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**Addendum for experiment 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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## 1 Abstract

The neutron-rich nuclei $^{28,29,30}$Na are subject of the ISOLDE experiment IS482 which was approved in November 2008 by the INTC. 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 (MCSM) calculations for $^{28,29,30}$Na of the Tokyo group [Uts04] show a gradual transition into the intruder dominated ground state configuration. Already for $^{30}$Na at N=19 the inversion of the levels occurs due to the spin-isospin dependence of the nucleon-nucleon interaction. The transition from a pure sd-shell configuration to the $2p2h$ configuration is calculated to go through the intermediate nucleus $^{29}$Na with a predicted 50% mixing of $0p0h$- and $2p2h$ configurations. A first Coulomb excitation experiments using the REX-ISOLDE facility coupled with the highly efficient 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 preliminary $B(E2)$ value indicates a higher collectivity than a recent measurement at MSU. Moreover clear indications for the de-excitation of the second excited state can be observed for the first time. In order to conclude this experiment with a reasonable small statistical error and a publishable result we ask for additional 9 shifts of $^{30}$Na beam with the nominal ISOLDE yields.

## 2 Introduction

The chain of the three $^{28,29,30}$Na isotopes is an ideal testing ground to study the underlying mechanism which facilitates the transition from a normal sd-configuration in $^{28}$Na via the transition in $^{29}$Na into the highly deformed fp-intruder configuration $^{30}$Na. The main goal of the approved experiment IS482 is a refined understanding of the interrelations between N=20 shell closure and energy gap, the proton-neutron interaction, the correlation energy and the impact of deformation. The collective and single particle properties of excited states can be probed via E2 and M1 matrix elements. Coulomb excitation at safe bombarding energies allows an accurate determination of the E2 and M1 transition strengths. These observables provide additional information in order to test the theoretical predictions. Especially the high collectivity of excited rotational states in $^{29,30}$Na should be favored in these measurements.
End of 2008 the INTC approved 24 shifts of beam time for experiment IS482 and a first IS482 experiment was scheduled in September 2009.
We were able to obtain first experimental results on $^{29}$Na and $^{30}$Na. The measured transition strength for the first excited state in $^{30}$Na appears to be much more collective than in a previous measurement at MSU. Additionally we observe an indication for an excitation to the second excited state for the first time, which is split into two different branches. These observations should be easily verifiable by an experiment with nominal ISOLDE yields.

## 3 Status of IS482, experimental results from 2009

### $^{29}$Na

The measurement on $^{29}$Na was performed in September 2009. In total 9 shifts were used to set-up the $A = 29$ beam and to deliver radioactive ions to MINIBALL for nearly 64 hours. The post-accelerated beam intensity was about 2700 ions/s, incident onto a 4.1 mg/cm$^2$ thick $^{104}$Pd target. With an average proton beam current of 1.4 $\mu$A this corresponds to only a quarter of the proposed beam intensity of 10000 ions/s, calculated with the values of the ISOLDE yield database.
The first excited state in $^{29}$Na was clearly observed at 72 keV (see Fig. 1) and its transition rate was determined to be $B(E2; 3/2^+ \rightarrow (5/2^+)) = 189(40)$ e$^2$fm$^4$. This value is in agreement with a recently published experiment, performed by Hurst *et al.* at TRIUMF; a value of $B(E2) = 140(25)$ e$^2$fm$^4$ [Hur09] is given. Despite the higher beam intensity at ISOLDE and more statistics in the 72 keV peak – compared to the TRIUMF measurement – it was not possible to reduce the statistical error due to a background contamination coming from X-rays of $^{200}$Po daughter products, previously measured at MINIBALL. $\gamma$-ray decays from higher lying states could not be observed and an upper limit for the collectivity of these potential states in $^{29}$Na is obtained.

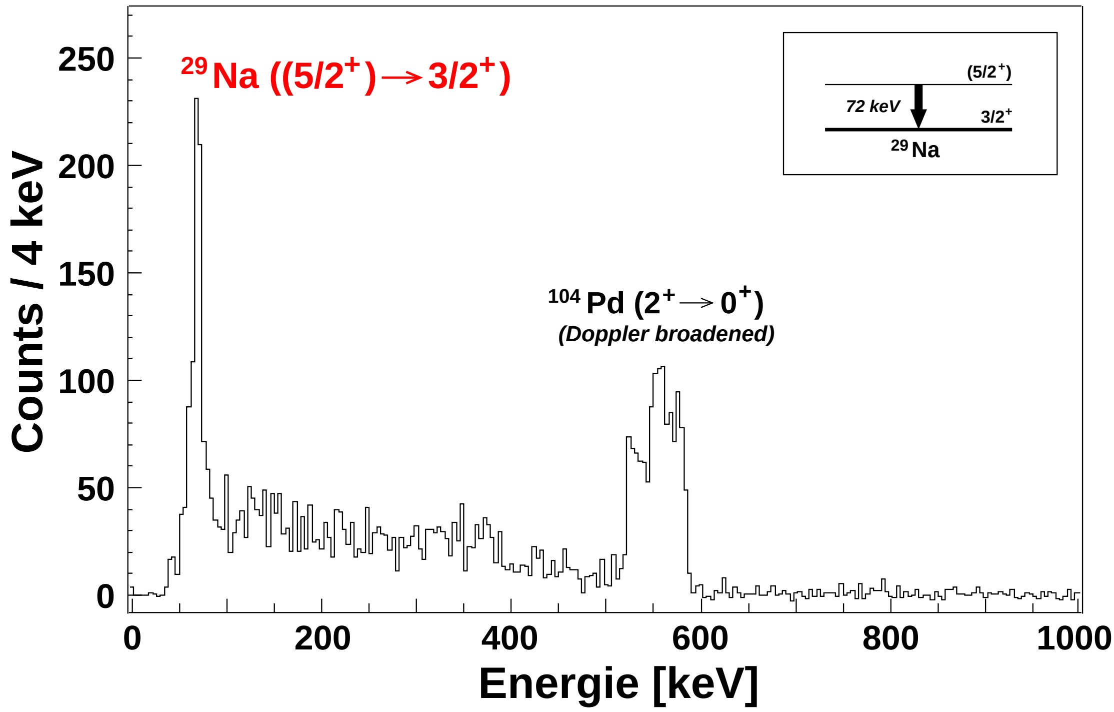


***Figure 1:*** *Coulomb excitation spectrum for $^{29}$Na on a $^{104}$Pd target. The spectrum is Doppler corrected for the detected projectile particle and background subtracted. The spectrum is dominated by a 72 keV transition from the first excited state in $^{29}$Na. The transition rate is $B(E2; 3/2^+ \rightarrow (5/2^+)) = 189(40)$ e$^2$fm$^4$.*

### $^{30}$Na

The first Coulomb excitation run on $^{30}$Na took place in September 2009 and delivered nearly 84 hours radioactive $A = 30$ beam to MINIBALL within 12 shifts. For technical reasons the run was scheduled in two separated beam time periods (7 shifts and 5 shifts, respectively) with a MINIBALL experiment on $^{200}$Po in between. For the first measurement a 4.0 mg/cm$^2$ thick $^{120}$Sn target was employed. After the break a 4.1 mg/cm$^2$ thick $^{104}$Pd target was placed inside the target chamber for the second part. The post-accelerated $^{30}$Na intensity was 550 ions/s. A high proton beam current of 1.5-1.6 $\mu$A was delivered on average by the PS booster. However only a fraction of 12-14% of the expected ISOLDE beam intensity of about 4500 ions/s were detected at the MINIBALL target.
Due to the broken ISOLDE fast tape station it was not possible to do a direct ISOLDE yield measurement for the neutron-rich Na isotopes. Aditionally it was not possible to test the ISCOOL transmission for light ions nor optimize it due to lack of a light mass marker. The reasons for the significantly lower Na beam intensity were not resolved at this time.

Coulomb excitation events of $^{30}$Na were observed at a known transition energy of 424 keV (see Fig. 2). The reduced transition probability $B(E2; 2^+ \rightarrow (3^+)) = 252(45)$ e$^2$fm$^4$ is significantly higher and more collective than the result obtained with intermediate-energy Coulomb excitation at NSCL/MSU. Ettenauer *et al.* measured $B(E2) = 147(21)$ e$^2$fm$^4$ [Ett08]. Very strong indication for a new higher lying state in $^{30}$Na at 920(5) keV was found. Two weak $\gamma$-ray transitions at 920(5) keV and 495(5) keV provide strong evidence for a $(4^+)$ state at 920(5) keV. Its de-excitation is split into the two branches, connecting this state to the $2^+$

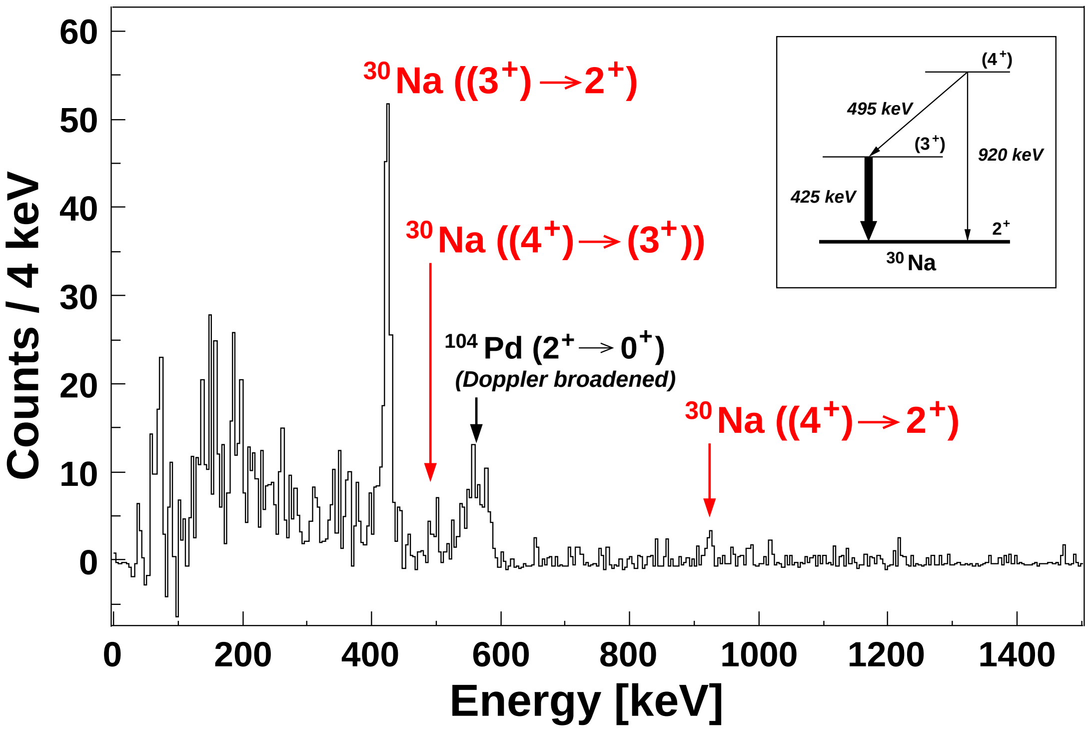


***Figure 2:*** *Sum of the Coulomb excitation spectra obtained during 2009 run with $^{30}$Na on a $^{120}$Sn target and a $^{104}$Pd target, respectively. The spectrum is Doppler corrected for the detected projectile particle and background subtracted.*

ground state and the first excited $(3^+)$ state, respectively. A preliminary transition strength $B(E2; 2^+ \rightarrow (4^+)) = 108(33)$ e$^2$fm$^4$ was determined. This value is in agreement with theoretical predictions made by the MCSM group [Uts04]. An excited $4^+$ state at 860 keV was calculated. The theoretical transition strength $B(E2; 2^+ \rightarrow (4^+)) = 90$ e$^2$fm$^4$ compares well with the preliminary experimental value.
The spectrum of Fig. 2 illustrates the obvious lack of $^{30}$Na beam intensity and the need for additional beam time to verify the intriguing findings. Moreover several candidates for other $\gamma$-ray transitions are visible. In the energy range below 600 keV of Fig. 2 improved background conditions for $\gamma$-ray spectroscopy with MINIBALL are meanwhile realized in the experimental area close to the MINIBALL spectrometer by a solid and hermetically closed radiation shield of the REX-ISOLDE accelerator components.

## 4 Beam time in 2010

In September 2009 the delivered beam intensity has been far below the expected and documented ISOLDE yields, which were the basis of the proposal. The $^{30}$Na beam intensity of 550 ions/s at MINIBALL was only a small fraction of the expected 4500 ions/s. This number is taken from the ISOLDE database and includes measured ISOLDE yields of $5.1{\times}10^4$ atoms/$\mu$C, a reasonable proton intensity of 1.5$\mu$A, HRS efficiency of 90%, a REX overall efficiency of 7.5%, and decay losses during the trapping and charge breeding period.

The count rate estimate of the proposal does not include an efficiency loss from the ISCOOL device, which was not operational as a standard component in the low energy beam line in 2008.
The remaining shifts of experiment IS482 were scheduled for another Coulomb excitation experiment with $^{30}$Na in August 2010 to establish the candidate state at 920 keV in $^{30}$Na and to investigate the discrepancy in the transition strength of the 424 keV state. The standard ISOLDE yield of $^{30}$Na and a better low-energy background suppression by additional 9-gap shielding should at least double the statistics and reduce significantly the error from background contributions. However the second attempt also failed completely due to insufficient beam intensity at the MINIBALL target. A first yield measurement with moderate ISOLDE target heating determined $2.1\times10^3$ atoms/$\mu$C for $^{30}$Na at the ISOLDE fast tape station: a factor of almost 25 below the nominal ISOLDE yield, given in the database. One shift was used setting up REX and trying to get more Na out of the primary target by heating it up to $\sim$2000°C. A further increase of the target temperature to its nominal values around/above 2100°C was not done at this point due to other experiments, making use of this $UC_x$ target. Additionally losses of $\sim$50% at the low-energy side of REX-ISOLDE were observed.
Finally a post-accelerated beam intensity of less than 150 ions/s was hitting the MINIBALL target. This low intensity was deduced from elastic scattering and the absence of any target and projectile excitation event in the MINIBALL data (see Fig. 3). The beam current limit of 150 ions/s corresponds to less than 5% of the expected beam intensity and hence a much lower value than needed and proposed. Therefore the IS482 beam time was stopped and the remaining time was successfully used by the MINIBALL collaboration to perform a Coulomb excitation experiment with $^{93,95,97,99}$Rb beams for experiment IS493 lead by G. Georgiev.

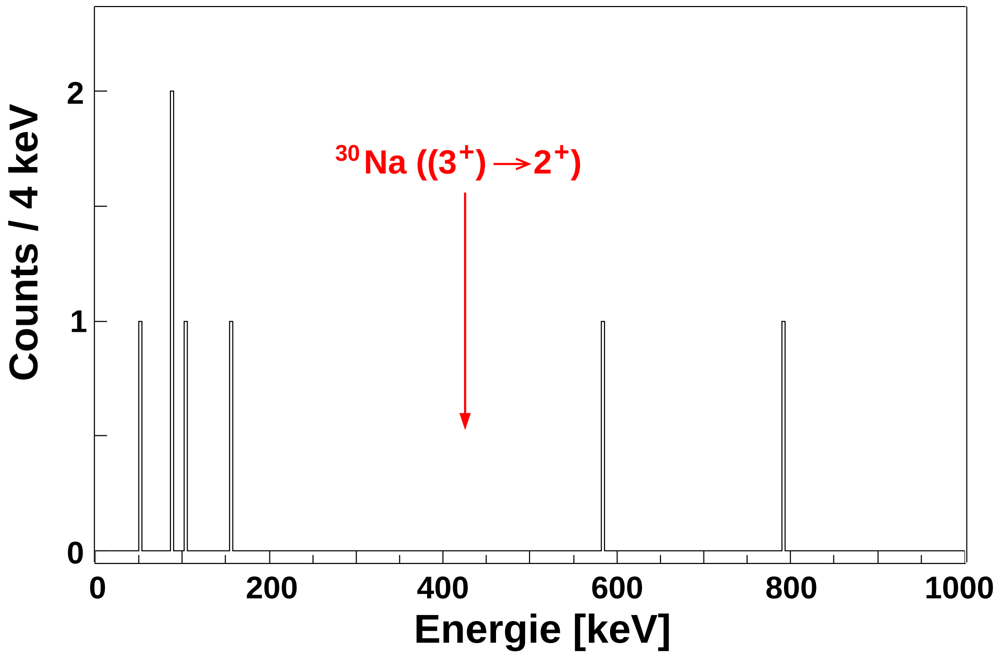


***Figure 3:*** *Coulomb excitation spectrum obtained during a 3-hour run in 2010 with $^{30}$Na on a $^{104}$Pd target. The spectrum is Doppler corrected for the detected projectile particle. No evidence is found for any projectile excitation at 424 keV, nor target excitation at 556 keV. This result corresponds to a very low beam intensity of less than 150 Na-ions/s.*

After the August attempt Na yield tests were finally scheduled on September 10th. A detailed analysis of the sodium yields out of an $UC_x$ target with W surface ionizer, depending on different parameters like target/line temperatures, was not performed due to a tight time schedule and lack of experts for the ISOLDE fast tape station.

## 5 Beam time request

In order to finish the experiment IS482 with a publishable result we ask for 9 additional shifts for a Coulomb excitation experiment on $^{30}$Na using the REX-ISOLDE facility coupled with the highly efficient MINIBALL array. Main goal of the measurement will be to establish (i) the new found state at 920 keV and its decay pattern and (ii) to confirm the high transition strength of the first excited state at 424 keV. Improved experimental conditions for in-beam $\gamma$-ray spectroscopy can be exploited due to the radiation shielding of the REX linac 7-gap and 9-gap resonators.
A beam intensity at the MINIBALL target of 4000-5000 incoming $^{30}$Na ions is requested. The beam intensity is based on numbers taken from the ISOLDE database and includes a measured ISOLDE yield of $5.1\times10^4$ atoms/$\mu$C, a reasonable proton intensity of 1.5$\mu$C, HRS efficiency of 90%, a REX overall efficiency of 7.5%, and decay losses during the trapping and charge breeding period. After two beam times suffering from insufficient beam intensity a careful re-investigation of the published sodium yields [Hab97] seems to be necessary prior the next experiment. This measurement should concern also the up to now unknown potential efficiency loss of ISCOOL for light Na ions. From this investigations also experiment IS502 'Study of single particle properties of neutron-rich Na isotopes on the 'shore of the island of inversion' by means of neutron-transfer reactions' will benefit.

Data of experiment IS482 are part of the PhD thesis project of Michael Seidlitz, University of Cologne.

## References

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