EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Energy of the 2p1h intruder state in ^{34}Al: an extension of the "island of inversion"?

May 30, 2013

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Abstract

The second 0^+ state in ^{34}Si, of high importance for the understanding of the island of inversion at N=20, has been recently observed [Rotaru12] through the beta decay of a predicted long-lived low-lying isomeric 1^+ state in ^{34}Al. We intend to measure the unknown excitation energy of this isomer using the ISOLTRAP Penning-trap mass spectrometer. Since a recent experiment at ISOLDE (IS-530) [Negoita13] showed that the full beta strength in the decay of ^{34}Mg goes through this 1^+ state in ^{34}Al, we propose to perform a direct mass measurement of the daughter ^{34}Al ions trapped after the decay of ^{34}Mg.

Mass measurements indicate that the 4^- ground state in ^{34}Al may be an excited state, the ground state being therefore the intruder 1^+ state. In another run, we propose to perform a remeasurement of the mass of the 4^- ground state.

Requested shifts: 19 shifts, split into 2 runs

1. Motivation

The so-called island of inversion around N=20 is one of the most important discoveries in the last decades of exotic nuclei studies. This island refers to a region where the ground states are dominated by neutron excitations across the N=20 shell gap, called intruder states. The first unexpected observations date from the 1970's [Thibault75][Huber78] when ^{31}Na and ^{32}Mg showed atypical binding energies and charge radii. This was interpreted as strong deformation, decreasing the N=20 shell gap, and allowing excitations to the fp shell.

In this context, the isotope ^{34}Si located at the boundary of the island was studied to better understand the inversion mechanism and in particular, to follow the developement of the intruder configuration from the spherical ^{36}S to the deformed ^{32}Mg. For these studies, the beta decay of ^{34}Al was investigated in several experiments [Baumann89][Nummela01][Rotaru12] to establish a detailed decay scheme and thus reach the energy of the first excited states of ^{34}Si. In particular, the first excited 0^+ state (0^+_2) was searched for, in order to probe the deformation of this transitional nucleus.
Despite 30 years of experimental efforts, the quest for this 0^+_2 state in ^{34}Si failed until a recent experiment at GANIL [Rotaru12]. This experiment was based on a hypothesis that the 0^+_2 state could be populated by the β^- decay of a predicted isomeric state in ^{34}Al. Shell-model calculations using the SPDF-M and SPDF-M' interactions [Himpe08] predicted for this state a spin/parity of 1^+ with a wave function dominated by the excitation of one neutron across the N=20 shell gap, leading to a two-particle-one-hole (2p1h) intruder configuration, leaving a hole in the neutron $d_{3/2}$ orbit (see Figure 1). Following this prediction, the 1^+ state would decay mostly by a transition $\nu d_{3/2} \rightarrow \pi d_{5/2}$ leading mostly to the 2p2h 0^+_2 state in ^{34}Si.

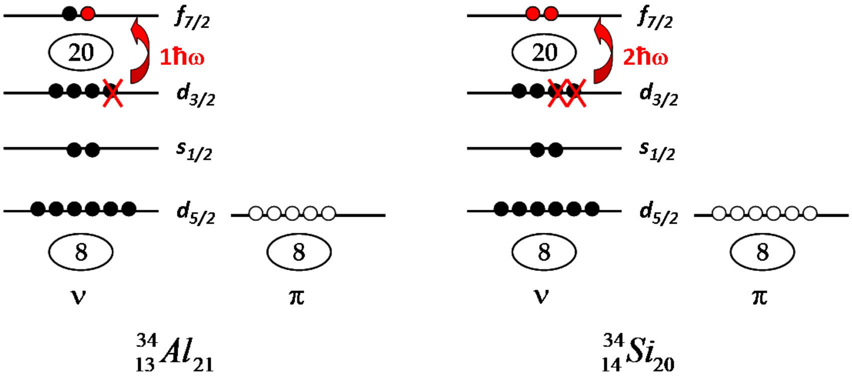

Figure 1: *Scheme of the shell orbitals for* ^{34}*Al and* ^{34}*Si. In red are shown the neutron excitations across the shell gap, i.e the* 1^+ *state in* ^{34}*Al (2p1h configuration) and the* 0^+_2 *state in* ^{34}*Si (2p2h configuration).*

The results of the experiment are in agreement with this hypothesis: the 0^+_2 state of ^{34}Si was observed for the first time after the beta decay of implanted ^{34}Al ions, the excitation energy and the lifetime of this state could be measured from e^+e^- pair energy measurements (see Figure 2). Although the half-life of the beta-decaying state of ^{34}Al was determined to be 26(1)ms, distinctly different from the known half-life of the ^{34}Al ground state (56.3(5) ms), the excitation energy of this state could not be measured.

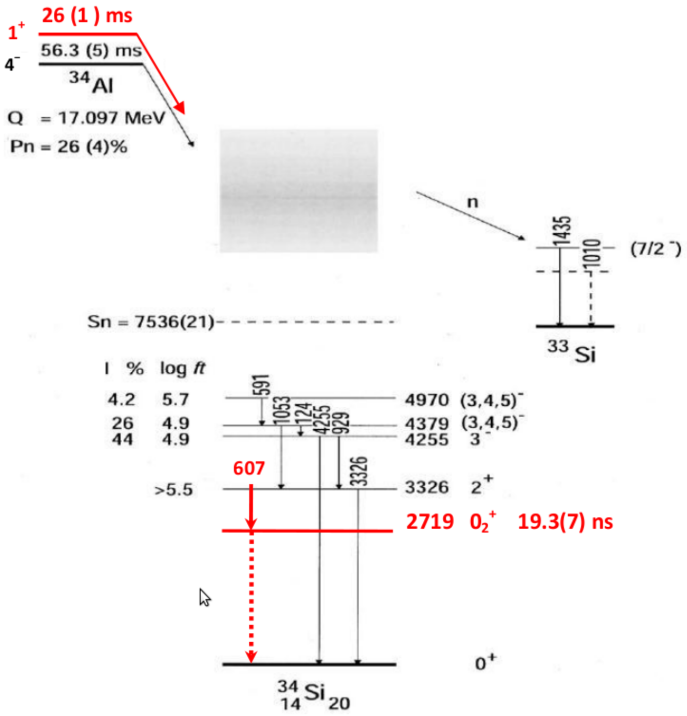

Figure 2: *Beta-decay scheme of* ^{34}*Al [Nummela01]. The information in red correspond to the new data from [Rotaru12].*

Few experiments have investigated the level scheme of ^{34}Al. From the measured g-factor of the ground state $|g|=0.539(2)$ [Himpe08], a spin/parity of 4^- was assigned to the ground state. This conclusion was partly based on the beta-decay studies mentioned above. This magnetic moment measurement allowed to conclude that ^{34}Al is a transition isotope of the island of inversion, from the normal $Z=14$ to the deformed $Z=12$.

Another way to study the ^{34}Al level scheme and characterize the recently discovered 1^+ state is to investigate the beta decay of ^{34}Mg. This was performed in a recent experiment at ISOLDE (IS-530) [Negoita13]. One of the main goals of this experiment was to measure the energy of the 1^+ state in ^{34}Al, assuming that the decay populates both 1^+ and 4^- states, directly or indirectly. However, it turned out that all the beta strength in the decay of ^{34}Mg proceeds through the 1^+ state in ^{34}Al since none of the gamma transition in ^{34}Si known to be strongly populated in the beta decay of the 4^- state were observed, in particular the 124 keV transition which can be populated only by the 4^- state (see Figure 2). This experiment allowed to remeasure the half-life of ^{34}Mg to 63(1) ms [Negoita13], which is not in agreement with the value obtained in a previous experiment (20(10) ms) [Langevin84], and to measure the branching ratio of the beta-delayed neu-

tron emission (βn and β2n) to $P_n = 35(10)\%$. A first level scheme of ^{34}Al could also be established; the analysis is still in progress.
Therefore the only way to measure the energy of this isomer is to perform a direct mass measurement, which is the subject of this proposal. Since it has been demonstrated that the decay of ^{34}Mg populates mostly the 1^+ state of ^{34}Al (with a branching ratio of 65(10)%), one can produce a ^{34}Mg beam, and perform a direct mass measurement on the daughter ions.

Measuring the excitation energy of this isomer will be an important input to better understand the inversion mechanism in this region. In addition, it could explain unexpected behavior observed from mass measurements of Mg and Al isotopes around N=20 [Audi12]. Figure 3 shows the two-neutron separation energies S_{2n} of Al and Mg isotopes for $20 \leq N \leq 22$. Within the error bars the curves touch at N=21, with an S_{2n} value for ^{34}Al of 8110(70) keV and a value of 8058(4) keV for ^{33}Mg. This behavior is unusual because generally, for a given N, when one proton is added, the nucleus is stabilized due to the attractive character of the proton-neutron interaction, leading to a higher value of S_{2n}.
In addition, a recent experiment was performed using the TITAN spectrometer at ISAC [Dilling13] to measure the mass of the isotopes around this region. The new mass excess of ^{34}Al and ^{33}Mg measured with a higher precision confirm this trend, and even show a lower value of S_{2n} for ^{34}Al compared to ^{33}Mg.

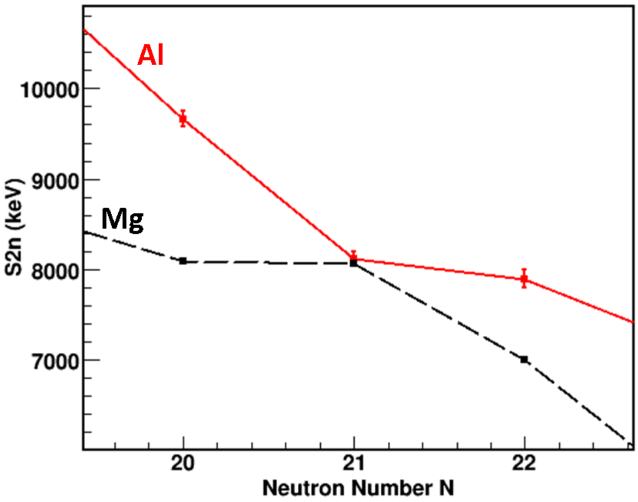

Figure 3: *Two neutron separation energies* (S_{2n}) *in keV for the Al and Mg isotopes for* $20 \leq N \leq 22$.

This odd behavior could be explained by an erroneous assignment of the ground state and the isomeric state in ^{34}Al. If the measured mass of ^{34}Al corresponds to the isomeric state, the binding energy of ^{34}Al is underestimated, which would explain the overlap of the S_{2n} values at N=21.

Based on this assumption, we propose here to measure for the first time the binding energy of the 1^+ state populated by the beta decay of ^{34}Mg. In another run, we request ^{34}Al to measure the binding energy of the 4^- state. By comparing the two masses, not only will the ordering of the states be clarified but also the excitation energy will be determined.

If the intruder state is indeed assigned to the ground state, it would mean that the island of inversion is larger than previously thought.

2. In-trap decay measurement with ISOLTRAP

We request a ^{34}Mg beam from an UC$_x$ target using the resonance ionization laser ion source (RILIS). The ^{34}Mg beam from ISOLDE will be delivered to the Penning-trap mass spectrometer ISOLTRAP, in order to perform a direct mass measurement of the state in the trapped daughter nuclide ^{34}Al that is populated by the decay of ^{34}Mg. Such an in-trap decay mass measurement has already been demonstrated with ISOLTRAP for $^{61-63}$Fe [Herlert12].

2.1 ISOLTRAP set-up

High-precision mass measurements have been performed for many years with the ISOLTRAP set-up, reaching a relative uncertainty of typically 10^{-8}. This spectrometer is described in detail in [Mukherjee08][Wolf13] and a scheme of the set-up is shown in Figure 4.
To reach a high precision, the method requires an isobarically pure, low-emittance beam. For this purpose, the 50-keV continuous beam from ISOLDE is first injected in a gas-filled radio-frequency quadrupole (RFQ) where the ions are cooled via collisions with helium buffer gas. The ions leave the cooler as ion bunches towards the recently installed multi-reflection time-of-flight mass separator (MR-TOF MS) for purification with a resolving power on the order of 10^5. As a third preparation step, the ions are injected in the preparation Penning trap where they are cooled and cleaned by buffer gas cooling [Savard91], before being transferred to the so-called precision trap for the mass measurement, using the time-of-flight ion-cyclotron resonance (TOF-ICR) technique [Koenig95].

2.2 Recoil-ion trapping and excitations cycle

The ^{34}Mg ions will be sent to the ISOLTRAP spectrometer and, after the steps mentioned above, trapped in the preparation trap. Usually, the ions are kept in this gas-filled Penning trap for a few 10 ms to axially cool them before the application of rf excitations. During this "waiting" time, the ^{34}Mg ions, which have a half-life of 63 ms [Negoita13], will decay and populate the 1^+ state of ^{34}Al. These daughter nuclei will also decay over the time, with a half-life of 26 ms [Rotaru12]. From these considerations, one can calculate the optimum waiting time for which we have a maximum production of ^{34}Al ions, determined to be 66 ms, for which we get 20 ^{34}Al ions from 100 ^{34}Mg ions. This value takes also into account the branching ratio for beta-delayed neutron emission of 35(10)%.

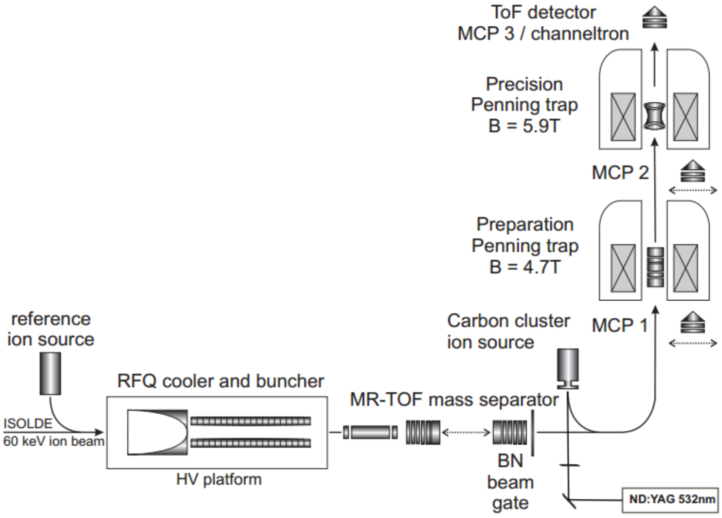

Figure 4: *Schematic view of the ISOLTRAP set-up. For details, see text.*

With a Q_β value of 11.39 MeV, the maximum recoiling energy of the daughter nucleus is 2.3 keV. The ions recoiling axially with an energy higher than the endcaps voltage (100V) are lost. The ions recoiling radially have a maximum radius of 16.8 mm, which is smaller than the trap radius of 20 mm. Simulations have been performed with the SIMBUCA program [VanGorp11][Herlert12] to estimate the trapping efficiency of the recoiling ions in the preparation trap. From these simulations, 75% of the ions are lost due to their excessive energy.

The very short ^{34}Al half-life of 26(1) ms is an important constraint for the duration of all different excitations, which have to be minimized.

After a magnetron excitation of about 10 ms, the daugther ^{34}Al nuclei can then be centered selectively by resonant buffer gas cooling. The resolving power needed to separate the mother ^{34}Mg ions is 2700, thus an excitation time for the quadrupolar excitation of 20 ms is sufficient. Moreover, since the excitation frequency for the ^{34}Al 1^+ state is not known, a low conversion time is needed for a broad-band excitation. After a cooling time for the cyclotron motion of 10 ms, the ions are then transferred into the precision trap for the actual mass measurement. A magnetron excitation (10 ms) and a quadrupolar excitation (40 ms) are applied, before ejecting the ions towards the channeltron detector to perform the TOF measurement.

In parallel to the rf excitations in both traps, any ^{34}Si ions created from the decay of ^{34}Al can be cleaned by a permanent dipolar excitation at the modified cyclotron frequency of the contaminant.

Finally, the total time needed for the different excitation steps is 90 ms. One should notice that the waiting time of 66 ms in the preparation trap, during which a quadrupolar excitation to center the daughter ions can also be applied, is not taken into account in the total time since it is the time needed for the production of the ions, thus a gain and not a loss of ions.

3. Beam time requests

The yield from the ISOLDE data base is 140 ^{34}Mg/μC from a 50g/cm^3 thickness UC$_x$ target using RILIS. However, a yield of 600 ^{34}Mg per proton pulse was obtained during the last experiment at ISOLDE [Negoita13], due to recent RILIS improvements. The estimations below are based on this yield. Assuming 20 proton pulses per minute delivered to ISOLDE, 12000 ^{34}Mg ions per minute can be obtained from the target. The only possible contamination comes from surface ionized ^{34}Al ions with a yield of approximately 15/μC, these ^{34}Al contaminants could be well separated by the HRS at the last experiment [Negoita13].

With a transmission efficiency from ISOLDE to the RFQ of 90% and an overall transport efficiency from the RFQ to the channeltron detector of 1% (including the detection efficiency of the channeltron), an efficiency of 0.9% has to be considered.
Considering the half life of ^{34}Mg (63 ms) and that 90% of the ions are released in about 100 ms [Gottberg13], not all the ions can be accumulated in the RFQ. From these considerations, the optimum beam gate for the RFQ is 49 ms for which 40% of the total number of ions can be accumulated.
In addition, we have to consider the cooling time in the RFQ of 5 ms and the time spent in the MR-TOF, during which some ions decay. Since no contamination is expected, the time in the MR-TOF can be very short (1.5 ms). From these considerations, an efficiency of 93% has to be added.
Concerning the losses in the purification trap before the rf excitations, as already mentioned, 20 ^{34}Al daugther ions can be produced from 100 ^{34}Mg ions and the trapping efficiency of these recoiling ions has been estimated to be 25%.
The losses due to the time needed for all the different excitation steps in the preparation trap and in the precision trap, during which the ions decay, has to be considered. We do not consider the production of ^{34}Al during the purification cycle of the preparation trap because we consider that all the ^{34}Al ions produced during this time are lost due to the high magnetron radius of the mother ions. Consequently, this decay time has been estimated to be 90 ms, leading to an efficiency of 9%.
In total, from all the considerations above, an overall efficiency of $1.5.10^{-5}$ is obtained, leading to 10 ^{34}Al ions detected on the channeltron every hour. A TOF resonance with 300 ions can then be obtained in 4 shifts.
One sould also consider the background on the detector coming from different sources (electronics, ions...) on the level of 0.5-1mHz. Therefore, for a sufficient signal-to-noise ratio, we request 12 shifts to determine the value of the binding energy of the 1^+ state in ^{34}Al. In addition, 1 shift will be needed for the stable-beam tuning as well as 1 shift for the optimization of the in-trap production of ^{34}Al.

In another run, we propose to produce an ^{34}Al beam, in order to remeasure the binding energy of the 4^- state in ^{34}Al which has a half-life of 56.3 ms. The yield from the ISOLDE data base is 86 ^{34}Al/μC from a 50g/cm^3 thickness UC$_x$ target using RILIS. Offline enhancements with RILIS showed that a factor of 70 more for the yield could be reached [Marsh13]. Since such a standard measurement is well established at ISOLTRAP, 4 shifts are requested, as well as 1 shift for the stable-beam tuning.

Summary of requested shifts:
We request 19 shifts split into 2 runs as follows:
14 shifts for the measurement on the 1^+ state in ^{34}Al: ^{34}Mg at maximum yield, first users on the target
5 shifts for the measurement on the 4^- state in ^{34}Al: ^{34}Al at maximum yield, first users on the target
For both runs, we request an UC$_x$ target, the laser ionisation with RILIS, the HRS and the slits for suppressing contaminants.
The second run should preferably be scheduled right after the first one since the whole ISOLTRAP apparatus will be already tuned for the mass 34, allowing 1 shift in between for the laser tuning from Mg to Al [Marsh13].

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: ISOLDE central beam line and ISOLTRAP setup. The preliminary safety file is the document “safety-requirements-ISOLDE-ISOLTRAP” with the corresponding attached documents dealing with the different hazards: acetone, cadmium, ethanol, helium, isopropanol, nitrogen, and noise. Furthermore, the ISIEC file “ISIEC_ISOLTRAP_2010-11-18” is also part of the safety documents made available for the ISOLTRAP experiment.

Part of the	Availability	Design and manufacturing
ISOLTRAP setup	☒ Existing	☒ To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed ISOLTRAP installation.