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Published in:

Journal of Physics. G: Nuclear and Particle Physics

DOI:

[10.1088/1361-6471/aa594d](https://doi.org/10.1088/1361-6471/aa594d)

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Document Version

Publisher's PDF, also known as Version of record

Publication date:

2017

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Rahaman, A., Datta, U., Aumann, T., Beceiro-Novo, S., Boretzky, K., Caesar, C., Carlson, B. V., Catford, W. N., Chakraborty, S., Chartier, M., Cortina-Gil, D., De Angelis, G., Diaz Fernandez, P., Emling, H., Ershova, O., Fraile, L. M., Geissel, H., Gonzalez-Diaz, D., Johansson, H., ... Zoric, M. (2017). Coulomb breakup of neutron-rich Na-29,Na-30 isotopes near the island of inversion. *Journal of Physics. G: Nuclear and Particle Physics*, 44(4), [045101]. <https://doi.org/10.1088/1361-6471/aa594d>

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PAPER

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To cite this article: A Rahaman *et al* 2017 *J. Phys. G: Nucl. Part. Phys.* **44** 045101

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Coulomb breakup of neutron-rich $^{29,30}\text{Na}$ isotopes near the island of inversion

A Rahaman¹, Ushasi Datta^{1,2}, T Aumann^{2,3},
S Beceiro-Novo⁴, K Boretzky², C Caesar², B V Carlson⁵,
W N Catford⁶, S Chakraborty¹, M Chartier⁷, D Cortina-Gil⁴,
G De Angelis⁸, P Diaz Fernandez⁴, H Emling², O Ershova²,
L M Fraile⁹, H Geissel^{2,10}, D Gonzalez-Diaz², H Johansson¹¹,
B Jonson¹¹, N Kalantar-Nayestanaki¹², T Kröll³, R Krücken¹³,
J Kurcewicz², C Langer², T Le Bleis¹³, Y Leifels²,
J Marganec^{2,14}, G Münzenberg², M A Najafi¹², T Nilsson¹¹,
C Nociforo², V Panin², S Paschalis³, R Plag², R Reifarh²,
M V Ricciardi², C Rigollet¹², D Rossi², C Scheidenberger^{2,10},
H Scheit³, H Simon², J T Taylor⁷, Y Togano², S Typel²,
V Volkov³, A Wagner¹⁵, F Wamers², H Weick², M Weigand²,
J S Winfield², D Yakorev¹⁵ and M Zoric²

¹ Saha Institute of Nuclear Physics, Kolkata 700064, India

² GSI Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany

³ Technische Universität Darmstadt, D-64289 Darmstadt, Germany

⁴ Universidade de Santiago de Compostela, E-15706 Santiago de Compostela, Spain

⁵ Instituto Tecnológico de Aeronáutica, São José dos Campos, Brazil

⁶ University of Surrey, Guildford GU2 5XH, United Kingdom

⁷ University of Liverpool, Liverpool L69 7ZE, United Kingdom

⁸ INFN, Legnaro, Italy

⁹ Universidad Complutense de Madrid, CEI Moncloa, E-28040 Madrid, Spain

¹⁰ II. Physikalisches Institut, D-35392 Giessen, Germany

¹¹ Fundamental Fysik, Chalmers Tekniska Högskola, SE-412 96 Göteborg, Sweden

¹² KVI-CART, University of Groningen, Groningen, The Netherlands

¹³ Physik Department E12, Technische Universität München, D-85748 Garching, Germany

¹⁴ EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany

¹⁵ Helmholtz-Zentrum Dresden-Rossendorf, D-01328 Dresden, Germany

E-mail: ushasi.dattapramanik@saha.ac.in

Received 5 February 2016, revised 10 January 2017

Accepted for publication 13 January 2017

Published 21 February 2017

CrossMark

Abstract

First results are reported on the ground state configurations of the neutron-rich $^{29,30}\text{Na}$ isotopes, obtained via Coulomb dissociation (CD) measurements. The invariant mass spectra of these nuclei have been obtained through measurement of the four-momenta of all decay products after Coulomb excitation of those nuclei on a ^{208}Pb target at energies of 400–430 MeV/nucleon using the FRS-ALADIN-LAND setup at GSI, Darmstadt. Integrated inclusive CD cross-sections (CD) of 89 (7) mb and 167 (13) mb for one neutron removal from ^{29}Na and ^{30}Na , respectively, have been extracted up to an excitation energy of 10 MeV. The major part of one neutron removal, CD cross-sections of those nuclei populate the core, in its ground state. A comparison with the direct breakup model, suggests the predominant occupation of the valence neutron in the ground state of ^{29}Na ($3/2^+$) and ^{30}Na (2^+) is the d -orbital with a small contribution from the s -orbital, which are coupled with the ground state of the core. One of the major components of the ground state configurations of these nuclei are $^{28}\text{Na}_{gs}(1^+) \otimes \nu_{s,d}$ and $^{29}\text{Na}_{gs}(3/2^+) \otimes \nu_{s,d}$, 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 s and d orbitals for these nuclei in the ground state have been extracted and reported for the first time. 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 .

Keywords: neutron-rich nuclei, RIB, Coulomb breakup, ground state configuration, spectroscopic factor, island of inversion

(Some figures may appear in colour only in the online journal)

1. Introduction

The magic numbers [1, 2] of nuclei are a benchmark of nuclear structure. The underlying shell gap is a characteristic of the mean nuclear field which takes into account of many ingredients of the nucleon–nucleon interactions. 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 the neutron-rich $^{31,32}\text{Na}$ [3]. The experimental observation of the higher binding energies of these nuclei is a direct consequence of the large deformation [3]. Later large deformation was also reported in the ground state of ^{32}Mg [4]. The large deformation was explained by considering the intruder effects which suggested a clear vanishing of the shell gap between sd and pf shell around $N = 20$. The $N = 20$ isotones with $Z \sim 10 - 12$ are considered to belong to the so-called island of inversion [5] where the intruder configurations dominate the ground state wave function. Recently, it has been observed that the shell gaps at $N = 20$ and 28 are significantly reduced in the ground state of ^{33}Mg [6]. Otsuka *et al* considered a strongly attractive monopole interaction of the tensor force to describe the shell evolution for several nuclei [7]. The attractive $T = 0$ monopole interaction between the $\pi d_{5/2}$

Figure 1. Identification plot for a mixed radioactive beam impinging on the secondary targets.

and $\nu d_{3/2}$ orbits changes the size of the $N = 20$ effective energy gap as the protons fill the $d_{5/2}$ orbital.

The availability of radioactive ion beam provides an unique opportunity to study the evolution of the shell structure of the nuclei far away from the β -stability line and many experimental observations on the non magic behavior of the neutron-rich nuclei around the so-called magic numbers have been reported. It is of particular interest to understand the shell evolution for the nuclei where the transition from the normal ground state configuration to the intruder dominated ground state configuration occurs. Experimental studies in this direction may provide a stringent test for the validation of various theoretical predictions for the nucleon–nucleon interactions. In other words, to understand the change of the nucleon–nucleon interaction, with the iso-spin quantum number, the key ingredients are experimental information on the ground state configurations of these transition nuclei. So far several studies have been performed using different techniques to investigate this region [8, 9, 11–15]. 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. The ground state configuration of transitional nuclei from normal to ‘island of inversion’ and experimental information for the transitional nuclei are often contradictory. Terry *et al* [16] observed a pf orbital occupation of the valence neutron in the ground state of neutron-rich $^{28,30}\text{Ne}$ ($N = 18, 20$) via knockout measurements. However, the situation is different for ^{30}Mg ($N = 18$). Both knockout [17] and Coulomb excitation data [18] are in agreement with a sd -shell ground state configuration of this nucleus. No detailed ground state configurations of $^{29,30}\text{Na}$ ($N = 18, 19$) is available in the literature. The low-energy level structure of the exotic $^{28,29}\text{Na}$ isotopes have been investigated through β -delayed γ spectroscopy [13] and the authors proposed that a $\sim 46\%$ intruder configuration in the ground state of ^{29}Na [8] is necessary to explain the experimental data. Several theoretical model calculations and experimental results [8, 9, 12–14, 19] suggest a significant reduction of the sd – pf shell gap and the ground states of $^{29,30}\text{Na}$ are dominated by intruder states. ^{30}Na has been investigated using Coulomb excitation at intermediate energies [9] and a transition probability $B(E2 : 2^+ \rightarrow 3^+) = 147(21) e^2 fm^4$ was reported. The Knockout reaction by Tajes *et al* [20] showed that the momentum distributions of both $^{29,30}\text{Na}$ are almost identical (137 MeV/ c and 130 MeV/ c respectively) although ^{29}Na ($S_n = 4.4$ MeV) is more deeply bound than ^{30}Na ($S_n = 2.27$ MeV). This unconventional experimental observation encourages more experimental investigation. An experimental program (GSI:s306) has been initiated

Figure 2. Outgoing fragments charge distribution.

to explore the ground state configurations of the neutron-rich nuclei around $N \sim 20$ via direct probes at GSI, Darmstadt. Coulomb breakup is a direct method to probe the quantum numbers of the valence nucleons of loosely bound nuclei [21–24]. In this article, first results on the wave-function decompositions of the ground state of $^{29,30}\text{Na}$, studied via Coulomb breakup, are being reported.

2. Experiment

The secondary beam containing $^{29,30}\text{Na}$ isotopes along with others were populated by fragmentation of the ^{40}Ar primary beam with energy 540 MeV/nucleon and separated at fragment separator (FRS) [25]. The incoming projectiles were identified event-by-event by measuring the magnetic rigidity, time of flight and relative energy loss of the exotic nuclei. The incoming beam-identification plot is shown in figure 1. The beam intensity of $^{29,30}\text{Na}$ were around 14% , 5.5% respectively, of the total incoming beam. Total 4.4 and 1.8 million good events of $^{29,30}\text{Na}$, respectively were used for Pb target.

The secondary beam (figure 1) was transported to the experimental site, a neighboring cave C where the complete kinematic measurements were performed using the FRS-ALADIN-LAND setup. The position of the incoming beam before the secondary target and the position of the reaction fragments after the target were accurately measured using double sided silicon strip detectors (DSSD). The target was surrounded by 162 NaI(Tl) detectors [29], which cover almost 4π solid angle. That detector-array was used for detecting the γ -rays from the excited core of the projectile after the Coulomb breakup. After reaction at the secondary target the reaction fragments as well as the unreacted beam were bent by a large dipole magnet (ALADIN) and ultimately were detected at the time of flight wall detector (TFW) via two scintillator detectors (GFI) [26, 27]. The outgoing fragment charge distribution can be obtained from the energy loss at TOF and silicon strip detector (DSSD). Figure 2 shows the charge distribution of outgoing fragments, Z_{TFW} , obtained from the energy loss at the TFW against Z_{DSSD} , obtained from measurement of energy loss at DSSD. The decay products, neutrons were forward focused due to Lorentz boosting and detected by the large area neutron detector (LAND) [28] for the time of flight and position measurements. The reaction fragments were bent at different angles inside ALADIN depending on their charge to momentum ratios. Those relative deflection angles were measured using the GFI detectors placed at two different distances at an angle of 15° from the original beam direction

Figure 3. Outgoing fragments mass identification plot after one neutron breakup of ^{29}Na beam on a lead target.

Figure 4. (Top) The yields of one neutron breakup reaction of ^{29}Na against excitation energy using a Pb target and without any target are represented by filled circles and triangles, respectively. (Bottom) One neutron inclusive breakup cross-sections of ^{29}Na against excitation energy using Pb-target (Coulomb+nuclear), C-target (nuclear) and inferred pure Coulomb breakup of Pb are denoted by circles, triangles and squares, respectively.

after ALADIN. The mass of the outgoing reaction fragments was reconstructed using the deflection angles measured from GFI, the energy loss at TFW, the time of flight measurement of the reaction fragments and the magnetic rigidity of ALADIN. Figure 3 represents the mass

Figure 5. (Top) The yields of one neutron breakup reaction of ^{30}Na against excitation energy for a Pb target and with no target are represented by filled circles and triangles, respectively. (Bottom) One neutron inclusive breakup cross-sections of ^{30}Na against excitation energy using Pb-target (Coulomb + nuclear), a C-target (nuclear) and inferred pure Coulomb part are denoted by circles, triangles and squares, respectively.

of the outgoing fragment against speed, after one neutron breakup of ^{29}Na . For details of the experimental setup and calibrations of the detectors see [6, 30, 31] and references therein.

3. Analysis

In this experiment the excitation energy E^* of $^{29,30}\text{Na}$ are determined by measuring four momenta of all the decay products of those nuclei after breakup [21, 22].

The excitation energy E^* of $^{29,30}\text{Na}$ were measured using Pb and C targets. The background contributions due to the reactions induced by the materials of the detectors and air column were determined from the data taken without any target and the background data were subsequently subtracted from the Pb and C target data. Figure 4 (top) shows the reaction yields of one neutron breakup against the excitation energy of ^{29}Na using the Pb-target (filled circle) and without any target (filled triangle). Similarly, figure 5 (top) shows the reaction yields of one neutron breakup against the excitation energy of ^{30}Na using Pb-target (filled circle) and without any target (filled triangle). The one neutron breakup data of $^{29,30}\text{Na}$ using Pb target contain both Coulomb part and nuclear part. The nuclear part can be obtained from one neutron breakup data using C-target with proper scaling and certain assumptions. The assumptions are as follows: the C target breakup cross section is purely nuclear and the shapes

Figure 6. The observed sum-energy spectrum (filled circles) of the γ -rays transitions from the excited states of ^{28}Na after Coulomb breakup of ^{29}Na . The inset shows a partial scheme of levels in ^{28}Na and the population of those states after Coulomb breakup. The solid line (black) represents the sum of simulated sum-energy spectra of γ -rays decaying from various core excited states and experimental atomic background. The experimental atomic background is represented by smaller dashed line (violet). The simulated sum-energy spectra of γ -rays decaying from the 3.5, 3.29, 2.7, 2.1, 1.2, 1.1 MeV excited states are represented by various types of lines.

of the differential cross sections for dissociation, $d\sigma_{\text{nuclear}}/dE^*$ are the same for the C and Pb targets and differ only in magnitude. The Coulomb dissociation (CD) cross sections of those neutron-rich nuclei using the ^{208}Pb target (2.0 g cm^{-2}) were determined after subtracting the nuclear contributions inferred from the data with a ^{12}C target (0.9 g cm^{-2}) with a scaling factor(1.8), obtained from soft sphere model [32]. Filled circles, triangles and squares in the lower panel of figures 4 and 5, respectively show one neutron breakup reaction cross-section of $^{29,30}\text{Na}$, for the Pb-target (Coulomb and nuclear), the C-target (nuclear) and inferred pure Coulomb part from Pb target, respectively. The CD cross section for different core excited states can be further differentiated experimentally by the coincidence observation of the characteristic γ -ray(s) of the core with the fragment and neutron [21]. The situation of low-energy excitation in odd-Z is very complex and the density of states at low-energy is high. With the help of information available in the literature and simulation using those information along with present experimental data, the detection efficiency and feeding correction of the γ -rays from higher lying states have been obtained. Utilizing these efficiency factors, the CD cross-sections for populating different core excited states can be deduced after feeding correction.

Figure 6 shows the sum-energy spectrum of the γ -rays (filled circles) decaying from the excited states of ^{28}Na after Coulomb breakup of ^{29}Na . This spectrum is obtained in coincidence with the incoming beam ^{29}Na , the outgoing fragment ^{28}Na and one neutron. The γ -ray spectra from reactions with high energy projectiles on high-Z targets are strongly affected (up to energies of a few MeV) by the low-energy background. This background originates from atomic interactions of the beam with the lead target [33]. The shape of the low-energy background was obtained from the γ -ray spectrum in coincidence with the noninteracting Na beam, represented by short dashed line (violet) in figure 6. A detailed response of the NaI detector array for detection of the sum-energy spectrum of the γ -rays decaying from a particular excited state in the experimental situation, has been generated using the GEANT code. In the figure 6, solid line (black) represents the sum of the simulated sum-energy spectra

Figure 7. The observed sum-energy spectrum (filled circles) of γ -rays transitions from the excited states of ^{29}Na after Coulomb breakup of ^{30}Na . The inset shows a partial scheme of levels in ^{29}Na and the population of those states after Coulomb breakup. The solid line (black online) represents the sum of simulated sum-energy spectra of γ -rays decaying from various core excited states and experimental atomic background. The experimental atomic background is represented by dotted-dashed line (black). The simulated sum-energy spectra of γ -ray decaying from the 4.1, 3.7, 3.06, 2.2, 1.6, 1.2 MeV excited states are represented by various types of lines.

of γ -rays decaying from various excited states of ^{28}Na and the experimental atomic background. In the simulation, the decay scheme of various excited states of ^{28}Na were considered as reported in the literature [34] and the partial level schemes of ^{28}Na is shown in the inset of figure 6. The partial exclusive Coulomb breakup cross-sections of ^{29}Na for populating various excited states of ^{28}Na have been extracted from the invariant mass spectra in coincidence with the sum-energy of γ -rays in the three different energy ranges. The detection efficiencies and feeding corrections from higher states of γ -rays have been obtained from detailed simulations. The detection efficiencies of the sum-energy of γ -rays from 0.8 MeV to 1.5 MeV, 1.8 MeV to 2.4 MeV and 2.4 MeV to 3.7 MeV are 0.66(7), 0.56(6) and 0.58(6), respectively. Thus summing the above cross-sections that amounts to 30(4) mb, can provide the exclusive CD cross-sections for populating the excited states of ^{28}Na , as shown in figure 6. These cross-sections are obtained from the Pb-target data after subtracting its nuclear part. The exclusive CD cross-section for populating the ground state is 59(8) mb. This is obtained from the difference between the total CD cross-section and the CD cross-sections which populate the fragment in the excited states.

Similarly, the exclusive CD cross-section of ^{30}Na which populates various excited states of ^{29}Na , has been obtained. Figure 7 shows the sum-energy spectrum of the γ -rays (filled circles) decaying from the excited states of ^{29}Na after Coulomb breakup of ^{30}Na . The low-energy atomic background was obtained from noninteracting Na beam and is represented by dotted-dashed line (black) in figure 7. In figure 7, solid line (black) represents the sum of various simulated sum-energy spectra of γ -rays decaying from various excited states of ^{29}Na and the experimental atomic background. In simulation, the decay schemes of various excited states of ^{29}Na were considered as reported in the literature [34], except, 2.2 MeV excited state and the partial level schemes of ^{29}Na is shown in the inset of figure 7. The exclusive Coulomb breakup cross-sections of ^{30}Na for populating various excited states of ^{29}Na have been extracted from the invariant mass spectra in coincidence with the sum-energy of γ -rays in the

three different energy ranges. The detection efficiency and feeding corrections from higher states of γ -ray have been obtained from detailed simulations. The detection efficiencies of the sum-energy of γ -rays from 0.9 MeV to 1.8 MeV, 1.8 MeV to 2.8 MeV and 2.8 MeV to 4.7 MeV are 0.69(7), 0.63(6) and 0.62(6), respectively. Thus summing the above cross-sections, the exclusive CD cross-sections for populating the excited states of ^{29}Na , as shown in figure 7 is 46(6) mb. The exclusive CD cross-section for populating the core in the ground state is 121(14) mb which is obtained from the difference between the total CD cross-section and the cross-sections populating the excited states.

The measured invariant mass spectra have been analyzed using the direct breakup model. The neutron-rich nucleus around $N = 20$, has been considered as a combination of the core and a loosely bound valence neutron which may occupy one or more orbitals e.g. s , d , p etc. When the projectile passes by a high Z target it may be excited by absorbing the virtual photons from the time dependent Coulomb field [35] and the nucleus breaks up into a neutron and the core. The electromagnetic excitation of loosely bound neutron-rich nuclei in heavy ion collisions at intermediate energy is dominated by the dipole excitation due to smaller effective charge for higher multi-polarities [36]. Thus one neutron removal differential CD cross section for dipole excitation $d\sigma/dE^*$ decomposes into an incoherent sum of components $d\sigma(I_c^\pi)/dE^*$ corresponding to different core states (I_c^π), populated after one neutron removal. For each core state, the cross-section further decomposes into incoherent sum over contribution from different angular momenta j of the valence neutron in its initial state. The differential cross-section of $^{29,30}\text{Na}$ can be expressed through the following equation [21]:

$$\frac{d\sigma(I_c^\pi)}{dE^*} = \frac{16\pi^3}{9\hbar c} N_{E1}(E^*) \sum_j C^2S(I_c^\pi, nj) \times \sum_m |\langle q|(Ze/A)rY_m^l|\psi_{nlj}(r)\rangle|^2. \quad (1)$$

Here, $N_{E1}(E^*)$ is the number of virtual photons as a function of excitation energy E^* which can be computed adapting a semi-classical approximation [35]. $\psi_{nlj}(r)$ and $\langle q|$ represent the single-particle wave function of the valence neutron in the projectile ground state (before breakup) and the final state wave-function of the outgoing neutron in the continuum (after breakup), respectively. The wave function of the outgoing neutron in the continuum is approximated by a plane wave. $C^2S(I_c^\pi, nj)$ represents the spectroscopic factor of the valence neutron with respect to a particular core state I_c^π .

Equation (1) indicates that the dipole strength distribution is very sensitive to the single-particle wave function which in turn depends on the orbital angular momentum and the binding energy of the valence neutron. Thus, by comparing the experimental CD cross section with the calculated one, information on the ground state properties such as the orbital angular momentum of the valence nucleon and the corresponding spectroscopic factor may be gained. The core states can be identified by detecting the characteristic γ -rays. The Coulomb breakup cross section that leaves the core in its ground state is obtained from the difference between the total cross section and the excited-state(s) contribution(s).

In order to compare the experimental result with the calculated data, one needs to convolute the instrumental response function with the later. The instrumental response for a given value of E^* has a Gaussian distribution to a good approximation [37–40] at excitation energy of 0.5 MeV or more above neutron threshold but below that, it is asymmetric. The results of all the calculations, shown in this article, are convoluted with the response function.

The errors of present experimental data are dominated by statistical errors compared to the other systematic errors. The total CD cross-sections quoted for $^{29,30}\text{Na}$ in the text of the manuscript are combined errors of the statistical errors and the neutron detection efficiency errors (3%) for one neutron detection. However, the subcomponents of the CD cross-sections

Figure 8. (a) and (b) 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. (c) and (d) The experimental differential inferred pure Coulomb dissociation cross-section of ^{30}Na against excitation energy. 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 d and s wave components. The inset of every figures show the χ^2/N of the fit of the experiment data against the spectroscopic factor for the valence neutron of that orbital. The shaded region in the figure represents the errors associated with the fitted curve. This error is associated with the spectroscopic factors, obtained by fitting the experimental data.

i.e. contributions for populating core excited states, additional gamma-detection efficiency errors of 10% has been included. The errors in the CD cross-section which populates the core in ground state contribution also includes γ detection efficiency. Because it was obtained after subtracting the core excited state contribution from the total one, hence subsequent error propagation was considered. Further sources of the systematic errors are graphical cut used in the analysis for both mass and charge. It has been observed that it is limited to 1%–2% which

leads to 4%–5% for overall entire analysis. This is much less compared to the statistical errors. With change of the scaling factor of 10%, the total cross-section of CD would change 1.4%.

4. Result

The total inclusive CD cross section for ^{29}Na into ^{28}Na and one neutron amounts to 89 (7) mb, after integration up to 10 MeV excitation energy or 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 ($\sim 67(11)\%$) of the breakup cross section leaves the core ^{28}Na in its ground state and approximately ($\sim 33(5)\%$) 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. Left panel of the figure 8 shows the experimental differential CD cross section with respect to the excitation energy (E^*) of ^{29}Na which breaks up into a neutron and a ^{28}Na fragment in its ground state (filled circles). The spectrum was obtained after subtracting contribution due to the excited states from the total differential cross-section of pure Coulomb breakup of ^{29}Na . The valence neutron of ^{29}Na is loosely bound ($S_n = 4.4$ MeV). Considering the nucleus as a core and loosely bound neutron, the calculation for CD cross-section using the direct breakup model [21] have been performed using various valence neutron occupying orbitals. The outgoing neutron in the continuum is approximated by a plane-wave. To understand the valence neutron occupying orbital, the experimental CD cross-section $d\sigma(I_c^\pi)/dE^*$ of ^{29}Na into the ground state of ^{28}Na and one neutron have been compared with direct breakup model calculation. All experimental $d\sigma/dE^*$ distributions are shown in the figures without acceptance and efficiency corrections for the neutron detector. Instead, the calculated cross sections were convoluted with the detector response obtained from detailed simulations.

Comparison between the experimental data on CD with direct breakup model calculation using the p , and combination of the s and d orbitals, respectively are shown in the figures 8(a), (b), respectively. The experimentally observed shape of the spectrum is in good agreement with the calculated one considering the valence neutron in the s and d orbitals. The solid curve in the figures 8(a), (b) represent the calculated $d\sigma(I_c^\pi)/dE^*$ using the direct-breakup model with the valence neutron in the p and combination of the s and d orbitals, respectively. The inset of figure 8(a) show the χ^2/N for fitting against the spectroscopic factors of the valence neutron in the p orbital. The inset of figure 8(b), shows three-dimensional plot of the χ^2/N for fitting (z -axis in color shade) against the spectroscopic factors of the valence neutron in the s , d orbital (x and y axis). It is evident from figure 8(b) that the best fit of the experimental data can be obtained with calculation where the valence neutron is occupying combination of the s and d orbitals. 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. The errors quoted in the spectroscopic factors are obtained from the χ^2 distribution and the errors are one sigma i.e., within 68% confidence limit. The dashed and dotted–dashed line in figure 8(b) represent the calculated CD cross-section with valence neutron in the d and s orbitals with above mentioned spectroscopic factors. The shaded region in the figure represents the error associated with fitted curve of calculation. This error is associated with the spectroscopic factor, obtained from fitting with experimental data.

The total inclusive CD cross section for ^{30}Na into ^{29}Na and a neutron amounts to 167 (13) mb, after integration up to 10 MeV excitation energy or 7.7 MeV relative energy between core and neutron. No resonance-like structure has been observed. The data analysis for ^{30}Na

Table 1. Experimental exclusive Coulomb dissociation cross sections of $^{29,30}\text{Na}$ for various core states. The cross sections are integrated up to $E_c + 10$ MeV excitation energy i.e. 5.6 MeV, 7.7 MeV relative energy between core and neutron for ^{29}Na and ^{30}Na , respectively. The experimental spectroscopic factors for the valence neutron occupying $s_{1/2}$ and $d_{3/2}$ orbitals of the ground states of those nuclei are also included.

Isotope	Core state $I_c^\pi(E_c; (\text{MeV}))$	Neutron orbital	Cross section (mb) Expt.	Spectroscopic factor Expt.
^{29}Na	$1^+ (0.0)$	$1s$	59(8)	0.07(7)
		$0d$		2.1(3)
	$0 < E_c < 3.7$		30(4)	
^{30}Na	$3/2^+ (0.0)$	$1s$	121(14)	0.05(5)
		$0d$		2.03(30)
	$0 < E_c < 4.7$		46(6)	

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. Right panel of figure 8 shows the experimental differential CD cross section with respect to the excitation energy (E^*) of ^{30}Na breaking up into a neutron and a ^{29}Na fragment in its ground state (filled circles). That spectra was obtained after subtracting excited state contribution from the spectra of total differential cross-section of pure Coulomb breakup of ^{30}Na . The valence neutron of ^{30}Na is sufficiently loosely bound ($S_n = 2.27$ MeV). The experimental CD cross-section ($d\sigma/dE^*$) of ^{30}Na into ground state of ^{29}Na and one neutron have been compared with direct breakup model calculation considering the valence neutron in the p , or combination of the s and d orbitals. Inset of the figure shows χ^2/N obtained from fitting with variation of spectroscopic factors. The data can be well reproduced by a fit including contributions from the wave functions involving $l = 0$ and $l = 2$ neutrons, as shown in figure 8(d). The inset of figure 8(d) shows the spectroscopic factors of the s and d orbitals occupation of the valence neutron corresponding to the distribution of the χ^2/N . The spectroscopic factors 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 dashed and dotted-dashed line in figure 8(d) represent the calculated CD cross-section using the valence neutron in the d and s orbitals with their respective spectroscopic factors. The ground state spin and parity of ^{30}Na from the present experimental results favor $3/2^+ \otimes 3/2^+$ i.e. either 3^+ or 2^+ or 1^+ . The shaded region in the figure represents the errors associated with the fitted curve. This error is associated with the spectroscopic factor, obtained by fitting the experimental data.

5. Discussion

The ground state spin and parity of $^{29,30}\text{Na}$ were measured by magnetic resonance [42], but no detailed measurement of their ground state configurations is available in the literature. The γ -ray spectroscopy data [12–14, 19] were interpreted as an intruder dominated ground state configuration. Present experimental CD cross sections of $^{29,30}\text{Na}$ along with the obtained spectroscopic factors have been summarized in table 1. The dominant ground state configuration of ^{29}Na is $^{28}\text{Na}_{gs}(1^+) \otimes \nu_{s,d}$. The ground state spin and parity of ^{29}Na from this

Figure 9. The spectroscopic factors of the valence neutron occupying in the $d_{3/2}$ orbital in the ground state of ^{29}Na and ^{30}Na nuclei. The filled square represents that which is obtained from the Coulomb breakup data fitted with the direct breakup model. The solid line (black) and dashed line represent errors within 1σ i.e., 68% confidence limit and 4σ i.e., 99.99% confidence limit, respectively. The filled circle (red) represents the same obtained from shell model calculation with USD-B interaction.

experiment favor $1^+ \otimes 3/2^+$ i.e., either $5/2^+$, $3/2^+$ or $1/2^+$. Both the USD-B [41] shell model calculation, and the MCSM shell model calculations [8] favor $3/2^+$ as the ground state spin and parity of ^{29}Na . This is in agreement with the earlier experimentally measured values [42]. Utsuno *et al* [8] showed that the measured two neutron separation energy, magnetic and electric moments of ^{29}Na can be explained by both the USD and the $sdpf$ -M. A comparison between the spectroscopic factors obtained from the experimental data and the shell model calculation using USD-B interaction is shown in figure 9. In the figure 9 the filled square represents the experimental spectroscopic factor, obtained from the Coulomb breakup data fitted with the direct breakup model. The solid line (black) and dashed line represent the errors within 1σ i.e., 68% confidence limit and 4σ i.e., 99.99% confidence limit, respectively. The contribution of the excited core in their ground state configuration is around $\sim 33(5)\%$ according to present experimental observation for ^{29}Na isotopes and the core excited state contribution above 2.0 MeV is around 27%. To a simple approximation, if this amount is considered wholly due to $2p-2h$ configurations, then according to the MCSM [8] calculations, one can obtain ~ 4.0 MeV as lower limit of the sd - pf shell gap in ^{29}Na . It is clear from figure 8(b) that the experimental spectroscopic factor for the valence neutron in the d orbital coupled with ^{28}Na $^{28}\text{Na}_{gs}(1^+)$ is 2.1 (3) and this is in good agreement with the USD-B shell model calculation (2.18). Earlier it was shown that the measured mass of ^{29}Na could be explained by the sd -shell model calculation [5, 45].

The ground state spin and parity of ^{30}Na has been measured earlier as being 2^+ [42] and that value can be reproduced by both USD [41] shell model and MCSM shell model calculations [8]. No experimental data on the ground state configuration of this nucleus is available. To explain the measured reduced matrix element of this isotope, the ground state has been considered to be a pure two-particle–two-hole deformed ground state [19]. But

present experimental data favor $^{29}\text{Na}_{gs}(3/2^+) \otimes \nu_{s,d}$ as one of the major ground state configuration of ^{30}Na ($N = 19$). The contribution of the core, ^{29}Na , in the excited state i.e., particle hole configurations in the ground state is around 46 (6) mb (28(4)% of the total CD cross-section). If it is assumed that the excited state contributions are entirely due to $2p-2h$ configurations then a comparison of our experimental findings with shell-model calculation using the MCSM [8] suggests a lower limit of the sd - pf shell gap, of about 4.3 MeV in this nucleus. For the first time experimental quantitative spectroscopic factors of the valence neutron in the s and d orbital have been measured. Unlike ^{29}Na , for ^{30}Na , the experimental spectroscopic factor for occupation of the d -orbital (2.03) deviates from the sd -shell (USD-B) calculation (2.97). The reduced spectroscopic factor of the valence neutron occupying the d -orbital could be due to particle-hole configurations across the sd - pf shell gap. Since the ground state spin and parity of this neutron-rich nucleus is 2^+ , the valence neutron occupying the pf orbital, should be coupled with negative parity excited states of ^{29}Na . So far very little is known about the excited states of ^{29}Na . On the other hand, the Coulomb breakup cross-section using direct breakup model for the valence neutron in the $f_{7/2}$ orbital coupled with a core excited state of 1.5 MeV is around 21 mb and is further reduced to 10 mb when coupled with a 3.0 MeV excited core state. When the valence neutron occupies the p orbital, the direct breakup model calculation for the same situation is 108 mb and 67 mb, respectively. Considering the experimental excited state CD cross-section, 46 (6) mb, it may be possible that the valence neutron across the shell gap is occupying either a pure f or p orbital or admixture of the p and f orbitals.

In a nut-shell, present experimental data of the Coulomb breakup suggests that the ground state properties of ^{29}Na can be explained by the USD-B shell model calculation. The situation is different for ^{30}Na . The spectroscopic factor for the valence neutron in the d orbital is reduced by almost 1/3 compared to the USD-B calculation. This could be tentatively, due to the particle-hole configuration across the shell gap and the valence neutron may occupy either f or p orbital or mixing of both the pf orbital. Thus, it may be concluded that boundary of the so-called island of inversion begins at ^{30}Na , instead of ^{29}Na . Wildenthal *et al* [45], showed that the measured mass of ^{29}Na can be explained by the USD shell model calculation but that of ^{30}Na was not fully reproduced by a sd -shell model calculation. The measured $B(E2; 2^+ \rightarrow 3^+)$ value for ^{30}Na [9, 10] is around 30% lower than the value calculated by the MCSM with the $sdpf$ -M interaction. However more detailed theoretical calculations are necessary to understand the nucleon-nucleon interaction for these neutron-rich nuclei near the so-called island of inversion.

6. Conclusion

First results on Coulomb breakup measurements of the neutron-rich $^{29,30}\text{Na}$ nuclei, at energies of 400–430 MeV/nucleon have been reported. The observed low-lying dipole strength in these neutron-rich Na isotopes can be understood by a direct-breakup mechanism and no resonance like structure has been observed. The shape of the experimental differential CDn cross sections and their comparison with the calculated cross sections suggest the predominant ground-state configuration for ^{29}Na and ^{30}Na as $^{28}\text{Na}(1^+) \otimes \nu_{s,d}$ and $^{29}\text{Na}(3/2^+) \otimes \nu_{s,d}$, respectively. The ground state spin and parity of these nuclei, obtained from present measurements are in agreement with earlier reported values. Thus the first results on the ground state configurations and quantitative spectroscopic information of the valence neutron occupies the s , d orbitals, obtained via direct method have been reported in this article. According to the experimental results, the valence neutron is occupying mainly d

orbital for both the neutron-rich Na nuclei ($N = 18, 19$). 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 (USD-B) calculation (2.18). On the other hand the same for ^{30}Na is different and experimentally obtained spectroscopic factor for valence neutron in the d orbital 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. A comparison of our experimental findings on the core excited state contributions in the ground state configuration with the shell-model calculation using the MCSM suggests a lower limit for the sd – pf shell gap in ^{30}Na of around 4.3 MeV. Thus the present experimental data suggests that ^{30}Na is the boundary of the so-called island of inversion, instead of ^{29}Na . However more detailed theoretical calculations are necessary to understand the nucleon–nucleon interaction for these neutron-rich nuclei near the so-called island of inversion.

Acknowledgments

We are thankful to the accelerator people of GSI for their active support during the experiment. Authors are thankful to Prof B A Brown, Michigan State University for providing the shell model calculations and Prof Sudeb Bhattacharya, Kolkata for critically reviewing the manuscript and suggestions. The author UD acknowledges Alexander von Humboldt Foundation, Germany and SEND project grants (PIN:11-R&D-SIN-5.11-0400) from Department of Atomic Energy (DAE), Govt. of India for financial support for this work.

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