Weakly Bound Neutron-Rich Nuclei and Cosmic Phenomena

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The single particle and bulk properties of the neutron-rich nuclei constrain fundamental issues in nuclear physics and nuclear astrophysics like the limits of existence of quantum many body systems (atomic nuclei), the equation of state of neutron-rich matter, neutron star, nucleosynthesis, evolution of stars, neutron star merging etc. The state of the art of Coulomb breakup of the neutron-rich nuclei has been used to explore those properties. Unambiguous information on detailed components of the ground-state wave-function along with quantum numbers of the valence neutron of the nuclei have been obtained from the measurement of threshold strength along with the $\gamma$-rays spectra of the core following Coulomb breakup. The shape of this threshold strength is a fingerprint of the quantum numbers of the nucleon. We investigated the ground-state properties of the neutron-rich Na, Mg, Al nuclei around $N \sim 20$ using this method at GSI, Darmstadt. Very clear evidence has been observed for melting and merging of long cherished magic shell gaps at $N = 20, 28$. The evanescent neutron-rich nuclei imprint their existence in stellar explosive scenarios ($r$-process etc.). Coulomb dissociation (CD) is one of the important indirect measurements of the capture cross-section which may provide valuable input to the model for star evolution process, particularly the $r$-process. Some valuable bulk properties of the neutron-rich nuclei like the density dependent symmetry energy, neutron skin etc. play a key role in understanding cosmic phenomena and these properties have been studied via electromagnetic excitation. Preliminary results of electromagnetic excitation of the neutron-rich nucleus, $^{32}$Mg are presented.

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1 Introduction

Recent advancement of accelerator physics along with detector technologies provide a unique laboratory of neutron-rich nuclei where one can explore various fundamental issues in nuclear physics and astrophysics. One of the major challenging open problem is what are the limits of the existence of nuclei. A lack of detailed understanding of nucleon-nucleon interaction and its co-relation are the main reasons behind it. Experimental observations of the failure of validation of 'old magic number' \cite{1} in the nuclei near drip-line further indicate that also \cite{2,3}. Recently, it has been notified that a number of ingredients in nucleon-nucleon interaction such as spin-isospin monopole interaction, three body interaction, tensor interaction part \cite{4,5} etc. are essential to explain experimentally observed properties of nuclei around the drip-line. The experimental data on nuclear shell structure around drip line is very essential and may provide important information on nucleon nucleon interaction. Investigation of nuclear shell structure around magic numbers are particularly important in this respect. 'Island of Inversion' are neutron-rich Ne, Na, Mg nuclei around $N \sim 20$ where first failure of magic number had been reported \cite{2}. It has been observed that the ground state properties of these nuclei can be explained only by considering pf shell contribution in addition to sd shell contribution and often, it has been concluded that these nuclei exhibit large deformation. The state of the art of Coulomb breakup of the neutron-rich nuclei has been used to explore those properties. The unambiguous information on detailed components of the ground-state wave-function along with quantum numbers of the valence neutron of the nuclei has been obtained from the measurement of threshold strength along with the $\gamma$-rays spectra of the core following Coulomb breakup \cite{6}. In this article, several previous successful measurements will be mentioned to explain validity of the method. New experimental results on the “microscopic picture“ of the ground state wave-functions of 'Island of Inversion' nuclei, explored through Coulomb breakup will be presented \cite{3,7,8}. Coulomb dissociation (CD) is a successful indirect measurement for capture cross-sections of the neutron-rich nuclei which may provide input to the model for the stellar evolution process \cite{9}. Some valuable bulk properties of the neutron-rich nuclei like the density dependent symmetry energy, neutron skin etc. play a key role in understanding cosmic phenomena \cite{10,11,12}. Electromagnetic excitation using intermediate energy radioactive beam provides a unique opportunity to access key information to understand those cosmic phenomena \cite{10,11}. A preliminary experimental investigation on the bulk properties of the neutron-rich nucleus, $^{32}$Mg are reported.
2 Experimental setup and analysis

Short-lived radioactive nuclei were produced by the fragmentation of the primary beam $^{40}\text{Ar}$ at 530 MeV/u on a $^{9}\text{Be}$ production target (8 g/cm$^2$) at GSI, Darmstadt. The secondary beams, ($^{29-31}\text{Na}$, $^{31-33}\text{Mg}$, $^{34,35}\text{Al}$ etc.) with A/Z between 2.55 to 2.85 (Fig. 1-left) were separated according to the magnetic rigidities by the fragment separator (FRS). The secondary cocktail beam was bombarded on lead (2 g/cm$^2$) and carbon (0.9 g/cm$^2$) targets for studying electromagnetic and nuclear excitation, respectively. The $\gamma$-rays from the excited projectile or fragments were detected by the 4 $\pi$-crystal ball spectrometer. Eight double-sided Silicon Strip Trackers (SSTs) were placed enclosing the reaction target in 4$\pi$ solid angle. After reaction at the secondary target, reaction fragments and neutron(s) are forward focused due to Lorentz boost and pass through A Large Dipole Magnet (ALADIN). Reaction fragments, deflected by ALADIN according to their A/Z ratios, were tracked by two scintillating fiber detectors (GFIs) and detected by the time of flight wall (TFW). The trajectories of neutrons remain unchanged and were detected by the Large Area Neutron Detector (LAND). Fig. 1-right shows a reconstructed outgoing mass identification plot after the secondary target. Data analysis has been performed using CERN-ROOT platform and programs developed at GSI, Darmstadt and SINP, Kolkata [3, 7, 8]. The excitation energies $E^*$ of the neutron-rich Na, Mg and Al nuclei, were reconstructed event by event by measuring four momenta of all decay products of those nuclei after breakup at the secondary target via invariant mass analysis, The Coulomb dissociation (CD) cross section for the $^{208}\text{Pb}$ target (2.0 g/cm$^2$) has been determined after subtracting the nuclear contribution which was obtained from the data with a $^{12}\text{C}$ target (0.9 g/cm$^2$) with proper a scaling factor. Background contributions from reactions induced by detectors materials were determined from data taken without any target and were subtracted. The state of the art of one neutron threshold strength via Coulomb dissociation has been employed to explore single particle properties of the...
neutron-rich nuclei. On the other hand electromagnetic excitation via inverse kinematics of the neutron-rich nuclei up to several neutrons and proton threshold energy provide access to several bulk properties of neutron-rich nuclear matter. Below we are discussing in separate sub-section both single particle and bulk properties of the neutron-rich nuclei. We shall discuss impact of those properties on cosmic phenomena in another sub-section.

3 Threshold strength and single-particle properties of neutron-rich nuclei

When a projectile with relativistic energy passes a high Z target, it may be excited by absorbing virtual photons from the time dependent Lorentz-contracted Coulomb field \[13\] and breakup into a core and a neutron. This one neutron removal differential CD cross-section can be expressed by the following equation \[6\]:

\[
\frac{d\sigma_c}{dE^*} = \frac{16\pi^3}{9\hbar c} N E_1(E^*) \Sigma_j C^2 S(I_c, nlj) \times \Sigma_m | < q|(Ze/A)rY_{m\ell}\psi_{nlj}(r) > |^2
\]  

(1)

\( \psi_{nlj}(r) \) and \( < q| \) represent the single-particle wave function of the valence neutron in the projectile ground state and the final state in the continuum respectively.

Figure 2: [Left] E1 virtual photon spectrum for \(^{15}\)C projectile of 35 MeV/u, 70 MeV/u and 600 MeV/u energies respectively, on a Pb target. [middle] Differential Coulomb dissociation (CD) cross-section with respect to the excitation energy \((E^* )\) of \(^{15}\)C breaking up into a neutron and a \(^{14}\)C fragment in its ground-state (filled circles). The solid curve displays the result from the direct-breakup model in a plane-wave approximation with the valence neutron occupying the s-wave. [right] The sum-energy spectrum of \(\gamma\)-decay transitions from \(^{16}\)C after Coulomb breakup of \(^{17}\)C. The inset shows a partial scheme of levels in \(^{16}\)C and their population after Coulomb breakup of \(^{17}\)C. Figure [middle and right] reprinted from Datta Pramanik et al. PLB 551, 63 (2003).
Figure 3: [top] The differential CD cross-section with respect to the excitation energy $E^*$ of $^{29}\text{Na}$ and of $^{35}\text{Al}$ breaking up into a neutron and a fragment in its ground state or isomeric state (filled circles). The solid curve displays the result from the direct-breakup model where the valence neutron(s) is occupying $s,d$ and $p,d$ orbitals for the top-panel and the bottom-panel of the figure, respectively.

$C^2S(I^\pi_c,nlj)$ represents the spectroscopic factor with respect to a particular core state $I^\pi_c$ of that. $N_{E1}(E^*)$ is the number of virtual photon as a function of excitation energy $E^*$ [13]. Fig. 2-left shows the variation of the E1 virtual photon spectrum with different projectile energies for $^{15}\text{C}$ on Pb target. It is evident from the virtual photon spectra that the number of electric dipole virtual photons, $N_{E1}$ decreases with excitation energy ($E^*$) for low energy projectile due to the adiabatic cutoff. Fig. 2-middle shows the measured differential CD cross-section at an energy 600 A MeV with respect to excitation energy ($E^*$) of $^{15}\text{C}$ breaking up into a neutron and a $^{14}\text{C}$ fragment in its ground state (filled circles) [6]. The solid curve displays the cross-section obtained from the direct-breakup (DB) [equation (1)] model considering the valence neutron occupying the $s_{1/2}$ orbital. Thus it is evident from the Fig. 2 that the data is in agreement with the configuration $^{14}\text{C}_{gs} \otimes \nu_{s_{1/2}}$ and the spectroscopic factor of the valence neutron orbital is in agreement with the transfer reaction and knockout reaction data (see [6] for details). However, in some of the neutron-rich nuclei due to specific effects of the n-n interaction, various types of particle-hole excitation are possible in the ground state of neutron-rich nuclei. Those components can be identified by measuring $\gamma$-rays in coincidence with core after CD. That was demonstrated by measuring CD of $^{17}\text{C}$. Fig. 2-right shows the sum-energy spectrum of $\gamma$-decay transitions from $^{16}\text{C}$ after Coulomb breakup of $^{17}\text{C}$. The inset shows a partial scheme of levels in $^{16}\text{C}$ and their population after Coulomb breakup. The ground state spin and parity of exotic nuclei can be obtained by coupling the spin and parity of the core state with that of valence neutron.
3.1 Shell evolution in the neutron-rich nuclei

The modification in the shell gaps through effects such as the tensor component of the NN force become pronounced with large neutron-proton asymmetries in the exotic nuclei far away from stability. These lead to the disappearance of established magic numbers and the appearance of new ones. The first observation of the disappearance of so-called magic number \( (N = 20) \) was reported, based on the mass measurements in neutron-rich \(^{31,32}\)Na and BE2 measurement in \(^{32}\)Mg [2]. For a deeper understanding of the n-n interaction microscopic information on the ground state wave-function is essential. The state of the art of Coulomb breakup has been utilized to explore the detailed components of the ground-state wave-function of the neutron-rich Na, Mg, Al around N~ 20. Monte-Carlo shell model calculation [4] has predicted the lowering of \( 2p_{3/2} \) orbital for aluminum isotopes around the N~20 shell gap. On the other hand to explain the knockout data [14, 5] for \(^{33}\)Mg, the shell gap was reduced from 6 MeV to 3 MeV in \( sd_{p}f - M \) calculation. We describe below our observation in this respect via Coulomb breakup method.

\(^{29,30,31}\)Na:

The first results were reported on the ground state configurations of the neutron-rich \(^{29,30}\)Na isotopes, obtained via CD measurements [7]. A comparison with the direct breakup model, suggests the predominant components of the ground state configurations of these nuclei are \(^{28}\)Na\(_{gs}(1^+ ) \otimes \nu_d \) and \(^{29}\)Na\(_{gs}(3/2^+ ) \otimes \nu_d \), respectively. The ground state spin and parity of these nuclei obtained from this experiment are in agreement with earlier reported values. The spectroscopic factors for the valence neutron occupying the \( d \) orbital for these nuclei in the ground state have been extracted and reported for the first time. This is in agreement with a USDB calculation for \(^{29}\)Na but that the factor is reduced in comparison with the USDB for \(^{30}\)Na. A comparison of the experimental findings with shell model calculation using the MCSM suggests a lower limit of around 4.3 MeV of the \( sd - pf \) shell gap in \(^{30}\)Na. In the case of \(^{31}\)Na, the major component of the ground state configuration (\( \sim 60 \% \)) is multi-particle-hole in nature, which indicates a narrower \( N = 20 \) shell gap.

\(^{31,33}\)Mg:

The valence neutron in the ground state of \(^{33}\)Mg should occupy the \( f_{7/2} \) orbital as in \(^{41}\)Ca. But experimental evidence is different. We reported the first direct experimental evidence of a multi-particle-hole ground-state configuration obtained via a (400 A MeV) CD measurement [3]. The major part \( \sim (70 \pm 13)\% \) of the cross-section is observed to populate the excited states of \(^{32}\)Mg after the CD. Various components of the wave-function, obtained from this experiment are shown in Fig [3]. The shapes of the differential CD cross sections in coincidence with different core excited states favor that the valence neutron occupies both the \( s_{1/2} \) and \( p_{3/2} \) orbitals. These experimental findings suggest a significant reduction and merging of the \( sd - pf \) shell gaps at \( N \sim 20 \) and 28. The experimentally obtained quantitative spectroscopic information for
the valence neutron occupation of the $s$ and $p$ orbitals, coupled with different core states is in agreement with MCSM calculation using 3 MeV as the shell gap at $N = 20$ (Fig. 4 right).

![Graph](image1.png)

Figure 4: [left] The total experimental inclusive (black filled-circle data) differential CD cross-section of $^{33}\text{Mg}$ is overlaid with the sum of calculated exclusive CD cross-sections (red solid line) for four components of the ground-state. The (red on-line) mesh shaded region is the associated errors obtained from the various contributions. Other shaded regions as mentioned in the figure represent different components of the ground state wave function obtained from exclusive CD cross-sections with the core excited states. Figure reprinted from Ushasi Datta et al, PRC 94, 034304 (2016). [right] The spectroscopic factors for the occupying orbitals obtained from $spdf$-M calculation [black square], knockout reaction [14] [red square] and Coulomb breakup measurement [blue square] [3] are shown.

$^{34,35}\text{Al}$:
Similarly, the valence neutron in $^{35}\text{Al}$ ($N = 22$) should occupy the $f_{7/2}$ orbital but the observed differential CD cross section of $^{35}\text{Al} \rightarrow ^{34}\text{Al} + n$ could not be interpreted in the light of direct breakup model with that configuration. It suggests that the possible ground state spin and parity of $^{35}\text{Al}$ could be tentatively, $1/2^+$ or $3/2^+$ or $5/2^+$. If $5/2^+$ is the ground state spin/parity of $^{35}\text{Al}$ as suggested in the literature, then the major ground state configuration of $^{35}\text{Al}$ is a combination of $^{34}\text{Al}(g.s.; 4^{-}) \otimes \nu_{p3/2}$ and $^{34}\text{Al}(isomer; 1^+) \otimes \nu_{d5/2}$ states. The result from this experiment has been compared with that from previous knockout measurement and $spdf$-M calculations [8]. This hints at a particle-hole configuration of the neutron across the magic shell gaps at $N = 20,28$ which suggests narrowing the magic shell gap. Fig. 3 shows the differential CD cross section with respect to excitation energy ($E^*$) of $^{30}\text{Na}$ [top] and $^{35}\text{Al}$ [bottom] breaking into core and neutron. The solid line represents the calculation where valence neutron is occupying the $s$ and $d$-wave for $^{30}\text{Na}$ and the $p$ and $d$-wave for $^{35}\text{Al}$. 
4 Bulk properties of neutron-rich nuclei

The bulk properties of neutron-rich nuclei would access valuable information on nucleon-nucleon correlations, the validation of new mean-field calculations with different interactions, the density dependent symmetry energy etc. [10, 11, 12, 15]. Relativistic mean-field calculations using a Density Dependent Meson Exchange coupling (DDME2) [15] have been used to calculate the strength function for the isovector giant dipole resonance of $^{32}\text{Mg}$ as a function of excitation energy. In this model, only the linear terms for the mesonic fields are considered. The non-linear contribution of the meson fields are realized through the density dependence of the coupling constants for the nucleon-meson interactions. Fig. 5 shows the IVGDR response and density profile for $^{32}\text{Mg}$ nucleus, calculated by DDME2. This calculation predicts a neutron skin of 0.3 fm. As predicted theoretically, additional low-lying dipole strength below the giant resonance in a number of neutron-rich nuclei has been observed [10]. This strength is known as the pigmy resonance. The excitation energy of $^{32}\text{Mg}$ has been studied via electromagnetic excitation using intermediate energy RIB. Preliminary data analysis shows a low-lying dipole or pigmy resonance at an excitation energy around 7-11 MeV (Fig. 6) which may provide information on neutron skin thickness. A detailed comparison between the data and new mean-field calculations with a modified interaction may provide insight of nucleon-nucleon interaction with large isospin degrees of freedom. A more details analysis is in progress.

5 Neutron-rich nuclei and cosmic phenomena
The nuclei around the drip-line are short-lived but surprisingly, evanescent rare isotopes imprint their existence in stellar explosive scenarios (r-process etc.). Due to their fleeting existence, indirect measurements are often the only possible access to the information which is a valuable input to the model for star evolution process. A number of indirect methods are being explored by experimental nuclear physicists to avoid radioactive targets and other difficulties of direct measurements of radiative capture cross sections [9]. The Coulomb dissociation of radioactive ion beams at intermediate energy is one of the most powerful indirect methods for measuring capture cross sections, and is being explored at various laboratories in the world. \(^{14}\)C(n,g)\(^{15}\)C was studied by direct and indirect method and a detailed comparison with both methods along with various theoretical calculation was performed and results are consistent [9]. The recent discovery of neutron stars merging [16] provides a center of attention among nuclear physicists to study the equation of state of neutron-rich matter. To understand the properties of neutron stars, neutron star merging etc., information on the neutron skin and the density dependent symmetry energy at saturation density is important [12, 15]. A number of experimental approaches are being pursued [11, 17, 18]. By measuring low lying dipole strength and dipole-polarizability, neutron skin measurements have been attempted [11]. But a better co-relation among physical quantities is still being searched for. We are investigating in this respect to further improve information on neutron skin from the \(^{32}\)Mg data.

6 Conclusion

The state of the art of Coulomb breakup has been used to explore both single particle and bulk properties of the neutron-rich nuclei Na, Mg, Al around the ‘island of inversion’ where the first disappearance of magic number has been observed. The one neutron dipole threshold strength is sensitive to the quantum numbers and binding energy of the valence neutron. Using that property, clear evidence has been observed for the melting and merging of the magic shell gaps at \(N = 20, 28\) in \(^{31}\)Na, \(^{33}\)Mg and \(^{35}\)Al. On the other hand the predominant ground-state configurations of \(^{29,30}\)Na redefines the boundary of ‘Island of Inversion’. “r-process” has been known as a basic formation process for the heaviest elements. CD can be used for indirect
measurements of the capture cross-sections of the neutron-rich nuclei which may provide valuable information to model the r-process. Some valuable bulk properties of the neutron-rich nuclei like the density dependent symmetry energy, the neutron skin etc. play a key role in understanding cosmic phenomena. The excitation energy of $^{32}\text{Mg}$ has been studied. A preliminary data analysis shows low-lying dipole or Pigmy resonance at an excitation energy around 7-11 MeV which may provide information on its neutron skin thickness. Details analysis are in progress.

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