EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

IS532: Seeking the Purported Magic Number $N = 32$ with High-Precision Mass Spectrometry

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Abstract: We request 6 extra shifts to complete the experimental program of IS532 (for which 3 shifts remain), by performing mass measurements of the isotopes $^{52-55}$Sc with the ISOLTRAP mass spectrometer. The scandium mass measurements, already approved by the INTC, would probe the extension of the $N = 32$ shell-closure effect, revealed in the mass surface by the successful calcium measurements of this experiment. The program now also benefits from the development of a new mass-measurement technique, which uses the multi-reflection time-of-flight mass spectrometer of ISOLTRAP, and was developed for determining the masses of ^{53,54}Ca.

Requested shifts (in total): 9 shifts (6 extra) on a UC_x target, with RILIS.

The present Addendum follows the status report INTC-SR-034.

1 Motivation and experimental setup

The shell model is the central paradigm of nuclear physics today. Nuclei exhibiting enhanced binding with respect to their neighbours, or large energy gaps in their excitation spectrum, are said to be "magic" and are associated to closed configurations of protons and neutrons, orbiting in an independent-particle potential, which is the effective, average result of the many nucleon-nucleon interactions. As such, the properties of magic nuclei and, more recently, the evolution of these properties with neutron-to-proton asymmetry (isospin), are considered one of the most promising experimental methods of accessing the properties of the nuclear force. Consequently, a lot of effort has been put, on the one hand, in systematically studying how the signatures of magicity are weakened for some "traditionally" closed-shell nuclei (see [1] for a recent review) and, on the other hand, in revealing new nuclei for which such signatures of magicity are present ([2],[3],[4]). The IS532 experiment (INTC-P-317) was proposed as a step forward in this latter direction, by measuring with ISOLTRAP the masses of calcium, scandium and chromium isotopes across the $N = 32$ isotonic line, to investigate the possibility of the "new magic number" $N = 32$ and the way it is reflected in the ground-state binding energies.

For a more detailed description of the ISOLTRAP experiment, including recent developments, see the "Experimental setup" section of the ISOLTRAP Status Report, INTC-SR-034, as well as [5, 6, 7] and the references therein. For IS532, two modes of ISOLTRAP operation have been proposed. The first is the Penning-trap mass-measurement technique, which means that the ion beam from ISOLDE is cooled and bunched in the buffer-gas-filled radiofrequency quadrupole (RFQ), then purified from contaminants in the multi-reflection time-of-flight mass spectrometer (MR-TOF MS) and/or in the buffer-gas-filled preparation Penning trap, and finally is sent for measuring the cyclotron frequency of the ion of interest in the precision Penning trap, from which its mass can be determined. The second mode uses the MR-TOF MS as a mass-measurement tool, developed for the calcium result. The multiple reflections of the ion bunch coming from the RFQ between the electrostatic mirrors of the MR-TOF MS leads to a separation of its different isobaric components due to their slightly different masses. Sending the ion bunch to a time-of-flight (TOF) detector placed behind the MR-TOF device makes it possible to acquire a TOF spectrum, in which the different ion species are resolved with a mass resolving power on the order of $10^4 - 10^5$. Ions of known mass can be used as reference ions to calibrate the TOF spectrum. The mass of any ion of interest can then be determined with respect to the masses of the reference ions.

Using the MR-TOF MS for mass measurements has several advantages compared to the Penning-trap technique. First of all, the total measurement cycle of the MR-TOF MS is as short as a few milliseconds. Second, once the contaminants are separated in time-of-flight from the ion of interest, the technique does not require them to be suppressed, but uses them for calibrating the device and eliminating errors which result, for example, from temperature drifts of the power supplies connected to the electrodes of the MR-TOF MS. Finally, as a particularity of the ISOLTRAP experiment, the transport efficiency to the MR-TOF MS is typically one order of magnitude higher than to the precision Penning trap, because the latter requires, additionally, a 90 degree bending of the beam, an extra deceleration and the transport in the gradients of two superconducting magnets.

2 Addendum

The decision of the INTC committee on the proposal of the IS532 experiment was [8]: "The aim of the proposal is to study the possible shell closure at $N = 32$ via mass measurements in neutron-rich Cr, Sc, and Ca isotopes. Only Ca isotopes seemed to be available without additional beam developments. Therefore the Committee recommended for approval by the Research Board 21 shifts for the studies on Ca and Sc isotopes, with the requirement not to schedule the Sc measurements before the Ca measurements are successfully completed."

The only beam time of the IS532 experiment so far was thus scheduled to produce and measure the calcium isotopes $^{52-54}$Ca. In a first stage, the masses of ^{51,52}Ca, already measured at the time with the TITAN experiment at TRIUMF [9], were remeasured using the Penning-trap technique. This was necessary, because the TITAN measurements showed significant deviations from the masses of AME2003 [10] and, in the case of ^{52}Ca, gave an uncertainty of only 60 keV. The ISOLTRAP measurements are in agreement with the TITAN ^{51,52}Ca values and improve the precision to below 1 keV. However, to advance to ^{53,54}Ca, the MR-TOF MS was used for the mass measurement. The chromium isobars of the calcium isotopes were used as reference ions, together with stable ^{39}K from the off-line ion source of ISOLTRAP. In total, some 6400 counts of ^{53}Ca were recorded in about 13 hours of acquisition time, as well as some 2300 counts of ^{54}Ca in 18 hours of acquisition time. In addition, over half a shift were spent on each isotope to optimise the beam-gate length and to balance the chromium-to-calcium ratio using the HRS slits, in order to obtain a good collection rate of calcium without having significant saturation effects on the chromium peak used for calibration. Parts of the beam time were also dedicated to collecting the necessary off-line spectra for calibration. In the end, the achieved precision on the masses of ^{53,54}Ca for a conservative data analysis was of 40-50 keV (corresponding to a relative precision of several 10^{-7}). Different on-line spectra collected during the 2012 beam times as a by-product are currently under investigation for determining the systematic limits of the device. Preliminary, relative uncertainties of a few 10^{-7} seem to be possible. A direct cross-check during the calcium beam time was performed on mass $A = 52$, where both the Penning trap and the MR-TOF MS were used to determine the mass of ^{52}Ca. With an uncertainty of 10 keV, the MR-TOF MS mass agrees within 1 standard deviation with the Penning-trap measurement, of 0.7 keV uncertainty. All these results are discussed in [3].

The measured masses allowed the calculation of the two-neutron separation energies S_{2N} across $N = 32$, and of the $N = 32$ two-neutron shell gap, $\Delta_{2N}(Z, N) = S_{2N}(Z, N) - S_{2N}(Z, N + 2)$. In Fig. 1, Δ_{2N} is plotted for the $N = 32$ and $N = 50$ isotones. One notices that the $N = 32$ gap is enhanced for calcium to a value comparable to that of the $N = 50$ shell gap close to the doubly-magic ^{78}Ni ($Z = 28$), suggesting that $N = 32$ is a prominent shell closure.

The results have been compared to state-of-the-art microscopic calculations using phenomenological, as well as realistic interactions. Noteworthy is the very good agreement between experiment and the predictions of shell model calculations using an interaction derived from chiral effective field theory, including three-nucleon forces [9, 3], which is constrained only on nucleon-nucleon scattering data and on the properties of light nuclei.

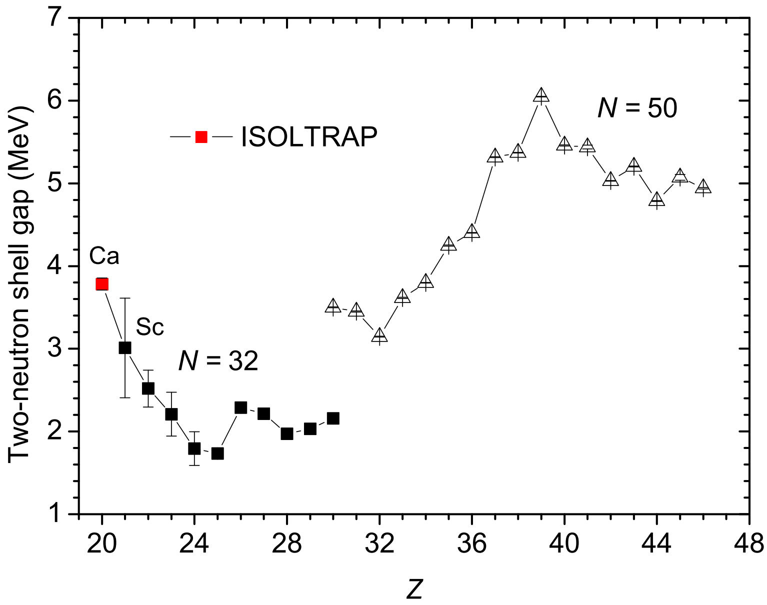

Figure 1: Experimental two-neutron shell gap for the $N = 32$ and $N = 50$ isotones (data from AME2012 [11] and from IS532 [3]). An enhancement of the $N = 32$ shell gap for calcium ($Z = 20$) is observed.

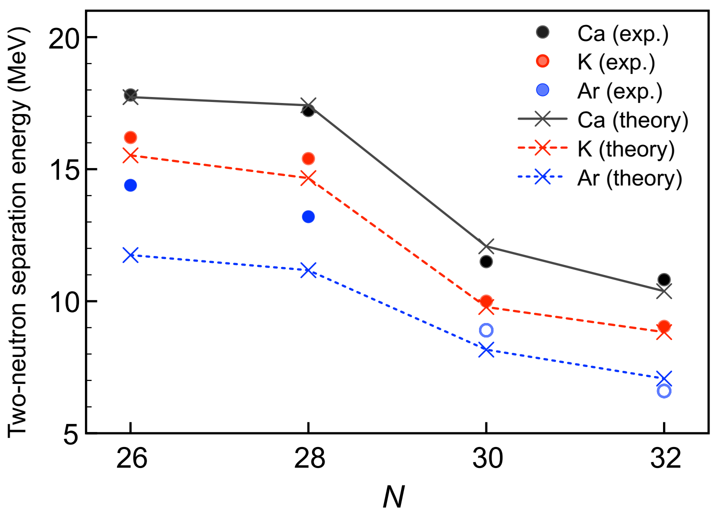

Figure 2: Ab-initio calculations using Gorkov-Green's Function theory [12] for the calcium, potassium, and argon isotopes. Experimental values are taken from AME2012 [11] and are partly extrapolated from systematics (open symbols).

Future plans with all requested shifts (including available shifts):
The outcome of the calcium experiment raises the question of whether similar effects can be observed in the mass surface for $Z \neq 20$ or whether the observed enhancement of the two-neutron shell gap is restricted to the calcium isotopic chain, where signatures for neutron shell closures are enhanced by the double magicity. The measurements of ^{50,51}K by TITAN [9] show similar deviations from the AME2003 [10] as for ^{51,52}Ca. The

^{52,53}K isotopes are present as surface-ionized contaminants in the $A = 52, 53$ MR-TOF MS spectra, allowing the determination of the masses of ^{52,53}K. The data analysis is ongoing and the preliminary results show that the $N = 32$ shell gap is also enhanced for potassium ($Z = 19$). By also measuring the masses of scandium isotopes ($Z = 21$), one would gain the full information on the $N = 32$ shell gap immediately above and below the $Z = 20$ proton magic number. This would extend the range of comparison with theoretical calculations using realistic interactions, including ab-initio calculations, for which efforts are under way to go beyond the proton-magic chains, as shown in Fig. 2 [12]. The masses of the proposed scandium isotopes are known in the atomic-mass evaluation [11], but the uncertainties of several hundred keV do not allow drawing a clear conclusion regarding the $N = 32$ shell gap, as reflected in Fig. 1.
Of the 21 shifts approved by the INTC, 9 had been requested for the measurement of scandium (8 for the actual measurement, 1 for MR-TOF MS calibration/set-up with on-line beam). After the calcium beam time, only 3 shifts are left for IS532. We would thus like to request for the original 9 shifts to be restored to IS532 for the measurement of scandium isotopes (6 more shifts than currently available).
The only information on the requested scandium isotopes in the ISOLDE yield database is from the times of SC-ISOLDE: 13/μC of ^{52}Sc, for a UC$_x$ target and a tungsten surface ioniser [13]. As specified in the original proposal INTC-P-317, we would like to benefit from the RILIS ionization scheme for scandium [14, 15], which was shown to bring an enhancement factor of 400 with respect to the surface-ionized yield, without using a resonant ionization step. The use of an autoionizing state would enhance the scandium yield by two orders of magnitude with respect to non-resonant ionization as shown in [16]. The yields of ^{53,54}Ca estimated from the ISOLTRAP run are in the range 10-100/μC, too little to produce enough scandium through in-trap decay (on masses $A = 54, 55$). We thus ask for the ionization of scandium by RILIS.
The original proposal assumed that ^{52,53}Sc would be measured in the Penning trap, while ^{54,55}Sc would be measured with the MR-TOF MS. Keeping this layout, the shifts are re-distributed, based on the observed time requirements of the MR-TOF MS measurements. The quoted yields are an order-of-magnitude estimation/extrapolation, based on the old yield of surface-ionized ^{52}Sc and the demonstrated factor 400 enhancement by using the RILIS.

Isotope	Half-life (s) [17]	Yield (μC^{-1})	Target/ion source	Shifts (8h)
^{52}Sc	8.2(2)	10^3	UC$_x$/RILIS	1
^{53}Sc	2.4(6)	10^2	UC$_x$/RILIS	2
^{54}Sc	0.526(15)	10^1	UC$_x$/RILIS	2
^{55}Sc	0.096(2)	10^0	UC$_x$/RILIS	3
			MR-TOF MS set-up	1
				Total shifts: 9

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