CERN-INTC-2012-018 / INTC-P-332
06/01/2012

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Remeasurement of ^{32}Ar to test the IMME

January 6, 2012

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Abstract: The Isobaric Multiplet Mass Equation (IMME) has been subject to extensive studies in the low-mass region. Especially at the $A = 32$ quintet, the predicted quadratic form could not be confirmed, possible explanations being the insufficient accuracy of input parameters or higher-order interactions within the nucleon. For this quintet, the uncertainty on the mass-excess values of four of the five $T = 2$ multiplet members is extremely low: 0.6 keV for ^{32}Cl, 0.3 keV for ^{32}S, 0.2 keV for ^{32}P, and 0.7 keV for ^{32}Si. In the case of ^{32}Ar, however, the uncertainty is as large as 1.8 keV. State-of-the-art high-precision Penning-trap mass spectrometry makes it possible to decrease this uncertainty. We propose to remeasure the mass of ^{32}Ar at the Penning-trap mass spectrometer ISOLTRAP thus decreasing the uncertainty by a factor of 3-5. The proposed measurement is part of an experimental collaboration with JYFLTRAP, where the remaining masses of the $T = 2$ isospin quintet at $A = 32$ will be remeasured within a recently accepted research proposal.

Requested shifts: We request 9 shifts using a nano-structured CaO target with a VADIS ion source.

[a] The JYFLTRAP Collaboration is composed of the Department of Physics, University of Jyväskylä, Finland and the Helsinki Institute of Physics, University of Helsinki, Finland with J. Äystö as spokesperson.

1 Introduction

It was Heisenberg who in 1932 suggested that proton and neutron can actually be treated as two states of one particle, hence the nucleon was born [1]. He introduced the isobaric spin or short isospin T, which characterizes charge and mass of the particles involved and describes the charge independence of the nuclear force. In analogy to the spin, the isospin is treated as a quantum number and has also a z-component which is defined as the difference in neutron (N) and proton (Z)number

$$T_z = 1/2(N - Z) = -1/2(A - 2N) = 1/2(A - 2Z)\,, \tag{1}$$

where A is the mass number. All across the nuclear chart, one can find so-called mirror nuclei which form an isospin multiplet of different order. The participating nuclei all have the same A but differ in the number of protons and neutrons. In the 1950's, Wigner [2] as well as Weinberg and Treiman [3] followed up on this idea and introduced the Isobaric Multiplet Mass Equation (IMME) showing that the masses of the isobaric analog states of the members of an isospin multiplet should lie along a parabola under the assumption that the Coulomb interaction is treated by first-order perturbation theory:

$$m(T_z) = c_0 + c_1 \cdot T_z + c_2 \cdot T_z^2\,, \tag{2}$$

with c_n being the fit parameter. This equation has in the past not only been used to confirm the masses within a multiplet but also to successfully predict unmeasured (or insufficiently accurate) masses. In the case of the $T = 2$ quintet at $A = 32$, however, the IMME has been tested and its quadratic form has been found to fail [4, 5, 6].

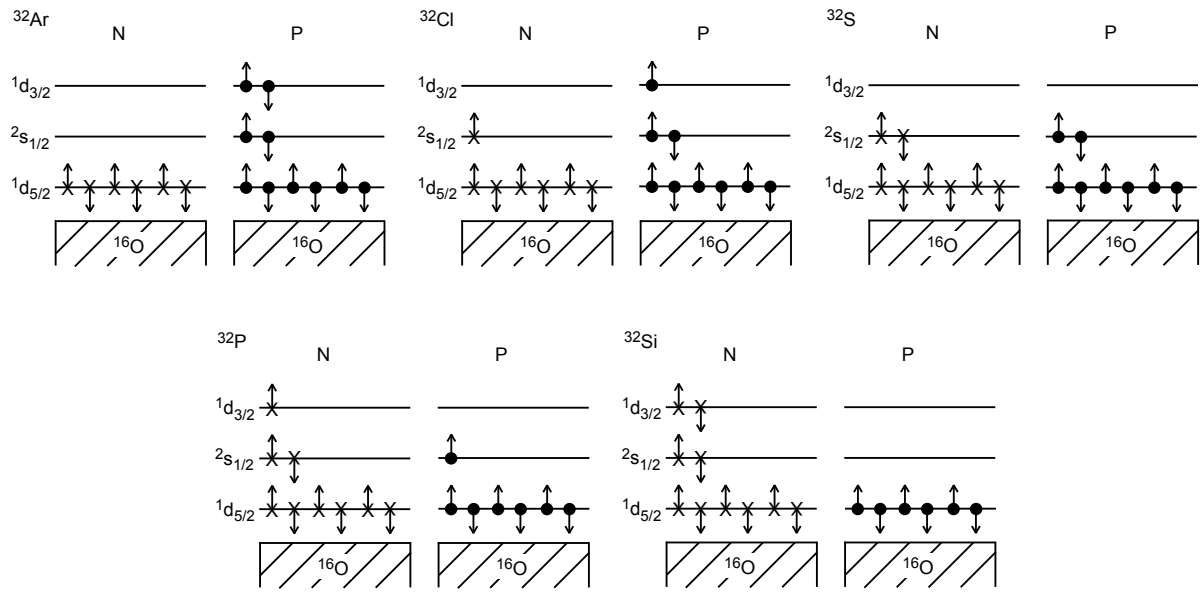


Figure 1: Occupation of nuclear states of neutron (N) and protons (P) within the shell-model representation for the $A = 32$ isospin quintet $T = 2$.

From a general point of view, a breakdown of IMME requires high-order Coulomb effects, nucleon-nucleon interaction or many-body forces. Recent shell-model calculations

by Signoracci and Brown show the importance of isospin mixing and even stress the need for a reduction of the error bars in the ^{32}Ar measurement [7]. In the last few years, the field of Penning-trap mass spectrometry has developed various new techniques to measure the masses of short-lived nuclei with a relative uncertainty well below 10^{-8}, such as the Ramsey technique [8, 9], the octupole excitation [10, 11] or the use of carbon clusters as reference ions [12, 13]. It has as such opened the possibility to unprecedented studies of the IMME within various multiplets such as the $A = 32$ quintet depicted in Fig. 1.

2 Physics Interest and Experimental Program

The masses of the $T = 2$ isospin quintet at $A = 32$ differ slightly because of the different occupation of states of neutron and protons as can be seen from Fig. 1. The occupation of nuclear states of neutrons and protons are shown in the shell-model representation using ^{16}O as a core. According to eqn. (2), the mass values of the isobaric analog states should lie on a parabola. A deviation from this behavior points towards additional interactions within the nucleon requiring higher-order corrections c_n that enter in second-order perturbation theory along with isospin mixing.

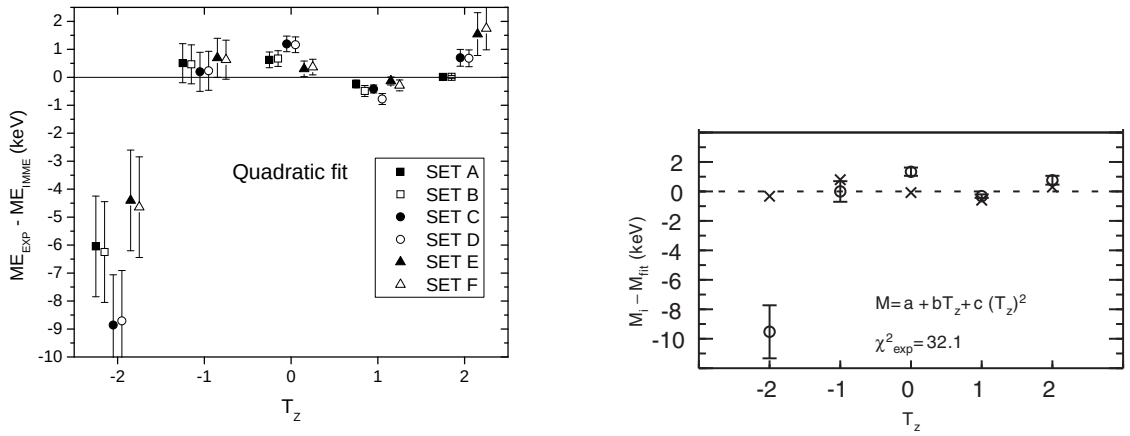
Table 1: The mass-excess values for the ground states (ME_{gs}) and the excitation energies (E_{ex}) of the $T = 2$ isobaric analog states at $A = 32$ used in [6]. For details, see text.

nuclide	T_z	set	ME_{gs} (keV)	Ref.	$E_{ex}(T=2)$ (keV)	Ref.
^{32}Ar	-2		-2200.2(18)	[14]	0	
^{32}Cl	-1		-13334.64(57)[1)]		5046.3(4)	[15]
^{32}S	0		-26015.5346(15)	[16]	12047.96(28)	[17]
^{32}P	1	A,C,E	-24304.94(12)[2),3)]		5072.48(9)[3)]	[18, 19]
		B,D,F	-24305.22(19)	[20]	5072.44(6)	[21]
^{32}Si	2	A,B	-24080.92(5)[4)]		0	
		C,D	-24077.68(30)	[4]	0	
		E,F	-24080.86(77)	[22]	0	

[1)] A weighted mean of [6] and [5].
[2)] Mass-excess value of ^{31}P [23] and S_n value for ^{32}P [18, 19] used.
[3)] An additional systematic error of 20 ppm was taken into account also for [18], where only a statistical error was given.
[4)] Mass-excess value of ^{28}Si [23] and S_n values for ^{29}Si - ^{32}Si used.

Various measurements have already been performed on the one hand by Penning-trap mass spectrometry directly. On the other hand, the mass values were deduced from two-neutron separation energies or (n, γ) reactions. The different available mass-excess values are listed in Tab. 1 and have been combined in six different ways (data sets A-F) to perform quadratic IMME fits as can be seen from Fig. 2a. It shows the difference of the experimental mass-excess value to different values obtained by fitting the IMME to extract the respective mass value. Tab. 1 and Fig. 2a are taken from [24] where a more

detailed discussion of the mass-excess values can be found. The overall result shows that a quadratic IMME fit fails significantly in all data sets. The obtained χ^2/n values – with n being the degrees of freedom – are all $\chi^2/n \geq 6.6$.



(a) Quadratic IMME fit.

(b) Shell-model calculations.

Figure 2: (a) Differences of the experimental values to the error-weighted quadratic fits of the mass-excess values in the $T = 2$ quintet at $A = 32$ from different measurements, cp. Tab. 1. The error bars represent only the uncertainties of the experimental mass-excess values. (b) Accuracy of the IMME with three terms (circles) and corresponding theoretical calculations with the USDB interaction (crosses). Taken from [7].

The need to remeasure ^{32}Ar is also supported from recent theoretical calculations by Signoracci and Brown who studied the effects of isospin mixing in the $A = 32$ quintet [7]. They performed shell-model calculations in the *sd*-shell model space with the USDB interaction [25] to determine energy levels and spectroscopic properties. Showing the same behavior as in Fig. 2a, the calculation for the quadratic form of the IMME deviates most in the case of ^{32}Ar, whereas the theoretical calculations coincide well with the IMME fit. The experimental values used are identical to Tab. 1, except for combining the two values for ^{32}P and using the recent direct measurement of the ^{32}Si mass [4].
To finalize the question of validity or breakdown of the IMME, the masses of ^{32}Ar ($T_z = -2$), ^{32}Cl ($T_z = -1$), ^{32}S ($T_z = 0$), ^{32}P ($T_z = 1$), and ^{32}Si ($T_z = -2$) have to be remeasured [24]. In the case of ^{32}Cl, ^{32}S, and ^{32}P also the excitation energies are needed, which can be unambiguously distinguished from the ground state by state-of-the-art high-precision Penning-trap spectrometry. In the case of ^{32}Ar, the use of the Ramsey technique would help to gain a factor of 2-3 in precision compared to the last measurement when this technique was not yet available [14]. Therefore, a remeasurement of ^{32}Ar will provide the complementary information needed for a comprehensive refined test of the IMME at $A = 32$ in order to really validate the breakdown of the IMME.

3 Mass Measurements at ISOLTRAP

The Penning-trap mass spectrometer ISOLTRAP has been performing mass measurements with high-precision for many years giving input to many physical topics reaching from nuclear structure studies to astrophysical applications and fundamental tests, which has been documented in many publications [26].

3.1 Experimental Setup

Precision mass measurements have been performed with the Penning-trap mass spectrometer ISOLTRAP with a relative uncertainty routinely reaching 10^{-8} [27]. A recent summary of all measured masses since 2006 is given in [28].

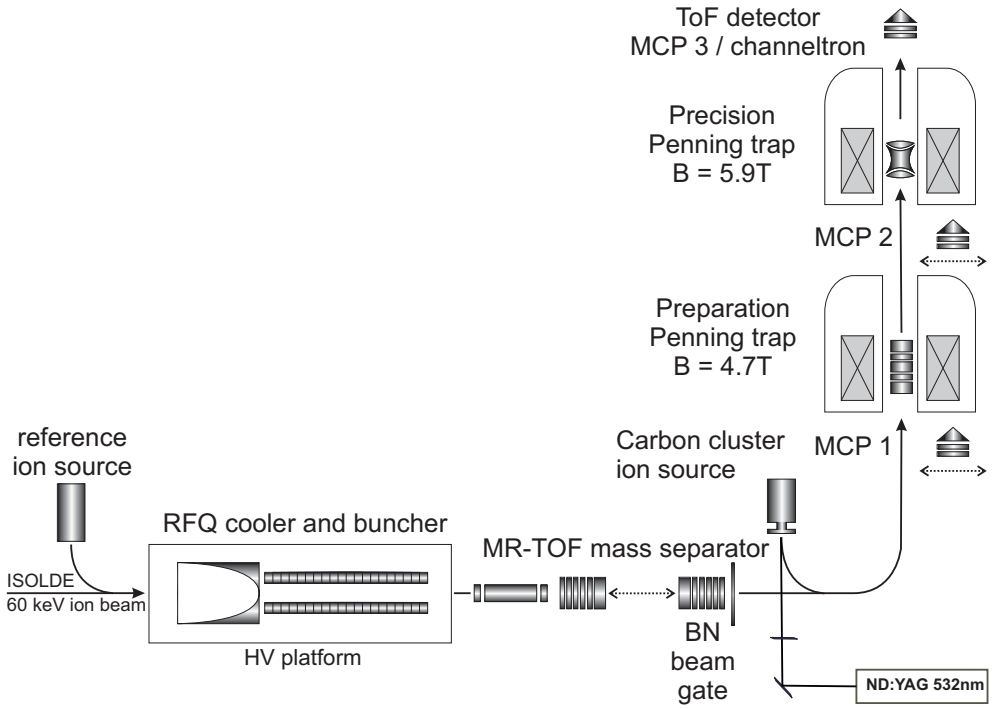


Figure 3: Schematic view of ISOLTRAP. For details see text.

Fig. 3 shows the current experimental setup which can be used without modifications for the proposed mass measurement. Up to recently, ISOLTRAP consisted of three parts: a radio-frequency quadrupole (RFQ) ion trap for beam preparation and two Penning traps [27]. The linear, gas-filled RFQ ion trap cools the $30 - 60$ keV quasi-continuous ISOLDE beam via buffer gas cooling. Furthermore, the ions are accumulated and leave the so-called buncher as ion bunches towards the preparation Penning trap where contaminants are removed with a resolving power of up to 100,000. The ions are then transferred to the second, precision Penning trap for the mass measurement. The time-of-flight detection technique is employed to determine the cyclotron frequency of an ion stored in a Penning trap, from which the mass can be extracted in conjunction with a reference mass measurement [29]. During the year 2010, a multi-reflection time-of-flight (MR-TOF) mass separator was installed and successfully commissioned [30, 31]. The MR-

TOF mass separator acts as an auxiliary device for isobaric purification of rare-isotope ensembles, which not only conserves a high ion-of-interest throughput – in the case of strong contamination, but also works on shorter time scales than the preparation trap, thus enhancing the capabilities of ISOLTRAP significantly. By that, it will be possible to gain in statistics for ^{32}Ar as compared to the previous ISOLTRAP measurement [14].

3.2 Current Performance of ISOLTRAP

High-precision mass measurements over the whole nuclear chart are possible with ISOLTRAP. The relative, mass-dependent systematic error over a wide mass range of 250 u was determined as an upper limit to $8 \cdot 10^{-9}$ [12]. The experiment is performed at room temperature with a high vacuum of roughly $1 \cdot 10^{-8}$ mbar at the position of the Penning traps yielding an overall transport and detection efficiency for short-lived nuclei between 0.3 % and 1% depending on the half-life or charge-exchange losses of the nuclide of interest. The system has adressed nuclei with half-lives down to 65 ms [32] with a yield of some few hundred ions per second. Isomeric states can be resolved well below 100 keV excitation energy [33]. With the newly installed MR-TOF mass separator with a pressure of $5 \cdot 10^{-9}$ mbar and usual trapping times of $5 - 30$ ms one can reach a resolving power of 200,000. A Bradbury-Nielsen beam gate installed directly behind the MR-TOF mass separator reaches a suppression factor for contaminating ions of four orders of magnitude, thus considerably enhancing the performance of ISOLTRAP when dealing with large contamination ratios [30, 31]. Furthermore, the MR-TOF mass separator can also be used in the stacking mode or could in principle even be used for a direct mass measurements. First studies have been performed at ISOLTRAP during the running period 2011, a furter systematic investiagtion of this measurement method under online conditions is part of the INTC proposal [34]. Finally, the Ramsey technique mentioned in section 2 has been developed at ISOLTRAP in 2007 [8, 9] and can be used to gain in precision.

4 Beam Time Requests

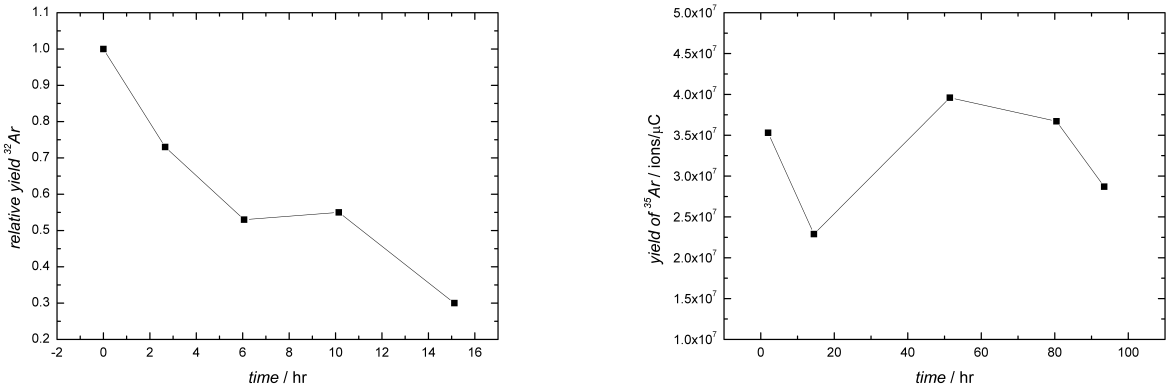
The beam time request of 8 shifts is listed in Tab. 2 together with the half-life and the current mass uncertainty of ^{32}Ar which are taken from [35], the expected yield for ^{32}Ar was communicated by Th. Stora [36]. Moreover, the required target-ion-source combination is listed. Again, we ask in addition for 1 shift to calibrate the MR-TOF mass separator.

Table 2: Proposed mass measurement

nuclei	half-life	δm/keV	yield (ion/μC)	shifts	target	ion source
^{32}Ar	98.0 ms	1.8	$8{\cdot}10^2$	8	nano-structured CaO	VADIS

We propose to use a nano-structured CaO-target studied during the running period 2011 in the ISOLDE Target Group [37]. In comparison to the target CaO#123 used for the former ISOLTRAP measurements, it performs significantly better. Fig. 4a shows that

after 15 hours of operation only about 1/3 of the original beam intensity was left with the target CaO#123. On the contrary, the newly developed unit CaO#469 has delivered constant beam of ^{35}Ar for more than 100 hours. In addition, it has been observed, that in the case of the CaO#469 target the release of ^{32}Ar is dominated by its short half-life as it has been the case for the CaO#123 target. Furthermore, the yield for ^{32}Ar seen with the novel target is a factor of 8 higher than in 2001, measured only after 10^{18} protons had already been impinged on the target [36].
The main contamination during the measurements of 2001 was $^{32}O_2$ with a resolving power of $R \approx 4000$. A comparable level of contamination can now be treated in addition with the fast purification cycle of the MR-TOF mass separator decreasing the time of a single measurement by roughly a factor of 2. Another contamination is expected to be ^{32}S, however due to the low resolving power of $R \approx 1000$, the ISOLDE HRS slits can be used to remove this contamination. Taking into account the developments for the novel CaO-target, it will be possible to perform the experiment with the envisaged improvement in accuracy of a factor of 3-5 within the proposed 9 shifts. Finally, the proposed measurements can be performed with the same target unit as is required for the WITCH experiment IS433 on the existing INTC proposal P111 [38].



(a) Relative yield of ^{32}Ar with target CaO#123.

(b) Yield of ^{35}Ar with target CaO#469.

Figure 4: (a) Relative yield of ^{32}Ar measured at ISOLTRAP as a function of time with target CaO#123 during the running period 2001. (b) Yield of ^{35}Ar measured at the ISOLDE tape station as a function of operation time with the newly developed nano-structured target CaO#469 during the running period 2011 with $8 \cdot 10^{12}$ protons per pulse.

Summary of requested shifts: In summary, 8 shifts are requested for the mass measurement as summarized in Tab. 2 and 1 shift for the calibration of the MR-TOF mass separator. They could be combined on a single target with shifts from WITCH experiment IS433, INTC proposal P111.

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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.