Study of Exotic Properties of Neutron Rich Nuclei around N~20 using Radioactive Ion Beam (RIB)

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Introduction

The magic numbers of the nuclei explained by Mayer and Jensen are a benchmark of nuclear structure [1]. The underlying shell gap is a characteristic of the mean nuclear field which takes into account many ingredients of the nucleon–nucleon interactions. With the advancement of experiments and advance computation it has been noted that these magic numbers are no longer valid in the exotic nuclei which are far away from the β-stable line and close to the drip line [2, 3]. Disappearance of established magic number and appearance of new one has been reported. Relatively large deformations in those nuclei were explained by considering the intruder effects which suggests a clear vanishing of the shell gap between sd and pf shell around N = 20. Island of Inversion' are neutron-rich Ne, Na, Mg nuclei around N ∼ 20 where first failure of magic number had been reported and it has been found that intruder configurations dominate the ground state wave function. So far several studies like knockout, transfer, etc. have been performed to investigate this region. Though it is established that the valence neutron(s) in the ground state of the neutron-rich Na, Mg, Ne isotopes at N = 20, occupies pf intruder orbitals, but this is not well established for the neighboring nuclei. 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 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. An experimental program GSI-S306 was initiated to explore the ground state configurations of neutron-rich nuclei around N~20 through Coulomb breakup of secondary beams at intermediate energy 400-500 AMeV [4]. Coulomb breakup is a direct method to probe the quantum numbers of the valence nucleons of loosely bound nuclei since it is sensitive to the tail part of wave function [5]. In this article the experimental outcome of ^{29,30}Na and ^{33}Mg which were populated in the same experiment will be reported.

Experiment

The radioactive beam of short lived isotopes was produced by fragmentation of a primary ^{40}Ar beam with energy 530 MeV/nucleon, delivered by the synchrotron SIS at GSI, Darmstadt on a beryllium target (8.0 gm/cm^2 [3,6,8]. The secondary beam was separated according to their magnetic rigidities using the Fragment Separator FRS. The separated cocktail beam containing various isotopes with similar mass-to-charge ratio was then transported to cave C where complete kinematic measurements were performed after Coulomb breakup at secondary target ^{208}Pb (2 gm/cm^2) using various tracking detectors e.g. double sided silicon strip detector, fiber detector GFI, Time of Flight Wall, Large Area Neutron Detector etc. A Crystal Ball detector consist of 162 NaI detectors was used to detect the γ-ray from the decay of the excited core of the reaction fragments after Coulomb breakup. A Large Dipole Magnet was used to separate the charge and non-charged particle after secondary reaction and to reconstruct the mass of the fragments.

Analysis and results

The excitation energy E* of ^{29,30}Na and ^{33}Mg were obtained after measuring the fourmomenta of all the decay products using various tracking detectors. The electromagnetic excitation of loosely bound neutron rich nuclei in heavy ion collisions at intermediate energy is dominated by the dipole excitation. Thus one neutron removal differential CD cross section for dipole excitation dσ/dE* decomposes into an incoherent sum of components $d\sigma(I^{\pi}_{c})/dE^*$ corresponding to different core states (I^{π}_{c}), populated after one neutron removal [5]. The total inclusive CD cross section for ^{29}Na into ^{28}Na and one neutron amounts to 89 (7) mb, after integration up 5.6 MeV relative energy between core and neutron. No resonance-like structure has been observed. The data analysis for ^{29}Na shows that the major part (~67(11) %) of the breakup cross section leaves the core ^{28}Na in its ground state and approximately (~33(5) %) of the fragments are found in the excited states which could be deduced from the invariant mass spectra, obtained in coincidence with the sum energy spectra of the γ-ray with the core fragment (i.e., ^{28}Na) and one neutron. Similarly, The total inclusive CD cross section for ^{30}Na into ^{29}Na and a neutron amounts to 167 (13) mb, after integration up to 7.7 MeV relative energy between core and neutron. The data analysis for ^{30}Na. shows that the major part (~72 (10) %) of the breakup cross section leaves the core ^{29}Na in its ground state and approximately (~28 (4) %) of the fragments are found in the excited states. The resulting data have been analyzed using direct breakup model calculation. The solid curve with shaded region in Fig. 1, represent the calculated $d\sigma(I^{\pi}_{c})/dE^*$ using the direct-breakup model with the valence neutron in combination of the s and d orbitals, respectively. The χ^2/N for the fit suggests that the neutron is occupying the s and d orbitals with the spectroscopic factors 0.07(7) and 2.1(3), respectively. Similarly, the spectroscopic factors for ^{30}Na obtained from the fit to the data for the neutrons occupying the s and d orbitals are 0.05(5) and 2.03(30), respectively. The experimentally obtained spectroscopic factor 2.1(3) for valence neutron in the d orbital of ^{29}Na is in closer agreement with modified sd-shell model (USD-B) calculation (2.18). On the other hand, the same for ^{30}Na is much reduced 2.03(30) compared to the sd-shell (USD-B) calculation (2.97). This could be due to particle-hole excitation of the valence neutron across the shell-gap. Considering the contribution of the excited core in their ground state, a lower limit of the sd-pf shell gaps can be set at 4.0 MeV and 4.3MeV for ^{29,30}Na respectively [6]. In a very similar way the Coulomb breakup of ^{33}Mg in the same experiment has been analyzed. The major part ~(70±13)% of the cross section is observed to populate the excited states of ^{32}Mg after the Coulomb breakup of ^{33}Mg.

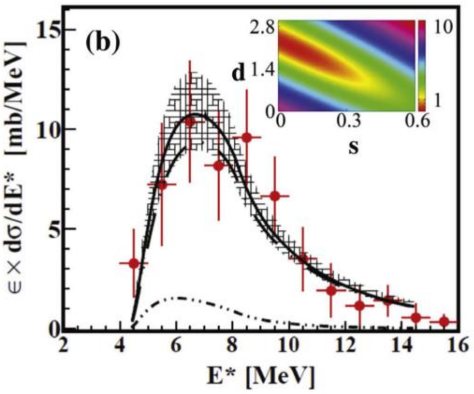

Fig:1: Experimental differential inferred pure Coulomb dissociation cross-section of ^{29}Na breakup into ^{28}Na (g.s.) and one neutron. The solid line represents the differential CD cross-section using a direct breakup model in which the valence neutron occupies the p-orbital, or a combination of the s and d-orbitals, respectively. The dashed and dotted–dashed line represent the calculated CD cross section with the valence neutron in the d and s orbitals with the respective spectroscopic factors [6].

The shapes of the differential Coulomb dissociation 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 [3]. The Coulomb dissociation of ^{33}Mg (N = 21) provides the first evidence of a multiparticle-hole ground state configuration and the valence neutron(s) is occupying the s and p orbitals [3, 7]. These observations confirm significant reduction and merging of shell gaps, at N = 20 and 28 for this neutron-rich nucleus. The valence neutron of this isotope occupies partially the $s_{1/2}$ orbital, which is an indirect evidence of large deformation (0.45).

Ref: 1. M. G. Mayer, Phys. Rev. 75 (1949) 1969
2. C. Thibault et al., PRC 12 (1975) 644
T. Motobayashi et al., PLB 346 (1995) 9
3. Ushasi Datta et al., PRC 94 (2016) 034304
4.Ushasi Datta et al., A proposal for an experiment using LAND-FRS setup at GSI, 2005
5. U. Datta Pramanik et al., PLB 551 (2003) 63
6. A. Rahaman et al., EPJ WoC 66 (2014) 02087
A. Rahaman et al., J. Phys. G: Nucl. Part. Phys. 44 (2017) 045101
7. V.Tripathi, et al., PRL 101 (2008) 142504
8. S. Chakraborty et al., PRC 96 (2017) 034301