EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Status Report to the ISOLDE and Neutron Time-of-Flight Committee

IS482:Coulomb excitation of neutron-rich ^{28,29,30}Na nuclei with MINIBALL at REX-ISOLDE: Mapping the borders of the island of inversion

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Abstract

The neutron-rich nuclei ^{28,29,30}Na are subject of the ISOLDE experiment IS482. The sequence of ^{28,29,30}Na nuclei approaches the N = 20 neutron closed shell and is expected to reach the so called 'island of inversion'. Monte-Carlo-shell model calculations (MCSM) for ^{28,29,30}Na show a gradual transition into the intruder dominated ground state configuration [1]. A first Coulomb excitation experiments using REX-ISOLDE coupled with the MINIBALL array was performed in September 2009. Despite a very low ^{30}Na beam intensity of 550 ions/s the experiment yielded the transition strength for the first excited state in ^{30}Na as a result. The B(E2) value is not compatible with results from an intermediate Coulex measurement and indicates a higher collectivity. Moreover a candidate for a (4+) state was identified and requires verification. Several unsuccessful attempts were made in 2010-2012 to get a sufficient ^{30}Na beam intensity to conclude this experiment. The preliminary results of IS482 yielded results for a PhD thesis, a diploma thesis and two publications in Phys. Rev. C. In order to finish the original aim of IS482 we ask for the remaining additional 11 shifts of ^{30}Na beam time with the nominal ISOLDE yield.

Remaining shifts: 11

1. Motivation, experimental setup/technique

A number of experimental and theoretical studies have been carried out in order to understand the coexistence of normal 0p0h and intruder 1p1h and 2p2h configurations at low energies for different isotopes in the region of the ‚island of inversion'. However, the driving mechanisms are not fully understood yet and the predictive power of most theories is not good enough to provide reliable information on the low-energy structure and experimental observables for many nuclei in this region. Detailed theoretical information is rare, especially for nuclei with odd *N* and/or odd *Z*, although these nuclei are a sensitive probe for the competing structure of 0p0h, 1p1h, and 2p2h configurations at low energies.

In the neutron-rich Mg isotopes with N = 20–22, the inverted level structure of normal and intruder configurations at low energies has been firmly established in a series of experiments [2–6]. More recently it could be confirmed that already at N = 19 the wave functions of the ground and low-lying states contain a dominant admixture of intruder configurations [7–9]. For the neighboring N = 18,19 Na isotopes, ^{29,30}Na, measurements of the magnetic dipole moments and electric quadrupole moments revealed significant deviations from the universal sd-shell (USD) model [10], indicating a dramatic change in the underlying shell structure also for these nuclei. In ^{30}Na normal and intruder configurations were supposed to compete with each other at low excitation energies. Detailed experimental studies of these states would reveal excellent information on the underlying shell-model modifications around $N = 20$.

To probe the predicted collective properties of the first and higher-lying excited states in ^{29,30}Na, Coulomb excitation experiments in inverse kinematics were proposed at REX-ISOLDE, CERN, employing post-accelerated radioactive ^{29,30}Na beams at "safe" energies, i.e., the distance of closest approach is>15 fm and the contribution of nuclear interaction to the total excitation cross section is negligible. The intruder configurations also at higher excitation energy were a subject of these experiments to obtain new information about the underlying shell structure and the evolution of the shell gaps far from stability. Compared to the results published by Ettenauer *et al.* [11] and Hurst *et al.* [12] and, the presented experiments benefit from the more intense radioactive ion beams at REX-ISOLDE, a reduced background at energies below 250 keV and the high energy resolution and detection efficiency of the MINIBALL setup.

Up to now Coulomb excitation experiments of radioactive ^{29,30}Na were carried out at REX-ISOLDE, at a beam energy of 2.85 MeV/u with much too low beam intensities. De-excitation γ-rays were detected by the MINIBALL in coincidence with scattered particles in a segmented Si-detector. Despite rather low beam intensities transition probabilities to the first excited states were deduced. Results of very recently published experiments at MSU and TRIUMF could be largely extended. The measured B(E2) values support the idea that in the sodium isotopic chain the ground state wave function comprises significant intruder admixture already at N = 18, with N = 19 having an almost pure 2p2h deformed ground state configuration.

2. Status Report

A measurement on ^{29}Na was performed in September 2009 with a reduced beam intensity of 25% of the proposed beam intensity, calculated with the values of the ISOLDE yield database. A consecutive Coulomb excitation run on ^{30}Na was based on a post-accelerated ^{30}Na intensity of 550 ions/s which is only a fraction of 12-14% of the expected ISOLDE beam intensity at the MINIBALL target. For exotic ^{29,30}Na nuclei the results of previous experiments could be largely confirmed and extended. Deduced collective properties of the first excited states are well described by Monte-Carlo shell model calculations using the SDPF-M interaction. The measured B(E2) values support the idea that in the sodium isotopic chain the ground state wave function comprises significant intruder admixture already at N = 18, with N = 19 having an almost pure 2p2h deformed ground state configuration. However, higher-lying states dominated by intruder configurations, as predicted by theory, are hardly populated in the present Coulomb excitation experiments. The ground state transitions of the assigned ($3/2^+$) state at 1588 keV in ^{29}Na is found to have a moderately large B(E2) value.

The observed collective properties of excited states in ^{30}Na are in agreement with intruder-dominated configurations, predicted by recent theoretical approaches. The transition strength of the (3+) → 2+ transition was measured to be high with B(E2)↑ = 230(41) e2fm4 and B(E2)↑ = 320(100) e2fm4 in the experiment, using different targets, respectively. These values exceed both the previously measured B(E2)↑ = 147(21) e2fm4 value published by Ettenauer et al. [11] and the MCSM predictions, which yield 168 e2fm4 [1]. In ^{30}Na a candidate for the (4+) state is identified at 925 keV by coincidence relations.

Results of the ^{29,30}Na experiment IS482 were published in Phys. Rev. C 89, 024309 (2014) and were part of the Cologne PhD thesis of M. Seidlitz.

Three unsuccessful attempts were made in 2010-2012 to deliver a ^{30}Na in order to corroborate the findings on the enhanced collectivity and to establish firmly the candidate for the new first (4+) state. As a by-product of these efforts a ^{26}Na beam was delivered in 2011 for a sufficient time period and a Coulomb excitation experiment was performed. As a result γ -ray transitions in ^{26}Na together with available spectroscopic data allowed us to determine E2- and M1-transitional matrix elements. These findings were compared to recent improvements to the empirical universal sd interaction (USD) describing nuclei within the sd shell. Two new interactions—USDA and USDB—cause changes in the theoretical description of these nuclei. An improved theoretical description of ^{26}Na by USDA could be validated. Remaining discrepancies between experimental data and theoretical predictions indicate the need for future experiments and possibly further theoretical improvements.

Results of the ^{26}Na experiment (as a by-product of IS482) were published in Phys. Rev. C (in press) (2015) and were part of the Cologne diploma thesis of B. Siebeck

Accepted isotopes: ^{26}Na, ^{29}Na, ^{30}Na

Performed studies: Coulomb excitation measurements with reduced intensity

3. Future plans

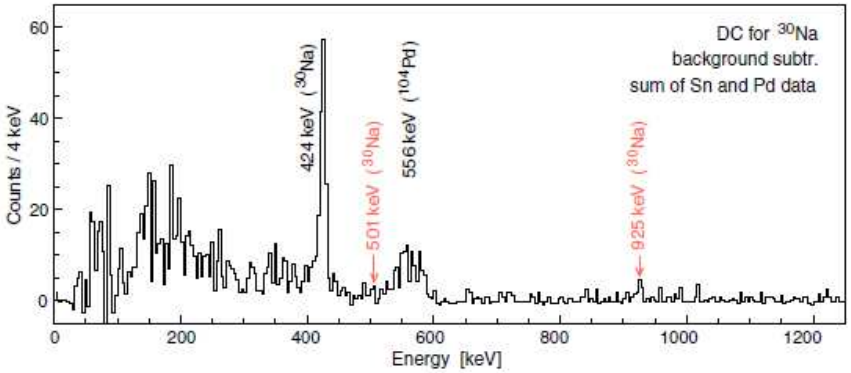

Fig. 1 Sum spectrum of the Coulomb-excitation experiments on ^{30}Na, using the data sets taken with a ^{104}Pd target and a ^{120}Sn target, background subtracted and Doppler corrected (DC) for ^{30}Na. In addition to the known 424-keV transition there is evidence for two weak transitions at 925(4) keV and 501(4) keV (arrows), depopulating an excited state at 925(5) keV. (Figur is taken from our publication M. Seidlitz et al; Phys. Rev. C 89, 024309 (2014).)

Coulomb excitation of ^{30}Na showed a peak at a known transition energy of 424 keV (see Fig. 1). The reduced transition probability B(E2; 2+→ (3+)) = 252(45) is significantly higher and more collective than the result obtained with intermediate-energy Coulomb excitation at NSCL/MSU. Ettenauer et al. [11] measured B(E2) = 147(21) e2fm4. Very strong indication for a new higher lying state in ^{30}Na at 925(5) keV was found. The prompt particle-γγ coincidence spectrum was investigated by gating on the 424 keV transition and on the newly observed 501-keV transition. Weak mutual coincident γ -ray transitions were observed, consistent with a decay branch of the 925 keV state via 501 keV, feeding the 424-keV level. These observations provide strong evidence for a (4+) state at 920(5) keV.

From Fig. 1 it is obvious that an improved statistics would resolve the remaining open questions related to the first results on ^{30}Na:

- Can the remaining discrepancy in B(E2) strength be hardened with a better accuracy?
- Can the candidate for the (4+) state unambiguously identified via coincidence relationship?
- Can other candidates of excited states from theoretical predictions [1] be verified?

Future plans with <u>available</u> shifts:

(i) Envisaged measurements, beam energy, and requested isotopes

Continuation of Coulomb excitation experiment, beam energy 3.0 MeV/u, (cross section increase at higher beam energy was calculated is 20% higher), ^{30}Na

(ii) Have these studies been performed in the meantime by another group?

Not to our knowledge

(iii) Number of shifts (based on newest yields and latest REX-EBIs and REX-trap efficiencies) required for each isotope

isotope	yield (/uC)	target – ion source	Shifts (8h)
^{30}Na	5.1×10^{4} atoms/μC	bulk Re surface ion source ISOLDE target studies were performed for this experiment by A. Gottberg in 2011 in order to achieve the previous ^{30}Na yields.	11 (remaining)

Total shifts: 11

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[12] A. M. Hurst *et al.*, Phys. Lett. B **674**, 168 (2009).

4. Appendix

Publications

Testing refined shell-model interactions in the *sd* shell: Coulomb excitation of ^{26}Na
B. Siebeck, M. Seidlitz, A. Blazhev, P. Reiter, R. Altenkirch, C. Bauer, P. A. Butler, H. De Witte, J. Elseviers, L. P. Gaffney, H. Hess, M. Huyse, T. Kröll,2,5 R. Lutter, J. Pakarinen, N. Pietralla, F. Radeck, M. Scheck, D. Schneiders, C. Sotty, P. Van Duppen, M. Vermeulen, D. Voulot, N. Warr, and F. Wenander
PHYSICAL REVIEW C 00, 004300 (2015) in press

Coulomb excitation of ^{29,30}Na - Mapping the borders of the island of inversion
M. Seidlitz, P. Reiter, R. Altenkirch, B. Bastin, C. Bauer, A. Blazhev, N. Bree, B. Bruyneel, P. Butler, J. Cederkäll, T. Davinson, H. De Witte, D. DiJulio, J. Diriken, L. Gaffney, K. Geibel, G. Georgiev, R. Gernhäuser, M. Huyse, N. Kesteloot, T. Kröll, R. Krücken, R. Lutter, J. Pakarinen, F. Radeck,M. Scheck,4 D. Schneiders, B. Siebeck, C. Sotty, T. Steinbach, J. Taprogge, P. Van Duppen, J. Van de Walle, D. Voulot, N. Warr, F. Wenander, K. Wimmer, P.J. Woods, K. Wrzosek-Lipska
PHYSICAL REVIEW C 89, 024309 (2014)

Theses

M. Seidlitz University of Cologne 2012

Nuclear shell effects in neutron-rich nuclei around N=20 and N=32,34

B. Siebeck University of Cologne 2013

Coulomb excitation of ^{26}Na with MINIBALL at REX-ISOLDE