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

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

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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, we propose to study ^{29}Na by a ^{28}Na (d,p) reaction at 3 MeV/u. The γ-rays will be detected by MINIBALL and the particles by T-REX. The main physics aims are to extract from the relative spectroscopic factors information on the configurations contributing to the wave functions of the populated states and, secondly, to identify and characterize negative parity states whose excitation energies reflect directly the N = 20 gap in this region. The results 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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Remaining shifts: 33

1. Motivation, experimental setup/technique

The study of the nuclei around and within the "island of inversion" has been the aim of many experimental and theoretical investigations since its discovery more than 40 years ago at CERN [1]. However, there are still open problems in the understanding how the island is formed. Quite often the chain of Mg isotopes has been studied, e.g. studies at ISOLDE with both low-energy and post-accelerated beams applying several complementary experimental approaches like β-NMR, laser spectroscopy, decay spectroscopy including fast timing and conversion electrons, Coulomb excitation and nucleon-transfer experiments [2-7]. Demonstrating the ongoing strong scientific interest in this region and the importance of nucleon-transfer reactions in this field, only in 2018 two new experiments at HIE-ISOLDE, ^{28}Mg(d,p) with ISS (IS651) and ^{28}Mg(t,p) with MINIBALL+T-REX (IS621), have been performed successfully.

Much less is known about the neighbouring Al and Na isotopes (list of older references in the original proposal). In particular, the properties of the nuclei at the border of the island are not well studied. Shell model calculations predict a much smoother transition into the island for Na compared to Mg with a 50%/50% mixture of normal sd-orbitals and intruder fp-orbitals in ^{29}Na, the nucleus just at the border. The level scheme of ^{29}Na known so far and predictions from theory do not agree well (see references in the original proposal [8]).

We propose to study the properties of excited states in neutron-rich Na isotopes with ^{29}Na as first experiment by a one-neutron transfer reaction. The obtained information is complementary to results from other methods like fast-timing, laser spectroscopy, β-NMR but also to results from Coulomb excitation performed at REX-ISOLDE (IS482) [9,10].

Excited states in ^{29}Na will be populated by a (d,p) reaction in inverse kinematics employing a CD_2 target. The protons will be detected by the T-REX Si array [11]. For the period after LS2, an improved version of T-REX consisting only of highly-segmented DSSSDs will be available. The ΔE-E telescopes allow for an identification of protons, deuterons and tritons and the different kinematics distinguishes elastically scattered protons (the target contains some hydrogen) from reaction products. From the angular distribution the transferred orbital angular momentum (and therefore also the parity) deduced and from the cross sections "empirical spectroscopic factors" can be determined by comparison with DWBA calculations. The optical potentials are obtained by extrapolation of systematics or a fit to the scattering data, see e.g. [12]. As the energy resolution for the protons is only moderate, the populated states are identified by their characteristic γ-decay measured with MINIBALL [13]. Of particular interest are the negative parity states in ^{29}Na which are experimentally not known so far. Their excitation energy is a direct measure of the shell gap at N=20. Theory predicts for these states large spectroscopic factors, hence the cross section starting from the normal ground state of ^{28}Na and adding a neutron to the empty intruder orbitals will be large. In conclusion, one-neutron transfer reactions are a promising tool to investigate this nucleus.

A detailed discussion of the motivation, the method and the experimental set-up with all references can be found in the original proposal [8]. This proposal has been re-evaluated positively already in 2015 [14].

2. Status Report

In the beginning of REX, Na beams were available with very good intensities, e.g. ^{25}Na with 10^6/s. The ^{25}Na(d,p) reaction was one of the first transfer reactions studied at REX with MINIBALL [15]. In the later years, the intensities of neutron-rich Na isotopes were much lower than before. Several experiments, like e.g. IS482, suffered from this fact. With these intensities only Coulomb excitation could be studied [9,10].

	^{26}Na	^{29}Na	^{30}Na
2009		2700(100)	650(250)
2010			< 140
2011	64000(5000)		60

Table 1: Intensities of secondary Na beams on target in particles/s (IS482).

IS502 requested 3 times the beam time in 2010/11/12, but so far the required intensity of 20000/s on target was out of reach and the experiment could not be scheduled.

The originally proposed beam energy of 3 MeV/u is still the preferred value. From the past experience with one- and two-neutron transfer reactions with radioactive ion beams in the region of the "island of inversion" have shown that the angular distributions are well pronounced and allow for the determination of the transferred orbital angular momentum. DWBA calculations performed already in the beginning of REX showed that the cross section is maximal at 3 MeV/u [16].

A higher beam energy furthermore increases the yield of charged particles originating from fusion-evaporation reactions with the ^{12}C in the CD_2 target. E.g. doubling the beam energy to 6 MeV/u increases the number of protons by a factor of 3 and the number of alpha particles by 50%. However, since the total numbers are small, the increase of background will not be dramatic.

A profit from a higher beam energy, to be honest, are the higher energies of the protons, in particular in backward direction which would allow for a better separation from the background and the noise. If the better separation pays off with the smaller yield cannot be decided a-priori as the spectroscopic factors are not known, the measurement of the spectroscopic factors is in fact the aim of the experiment.

Also the use of an even thicker target may be discussed (in the original proposal a target of 1 mg/cm^2 thickness was assumed). This would result in a higher count rate, but also in a larger energy loss and straggling in the target affecting the detection of the protons in backward direction. The latter two effects may partially be compensated by choosing a higher beam energy which on the other hand reduces the cross section.

In order to have a more quantitative estimate for the expected spectroscopic factors, we calculated them applying the spdf-m interaction (refs. the original proposal). We find that the single-particle strength is quite fragmented. However, large values in the range C^2S=0.2-

0.5 are predicted indeed only for the population of 5 negative parity states with spin $3/2^-$ to $9/2^-$ (compare to right part of Fig. 2 in the original proposal). For positive parity states, only the second $3/2^+$ state, predicted at an excitation energy of around 1.6 MeV, has a similar spectroscopic factor of $C^2S=0.17$, all other are smaller by a factor 2 or more.

Meanwhile, with ISS ("ISOLDE solenoidal spectrometer") a second experimental set-up dedicated to the study of nucleon-transfer reactions became operational in 2018. The achievable energy resolution of about 100 keV is better than with T-REX, but still much worse compared to gamma-ray spectroscopy with MINIBALL. However, the drop in statistics requiring an additional gamma-ray has to be taken into account. In particular in nuclei with odd neutron and/or proton number the level density is higher which requires the higher resolution offered by MINIBALL. This is not plain theory ... already in the commissioning of ISS, it turned out that e.g. the doublet in ^{29}Mg at 3223.7 keV and 3227.5 keV (no or only tentative spin-parity assignment) populated in ^{28}Mg(d,p) could not be resolved. Although an energy resolution in the order of 4 keV at 3 MeV is out of reach also for MINIBALL, the very different decay patterns of the two states would have enabled an analysis of the angular distributions of the protons populating the two states.

As the level scheme in ^{29}Na is not known well, we would like profit from the higher resolution offered by coincident gamma-ray spectroscopy. In addition, as the angular distribution only allows for conclusions on the orbital momentum transfer Δl, the decay pattern can help in doing spin-parity assignments.

Neutron-rich Na isotopes have been studied in the recent years by decay spectroscopy and direct reactions at TRIUMF, GANIL and NSCL which will summarised in the following.

The heaviest Na isotope studied so far in a transfer reaction is ^{26}Na by the ^{25}Na(d,p) reaction at TRIUMF (5 MeV/u, $3x10^7$/s) with the TIGRESS+SHARC set-up (very similar to MINIBALL+T-REX) [17]. Applying the same analysis of particle-gamma-ray coincidences the population of 16 excited states has been measured. For 7 of them the statistics was sufficient to analyse angular distributions and extract spectroscopic factors. Of particular interest were the 3^- and 4^- states where in comparison with the isotone ^{28}Al the enhanced importance of the $p_{3/2}$ orbital is evidenced by the relative spectroscopic factors. However, still far away from the border of the island of inversion, these states are at excitation energies of about 3 - 3.6 MeV.

The isotope ^{28}Na isotope has been studied by the β decay of ^{28}Ne at GANIL and in-beam with GRETINA at NSCL by nucleon-knockout from neutron-rich Mg beams [18]. The observed multiplets of both positive ($\pi d_{5/2}$-$\nu d_{3/2}$) and (tentatively) negative ($\pi d_{5/2}$-$\nu f_{7/2}$) parity agree with the "collaps of the N=20 gap and the inversion between the neutron $f_{7/2}$ and $p_{3/2}$ levels when removing protons from the $d_{5/2}$ orbital toward the drip line". Interesting fact is that the positive parity states are mainly populated in β decay and the negative parity states in reactions. The authors conclude that it would be important to confirm their spin-parity assignments by future (d,p) reactions (due to it's highly abundant isobar ^{27}Al, a ^{27}Na beam is currently not possible at ISOLDE). Setting in the knockout data a gate on outgoing ^{29}Na nuclei, also new transitions in this nucleus are observed (not published). Without additional information on spin-parity assignments, e.g. from the proposed transfer reaction, all conclusions remain tentative based on comparison with theory.

Also the more neutron-rich ^{30}Na has been studied in nucleon-knockout reactions on Na and Mg beams at NSCL, this time with gamma detection by SeGA [19]. Also here, states have been observed for which a tentative negative parity assignment has been proposed. The different reaction channels allowed for a qualitative distinction between 0p0h/2p2h and 1p1h/3p3h configurations, the latter two involving an intruder which allows for conclusions on sd-fp gap to be reduced to 3.3 MeV at N=19. Most of the observed states are at excitation energies well be low 1 MeV.

To our knowledge, there are no other new experimental results on excited states in ^{29}Na.

Therefore we retain our proposal to measure the d(^{28}Na,^{29}Na)p reaction at 3 MeV/u with the MINIBALL + T-REX set-up.

Accepted isotopes: ^{28}Na

Performed studies: /

3. Future plans

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

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

As described, we plan to perform the reaction d(^{28}Na,^{29}Na)p at 3 MeV/u.

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

No. Beam intensities on target available at TRIUMF allowed only for the study of ^{25}Na(d,p) with a similar experimental set-up [17]. The maximum reported production yield ever for ^{28}Na at TRIUMF is 1.6•10^{5}/s [20], hence more than an order of magnitude lower compared to ISOLDE assuming a proton current of 2 μA.

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

As described in the original proposal, the beam time estimate is based on a beam intensity obtained by scaling the experimental beam intensities obtained for ^{29,30}Na (IS482, run August 2009, see Table 1) taking into account the larger production yield (from the ISOLDE yield data base) and larger losses due to the shorter lifetime of ^{28}Na (decay in REX-TRAP and REX-EBIS).

It has been assumed that the efficiency of HIE-ISOLDE is comparable to REX-ISOLDE.

Isotope	Yield (/uC)	Target – ion source	Shifts (8h)
28Na	9.6E+05	UCx - surface ion	33

Total shifts: 33

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