beam experiments not only the laboratory frame γ-ray energy, but also the emission angle and velocity vector of the emitting nucleus must be measured. Uncertainties in the emission angle and the absolute value of the velocity give rise to Doppler broadening, which often dominates the energy resolution in fast beam experiments.

The angular uncertainty is influenced not only by the spatial resolution of the γ-ray detectors but also the uncertainty in the position of the emitting nucleus, due to the thickness of the reaction target and the lifetime of the populated excited states. For instance, in a recent experiment, a 1.4 cm thick C target [25] was used and at beam energies of 200 MeV/u a lifetime of 100 ps corresponds to a flightpath of 1–2 cm. Thus, even with a perfect position resolution of the γ-ray detectors, the minimum angular resolution is only about 50 mrad, assuming a target detector distance of about 25 cm. This corresponds to a Doppler broadening of 3% at RIBF beam energies.

At the RIBF the beam velocity vector after the secondary target can be measured very well by the ZeroDegree spectrometer. Therefore, the momentum spread of the incident secondary beam does not contribute to the Doppler broadening. However, typical target thickness can correspond to an energy loss of the incident beam of 10–20%, so the velocity changes considerably while the beam particles traverse the target. If the lifetime of the excited states is short compared to the passage time through the target, the final velocity measured after the target does not correspond to the velocity at γ-ray emission and there will be a Doppler broadening. If the lifetime is long, however, most nuclei decay after the target and there will be no Doppler broadening due to the uncertainty in the beam velocity. In the case of a short lifetime, an energy loss of 10% in the target will result in a Doppler broadening of about 3–4%.

In conclusion, the contribution of the Doppler broadening to the energy resolution of in-beam γ-ray spectra at the RIBF is in most cases not better than 3% even when a perfect position resolution of the γ-ray spectrometer is assumed. Only in special cases, when the lifetime of an excited states is short and when a thin target is used, the Doppler broadening can be smaller as summarized in figure 6.
Figure 6. Schematic overview of achievable angular and velocity resolutions, which contribute to the Doppler broadening in an in-beam $\gamma$-ray experiment with fast beams.

The intrinsic energy resolution of the new scintillator material LaBr$_3$(Ce) is ideally matched to this Doppler broadening. It was developed in 2001 and shortly thereafter commercialized under the name BrillanCe 380. Its most outstanding property is the excellent energy resolution of <3% at 662 keV. Besides that LaBr$_3$(Ce) has a large attenuation coefficient due to the high $Z$ of La and Br (57 and 35) and its high density. It is very fast with a decay time of the scintillation light of only 16 ns. Its emission wavelength of 380 nm is well matched to Bi-alkali photo cathodes. In addition, the light output of LaBr$_3$(Ce) is highly linear. In table 1 some properties of LaBr$_3$(Ce) are compared to those of other scintillators.

Currently, we assume a detector array of about 1000 crystals. Each crystal has the same shape and size: a cuboid with dimension $1.5 \times 4 \times 8$ cm$^3$. All crystals are arranged such that the long axis is pointing to the target position with the opening angle (in $\theta$ direction) being given by the smallest dimension (1.5 cm). The crystals are arranged in concentric rings around the beam axis and the distance from the target is chosen such that the $\Delta \theta$ contribution to the Doppler broadening remains below 3%. A 3D rendering is shown in figure 7.

The performance of the SHOGUN array in terms of resolution and efficiency is shown in figures 8 and 9 as a function of the original $\gamma$-ray energy for various beam energies. For instance at 1 MeV photon energy and a beam energy of 250 MeV/u a full energy peak efficiency of more than 30% is obtained and the resolution is about 3.7%.

There are multiple benefits offered by a LaBr$_3$(Ce) based array and, as far we know, no drawbacks in comparison to a NaI(Tl) based array, except for the cost. Some of the advantages of LaBr$_3$(Ce) with respect to NaI(Tl) are

- a higher rate capability ($4 \cdot 10^5$/s $\rightarrow$ $1.5 \cdot 10^6$/s), which allows for (i) large cocktail beams to be used, allowing to study several nuclei in one experiment, (ii) very detailed studies using intense beams, and (iii) the toleration of the buildup of large amounts of radioactivity in or near the secondary target,
- a higher efficiency (20% $\rightarrow$ 30%), which allows to (i) reach further into the unknown, (ii) reduce the overall measuring time, and (iii) make $\gamma$-$\gamma$($-\gamma$) coincidence measurements...
Figure 7. SHOGUN: 3D rendering. Only the crystals are shown.

Figure 8. SHOGUN resolution as a function of γ-ray energy for various beam energies. Since the energy resolution is dominated by Doppler broadening the result depends strongly on the beam energy, in particular at high photon energies.

possible, which are crucial to build level schemes,

- a better energy resolution (10% → 3.5%), which allows for (i) higher precision due to improved peak-to-background ratio, (ii) the identification of so-far not resolved transitions, (iii) better access to regions of higher level density, in particular odd-\(A\) and odd-odd nuclei, and (iv) line shape analysis to extract lifetimes of excited states,

- a better time resolution (3 ns → 0.5 ns), which allows for (i) a strong background reduction by suppressing random and delayed-coincident background, and (ii) direct lifetime measurements.

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Figure 9. SHOGUN full-energy peak efficiency as a function of $\gamma$-ray energy for various beam energies. Due to the large attenuation coefficient especially for high-energy $\gamma$-rays the efficiency is largely independent of the beam energy. In the frame of the decaying nucleus the $\gamma$-rays were emitted isotropically. Add-back was used to determine the efficiency.

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