**Proposal to the INTC Committee**

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

P. Reiter[1], M. Seidlitz[1], A. Blazhev[1], B. Bruyneel[1], F. Finke[1], K. Geibel[1], H. Hess[1], A. Holler[1], M. Kalkühler[1], D. Lersch[1], B. Siebeck[1], A. Wendt[1], N. Warr[1],A. Wiens[1], J. Van De Walle[2,3], P. Van Duppen[2], M. Huyse[2], P. Delahaye[3], F. Wenander[3], D. Voulot[3], V. Bildstein[4], T. Behrens[4], R. Gernhäuser[4], T. Kröll[4], R. Krücken[4], R. Lutter[4], J. Cederkäll[3,5], A. Ekström[5], D. Jenkins[6], P. Butler[7], M. Scheck[7], T.Davinson[8], P.J. Woods[8], J. Leske[9], N. Pietralla[9], I. Stefanescu[10] and the REX-ISOLDE collaboration

Institut für Kernphysik, Universität Köln, Germany[1]; IKS Leuven, Belgium[2]; CERN, Switzerland[3]; Technical University München, Germany[4]; University of Lund, Sweden[5]; University of York, United Kingdom[6]; University of Liverpool, United Kingdom [7]; University of Edinburgh, United Kingdom [8]; Technical University Darmstadt, Germany[9]; Argonne National Laboratory, United States of America[10]

Spokesperson: P. Reiter
Contact persons: J. Van De Walle

CERN-INTC-2008-039 / INTC-P-252
05/10/2008

## Abstract

We propose to study the properties of neutron-rich nuclei $^{28,29,30}$Na via Coulomb excitation experiments using the REX-ISOLDE facility coupled with the highly efficient MINIBALL array. Reliable B(E2,$0^+ \rightarrow 2^+$) values for $^{30,32}$Mg were obtained at ISOLDE. Together with recent new results on $^{31}$Mg, collective and single particle properties are probed for Z=12 at the N=20 neutron closed shell, the 'island of inversion'. We would like to extend this knowledge to the neighbouring $^{28,29,30}$Na isotopes where a different transition from the usual filling of the neutron levels into the region with low lying 2p-2h cross shell configurations is predicted by theory. Detailed theoretical predictions on the transition strength in all three Na nuclei are awaiting experimental verification and are subject of this proposal. At REX beam energies of 3.0 MeV/nucleon the cross-sections for Coulomb excitation are sufficient. Moreover the results from the close-by $^{30,31,32}$Mg nuclei demonstrated the feasibility of the these experiments under comparable conditions. We request 24 shifts of beam time for post-accelerated REX beams of $^{28,29,30}$Na.

## Motivation

Shell structure in nuclei far from stability is a key subject of nuclear structure research with unstable beams providing access to the nucleon-nucleon residual interaction and the one-boson-exchange potential. New shell model calculations of exotic nuclei also provide important results for astrophysical applications like the abundances of r-process nuclei. Clear experimental evidence for a rearrangement of the known shell structure of stable nuclei is obtained in very neutron rich nuclei meanwhile along the N=8, 20 and 28 chain of isotopes. These findings could be traced down to the monopole part of the nucleon-nucleon (nn) residual interaction by new large scale shell model calculations. The $(\sigma\sigma)(\tau\tau)$ part of the nn-interaction is binding and strongest for the S=0 (spin-flip), $\Delta$L=0 (spin-orbit partner) and T=0 (proton-neutron) channel of the two-body interaction. The missing S=0 partner protons in neutron rich nuclei are the reason for large shifts of the neutron levels and subsequent potentially new (sub-) shell closures. This effect was discussed first for nuclei in the sd shell and later also nuclei in the pf shell were included [Ots01,Ots02]. For heavy nuclei and increasing spin-orbit-splitting in stable nuclei it is expected that the tensor part of the nn-interaction causes a comparable strong monopole interaction between S=0, $\Delta$l=0 and T=0 orbits of consecutive harmonic oscillator shells [Gra03,Ots05].

Therefore current and new experiments focus on the structure of neutron rich Ne, Na, and Mg, Si isotopes and their neighbours. After the determination of ground state properties in decay experiments and mass measurements, more refined in beam spectroscopy experiments are needed now to access important observables like transition matrix elements, spectroscopic factors and magnetic moments.

## Coulomb excitation of neutron-rich Mg isotopes with MINIBALL at REX-ISOLDE

The first successful spectroscopy experiments with the MINIBALL and REX-ISOLDE combination employed post-accelerated beams of $^{30}$Mg und $^{32}$Mg. The dramatic change in shell structure in this mass region - the 'Island of Inversion' - was verified independently by determining the $B(E2,0^+_{g.s.}\rightarrow 2^+_1)$ values for both nuclei utilizing the method of 'safe' Coulomb excitation [Nie05] in contrast to previous work done after fragmentation reactions at intermediate energies. The B(E2) value for the first $2^+$-state in $^{30}$Mg of 241 $e^2fm^4$ was found to be in good agreement with the single particle structure reproduced by pure sd shell model calculations. This located the nucleus $^{30}$Mg clearly outside the 'Island of Inversion'. An almost doubly high $B(E2,0^+_{g.s.}\rightarrow 2^+_1)$ value was measured in the semi-magic N=20 nucleus $^{32}$Mg with 434 $e^2fm^4$. This result is consistent with a strongly deformed two-particle two-hole (2p-2h) intruder configuration of the $^{32}$Mg ground state. The $f_{7/2}$ orbital of the fp-shell is reduced in energy and allows for an inversion of the known sequence of shell model levels.

The questions related to the details of the underlying single particle structure and the position of the border line where the inversion of levels occurs motivated the MINIBALL experiment in the odd-even nucleus $^{31}$Mg between the two even-even cases. In previous theoretical and experimental work this nucleus was classified, to lie outside of the 'Island of Inversion'. Recently the direct determination of the spin and the magnetic moment of the ground state in $^{31}$Mg was done successfully at ISOLDE [Ney05]. These results indicated strongly that already the ground state of $^{31}$Mg should be a strongly deformed configuration similar to $^{32}$Mg. Predictions of a strongly deformed Yrast rotational band [Mar05,Kim07] motivated the additional Coulomb excitation experiment in $^{31}$Mg of our collaboration.

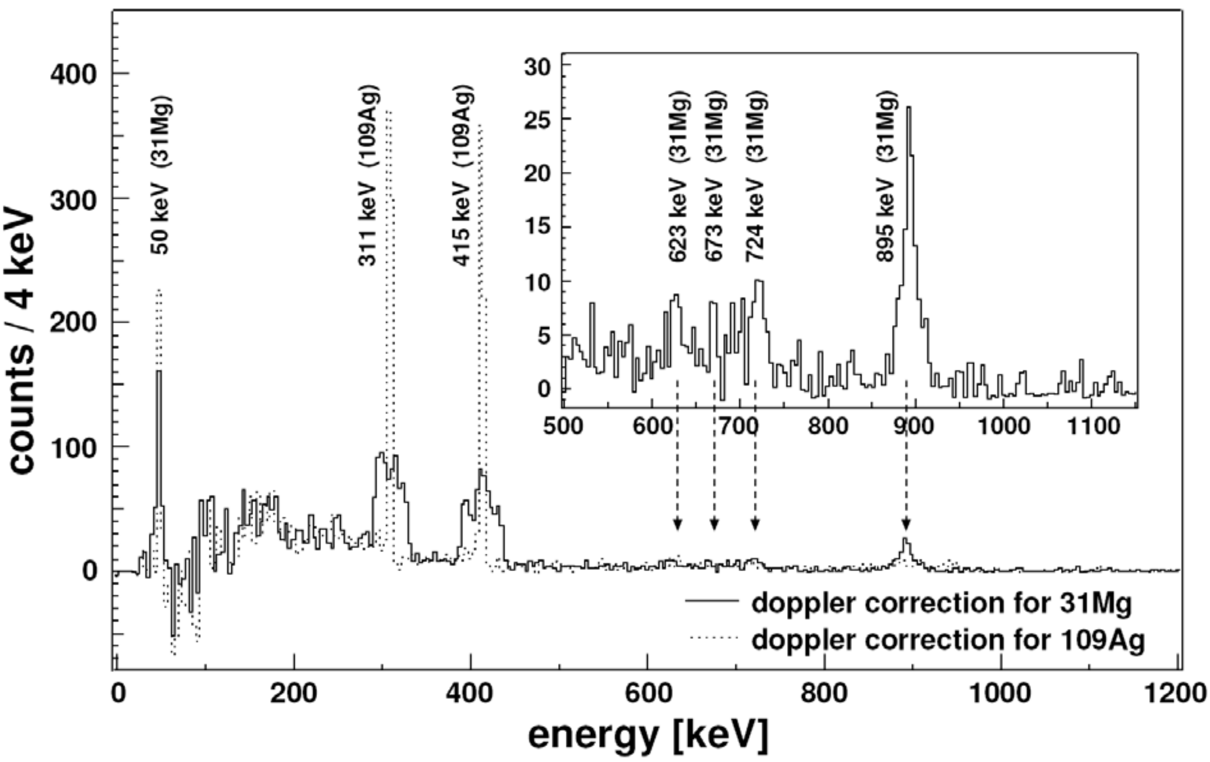


***Fig. 1:*** *γ-spectra after Coulomb excitation of $^{31}$Mg. The Doppler corrected spectrum in black shows lines at 50 kev and 895 keV caused by the decay of a state at 944.5 keV in $^{31}$Mg. Several candidates for additional transitions at 623 keV, 673 keV and 724 keV are consistent with the decay energies of other states known from β-decay studies. The uncorrected dotted spectrum shows the known transitions of $^{109}$Ag after target excitation. The lines are unshifted due to the long lifetime with respect to the stopping time in the target.*

After some difficulties with a too low beam intensity in June 2006 a second successful attempt was made for the experiment with a $^{31}$Mg REX-ISOLDE beam in late 2007. The $^{31}$Mg ions were accelerated by REX-ISOLDE up to 3.0 MeV/u beam energy. A beam current of ~$10^4$ part/s was provided. A $^{109}$Ag-target with a thickness of 4.0 mg/cm$^2$ was bombarded. A meanwhile standard coincidence measurement of γ-rays and forward scattered projectile particles was performed exploiting the eight MINIBALL cluster detectors and the highly segmented, double-sided Si-detector inside the scattering chamber.

The measured γ-spectrum show a strong transitions at 50 keV and 895 keV (see Fig.1), which are caused by the decay of the known state at 944.5 keV in $^{31}$Mg. Besides the excitation energy, no further information on the properties of this state could be obtained in previous β-decay studies [Klo93]. Therefore, this state is a promising candidate for the collective 5/2+ rotational state which would be populated preferentially via E2 Coulomb excitation. Theoretical shell model predictions [Mar05] calculate such a 5/2+-state with an excitation energy of 988 keV. Recently, a second theory publication calculated the excitation energy of the 5/2+-yrast state to be 990 keV [Kim07].

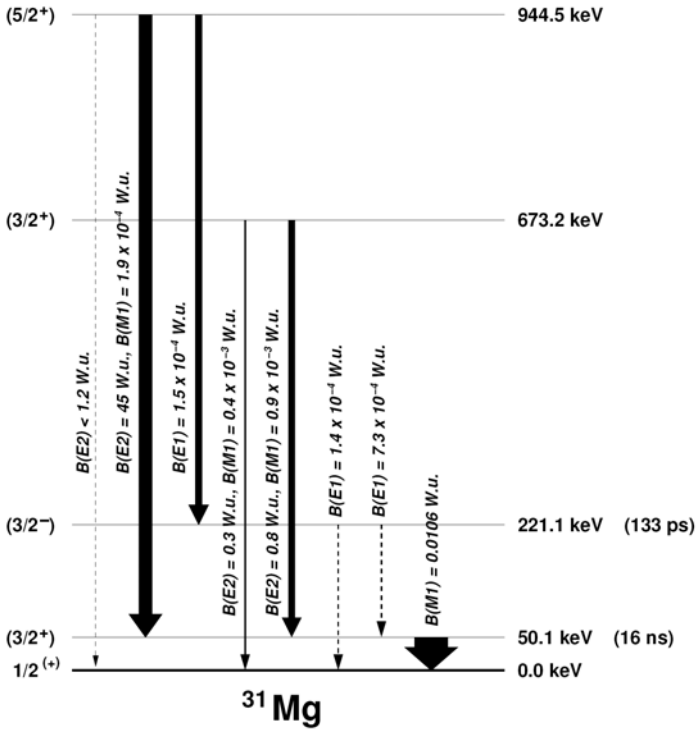


***Fig. 2:*** *Preliminary transition matrix elements of low lying states in $^{31}$Mg.*

The analysis of the transition matrix elements in $^{31}$Mg was done with the GOSIA code. The first four excited states were taken into account including the known half life of the two low lying states at 50.1 keV and 221.1 keV. The preliminary result of the analysis demonstrates the high collectivity of the 944.5 keV state. Indication of a mixed E2/M1 character of the transition could also be deduced from the result of the angular correlation analysis which was performed for the 895 keV transition. However the limited statistic did not allow here for a firm value. The data analysis was done by M. Seidlitz, as part of his Diploma thesis at University of Cologne, which will be submitted in October 2008. The future experiments on Na nuclei would be part of the thesis project of M. Seidlitz.

## Proposed experiment

The surprising and unexpected results of the ground state properties of $^{31}$Mg [Ney05] demonstrated that in contrast to previous shell model calculations, already at neutron number N=19 the transition sets in between the sd shell ground state configuration and the strongly deformed intruder configuration including higher lying states from the fp-shell. The proposed fringes of the \`Island of Inversion´ are not located at the N=20 isotone line. A refined investigation of the interplay between the monopole term in the residual interactions causing a decreased effective shell gap and the multipole term causing a correlation energy with opposite consequence were performed to understand these new findings. A small effective gap between the 0d3/2 orbital and the pf shell is caused for the neutrons by the strongly attractive interaction between protons in 0d5/2 and neutrons in 0d3/2. A further consequence is the disappearance of the N=20 semi-magic structure for proton numbers Z = 9 - 14 in exotic nuclei and the appearance of a new magic structure in $^{24}$O.

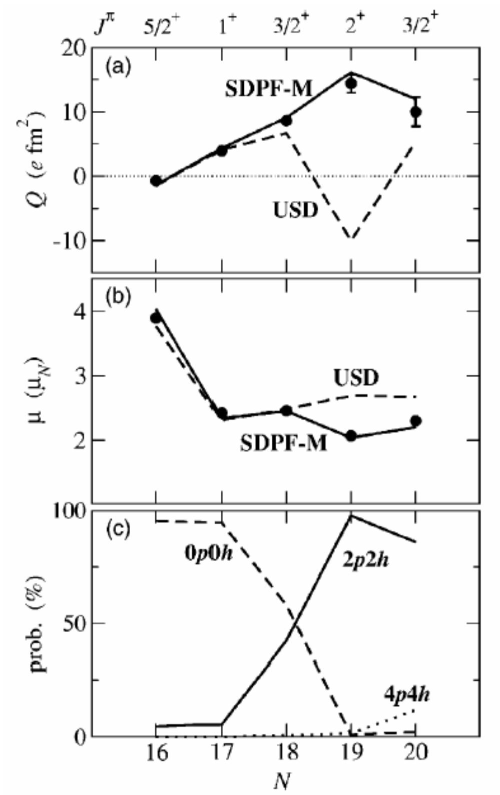


***Fig. 3:*** *(a) Electric quadrupole moments, (b) magnetic dipole moments, and (c) 2p2h probabilities of the ground states of neutron-rich Na isotopes, as a function of the neutron number N. The solid and the dashed lines denote, respectively, the MCSM calculation with the SDPF-M interaction and the USD model. Figure 2 is taken from Ref. [Uts04].*

New and interesting results from theory and experiment are now available for the neutron-rich Na Isotopes. 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 2p-2h configuration is calculated to go through the intermediate nucleus $^{29}$Na with even neutron number N=18. Theoretical results predict a 50% mixing of 0p0h- and 2p2h configurations which concur with experimental findings like two-neutron separation energies, electric quadrupole moment and magnetic moment see Fig. 3. New experimental results on $^{29}$Na were recently obtained from β-decay experiments at MSU [Tri05]. The level scheme and other related results also agree better with the proposed scenario of a strong fp intruder admixture in the ground state and also excited states.

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 experiment will be to elucidate the interrelations between N=20 shell closure and energy gap, the proton-neutron interaction, the correlation energy and the impact of deformation. Especially the collective and single particle properties of excited states can be probed via Eλ and M1 matrix elements. Coulomb excitation at safe bombarding energies allows accurate determination Eλ 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.

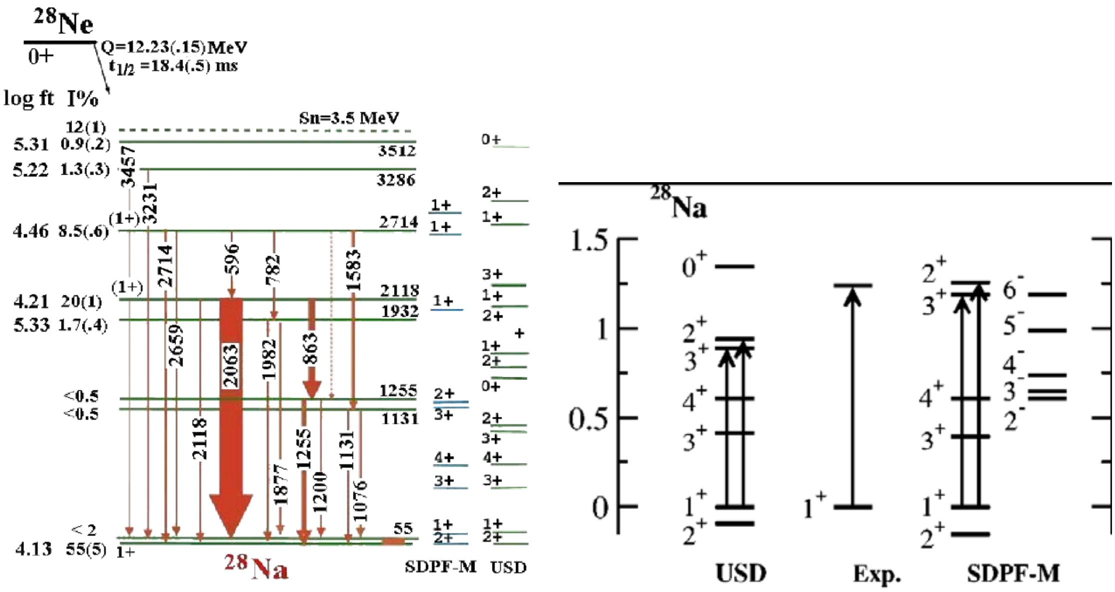


***Fig. 4:*** *The most recent level scheme of $^{28}$Na from $\beta$-decay experiments [Tri05] is shown on the left side. The comparison of the energy levels of $^{28}$Na relative to the experimental ground state among the experiment (Exp.) and the shell-model calculations by the SDPF-M and the USD interactions is taken from ref. [Uts04]. The energy level of $^{28}$Na is taken from [Pri02]. The calculated E2 strength is given in the text and discussed with respect to the proposed experiment.*

Up to now the chain of $^{28,29,30}$Na nuclei was subject to the following in-beam $\gamma$-spectroscopy experiments. For $^{28,30}$Na Coulomb excitation at intermediate beam energies was employed to identify one $\gamma$-transition from an excited state in each nucleus at MSU [Pri02]. Two measurements were performed with NaI detectors with an energy resolution which is not comparable with HPGe detectors like MINIBALL. A new result on $^{30}$Na was obtained with the SEGA Ge array and confirmed the previous measurement [Ett08]. A Coulomb excitation experiment at safe energies in $^{29}$Na was performed with the TIGRESS array at the ISAC-II facility at TRIUMF in July/August 2007 [Hur08]. A 70 MeV beam of $^{29}$Na with up to 600 ions/s impinged on a $^{110}$Pd target. A preliminary reduced transition matrix element of 0.229(20) eb for the first excited state at 72 keV was derived for $^{29}$Na.

The ground state spin of $^{28}$Na was measured to be J=1 at ISOLDE [Hub78]. For the first low lying $1^+$, $2^+$, $3^+$ und $4^+$ states a shell model configuration is expected where a $\nu(0d_{3/2})^1$ neutron couples weakly with a $J=3/2^+$ or $J=5/2^+$ proton. Results of the Monte-Carlo shell model calculation (MCSC) of the Tokyo group [Uts04] show energetically very close lying states (see Fig. 4). The theoretical E2 excitation strength values of B($E$2; $1_1^+ \rightarrow 2_2^+$)=69 $e^2$fm$^4$ and $B$($E$2;$1_1^+ \rightarrow 3_2^+$)=47 $e^2$fm$^4$ can be compared with the experimental result from MSU [Pri02]. Only one transition within the energy resolution of NaI was determined with an E2 strength of B($E$2$\uparrow$)=54(26) $e^2$fm$^4$. A MINIBALL experiment can clearly resolve the ambiguity related to the question of an unresolved and theoretically expected doublet of two close lying states. Moreover the ISOLDE experiment would probe the theoretical predictions for an E2-excitation of the first $2_1^+$ and $3_1^+$ states which are calculated to be B($E$2; $1_1^+ \rightarrow 2_1^+$)=19 $e^2$fm$^4$ and B($E$2; $1_1^+ \rightarrow 3_1^+$)=27 $e^2$fm$^4$.

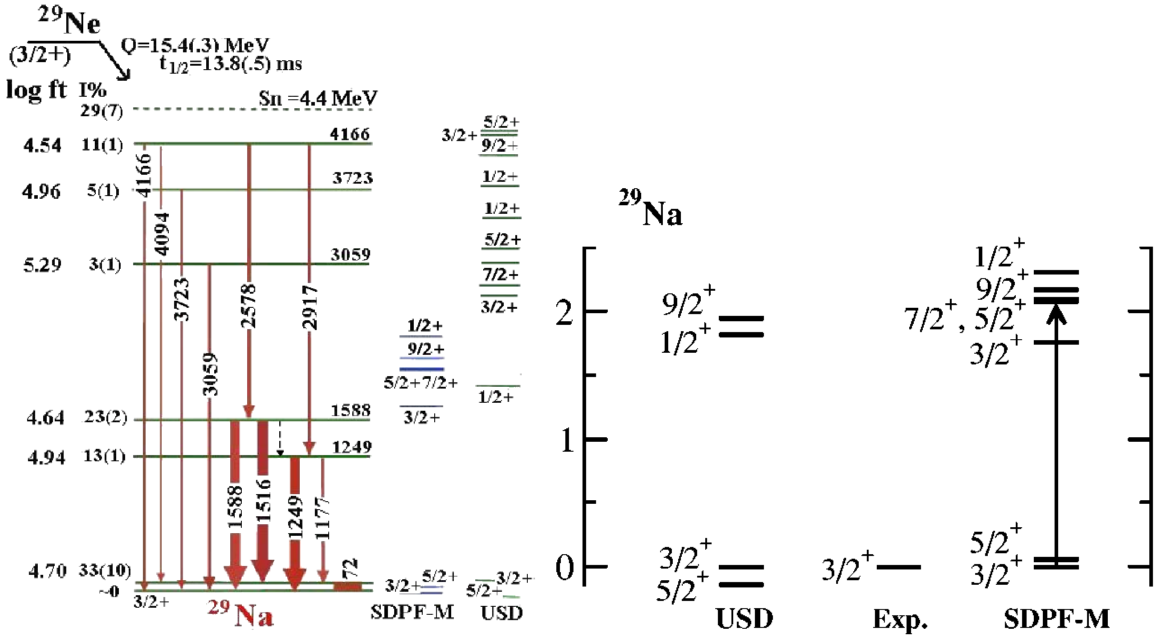


***Fig. 5:*** *The most recent level scheme of $^{29}$Na from β-decay experiments [Tri05] is given on the left side. The comparison of the energy levels of $^{29}$Na relative to the experimental ground state among the experiment (Exp.) and the shell-model calculations by the SDPF-M and the USD interactions is taken from ref. [Uts04]. A preliminary value for the E2 excitation of the first 5/2 energy level of $^{29}$Na is given by [Hur08]. The calculated E2 strength is given in the text and discussed with respect to the proposed experiment.*

In $^{29}$Na the ground state spin was determined to be J=3/2 [Hub78]. In β-decay experiments a first excited state was identified at 72 keV. MCSM calculations reproduce these close lying neighbouring states with spin values $3/2_1^+$ and $5/2_1^+$. The shell model calculation yields a large E2 excitation strength with a B(E2) value of $B(E2;\ 3/2_1^+ \rightarrow 5/2_1^+)$ =111-135 $e^2$fm$^4$. Higher lying excited $3/2_2^+$, $5/2_2^+$, $7/2_1^+$ states should be also governed by a large intruder admixture. These states are predicted around 2 MeV excitation energy. The related B(E2)-values are sensitive probes related to the intruder content and the shell gap. They can be experimentally verified; e.g. the MCSM value of $B(E2;\ 3/2_1^+ \rightarrow 7/2_1^+)$ =57 $e^2$fm$^4$ should be measurable with a sufficient beam intensity of more than $10^4$ part/s (see rate estimate below).

$^{30}$Na is the most crucial nucleus of the proposal. The observed two neutron separation energy shows no deviation from the USD model systematics at $^{30}$Na . The ground-state spin of *J*=2 [Hub78] can be explained by the USD model. The experimental magnetic moment of $^{30}$Na however deviates from the USD-model value (see Fig. 3). This deviation is resolved by the MCSM with the SDPF-M interaction as a consequence of the intruder ground state. Recently, the quadrupole moment has been measured [Kei00]. This value is different from the USD prediction and the new MCSM calculation with the SDPF-M interaction reproduces this quadrupole moment (see Fig. 3). The properties of the electromagnetic moments indicate that, in $^{30}$Na the ground state is dominated by the intruder configurations at *N*=19.

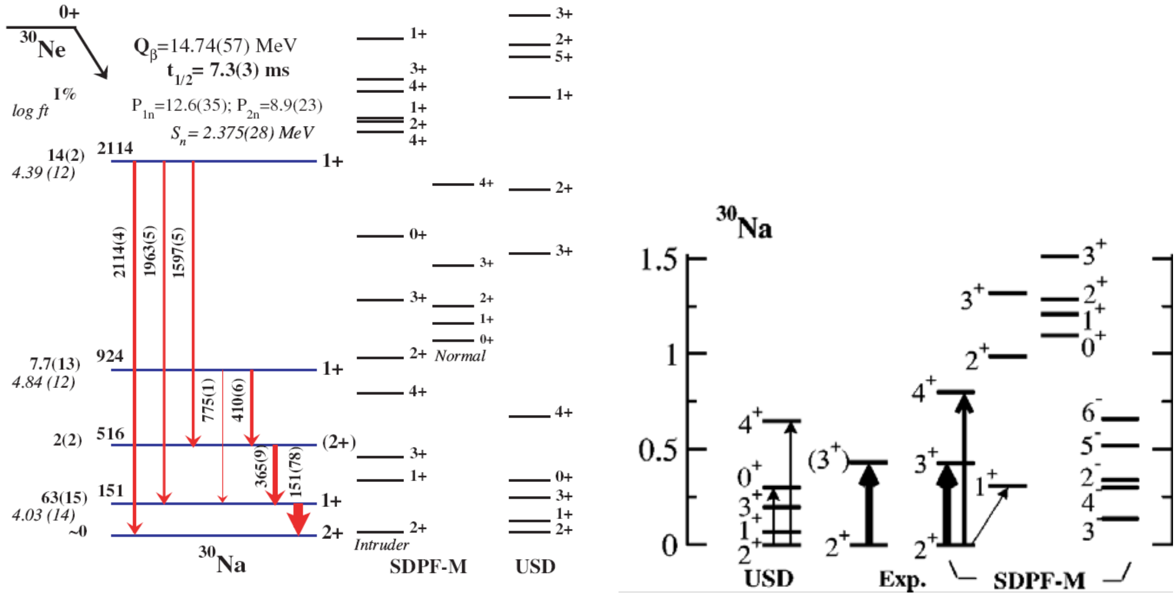


***Fig. 6:** The most recent level scheme of $^{30}$Na from β-decay experiments [Tri06] is given at the left side. The comparison of the energy levels of $^{30}$Na relative to the experimental ground state among the experiment (Exp.) and the shell-model calculations by the SDPF-M and the USD interactions is taken from ref. [Uts04]. Two values for the E2 excitation of the proposed 3+ energy level $^{30}$Na are given by [Pri02,Ett08]. The calculated E2 strength is given in the text and discussed with respect to the proposed experiment.*

The MCSM calculation yields a rotational band characterized by highly collective E2 inband transitions. The transition matrix elements amounts $B(E2;\, 2_1^+\rightarrow 3_1^+)$ =168 $e^2$fm$^4$ and $B(E2;\, 2_1^+\rightarrow 4_1^+)$ =90 $e^2$fm$^4$.The particle rotor model describes the strong prolate deformation with an intrinsic state which couples the deformed $^{28}$Ne rotor with a proton in the π[211]3/2$^+$ Nilsson orbit and the neutron in the ν[200]1/2$^+$ orbit. The MCSM-calculation predicts the K=2 Yrast band to be energetically favored with respect to the second possible K=1 Yrast band. The K=1 band head is calculated to be at 310 keV excitation energy. The new β-decay results show a 1$^+$ state at 150 keV which is a promising candidate for this band head. In a previous MSU experiment a transition energy of 433(16) keV was published with a $B(E2\uparrow)=130_{-65}^{+90}$ $e^2$fm$^4$ value. This γ-line is consistent with the decay of the first $3_1^+$ state. An independent measurement with high Ge energy resolution of the proposed $B(E2;\, 2_1^+\rightarrow 3_1^+)$ value would be an important goal of the proposed REX-ISOLDE experiment. The measurement of the $B(E2;\, 2_1^+\rightarrow 1_1^+)$ and $B(E2;\, 2_1^+\rightarrow 4_1^+)$ values should be feasible due to the high intrinsic quadrupole moment of the intruder state.

## Experimental setup and count rate estimate

The experimental instrument used with REX is the MINIBALL HP-Ge Array for in-beam γ-ray spectroscopy. The array consists of 24 6-fold segmented, encapsulated, HP-Ge detectors arranged in 8 triple cryostats. The detectors are mounted on an adjustable frame. The central core and six segment electrodes of each detector are equipped with a preamplifier with a cold stage and a warm main board. The charge integrated signals are subsequently digitized and analyzed online and onboard the DGF-4C CAMAC card. In addition to the MINIBALL array the annular charged particle detector telescope will be employed consisting of a 500 $\mu$m thick $\Delta E$ followed by a 500 $\mu$m thick $E$ detector. The $\Delta E$ detector is highly segmented (24x4 annular and 16x4 radial strips) to allow for a kinematic reconstruction of the events and covers an angular range from 15◦ to 50◦.

The proposed MINIBALL experiments with unstable beams of $^{28,29,30}$Na isotopes at REX-ISOLDE are from the ISOLDE point of view comparable with previous experiments employing $^{30,31,32}$Mg beams The ISOLDE values for Mg isotopes: 6 x $10^5$ ions/μC for $^{30}$Mg; 1.5 x $10^5$ part/s for $^{31}$Mg; and 3 x $10^4$ ions/μC for $^{32}$Mg. A recent REX-ISOLDE publication [Hab97] refers to the equally high Na yields from ISOLDE which are summarized in Table 1. Considering the half lives of the isotopes the yields up to $^{30}$Na are high enough to perform Coulomb excitation experiments. The accelerator efficiency for the complete REX-ISOLDE chain from REX-trap to the MININBALL target were determined for various $^{30,31,32}$Mg beams to be reproducible between 6%-10%. These values would imply average beam intensities around 1.6-0.8 x $10^5$ part/s for $^{28}$Na; 2.5-1.2 x $10^4$ part/s for $^{29}$Na; and 8-4 x $10^3$ part/s for $^{30}$Na. Indeed a beam of $^{29}$Na has already been accelerated with >$10^4$ part/s of $^{29}$Na at the MINIBALL target [ISO08].

| element | A | half life | Accelerator | Ions/μC | target material |
|---|---|---|---|---|---|
| Na | 28 | 30.5 ms | PSB | 9.6E+05 | $UC_x$ |
| Na | 29 | 44.9 ms | PSB | 1.5E+05 | $UC_x$ |
| Na | 30 | 48 ms | PSB | 5.1E+04 | $UC_x$ |

***Table 1****: ISOLDE beam intensity for $^{28,29,30}$Na isotopes from [Hab97].*

Coulomb excitation will be done at ‘safe’ energies of 3.0 Mev/u below the Coulomb barrier. There is no need to include effects from nuclear excitation which was done for two results obtained at intermediate beam energy at MSU. The most relevant improvements of the proposed measurement: (i) the high energy resolution of the MINIBALL HPGe detectors, (ii) the enlarged energy range for γ-ray detection, which is going down in a reliable and controlled way to a lower threshold of 50 keV and the (iii) good efficiency of the 8 triple cluster detectors of MINIBALL.

In order to probe the theoretical predictions of given matrix elements in the three $^{28,29,30}$Na isotopes and in order to check the competitiveness of the REX-ISOLDE-MININBALL setup a rate estimate was performed based on the following assumption. The beam intensity for $^{28,29,30}$Na were based on the measured value for $^{29}$Na and the two beam intensities for the neighbouring $^{28,30}$Na isotopes were calculated using the relative ISOLDE yields and assuming the same REX-EBIS efficiency. As target material $^{107,109}$Ag was used with a thickness of 4.0 mg/cm2 like in the previous experiments. The cross section for the direct excitation of the various states in $^{28,29,30}$Na were calculated with the Coulomb excitation code CLX. A beam energy value of 3.0 MeV/u was used. The cross section for projectile excitation while scattering into a certain angle was integrated for particle detection in the solid angle range covered by the CD detector. For γ-ray detection the measured energy dependent γ-efficiency was included. Effects of unknown E2/M1 admixtures, γ-ray angular distribution and possible branching ratios of excited states were neglected in the estimate.

For each nucleus out of $^{28,29,30}$Na two theoretical B(E2) values from MCSM calculations were given by Utsuno [Uts04]. We did not include the value for the $3/2_1^+ \rightarrow 5/2_1^+$ transition in $^{29}$Na which was already measured at TRIUMF recently. For the unknown $3/2_1^+ \rightarrow 7/2_1^+$ transition in $^{29}$Na a range for the transition energy of 1.5-2.0 MeV was considered. Here the energy value of 2.0 MeV would yield a photopeak line with 120 cts. This number is approaching the detection limit for a 72 hours experiment and corresponds to an integrated cross section of 14 mb for Coulomb excitation triggered by γ-particle coincidences in our setup. A similar case is given in $^{30}$Na where the unknown $2_1^+ \rightarrow 4_1^+$ transition is predicted by theory around 860 keV. This case is more advantageous due to the lower transition energy and the theoretical value should be in reach of the experiment. Even a five times lower cross section of ~30 mb should result in a peak of 100 counts. This level of sensitivity would be needed for an improved test and successful search for the $4_1^+$ state in $^{30}$Na. A very recent experiment at MSU did not confirm the calculated $B(E2;\, 2_1^+ \rightarrow 4_1^+) = 90$ $e^2$fm$^4$ and did not observe this $2_1^+ \rightarrow 4_1^+$ transition.

| | Primary ISOLDE yield (atoms/s) | REX beam intensity at MINIBALL (atoms/s)<br>*** measured** | Transition/ energy<br>**** unkown** | B(E2) values $e^2$fm$^4$<br>**theory** | integrated Coulex x-section (mbarn) | Events in the photopeak Count rate in hours | | shifts |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Cts/h | Cts/72 h | |
| **$^{28}$Na** | $9.6\times10^5$ | $> 7\times10^4$ | $1_1^+ \rightarrow 2_2^+$<br>1255 keV | 69 | 71 | 57 | 4090 | **6** |
| **$^{28}$Na** | $9.6\times10^5$ | $> 7\times10^4$ | $1_1^+ \rightarrow 3_2^+$<br>1131 keV | 47 | 40 | 32 | 2300 | |
| | | | | | | | | |
| **$^{29}$Na** | $1.5\times10^5$ | $> 1\times10^4$ * | $3/2_1^+ \rightarrow 5/2_1^+$<br>1255 keV | 120 | 360 | 43 | 3120 | **9** |
| **$^{29}$Na** | $1.5\times10^5$ | $> 1\times10^4$ * | $3/2_1^+ \rightarrow 7/2_1^+$<br>1.5-2.0 MeV ** | 57 | 36-14 | 1,7-4,3 | 120-310 | |
| | | | | | | | | |
| **$^{30}$Na** | $5.1\times10^4$ | $> 4\times10^3$ | $2_1^+ \rightarrow 3_1^+$<br>430 keV | 168 | 460 | 22 | 1580 | **9** |
| **$^{30}$Na** | $5.1\times10^4$ | $> 4\times10^3$ | $2_1^+ \rightarrow 4_1^+$<br>860 keV** | 90 | 160 | 7,6 | 550 | |

***Table 2**: Rate estimates and beamtime request.*

In conclusion, we request 8 days of beamtime for Coulomb exciation of the three sodium isotopes $^{28,29,30}$Na. Considering the beam intensities and the individual cases for each nucleus we ask for two days (6 shifts) of $^{28}$Na-, three days (9 shifts) of $^{29}$Na- and three days (9 shifts) of $^{30}$Na post-accelerated REX-ISOLDE beam at the MINIBALL target.

References:

[Ots01] T. Otsuka, et al., Phys. Rev. Lett. 87 (2001) 082502.
[Ots02] T. Otsuka, et al., Eur. Phys. J. A 13 (2002) 69.
[Gra03] H. Grawe, Acta Phys. Pol. B 34 (2003) 2267.
[Ots05] T. Otsuka, et al., Phys. Rev. Lett. 95 (2005) 232502.
[Nie05] O. Niedermeier et al., Phys. Rev. Lett. 94, 172501 (2005).
[Ney05] G. Neyens et al., Phys. Rev. Lett. 94, 022501 (2005).
[Mar05] F. Maréchal et al., Phys. Rev. C 72, 044314 (2005).
[Kim07] M. Kimura, Phys. Rev C 75, 041302(R) (2007).
[Klo93] G. Klotz et al., Phys. Rev C 47, 2502 (1993).
[Hub78] G. Huber et al., Phys. Rev. C 18, 2342 (1978).
[Uts04] Y. Utsuno et al., Phys. Rev. C 70, 044307 (2004).
[Tri05] V. Tripathi et al., Phys. Rev. Let. 94, 162501 (2005).
[Tri06] V. Tripathi et al., Phys. Rev. C 73, 054303 (2006).
[Pri02] B. V. Pritychenko et al., Phys. Rev. C 66, 024325 (2002).
[Kei00] M. Keim et al., Eur. Phys. J. A 8 (2000) 31.
[Hab97] D. Habs et al.; Nucl. Phys. A 616 (1997) 29.
[ISO08] http://isolde.web.cern.ch/ISOLDE/.
[Hur08] A. Hurst, Abstract of the DNP08 Meeting of The American Physical Society.
[Ett08] S. Ettenauer et al., Phys. Rev. C 78, 017302 (2008).