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Proposal to the INTC Committee

Exploring the shores of the "Island of Inversion": the structure of neutron-rich Al isotopes

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Abstract: We propose to study single particle states in the neutron-rich isotopes ^{31,32}Al. These nuclei are in the vicinity of the "island of inversion" where intruder states from the fp-shell favour deformed ground states instead of the normal spherical sd-shell states. The nuclei will be populated by one-neutron transfer reactions with ^{30,31}Al beams obtained from REX-ISOLDE impinging on a CD_2-target. The γ-rays will be detected by the MINIBALL array and the particles by a segmented Si-detector. Spectroscopic factors extracted from the cross sections will enable us to pin down the configurations 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 leading to the breaking of the magic number $N = 20$ in this region.

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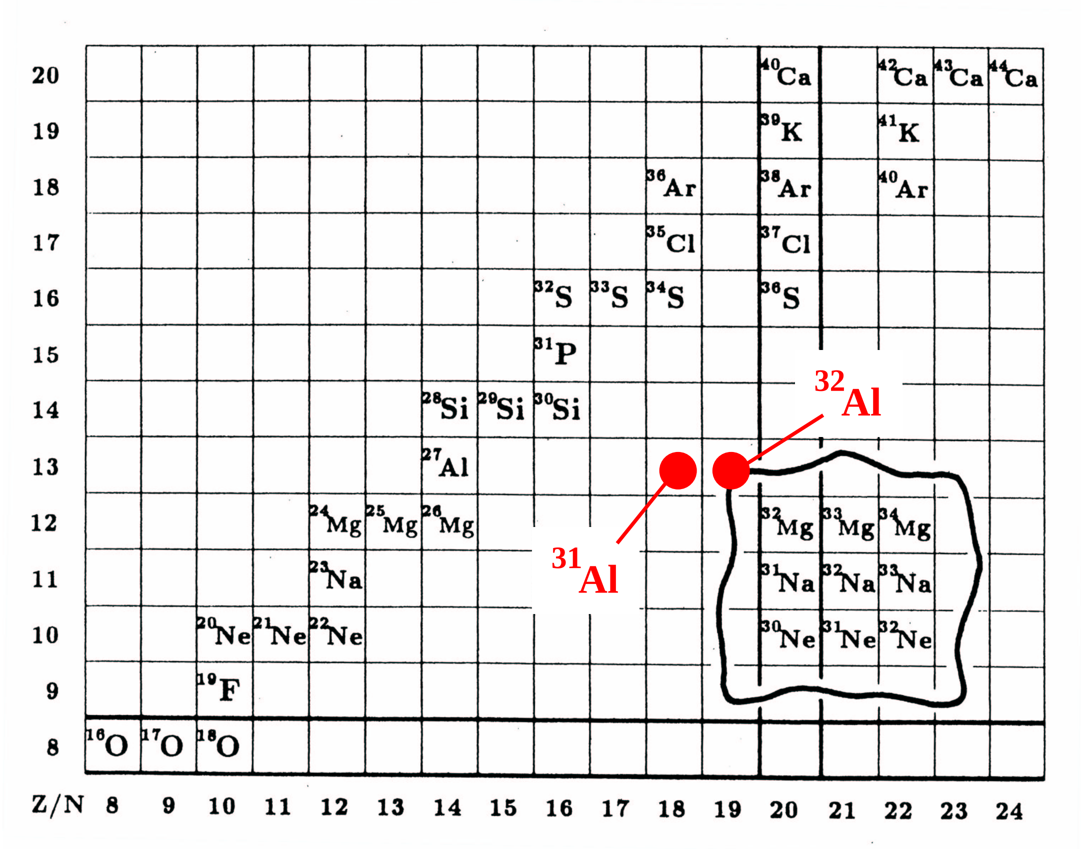

Figure 1: *"Island of inversion" (apart from the "island" only stable nuclei are shown) [2]. The red dots mark* ^{31,32}*Al.*

1 Physics case

For the last 50 years, the shell model has described successfully the existence of magic numbers for both neutrons and protons in stable nuclei. The advent of radioactive beams enabled the investigation if these magic numbers will persist or be altered in nuclei with extreme isospin, notably in neutron-rich nuclei, and a deeper insight into the residual interactions, which are relevant for their local occurrence, can be gained.

In recent years, the "island of inversion" (Fig. 1), a region of nuclei with deformed ground states in the sea of spherical sd-nuclei, has attracted much attention by experimentalists as well as theoreticians. First evidence came from anomalies in the binding energies for nuclei around $A \approx 32$ [1, 2] and was explained by the lowering of intruder fp-orbitals with respect to the sd-shell. This causes an inversion of spherical and deformed single particle configurations, allowing the later to become the ground states.

Both low $E(2^+)$ *and* the large $B(E2; 0_{\mathrm{gs}} \rightarrow 2^+)$ determined by intermediate Coulomb excitation were the first experimental evidence that ^{32}Mg has a deformed ground state [3]. Meanwhile, other isotopes of Ne, Na, and Mg have been proven to have deformed ground states.

Theoretically, the inversion can be described by conventional shell model calculations [4, 5]

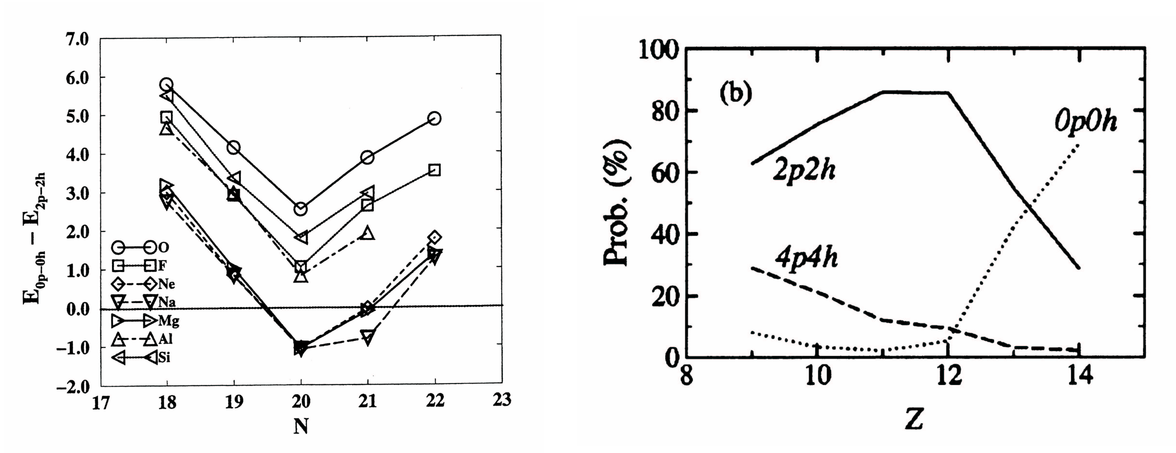

Figure 2: *Theoretical calculations for nuclei around $N = 20$: The conventional shell model predicts a gap of 1 MeV between normal sd-states and fp-intruder for ^{33}Al [4] (left). Therefore, the spherical configuration is favoured. On the other side, the MCSM calculations for $N = 20$ predict that the wave function of the ground state of ^{33}Al contains components of both normal and intruder configurations at equal magnitude [7] (right).*

as well as newer approaches, like the MCSM, involving new residual interactions [6, 7, 8]. Within these models, the ground state of ^{32}Mg is described by a $2p$-$2h$-configuration promoting two sd-neutrons to intruder fp-orbitals, hence by breaking the $N = 20$ shell. However, in detail the predictions differ considerably. For example, following the conventional approach in ^{34}Mg the intruder configuration should be ≈ 1 MeV above the normal configuration and the nucleus should be less deformed than ^{32}Mg, whereas the MCSM predicts an even larger deformation for ^{34}Mg than for ^{32}Mg. A recent experiment measured the $E(2^+)$ in ^{34}Mg at 660 keV (885 keV in ^{32}Mg) and the ratio $E(4^+)/E(2^+) = 3.2$ (2.6 in ^{32}Mg) to be near to rotor-limit of 10/3 [9]. Therefore, the well deformed intruder configuration for the ground state is clearly favoured. However, the $B(E2; 0_{\rm gs} \rightarrow 2^+)$ has not been measured yet.

The exact borders of this "island of inversion" are neither experimentally nor theoretically known. Along $N = 20$, the ground state of ^{32}Mg is deformed whereas the ground state of ^{34}Si is spherical, hence the knowledge of the nuclei in between, in particular ^{33}Al, is essential to define the shores of the "island of inversion" where the inversion happens. As shown in Fig. 2, the theoretical predictions for ^{33}Al vary from a clear separation between the sd-configuration and the fp-intruder [4] to a strong mixing [7].

Contrary to the neighbouring Mg and Si isotopes, the experimental information on neutron-rich Al isotopes is scarce (see Figs. 3 and 4).

Excited states in ^{31}Al are known from γ-spectroscopy after the β-decay of ^{31}Mg [10]. The identified levels agree only partly with states seen in reaction studies ^{15}N(^{18}O, 2p)^{31}Al [11] and ^{30}Si(^{18}O, ^{17}F)^{31}Al [12].

Only recently a precise measurement of the g-factor of 1.517(20) for the ground state of ^{31}Al allowed the assignment of spin and parity $I^\pi = 5/2^+$ [13]. This value is compared with shell model calculations using the USD interaction. Compared

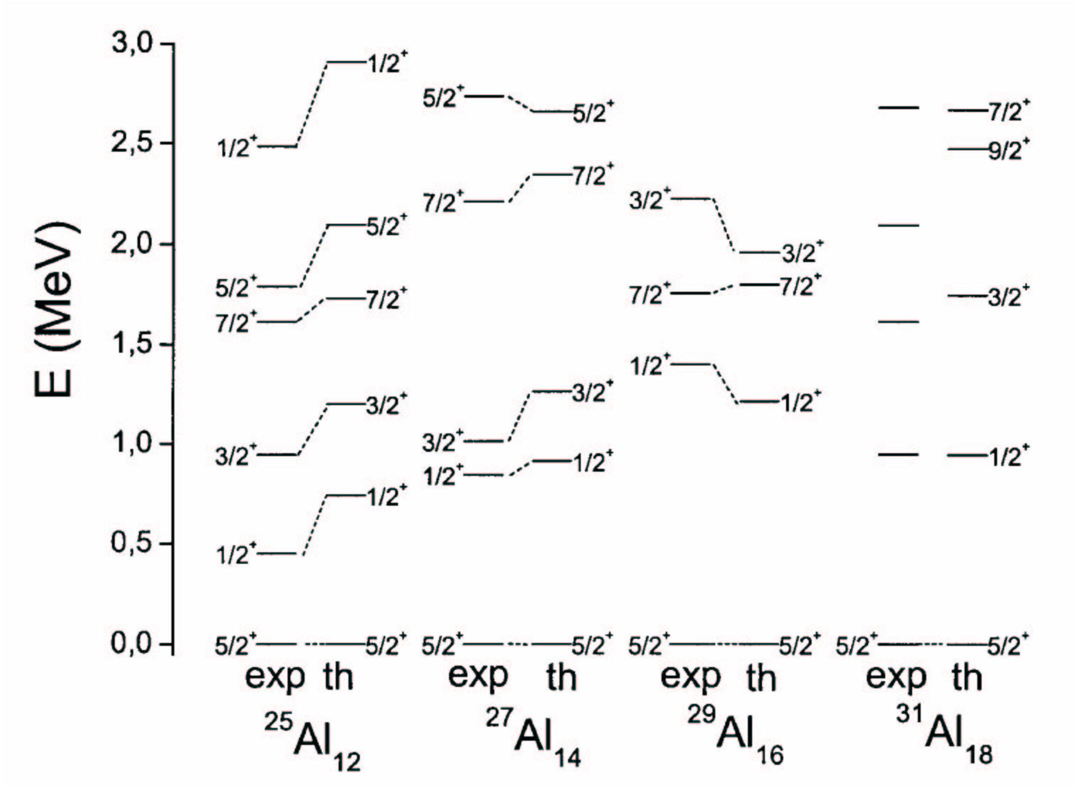

Figure 3: *Experimental and theoretical levels in the odd-even isotopes $^{25-31}Al$ [13].*

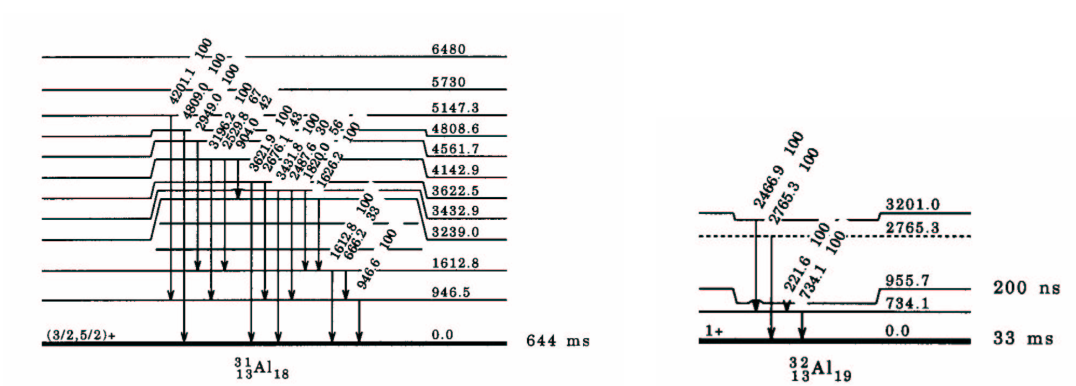

Figure 4: *Experimental levels in the isotopes $^{31,32}Al$ [14].*

to the lighter isotopes $^{25-29}$Al, ^{31}Al has a rather pure configuration with 57% of $\pi[(d_{5/2})^5]\nu[(d_{5/2})^6(s_{1/2})^2(d_{3/2})^2]$ configuration. For the first excited $3/2^+$ state, the 35% of $\pi[(d_{5/2})^4 s_{1/2}]\nu[(d_{5/2})^6(s_{1/2})^2(d_{3/2})^2]$ configuration is the largest contribution, the rest is spread among many other configurations. Conclusively, the low-lying spectrum is described with the *sd*-shell model and ^{31}Al is thus outside the "island of inversion". This agrees to the prediction in Ref. [4] that the gap between normal and intruder states in ^{31}Al is 4.67 MeV.

Approaching $N = 20$, this gap is expected to become smaller, 2.98 MeV for ^{32}Al and 0.82 MeV for ^{33}Al. Experimentally, four states in ^{32}Al are known from the β-decay of ^{32}Mg [10] and a fragmentation reaction study [15]. The ordering of the levels reveals evidence for inversion and a breaking of the $N = 20$ shell closure. The only existing information on ^{33}Al is a γ-ray at 730 ± 50 keV which fits to a prediction for the excitation energy of the $2p$-$2h$-configuration of 672 keV [16].

2 Proposed experiment

We propose to study the single particle structure of the neutron-rich Al isotopes ^{31,32}Al by a one-neutron transfer reaction. This proposal complements transfer studies in this mass region performed in the experiments IS379 and IS410.

Nucleon transfer reactions are a well established tool for the investigation of the single particle structure of nuclei. 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.

Neutron-rich Al isotopes will be populated by a one-neutron transfer reaction with a CD_2-target (deuterated PE foil), i.e. ^{2}H(^{30,31}Al, ^{31,32}Al)^{1}H. The Q-values for these reactions are positive, 4.93 MeV and 1.95 MeV respectively. A beam energy of 3.1 MeV/u, as it will be available after the completion of the REX-upgrade, is preferable compared to 2.2 MeV/u, because at larger beam energy the cross section increases [19].

The set-up consists of the MINIBALL array to detect γ-rays and the CD-detector for particles. The CD-detector is a double-sided segmented Si-detector (DSSSD) consisting of two layers, thus it acts as a $\Delta E - E$-telescope. The ΔE-detector has four quadrants, each of them is segmented in 16 annular stripes (ϑ-coordinate) on the front and in 24 radial segments (π-coordinate) on the back. The E-detector is segmented only in 4 quadrants. The CD-detector enables the identification of light particles (p,d,t), a determination of the kinematics of the reaction, an identification of the final state, and an improved Doppler correction of the γ-rays.

Downstream of the target a two-dimensional position-sensitive PPAC allows to control both the beam position and intensity. An additional Ge-detector behind the beam dump measures the decay of the implanted beam particles. This enables the identification of contaminants in the beam and again to control the beam intensity. Both detectors are essential for focussing the beam and monitoring the experiment.

Since the projectile-like nuclei are extremely forward focussed in the laboratory system ($\vartheta_{\mathrm{Lab}} < 4°$), their direct detection is difficult. In the experiments IS379 and IS410, neutron-rich Na and Mg isotopes have been studied with the same reaction by putting

the CD-detector in forward direction to detect the protons.
In principle, the protons can be detected also in the backward hemisphere for reactions with positive Q-value, for details see e.g. Ref. [17]. Such a set-up has been described in Ref. [18]. This may be advantageous because the cross section has its maximum at forward angles in the centre-of-mass system [19], especially for transfer with $l = 0$. However, the integrated cross section in the laboratory system is larger in forward direction, because the particle detector covers in the CM-system more than 50° compared to only 20° in backward direction (see e.g. Ref. [17]), both assuming the angular coverage of the CD-detector.
The CD-detector covers an angular range of $15° < \vartheta_{\mathrm{Lab}} < 50°$. For the reaction leading to ^{31}Al, this corresponds in the centre-of-mass system to the range $105° < \Theta_{\mathrm{CM}} < 157°$ at a beam energy of 3.1 MeV/u. Hence, in the CM-system backward angles are covered. The resulting energies of the emitted protons are in the range 13.9 MeV $< E_{\mathrm{p}} <$ 23.6 MeV.
In principle, the measurement of the energy and the angle of the protons enables the determination of the transferred excitation energy and, therefore, the final state of the transfer reaction can be identified. The γ-rays detected in coincidence can be assigned to the decay of this level. In particular, also the transfer to the ground state can be measured which is invisible to γ-spectroscopy. However, the complete spectroscopic information comes from both the protons and the γ-rays.
The energy resolution for the protons is limited by the target thickness and the size of the beam spot. Assuming a target thickness of $5 - 10$ μm and a beam spot of a radius of 5 mm, the width of the proton peaks is around $1 - 2$ MeV, mainly due to the energy loss of the beam in the target and the size of the beam spot. The contribution from the energy loss of the protons is comparatively small. Since the spacing between the levels in ^{31,32}Al can be as small as 200 keV, the identification of the final state cannot be achieved with the existing set-up.
Additionally, the light particles (p,d,t) in many cases will not be stopped in the CD-detector. Their total energies have to reconstructed from measuring twice a ΔE-value which will worsen the obtained energy resolution further.
In parallel, the detection of elastically scattered particles, i.e. the deuterons ($E_{\mathrm{d}} = 9 - 20$ MeV) from ^{2}H(^{30}Al, ^{30}Al)^{2}H and both the beam ($E_{\mathrm{Al}} = 30 - 70$ MeV) and the ^{12}C ($E_{\mathrm{C}} = 20 - 75$ MeV, $\vartheta_{\mathrm{Lab}} < 24°$) from ^{12}C(^{30}Al, ^{30}Al)^{12}C, enables the measurement of the integrated beam current. This information is essential to determine absolute cross sections.
Since the Q-value of the reaction populating ^{32}Al is less positive, the energies of the protons are lower 11 MeV $< E_{\mathrm{p,Lab}} <$ 18 MeV.
In order to extract spectroscopic factors, the cross sections to the individual levels will be analysed applying the coupled channel code FRESCO [20]. For reactions between heavy ions, such an analysis of particle-γ-coincidences has been proven to be a very sensitive tool [21]. The obtained values have to be compared with spectroscopic factors calculated by the recent shell model codes mentioned above.

^{30}Al	^{31}Al	^{32}Al	^{33}Al	^{34}Al	^{35}Al
$2.5 \cdot 10^6$	$2.5 \cdot 10^5$	$\approx 5 \cdot 10^{3\star}$	490	86	$4^\dagger$

Table 1: *ISOLDE yields [atoms/μC] for neutron-rich Aluminium isotopes using the RILIS (* interpolated value, † with a tungsten surface ion source) [22].*

3 Rate estimate and beam time request

We would like to study the single particle properties of the neutron-rich Al isotopes ^{31}Al and ^{32}Al by one-neutron transfer reactions with a deuterated PE target. The Al isotopes are produced with a standard UC$_x$/graphite target, ionised by the RILIS, and postaccelerated by the REX-ISOLDE facility.

Table 1 summarises the yields of neutron-rich Al isotopes obtained from a standard ISOLDE UC$_x$/graphite target combined with the resonance ionisation laser ion source (RILIS). The beam intensity from REX, measured in s^{-1}, is roughly a few percent of these numbers. It can be expected, that by optimising the RILIS (i.e. simultaneous excitation with 308.2 nm and 309.3 nm and use of mass marker for beam tuning) the intensity can be increased by a factor 3-10 [22].

The set-up consists of the MINIBALL array and the CD-detector. The efficiencies are $\epsilon_{\rm CD} = 93\%$ for the particle detector and $\epsilon_{\rm MINIBALL} = 10\%$ for γ-detection in the photopeak. Differential cross sections measured for the reaction ^{27}Al(d,p)^{28}Al ($Q = 5.5$ MeV) at $E_{\rm d} =$ 5 MeV, 7 MeV, and 12 MeV are in the range from 10 mb/sr for strong channels down to 0.2 mb/sr for weak channels in the angular range $\Theta_{\rm CM} < 100^\circ$ [23, 24]. As discussed above, in backward direction the differential cross sections are smaller. The cross section in the laboratory system integrated over the solid angle covered by the CD-detector is expected to be around 5 mb for strong channels. The total cross section is estimated to be around 25 mb.

Goal of this experiment is to maximise the statistics in the γ-peaks, since the obtainable resolution for the protons is not sufficient for spectroscopy, as pointed out above. Therefore, the target will be a CD$_2$ foil (deuterated PE foil) of 10 μm thickness. The energy spread of the recoiling Al nuclei, which limits the achievable Doppler correction, is below 2%. Conservatively, we estimate a beam intensity on target of $1.5 \cdot 10^5$ s^{-1} for ^{30}Al which assumes an efficiency of REX-ISOLDE of 3% and an improvement of the RILIS by a factor of 2 compared to the value given in Table 1. An efficiency of REX-ISOLDE of 3% has been achieved for reacceleration of a ^{30}Mg beam (IS410), therefore it is a realistic guess also for neutron-rich Al isotopes. Supposing a cross section of 5 mb, the rate is about 19 h^{-1} for γ-p-coincidences. Without requiring the protons, the total γ-rate is about 100 h^{-1}.

In 3 days of beam time with ^{30}Al beam, roughly 1400 γ-p-coincidences will be collected. A weak channel with a cross section in the order of 0.5 mb still has statistics of about 100 counts.

The ^{31}Al beam intensity is a factor 10 weaker. Therefore, only the strong channels will be seen in γ-p-coincidences. However, in 7 days of beam time, about 320 γ-p-coincidences will be collected, assuming again a cross section of 5 mb and a target thickness of 10 μm.

We would like to ask for 9 shifts of beam time with a ^{30}Al beam and 21 shifts with a ^{31}Al beam both at 3.1 MeV/u.

We request in total 30 shifts (10 days) of beam time.

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