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Proposal to the INTC Committee

# Study of single particle properties of neutron-rich Na isotopes on the “shore of the island of inversion” by means of neutron-transfer reactions

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**Abstract:** We aim at the investigation of single particle properties of neutron-rich Na isotopes around the “shore of the island of inversion”. As first experiment of this programme, we propose to study excited states in the isotope $^{28}$Na by a one-neutron transfer reaction with a $^{27}$Na beam at 3 MeV/u obtained from REX-ISOLDE impinging on a CD$_2$-target. The $\gamma$-rays will be detected by the MINIBALL array and the particles by the

T-REX array of segmented Si detectors. The main physics aim is to identify and characterize low-lying negative parity states whose appearance reflect the breaking of $N = 20$ in this region. Relative spectroscopic factors will enable us to extract information on the configurations contributing to the wave functions of the populated states. These will be compared to recent shell model calculations involving new residual interactions. This will shed new light on the evolution of single particle structure and help to understand the underlying physics relevant for the formation of the “island of inversion”.

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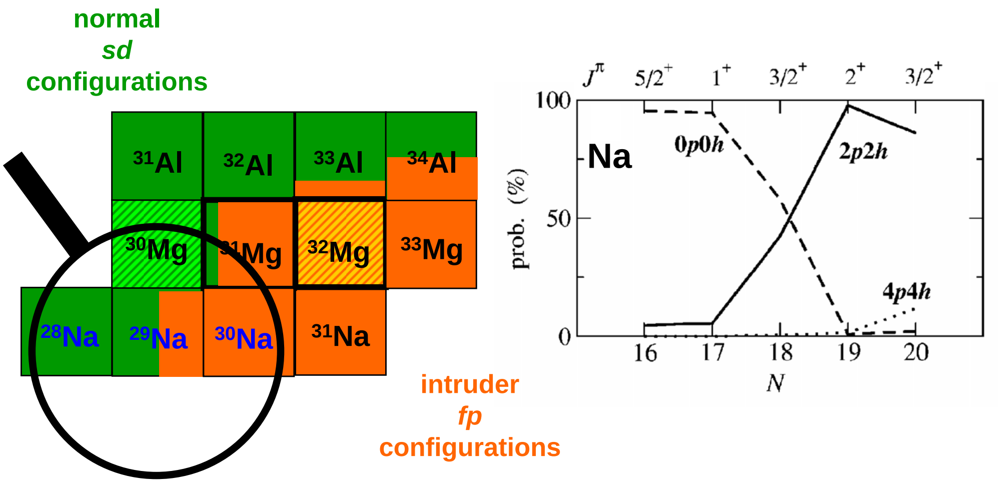

Figure 1: *Ground state wave functions on the "north-west coast" of the "island of inversion": normal (green) and intruder (red) contributions as extracted, except for* $^{30,32}$*Mg, from g-factors, for Refs. see text, (left) and predictions for the intruder contribution along the Na isotopic chain [1] (right).*

# 1 Physics case

For the last 60 years, the nuclear shell model has described successfully the existence of magic numbers for both neutrons and protons in stable nuclei. Experiments with radioactive beams have revealed that these magic numbers are not necessarily firm monuments of nuclear structure throughout the nuclear chart, but may be altered going away from the valley of stability as the interactions relevant for their existence change.

One of the classical regions to study such phenomena is the "island of inversion" for which first experimental evidence came from anomalies in the binding energies for nuclei around $A \approx 32$ [2, 3]. The magic shell closure at $N = 20$ for stable nuclei, e.g. in $^{40}$Ca, disappears going to neutron-rich nuclei. E.g. $^{28}$O is not even bound. Moreover, the last bound oxygen isotope $^{24}$O exhibits features of a doubly-magic nucleus, hence $N = 16$ has become a magic number [4]. Theoretically, this evolution can be explained by the monopole part of the tensor force, an attraction between protons and neutrons occupying spin-orbit-partner orbitals [5, 6]. As protons start to occupy the $d_{5/2}$-orbital from F to Ca, the $d_{3/2}$-orbital for neutrons is lowered. The $N = 16$ gap closes and the $N = 20$ gap opens. In between, no closed shell exists and neutron excitations to the $fp$-shell are energetically favoured causing the formation of the "island of inversion", a region of nuclei with deformed ground states in the sea of spherical $sd$-nuclei. The lowering of intruder $fp$-orbitals with respect to the $sd$-shell causes an inversion of spherical and deformed single particle configurations, allowing the latter to become the ground states.

However, the boundaries of this "island" are neither experimentally nor theoretically well established. The present knowledge based on experimental results for the ground states of nuclei on the "shore of the island" is sketched in the left part of Fig. 1.

The study of the nuclei around and within this "island" has been the aim of many experimental and theoretical investigations. Quite well studied is the chain of Mg isotopes. Although there are still open questions the results can be summarised in a way that $^{30}$Mg is outside the "island", then a steep transition into "island" happens going to $^{31}$Mg which has already more than 90% intruder configuration in its ground state wave function [18], and finally $^{32}$Mg is fully inside. This picture is based on experiments performed at (REX-)ISOLDE applying fast-timing, laser spectroscopy, $\beta$-NMR, Coulomb excitation, and transfer reactions, e.g. Refs. [7, 8, 9, 10, 11, 12, 13, 14, 15, 16], and elsewhere (RIKEN, GANIL, MSU), e.g. Refs. [17, 18, 19]. This picture is in good agreement with modern large scale shell model calculations using the conventional approach [20, 21, 18] or the Monte Carlo Shell Model (MCSM) [22, 23, 24, 25], but also with a beyond-mean-field approach [26].

Much less is known for the neighbouring isotopic chains of Na and Al, nearly all information comes from the study of g-factors. For Al isotopes, no significant intruder content is found for the ground states of $^{30,31,32}$Al [27, 28] whereas for $^{33}$Al neither experimental [29, 30] nor theoretical results [20, 21, 23, 31] on the intruder content of the ground state wave function are consistent. For $^{34}$Al, an intruder contribution larger than 50% has been found [32]. There is no experimental information available on the wave functions of excited states.

Similarly, the ground states of the neutron-rich Na isotopes have been studied. A much smoother transition from normal to intruder dominated wave functions has been found. The isotopes $^{27,28}$Na show no significant intruder configuration, whereas in $^{30,31}$Na the wave function is already completely intruder dominated. In between, for $^{29}$Na a 50%/50% mixture of the configurations has been found [33, 34]. In a recent study, excited states in the neutron-rich Na isotopes $^{27-30}$Na were populated in the $\beta$-decay of the respective Ne isotopes [35, 36]. The results are partially in agreement with theoretical predictions from the MCSM applying the SDFP-M interaction with the monopole part of the tensor force [1]. Applying the conventionally used USD interaction, similar predictions for $^{27,28}$Na have been obtained, of course only concerning the positive parity states.

However, the comparison of theoretical predictions and experimental results shows clear differences concerning the number and the excitation energies for higher-lying states. Additionally, no experimental spin assignments are available for the excited states. Therefore, no clear correspondence can be concluded.

We propose to study the properties of excited states in neutron-rich Na isotopes by one- and two-neutron transfer reactions. This information is complementary to results obtained by the other methods mentioned above. In particular, it has to be mentioned that in the run of experiment IS482 performed in August 2009 the collective properties of excited states in $^{29,30}$Na have been investigated in Coulomb excitation at REX-ISOLDE [37]. For experiments at REX-ISOLDE, the isotopes $^{28,29,30}$Na can be populated with sufficient statistics starting from beams of $^{27,28}$Na. Hence, the whole transition into the "island" can be covered. In the following, the knowledge on the structure of these nuclei will be discussed briefly.

The ground state and the first excited state in $^{27}$Na can be understood by assuming the last proton in the $d_{5/2}$ or $d_{3/2}$ orbital, respectively. By coupling with an additional neutron occupying the $d_{3/2}$ orbital to $^{27}$Na, the $1^+$ ground state and the first excited $2^+$

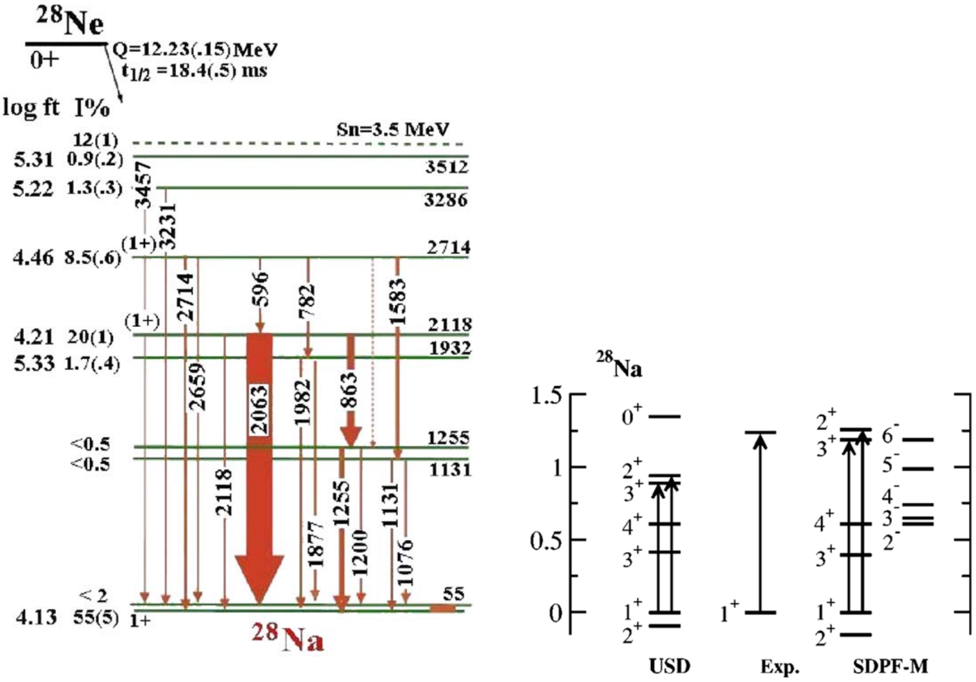

Figure 2: *Partial level scheme of* $^{28}$*Na as observed in the* $\beta$*-decay of* $^{28}$*Ne [35] (left) in comparison with predictions from shell model calculations using the USD and SDPF-M interactions [1] (right).*

state in $^{28}$Na can be interpreted. The experimental knowledge and the results of recent shell model calculations are shown in Fig. 2.

As a consequence of the weakening of the $N = 20$ shell closure caused by the monopole part of the tensor force, in $^{28}$Na low-lying negative parity states are predicted originating from the coupling of a neutron occupying an orbital of the $fp$-shell to the $^{27}$Na core [1]. So far, there exists no experimental information on these states. Their observation would allow to gain information on the position of the orbitals of the $fp$ shell and therefore on the size of the $N = 20$ shell gap.

In $^{29}$Na (Fig. 3, left), the ground state and the first excited state are again governed by the odd proton. However, as mentioned before, already 50% of the neutron component in the wave function corresponds to the excitation of a pair of neutrons to an intruder orbital in the $fp$ shell, as concluded from MCSM calculations applying the SDPF-M interaction. Predictions using the USD interaction obviously differ considerably. For the higher-lying states, some of them, e.g. the $1/2^+_1$ and $9/2^+_1$ states, are predicted to have a normal *sd* wave function of the neutrons. In contrast, other states, e.g. the $3/2^+_2$, $5/2^+_2$, and $7/2^+_1$ states, should contain a strong intruder component. Hence, there is a coexistence of both kinds of states at similar excitation energies.

Obviously, the predictions for $^{30}$Na using the two interactions differ even more (Fig. 3, right). Whereas calculations with the USD interactions explain the ground state by the

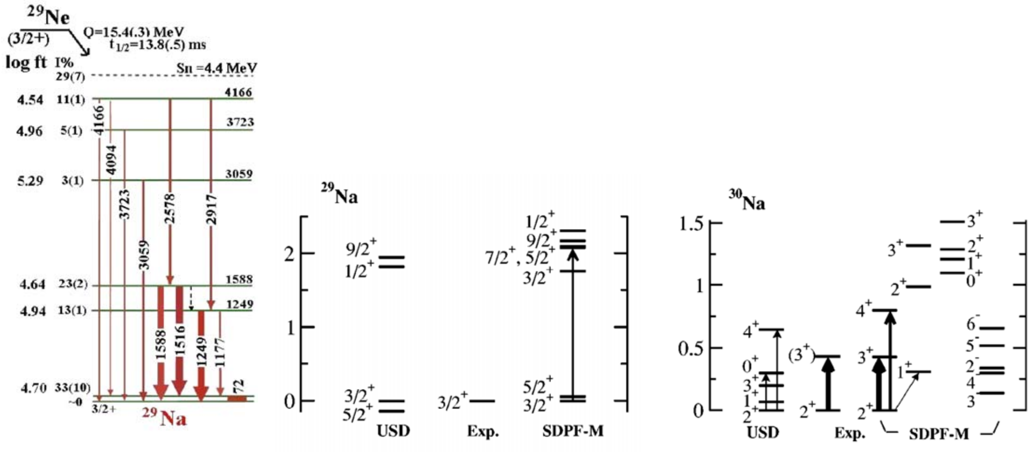

Figure 3: *Partial level scheme of $^{29}$Na as observed in the $\beta$-decay of $^{29}$Ne [35, 36] in comparison with predictions from shell model calculations using the USD and SDPF-M interactions [1]. Theoretical predictions for $^{30}$Na [1] (right)*

weak coupling of the $d_{3/2}$ neutron hole to the proton occupying the $d_{3/2}$ or $d_{5/2}$ orbital, the MCSM with the SDPF-M interaction predicts a strongly deformed ground state with a wave function dominated by intruder configurations. Both, low-lying positive and negative parity states are expected. Details on the mixing of normal and intruder configurations are given in Ref. [1].

Interestingly, this smooth transition into the “island of inversion” for Na is different to the neighbouring Mg isotopes where the transition is much steeper.

New information on the evolution of nuclear structure along the Na isotopic chain, in particular right at the boundary of the “island of inversion”, will further challenge modern shell model calculations and, eventually, improve the understanding of the underlying physics which causes the existence of the “island of inversion”.

## 2 Experimental method

Nucleon transfer reactions are a well established tool for the investigation of the single particle structure of nuclei. Relative spectroscopic factors extracted from transfer cross sections are a measure for the occupation numbers of single particle configurations (particles or holes). These can be directly compared to results from shell model calculations. Additionally, the neutron-pair transfer will allow the study of pairing correlations. The transferred orbital momentum leading to the spin assignment of a state is determined from the angular distribution of the particles.

The experience from experiments IS454 and IS470 has demonstrated that the selectivity of transfer reactions concerning the matching of kinematical conditions and nuclear structure indeed enables to draw conclusions on the structure of excited states and furthermore allows to populate states not accessible by other methods.

We propose to study the single particle structure of the neutron-rich sodium isotopes by neutron transfer reactions in inverse kinematics. The projectile-like nuclei are forward focussed in the laboratory system and cannot be measured with the current equipment (a 0°-spectrometer for HIE-ISOLDE is under development). We will measure the energies and angular distributions of the protons emitted from the (d,p) reaction in coincidence with $\gamma$-rays. Since the energy resolution obtained for the protons is usually not sufficient to disentangle states which differ by less than some 100 keV in excitation energy, the states populated in the reaction are identified by their characteristic $\gamma$-decay measured at high-resolution. This method has been demonstrated successfully in experiment IS454 [13].

The measured cross sections and angular distributions will be analysed in the frame of the DWBA applying the codes CHUCK [38] or FRESCO [39]. The optical potentials needed for this analysis can be scaled regarding mass of the projectile and beam energy from values fitted to experiments with stable beams applying a well established formula [40]. On the other hand, also the analysis of elastically scattered deuterons allows to fix the optical potential. The analysis of the respective data obtained in experiments IS454 (and IS470) is ongoing. Main problem are the low kinetic energies of the deuterons (and tritons) going down to zero towards 90°. This causes difficulties in the efficiency correction of the data. Therefore, the sensitivity of this method on the optical potentials is, so far, not clear.

The transfer to an odd-even (or odd-odd) nucleus is much more challenging compared to the transfer to an even-even nucleus. As the spin of the final state results from the coupling of the odd proton to the added neutron, its value cannot be deduced unambiguously from the measured orbital angular momentum transfer. This principle problem, of course, is true also for knock-out reactions at intermediate or relativistic energies, a possible alternative to the transfer reactions proposed here. However, applying such reactions the high-resolution $\gamma$-ray spectroscopy to assure an exclusive measurement for individual states is an additional challenge. Moreover, as discussed above, already the wave function of the beam nucleus may comprise different complex configurations and the expected statistics will not allow a detailed quantitative analysis of the spectroscopic factors aiming to pin down precisely the configurations. However, four kinds of information can be obtained, which already represent a data set which is rich of information:

- identification of new states from the proton energies and/or the decay $\gamma$-rays;
- determination of the transferred orbital angular momentum from the angular distribution of the protons. This will allow to distinguish transfers to normal orbitals from the *sd* shell from those to intruder orbitals from the *fp* shell. Intrinsically, this assigns already the parity of the populated states;
- the decay pattern of the populated states and the angular distribution, if statistics allows, of the $\gamma$-rays may allow to draw some conclusions concerning the spin assignments;
- the spectroscopic factors, measured relative to the spectroscopic factor for the ground state whose wave function is quite well known, will allow to identify directly states having a different neutron configuration, e.g. caused by the promotion

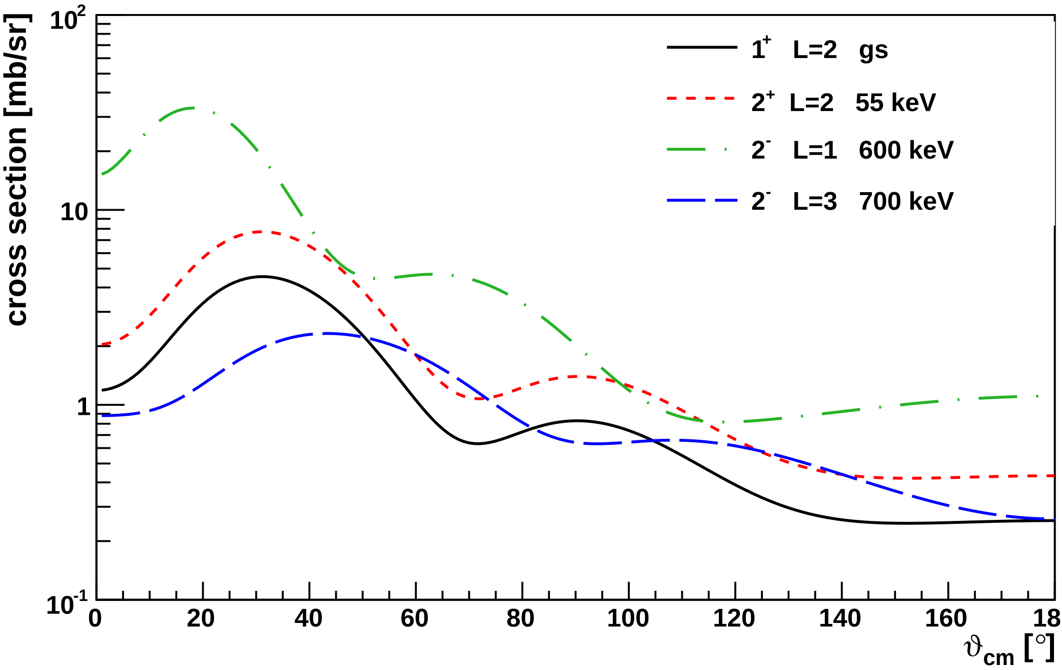

Figure 4: *Calculated angular distributions in the centre-of-mass system of the protons following a d($^{27}$Na,$^{28}$Na)p reaction at approximately 3 MeV/u. Reaction channels with orbital angular momentum transfer of* $\Delta\ell = 1, 2, 3$ *are shown.*

of a pair of neutrons, by a reduced spectroscopic factor. E.g. if the populated excited states in $^{28}$Na have, compared to the well-known ground state, reduced spectroscopic factors, this indicates an increasing intruder content in the wave function.

As example in Fig. 4 the calculated angular distribution of protons after populating states in $^{28}$Na by a (d,p) reaction are shown. The $1^+$ ground state, in the simplest configuration, can be reached by transferring the neutron to the $d_{3/2}$ orbital ($\Delta\ell = 2$). The corresponding angular distribution is well distinguishable from the population of a $2^-$ state (assumed at 600 keV or 700 keV excitation energy, respectively) whose configuration will involve a neutron occupying an intruder orbital. Shown are the transfers to the $p_{3/2}$ ($\Delta\ell = 1$) or $f_{7/2}$ ($\Delta\ell = 3$) orbitals. All spectroscopic factors in this calculation were set to unity.
At this point we would like to reiterate some arguments already discussed in the proposals of experiments IS454 and IS470 [41, 42]. A beam energy of 3 MeV/u is still low compared to the higher energies normally used in order to assure that the levels are populated only by direct reactions like transfer and not by fusion-evaporation reactions with the deuterium. A fusion reaction as statistical process usually populates, after particle emission, high-lying states where the level density is large (Q-value for fusion of the beam with deuterium is around 20 MeV). Therefore, the experimental signature is very different from that of a direct reaction: statistical energy spectrum of the protons and feeding of low-lying states mainly by cascades of $\gamma$-rays. Requiring in the analysis coincidences of $\gamma$-transitions with discrete proton lines having the correct kinematics enables to minimise contributions from non-transfer processes. Hauser-Feshbach-calculations for the similar

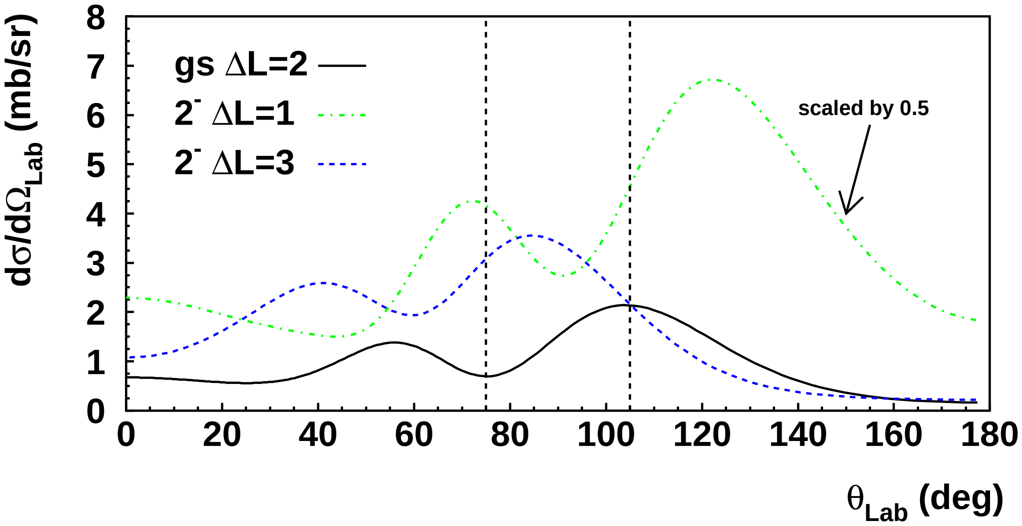

Figure 5: *Calculated angular distributions in the laboratory system of the protons following a d($^{27}$Na,$^{28}$Na)p reaction at approximately 3 MeV/u. Reaction channels with orbital angular momentum transfer of* $\Delta\ell = 1, 2, 3$ *are shown. The "blind" zone of the current configuration of T-REX is indicated.*

reaction d($^{30}$Mg, $^{31}$Mg)p also have shown that even at 2.2 MeV/u such compound contributions should be small for neutron-rich nuclei. This can be understood due to the fact that the separation energy increases with neutron number for protons and decreases for neutrons. Therefore, the emission of protons compared to neutrons is suppressed. And, in fact, such protons have not been observed experimentally [43].

The programme will be continued by investigating $^{29}$Na with a (d,p) reaction starting from $^{28}$Na. This is more challenging as the beam intensity is lower by a factor of 10 and the cross sections are expected to be reduced because of more mixed wave functions.

Of course, it is also worth to think about using a (t,p) reaction to map the transition into the "island of inversion" by identifying spherical states in $^{29,30}$Na starting from the spherical ground state of $^{27,28}$Na as it has worked nicely in experiment IS470 for the $^{30}$Mg to $^{32}$Mg case. Unfortunately, these reactions have negative Q-values of -0.52 MeV and -1.69 MeV. Therefore, they are kinematically disfavoured and, even more difficult, the outgoing protons have very low energies and will be practically only in forward direction observable. The decision whether such an experiment is feasible, and will be proposed to the INTC, will be postponed until the analysis of experiment IS470 is finished.

## 3 Experimental set-up

The set-up consists of the MINIBALL array to detect $\gamma$-rays in coincidence with particles detected by the new array of segmented Si detectors T-REX [44] (see Fig. 6).

The full set-up of T-REX comprises two double-sided segmented Si detectors (DSSSD),

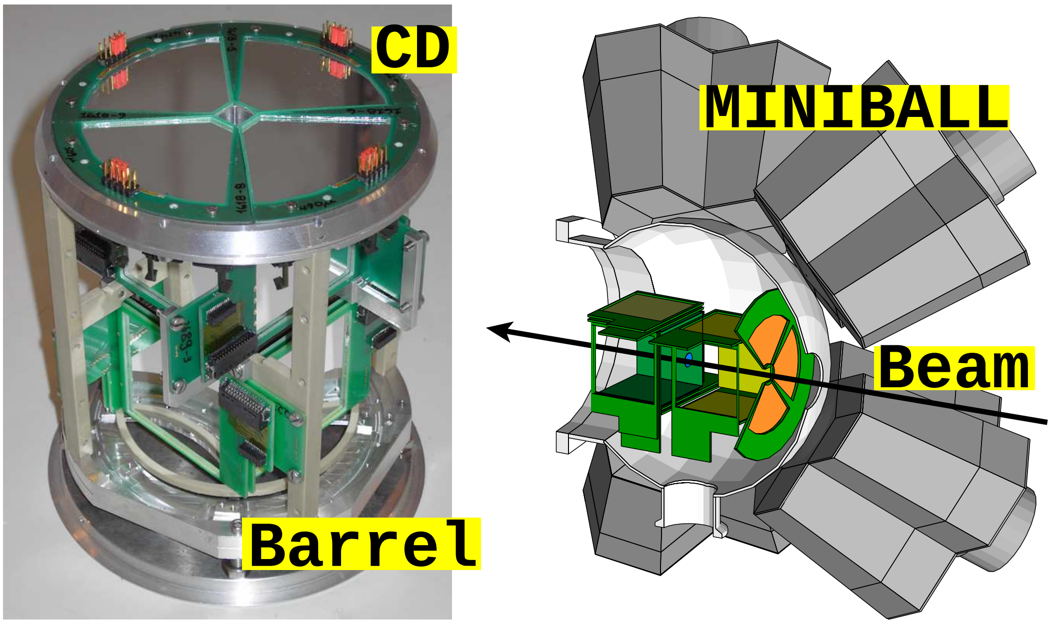

Figure 6: *Photo (left) and drawing mounted inside of MINIBALL (right) of the T-REX Si array.*

so-called CD detectors, in forward and backward direction and a barrel of eight planar detectors around 90° (the forward CD is missing in Fig. 6).

All detectors consist of two layers, thus they act as a $\Delta E - E$-telescope. This enables to distinguish light ions (p,d,t,$\alpha$) from elastic scattering and transfer reactions but also to identify electrons originating from the $\beta$-decay of scattered beam particles implanted in the scattering chamber.

Each CD detector is divided into four quadrants. The $\Delta E$-detectors (thickness 500 $\mu$m) are segmented in 16 annular stripes ($\vartheta$-coordinate) on the front and in 24 radial segments ($\phi$-coordinate) on the back. The $E$-detector (thickness 500 $\mu$m) is not segmented.

The barrel is formed by eight square detectors. The $\Delta E$-detector (thickness 140 $\mu$m) is segmented in 16 stripes perpendicular to the beam axis. Positional information along the stripes can be obtained from the charge division on a resistive layer. The $E$-detector is not segmented and has a thickness of 1000 $\mu$m.

The detectors in forward direction are protected by a Al or aluminised Mylar foil to stop both the scattered beam particles and recoiling C nuclei from the target.

The energy resolution for the protons ranges from 250 keV to 2 MeV depending on angle and energy. The angular resolution is typically below 5°.

However, as it can be seen in Fig. 5 which shows the cross section from Fig. 4 transformed into the laboratory system, quite some useful information and cross section is lost in the "blind" zone around 90°. Therefore, we intend to change the configuration of the barrel detectors on two sides of the barrel (the other two have to have the gap to allow the target ladder to enter). This will be done by either just closing the gap as much as technically possible or by mounting only one detector per side centred at 90°.

Since Na beams are not pure beams, the composition of the beam has to be determined and monitored. The Bragg chamber [45] or the IC - Si telescope, both can be mounted within the beam dump, are well suited for this purpose.

The main isobaric contaminants are the respective Mg isotopes from the $\beta$-decay of Na and the Al isotopes. From the experience in the 2009 run of experiment IS482 we expect a strong contamination with Al. Although the production rate of Al has its maximum at $A = 29$, for the lighter isotopes still a considerable rate is present. Since the half-lives of the Al isotopes ($^{27}$Al: stable, $^{28}$Al: 2.24 m) are considerably longer than those of the Na isotopes, the latter can be selected by a time gate covering only an appropriate period directly after the proton impact.

T-REX including the electronics has been funded and built by TU München (Germany), KU Leuven (Belgium), CSNSM Orsay (France), CERN (Switzerland), and the UK groups involved in MINIBALL. In the future, contributions will also come from TU Darmstadt (Germany).

# 4 Proposed experiment

The $^{28}$Na isotope will be populated by a one-neutron transfer reaction with a CD$_2$-target (deuterated PE foil), i.e. $^{2}$H($^{27}$Na, $^{28}$Na)$^{1}$H.

The Q-value for this reactions is positive, 1.32 MeV (for comparison even 2.19 MeV for the $^{2}$H($^{28}$Na, $^{29}$Na)$^{1}$H reaction), hence the population of states in the region of interest is kinematically favoured.

Other reaction channels like (d,t) ($Q = -0.47$ MeV) or (p,d) ($Q = -4.07$ MeV) have negative Q-values, therefore and because of the mass transfer to the target nuclei none of them is observed in backward direction (in the laboratory system).

The Q-value for the respective (d,p) reaction with Al is 5.50 MeV, hence high-lying states will be populated preferentially. The level scheme and the $\gamma$-rays of $^{28}$Al are well known [47], therefore the $\gamma$-rays from the (d,p) reaction with Al can be identified and distinguished from those originating from Na.

The $^{27}$Na isotopes are produced with a standard UC$_x$/graphite target. Previously, Na ions have been produced by surface ionisation. Also Al is an element which is surface-ionised (ionisation potential 5.98 eV compared to 5.14 eV for Na), and therefore cannot be suppressed easily. A laser ionisation scheme for Na exists and has been tested [46], but so far the RILIS has not been used for the production of a Na beam. Although this is not mandatory for the proposed experiment, the use of the more selective laser ionisation would be advantageous, because the increased efficiency for Na would enhance the Na/Al ratio.

# 5 Beam time request

We would like to study the single particle properties of the neutron-rich isotope $^{28}$Na populated by a one-neutron transfer reaction. In order to extract the relevant spectroscopic information a sufficient statistics in proton-$\gamma$-coincidences is necessary.

The efficiencies are $\epsilon_{\mathrm{part}} = 62\%$ for the particle detector and an average $\epsilon_{\mathrm{MINIBALL}} = 8\%$ ($\gamma$-energies between 50 keV and 2000 keV are of interest) for $\gamma$-detection in the photopeak with MINIBALL. The target will be a $CD_2$ foil (deuterated PE foil) of 5 $\mu$m thickness. Conservatively, we estimate a beam intensity on target of $2{\cdot}10^5$ $s^{-1}$ for $^{27}$Na. This estimate is based on the rates obtained for $^{29,30}$Na during the run of experiment IS482 in August 2009 which have been scaled with the larger production yields given in the ISOLDE data base.
From DWBA calculations (spectroscopic factor set to unity) typical cross sections are at least around 20 mb. This translates into a proton rate of 400/h for the population of a state in $^{28}$Na. The respective rate of proton-$\gamma$-ray coincidences will be 30/h. The total statistics in 4 days will be around 3000 counts. However, a possible intruder configuration in the final states will lower the spectroscopic factor and therefore the yields.
One aim of this experiment is to measure angular distributions of the protons in coincidence with $\gamma$-rays. In order to obtain a statistical error below 10%, sufficient to distinguish the different orbital angular momentum transfers, 100 counts per angular bin are needed. Hence, in 4 days of beam time the statistics will allow to subdivide the angular range covered by T-REX in 10 angular bins, each covering around 10°.
It is well worth mentioning that the $\gamma$-rate will be much higher than that obtained in the $\beta$-decay experiments [35, 36] where statistics in the order of 50 counts per peak has been measured ($\beta$-gated $\gamma$-rays). Even for $^{29}$Na populated by the (d,p) reaction an experiment at REX-ISOLDE would improve the statistics by an factor of about 5.
For completeness, it has to be noted that the (d,p) reaction on $^{27}$Na has been proposed also as part of a proposal at TRIUMF for ISAC-2 [48]. However, the beam intensity for $^{27}$Na there is expected to be at least 20 times smaller ($10^4$ $s^{-1}$) and the cross sections at 4.5 MeV/u are also 30-50% smaller (concerning the cross section, 3 MeV/u is the optimal energy for (d,p) reactions in this mass region [49]). To our knowledge the experiment has not been performed so far. Conclusively, the experiment proposed here for REX-ISOLDE can be expected to yield much better statistics. The next steps, (t,p) reactions and the use of a $^{28}$Na beam, are only possible at REX-ISOLDE taking into account the smaller cross sections and/or the smaller beam intensities.
In this proposal we request only beam time for the first experiment of our programme with the reaction $^2$H($^{27}$Na, $^{28}$Na)$^1$H in order to investigate the feasibility to extract spectroscopic information from the transfer to an odd-even nucleus in inverse kinematics at REX-ISOLDE. Concerning the physics case, the observation of negative parity states in $^{28}$Na would provide, as explained above, a very valuable piece in the understanding of the formation of the "island of inversion". Each of the further reactions discussed above to study $^{29,30}$Na isotopes requires a beam time in the order of 10 days, but for more reliable estimates we feel that we need first the outcome of the proposed experiment (and, of course, the final results from IS454 and IS470) and postpone the request to an addendum. Based on these estimates and the experience from our previous transfer experiments (IS454 and IS470), we request 4 days of beam time with a $^{27}$Na beam plus 1 day for preparing the beam. Additionally, we would like to apply laser ionisation to prepare the Na beam, although this is not mandatory for the experiment and we are well aware of the large demand for the RILIS.
**We request in total 15 shifts (5 days) of beam time.**

# References

[1] Y. Utsuno et al., Phys. Rev. C 70, 044307 (2004).

[2] C. Thibault et al., Phys. Rev. C 12, 644 (1975).

[3] E. K. Warburton et al., Phys. Rev. C 41, 1147 (1990).

[4] R. Kanungo et al., Phys. Rev. Lett. 102, 152501 (2009).

[5] T. Otsuka et al., Eur. Phys. J. A 15, 151 (2002).

[6] T. Otsuka et al., Phys. Rev. Lett. 95, 232502 (2005).

[7] H. Mach et al. Eur. Phys. J. A 25, s01, 105 (2005).

[8] O. Niedermaier et al., Phys. Rev. Lett. 94, 172501 (2005).

[9] O. Niedermaier, PhD Thesis (Univ. Heidelberg, 2006); to be published.

[10] G. Neyens et al., Phys. Rev. Lett. 94, 022501 (2005).

[11] M. Kowalska, PhD thesis (Universität Mainz, 2006).

[12] M. Seidlitz, Diploma Thesis (Universität zu Köln, 2008).

[13] V. Bildstein, ISOLDE Workshop 2008; PhD Thesis (TU München, expected for 2009).

[14] K. Wimmer, ISOLDE Workshop 2008; PhD Thesis (TU München, expected for 2010).

[15] W. Schwerdtfeger et al., Phys. Rev. Lett. 103, 012501 (2009).

[16] Th. Kröll et al., AIP Conf. Proc. 1165, 363 (2009).

[17] T. Motobayashi et al., Phys. Lett. B 346, 9 (1995).

[18] F. Maréchal et al., Phys Rev. C 72, 044314 (2005).

[19] J. A. Church et al., Phys. Rev. C 72, 054320 (2005).

[20] E. Caurier et al., Phys. Rev. C 58, 2033 (1998).

[21] E. Caurier et al., Nucl. Phys. A 693, 374 (2001).

[22] Y. Utsuno et al., Phys. Rev. C 60, 054315 (1999).

[23] Y. Utsuno et al., Phys. Rev. C 64, 011301(R) (2001).

[24] T. Otsuka et al., Eur. Phys. J. A 13, 69 (2002).

[25] Y. Utsuno et al., Nucl. Phys. A 704, 50c (2002).

[26] R. Rodríguez-Guzmán et al., Nucl. Phys. A 709, 201 (2002).

[27] D. Borremans et al., Phys. Lett. B 537, 45 (2002).

[28] H. Ueno et al., Phys. Lett. B 615, 186 (2005).

[29] A. C. Morton et al., Phys. Lett. B 544, 274 (2002).

[30] P. Himpe et al., Phys. Lett. B 643, 257 (2006).

[31] E. Caurier et al., Eur. Phys. J. A 15, 145 (2002).

[32] P. Himpe et al., Phys. Lett. B 658, 203 (2008).

[33] M. Keim et al., Eur. Phys. J. A 31, 8 (2000).

[34] G. Neyens et al., Eur. Phys. J. ST 150, (2007).

[35] V. Tripathi et al., Phys. Rev. Lett. 94, 162501 (2005).

[36] V. Tripathi et al., Phys. Rev. C 63, 054303 (2006).

[37] P. Reiter et. al., proposal CERN-INTC-2008-039, INTC-P-252 (2008).

[38] *http://spot.colorado.edu/˜kunz/DWBA.html*

[39] I. J. Thompson, Comput. Phys. Rep. 7, 167 (1988).

[40] H. Feshbach, "Theoretical Nuclear Physics: Nuclear Reactions" (Wiley, 1992).

[41] Th. Kröll et al., proposal CERN-INTC-2006-013, INTC-P-156 (2006).

[42] Th. Kröll et al., proposal CERN-INTC-2008-008, INTC-P-239 (2008).

[43] M. Pantea, PhD Thesis (TU Darmstadt, Germany).

[44] V. Bildstein et al., Prog. Part. Phys. 59, 386 (2007).

[45] W. Weinzierl, Diploma Thesis (TU München, 2006).

[46] U. Köster et al., Spectrochimica Acta Part B 58, 1047 (2003).

[47] *http://www.nndc.bnl.gov*

[48] W. N. Catford et al., TRIUMF - EEC Research Proposal S1101_200607S-2 (2006).

[49] H. Lenske, G. Schrieder, Eur. Phys. J. A 2, 41 (1998).