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ISOLTRAP results 2006–2009

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Abstract Since 2006 the ISOLTRAP mass spectrometer has provided high-precision masses of many short-lived nuclides located all across the nuclear chart with half-lives down to a few 10 ms. These nuclides range from the two-proton halo candidate ^{17}Ne, via the neutron-rich magic ^{80}Zn and ^{132}Sn, up to ^{229}Rn which was identified for the first time. The results show that ISOLTRAP is a versatile tool well suited to address physics topics such as nuclear structure, stellar nucleosynthesis, or the weak interaction.

Keywords Atomic masses · Penning trap mass spectrometry · Magic numbers · Nucleosynthesis · CVC hypothesis and CKM unitarity

Penning trap mass spectrometers are ideal tools for high-precision studies on very short-lived and rare nuclides [1]. In the years 2006–2009 the ISOLTRAP spectrometer at ISOLDE/CERN (as described recently in [2]) has allowed the determination of the masses of over a hundred exotic nuclides all over the nuclear chart (a list of the nuclides and references is given in Table 1). The physics topics addressed range from nuclear structure and astrophysics to the weak interaction. Below we give a short overview of these measurements, as well as of the technical developments at ISOLTRAP over that period.

Nuclear structure questions were investigated in several regions of the nuclear chart. In the light nuclei sudden structural changes were addressed with mass measurements of $^{17,19-22}$Ne [3] which provided input data for deriving precise nuclear

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Table 1 Nuclides whose masses were measured and/or published at ISOLTRAP in 2006–2009

Element	Mass numbers	References
Ne	17, 19–22	[3]
Na	21–23	[17]
Mg	22, 24	[17]
Al	26, 27	[20]
K	35–39, 43–46	[4, 17]
Ca	38, 39	[19–21]
Mn	58–66	(Naimi et al., unpublished)
Ni	57, 60, 64–69	[5]
Cu	65–74, 76	[5]
Zn	71–81	[6]
Ga	63–65, 68–78	[5]
Se	70–73	(Herfurth et al., unpublished)
Br	72–75	(Herfurth et al., unpublished)
Kr	72, 78, 80, 82, 84, 86–97	[7, 10] (Naimi et al., unpublished)
Rb	74–77, 79, 80, 83	[22]
Ag	98–101, 103, 112, 114–124	(Bretenfeldt et al., unpublished; Herfurth et al., unpublished)
Cd	99–109, 114–12-, 122–124, 126, 128	(Bretenfeldt et al., unpublished), [11]
Sn	127, 131–134	[9]
Xe	126, 129, 130, 136–146	[12, 13]
Cs	145, 147	[23]
Tl	181, 183, 186, 187, 196, 205	[23]
Pb	197, 208	[23]
Bi	190–197, 209, 215, 216	[23]
Rn	223–229	[14]
Fr	203, 205, 211–213, 229	[23, 24]
Ra	211	[24]

charge radii from laser spectroscopy. Comparison to theory showed an onset of two-proton halo formation for ^{17}Ne and strong clustering for ^{20,21}Ne. Relevant for symmetries in nuclei, the isobaric multiplet mass equation (IMME) was studied within the K chain, for which $^{35-38,43-46}$K masses were measured [4]. A deviation from the generally adopted quadratic form of IMME was observed at $A = 35$ for the $T = 3/2$ isospin quartet, with $d = -3.2(1.1)$ keV for the cubic term. However, further experimental investigations (especially for ^{35}Cl) and a data recheck are needed to confirm this new “breakdown” of IMME.

In the context of the disappearing and migrating magic numbers, several heavier isotopic chains were studied. The $N = 40$ subshell closure was addressed with measurements of neutron-rich $^{57,60,64-69}$Ni, $^{65-74,76}$Cu, and $^{63-65,68-78}$Ga [5]. In this region no evidence for its magicity was found in the two-neutron separation energies (S_{2n}) and in the pairing gap energies (the latter being based on 4 neighbouring masses). In addition, the masses of neutron-rich $^{58-66}$Mn (Naimi et al., unpublished), with ^{65,66}Mn studied only in 2009, flattened the S_{2n} trend and showed no sudden decrease across $N = 40$, also pointing to the absence of a strong shell gap for this isotopic chain.

The magicity of $N = 50$ and the rapid neutron capture (r-process) were addressed with the study of Zn isotopes up to ^{81}Zn [6]. The mass measurements confirmed the robustness of the $N = 50$ shell closure for $Z = 30$ and allowed a precise mapping of the astrophysical conditions required for ^{80}Zn and its associated abundance signatures to occur in r-process models. The S_{2n} of $^{84,86-95}$Kr [7] showed the quenching of the $N = 56$ spherical subshell gap for $Z = 36$. Between $N = 52$ and $N = 59$, the linear trend in S_{2n} pointed to a regular filling of the spherical neutron orbits, sign of no big structural changes in this region. In 2009, the first mass measurements of ^{96,97}Kr were performed (Naimi et al., unpublished). The resulting continuation of the linear trend in S_{2n} showed no large deformation for these two isotopes. This placed the Kr chain at the border of the nuclear quantum phase transition [8] known to occur at $N = 60$ in the higher-Z neighbours.

The magic number $N = 82$ was addressed far from stability with studies of $^{131-134}$Sn [9]. A 0.5-MeV deviation of the binding energy of ^{134}Sn from the literature value was found, which restored the neutron-shell gap at $N = 82$, previously considered to be a case of "shell quenching". The new shell gap value for ^{132}Sn turned out to be larger than that of the doubly magic stable ^{48}Ca. Furthermore, ^{132}Sn is a waiting-point in the rapid-neutron capture (r-process) and the $N = 82$ shell gap had considerable impact on fission recycling during this process. Below the Sn chain, the studies were extended to $^{112,114-124}$Ag and $^{114,120,122-124,126,128}$Cd (Breitenfeldt et al., unpublished).

On the neutron-deficient side, relevant for the rapid proton capture (rp-process), the masses of $^{70-73}$Se, $^{72-75}$Br, $^{98-101,103}$Ag were analysed (Herfurth et al., unpublished). In a more recent run, including $^{72-78,80,82}$Kr [10], ^{72}Kr turned out to be a strong waiting point in the rp-process and the ft value for beta decay of ^{84}Rb to ^{84}Kr gave an accurate isospin-symmetry-breaking parameter. The measurements on $^{99-109}$Cd [11] allowed the first direct mass measurement of ^{99}Cd which reduced the uncertainty of the abundance and overproduction created by the rp-process.

In the Xe chain, stable ^{126,129,130,136}Xe were investigated as doubly-charged ions [12] which survived the charge exchange process. Multiply-charged ions have correspondingly higher cyclotron frequencies. Thus, less ions are needed to reach a given uncertainty. This first-time study showed the feasibility of working with multiply-charged ions at an online Penning trap mass spectrometer, which can push further the precision and half-life limits of this technique. The singly-charged neutron-rich $^{136-146}$Xe [13], as well as neutron-rich $^{223-229}$Rn [14] were studied in 2008 using the newly developed high-efficiency arc discharge ion source VADIS. The new mass values allowed deriving the residual proton-neutron interaction (given by double mass differences), which showed a unique parabola-like behaviour. The effect might be connected to strong octupole correlations known to be present in both regions. In addition, this experiment marked the first discovery of a new nuclide, ^{229}Rn, by Penning-trap mass spectrometry.

In the past few years ISOLTRAP addressed also several superallowed beta-emitters whose masses provide valuable input to the tests of the conserved-vector-current (CVC) hypothesis of the electroweak interaction [15], especially concerning the theoretical corrections. The lightest example is ^{22}Mg [16] investigated together with the neighbouring $^{21-23}$Na, ^{22,24}Mg, and ^{37,39}Mg [17]. A detailed analysis of the local frequency-ratio network allowed determining the masses, including that of ^{22}Mg, with 1×10^{-8} relative precision and better. The next case is the isomeric state of ^{26}Al. The ground state mass of this nuclide, connected to ^{26}Al^m by its well-known excitation energy, was determined using the Ramsey excitation scheme based on time separated fields [18, 19]. This method was studied in detail using in addition ^{39}Ca and the stable ^{27}Al [20]. Another example is ^{38}Ca [21] (with a large isospin symmetry-breaking correction) investigated also with the Ramsey excitation technique. This scheme was used for the first time for an unstable nuclide and it allowed reaching a statistical uncertainty similar to the conventional scheme but up to 10 times faster. The heaviest super-allowed beta emitter investigated at ISOLTRAP is ^{74}Rb, studied together with other neutron-deficient Rb isotopes $^{75-77,79,80,83}$Rb [22]. With a 65-ms half-life, ^{74}Rb was the shortest-lived nuclide investigated at ISOLTRAP, a record which was improved in 2009 when ^{66}Mn was addressed (with $T_{1/2}$ =64.4 ms).

In the heavy-mass region close to the doubly magic ^{208}Pb over 30 nuclides were investigated and in most cases the high resolving power of the data allowed a clear mass-to-state assignment. The comparison of the resulting separation energies of ^{145,147}Cs, ^{181,183,186,187,196,205}Tl, ^{197,208}Pb, $^{190-197,209,215,216}$Bi, ^{203,205,229}Fr, and ^{214,229,230}Ra [23] with the existing charge radii data from laser spectroscopy studies showed correlations between both observables. In 2008, improved masses of $^{211-213}$Fr and ^{211}Ra [24] resulted from a preparatory run towards a decay-spectroscopy system at ISOLTRAP, which was commissioned later in 2009 (Kowalska et al., unpublished). This setup will allow performing beta- and gamma-spectroscopy on ion ensembles purified with the ISOLTRAP Penning traps. Such a system can be used to address nuclides whose decay studies are presently hampered by strong contamination, or alternatively to assist mass measurements in performing the mass-to-state assignment.

In summary, in the period from 2006 to 2009 the ISOLTRAP Penning trap mass spectrometer has provided over 100 high-precision masses of short-lived nuclides, ranging from the light systems below $A = 20$ up to heavy ones above ^{208}Pb. Among the investigated physics topics were the nuclear structure studies with shell closures and proton-neutron interaction, neutron and proton rapid capture processes in stellar environments, as well as weak interaction studies in the case of superallowed beta emitters. The recent technical developments included the first-time online studies with the Ramsey excitation technique and the implementation of a decay spectroscopy setup located behind the precision Penning trap.

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