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for experiment IS413 to the ISOLDE and Neutron Time-of-Flight Committee

HIGH-PRECISION MASS MEASUREMENTS OF EXOTIC NUCLEI WITH THE TRIPLE-TRAP MASS SPECTROMETER ISOLTRAP

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In the ISOLDE running period of 2004 the experiment IS413 asked for five beam times (^{22}Mg, ^{35}K, ^{62}Ga, $^{17-25}Ne$, ^{26m}Al) with a total number of 28 radioactive beam shifts (see Table 1). Since ISOLTRAP has been the only requester for an Al beam the run was not scheduled and postponed to next year. In addition to the requested runs ISOLTRAP was allowed to take once more radioactive beam. Due to a failure of REX-ISOLDE a Kr beam was available and only ISOLTRAP was able to take the radioactive beam on very short notice (within less than eight hours). The ^{62}Ga run was stopped after one day since a wrong ISOLDE target had been installed. The final number of radioactive beam shifts taken by ISOLTRAP can only be given by the ISOLDE Coordinator after the running period, with one more scheduled ISOLTRAP run to come.

Table 1: ISOLTRAP beam times scheduled in 2004.

Beam time	Dedicated for	No. of shifts	Remark	Separator	Target/ion source
Mai 2004	^{22}Mg, ^{22}Na (CVC)	6		HRS	Ti foil / RILIS
Mai 2004	^{35}K (IMME)	4		HRS	Ti foil W
June 2004	^{62}Ga, ^{62}Zn (CVC)	8	stopped	HRS	ZrO_2 / RILIS
July 2004	n-rich Kr (astroph.)	5	not request.	HRS	UC / CP
Nov. 2004	$^{17-25}Ne$ (halo, IMME)	7		HRS	MgO / CP
	^{26m}Al (CVC)	3	postponed	HRS	UC / HP

ISOLTRAP looks back on a very successful year with so far 22 measured masses, all of them with a relative uncertainty between $8 \cdot 10^{-9}$ and $3 \cdot 10^{-8}$. Table 2 gives the investigated nuclides with the half-lives, the literature and experimentally obtained mass uncertainties as well as the reached relative mass uncertainty. For most of the investigated nuclides the final data analysis is still in progress. Thus, only preliminary uncertainties can be given in the cases that are marked with an asterisk. At the time of the submission of this status report one ISOLTRAP run still has to take place ($^{17-25}Ne$).

Since the importance of the physics output of these mass measurements was already explained in detail in our proposal P160, only a few comments on the beam times and some specific highlights and problems will be addressed in the following.

^{21,22}Na, ^{22}Mg:

Direct high-precision mass measurements on superallowed β-emitters and their daughters contribute to tests of two fundamental postulates of the Standard Model: The conserved-vector-current hypothesis of the weak interaction and the unitarity of the Cabibbo-Kobayashi-Maskawa matrix. The required relative mass uncertainty of about $1 \cdot 10^{-8}$ is available today at ISOLTRAP. Recent measurements in this context are the determination of the decay energies of $^{74}Rb(\beta^+)^{74}Kr$ (measured in 2003 [1]) and $^{22}Mg(\beta^+)^{22}Na$ [2]. The mass excesses obtained for ^{22}Mg and its reaction partners ^{21}Na and ^{22}Na are: $D(^{22}Mg) = -399.92(27)$ keV, $D(^{21}Na) = -2184.71(21)$ keV, and $D(^{22}Na) = -5181.56(16)$ keV. A typical time-of-flight ion cyclotron resonance for the short-lived $^{22}Mg^+$ is shown in Figure 1.

Besides the determination of the comparative half-life (Ft value) for the superallowed β decay of ^{22}Mg also the resonance energy for the ^{21}Na proton capture reaction ($^{21}Na(p,\gamma)^{22}Mg$) has been determined using our high-precision proton separation energy value and the 2^+ level energy in ^{22}Mg, allowing direct comparison of observable γ radiation in nova explosions with the yield expected from models [2]. The so-called NeNa cycle for the production of ^{22}Na is shown in Figure 2(a), the energy level scheme of ^{22}Mg including our result is given in Figure 2(b).

Table 2: Radionuclides measured with ISOLTRAP in 2004. Some highlights are discussed in the text. For mass uncertainties marked by # , masses were obtained for the first time. For nuclides marked with an asterisk * the evaluation is in progress, thus only preliminary uncertainties are given. Literature values are taken from the Atomic-Mass Evaluation AME2003 [3]

Nuclide	Half-life $T_{1/2}$	δm_{lit} / keV	δm_{exp} / keV	$\delta m_{\mathrm{exp}}/m$
21Na	22.49 s	0.7	0.21	1.1E-8
22Na	2.6 y	0.4	0.16	8.0E-9
22Mg	3.857 s	1.3	0.27	1.3E-8
35K*	178 ms	20	0.53	1.6E-8
36K*	342 ms	8	0.39	1.2E-8
37K*	1.226 s	0.09	0.35	1.0E-8
38K*	7.636 m	0.4	0.34	9.6E-9
43K*	22.3 h	9	0.46	1.1E-8
44K*	22.13 m	40	0.35	8.5E-9
45K*	17.3 m	10	0.41	9.8E-9
46K*	105 s	16	0.49	1.1E-8
84Kr*	stable	2.8	1.1	1.4E-8
86Kr*	stable	0.10	0.9	1.1E-8
87Kr*	76.3 m	0.27	1.9	2.3E-8
88Kr*	2.84 h	13	1.7	2.1E-8
89Kr*	3.15 m	50	1.7	2.1E-8
90Kr*	32.32 s	19	1.9	2.3E-8
91Kr*	8.57 s	60	2.1	2.5E-8
92Kr*	1.84 s	12	1.4	1.6E-8
93Kr*	1.286 s	100#	2.3	2.7E-8
94Kr*	210 ms	300#	2.5	2.9E-8
95Kr*	114 ms	400#	2.5	2.8E08

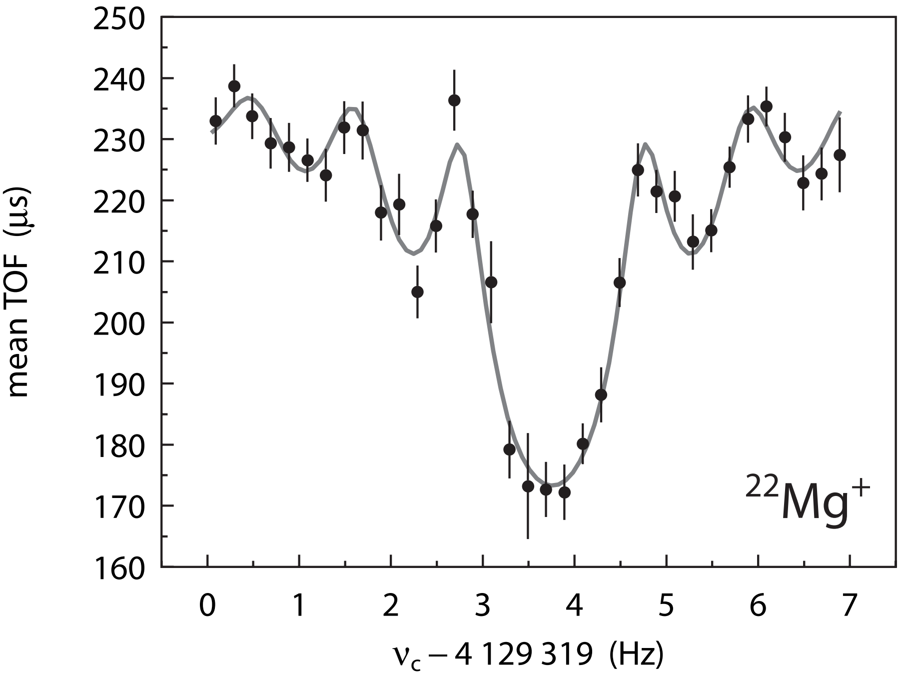

Figure 1: Typical time-of-flight (TOF) ion cyclotron resonance of $^{22}Mg^{+}$. The solid line is a fit of the theoretically expected line shape to the data.

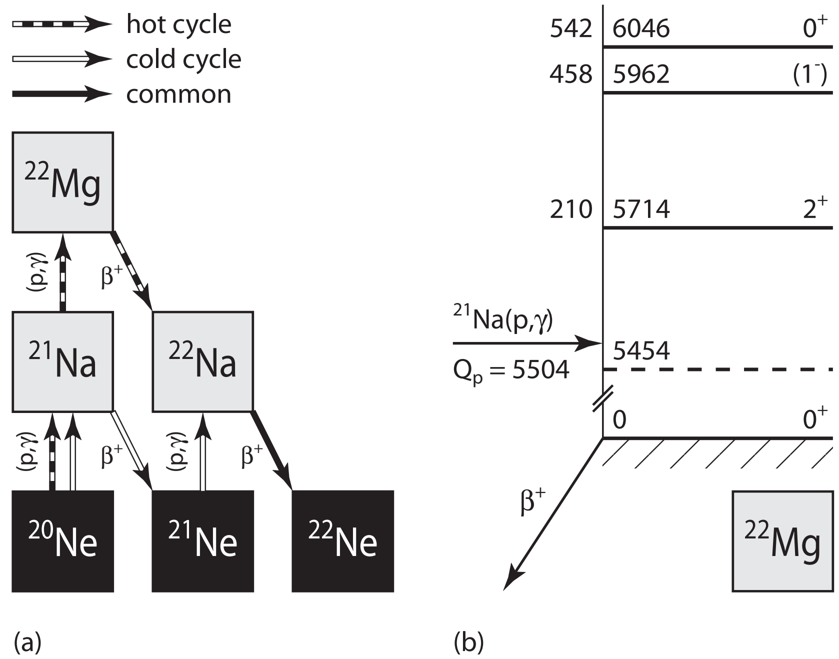

Figure 2: (a) ‘‘Hot’’ and “cold” reaction paths of the NeNa cycle. The bottom row (black boxes) are stable nuclides; (b) level scheme of ^{22}Mg, showing the levels with astrophysical relevance. The level energies E_x (center) are shown along with the center-of-mass energies E_x - Q_p (left; both in keV) and the spin parity (right).

^{62}Ga:

This nuclide is also a superallowed β-emitter and has thus the same physics interest as ^{22}Mg (see above). The ISOLTRAP run on the HRS separator was stopped since the wrong ISOLDE target material was used. From a previous run it was known that the high TiO contamination makes this target material an impossible option for the ISOLTRAP experiment. Better material was available but mistakenly not used.

^{35}K:

Mass measurements on ^{32}Ar ($T_{1/2}$ = 98 ms) and ^{33}Ar ($T_{1/2}$ = 173 ms) with relative uncertainties of $6.0\cdot10^{-8}$ and $1.4\cdot10^{-8}$, respectively [4], provide the so far most stringent test of the isobaric-multiplet mass equation (IMME). IMME relates the masses of the members of an isospin multiplet; ^{33}Ar is a member of a T = 3/2 quartet while ^{32}Ar is a member of a T = 2 quintet. Since the mass formula IMME is used to predict unmeasured nuclear masses and level energies that are necessary for, *e.g.*, calculations of astrophysical processes, such tests are of great practical importance to check the local reliability of IMME. ^{35}K ($T_{1/2}$ = 190 ms)[1] is a member of a $T = 3/2$ quartet where at present the quadratic form fails by 1.5 sigma. ISOLTRAP measured the mass of this nuclide with a relative mass uncertainty of $1.6\cdot10^{-8}$, *i.e.* with δm = 0.53 keV, and improved thus the mass value by a factor of 20. A final mass evaluation and IMME check is at present in progress. Preliminary mass values for all investigated potassium isotopes are shown in Figure 3 and listed in Table 2 (in comparison to the literature values taken from the AME2003 [3]).

[1] In the original proposal a wrong potassium isotope was named for this IMME test.

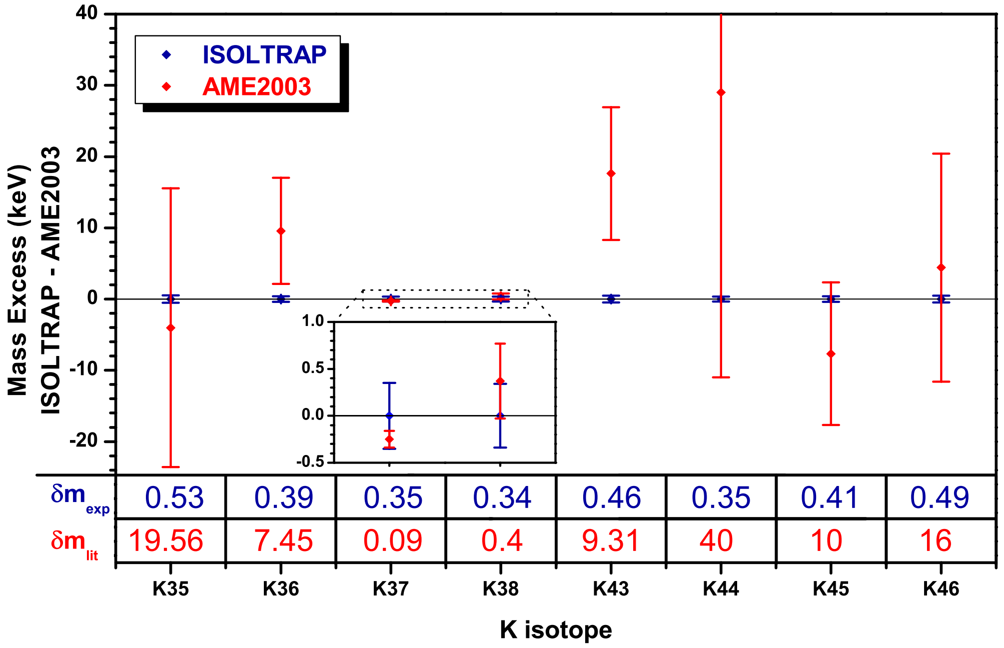

Figure 3: Uncertainties δm_{exp} of potassium mass measurements as preliminary determined. For comparison, literature values δm_{lit} are given from the Atomic-Mass Evaluation AME2003 [3]. The zero line is defined by the ISOLTRAP results.

$^{84-95}$Kr:

Masses are the most critical nuclear parameters for reliable nucleosynthesis calculations. The extension of experimentally known masses to regions far from the valley of stability is decisive for constraints on nuclear models with respect to predicting masses in the region where, *e.g.*, the *r*- and *rp*-process path may proceed. In the past the masses of many nuclides in the vicinity of the *rp* path have been measured with high precision at ISOLTRAP. Direct measurements have also been performed on two important waiting point nuclei, ^{72}Kr [5] and ^{76}Sr [6]. During a recent run on neutron-rich Kr isotopes ISOLTRAP managed to reach ^{95}Kr where the *r*-process path might go through. All measured neutron-rich Kr masses are listed in Table 2 together with the preliminary mass uncertainties.

Summary and shutdown plans 2004:

At present, the precise determination of nuclear binding energies far from stability includes nuclides that are produced at rates of 100 ions/s and with half-lives well below 100 ms. The mass resolving power reaches 10^7 and the uncertainty of the resulting mass values has been pushed down to $8 \cdot 10^{-9}$. Figure 4 shows all masses measured by ISOLTRAP.

To further improve the relative mass uncertainty and to strengthen the ISOLDE/ISOLTRAP forefront position in the field of on-line mass spectrometry several technical and experimental improvements are planned for the shutdown period 2004, *e.g.* the installation of a new high-efficient detector system and a new carbon cluster ion source for mass references. At present the precision of mass determinations is limited by temperature and pressure fluctuations in the helium and nitrogen reservoir of the superconducting magnets. They cause fluctuations in the magnetic susceptibility of the materials surrounding the precision Penning trap and thus in the magnetic field homogeneity. Hence, the effect of temperature and pressure variations will be determined and a stabilization system will be implemented in order to further reduce the systematic uncertainties.

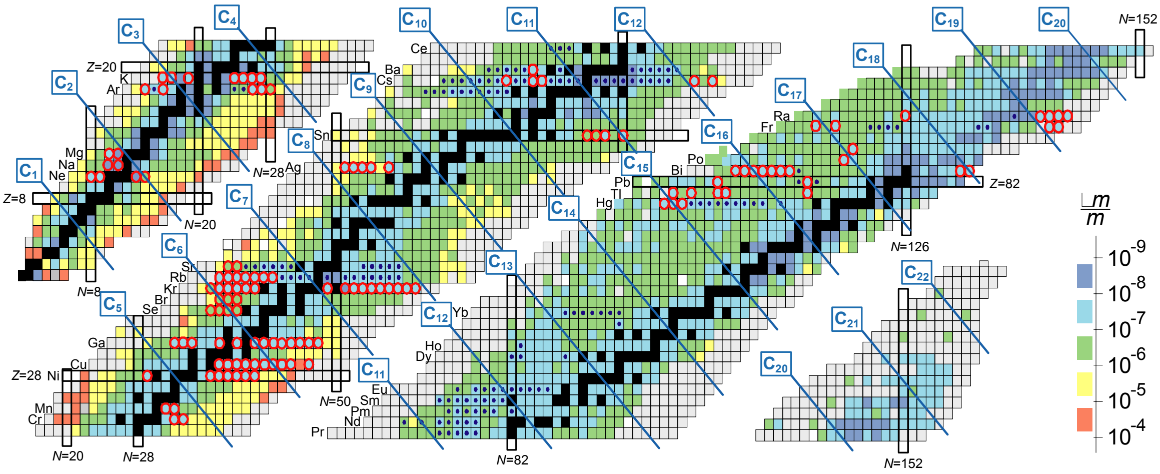

Figure 4: Nuclear chart with the relative mass uncertainties *δm/m* of all known nuclides shown in a color code (see scale bottom right, stable nuclides are marked in black). Masses of grey-shaded nuclides are estimated from systematic trends [3]. Masses measured with ISOLTRAP since 2002 are marked with red circles, earlier measurements with blue dots. The isobaric lines of the carbon clusters C_1 to C_{22} demonstrate the advantage of using a "carbon cluster mass grid" for calibration purposes.

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[1] A. Kellerbauer *et al.*, *Direct mass measurements on the superallowed emitter ^{74}Rb and its daughter ^{74}Kr: Isospin-symmetry-breaking correction for Standard-Model tests*, Phys. Rev. Lett. 93 (2004) 072502.

[2] M. Mukherjee *et al.*, *The mass of ^{22}Mg*, Phys. Rev. Lett., in print (2004).

[3] G. Audi *et al.*, *The AME2003 atomic mass evaluation*, Nucl. Phys. A 729 (2003) 337.

[4] K. Blaum *et al.*, *Masses of ^{32}Ar and ^{33}Ar for fundamental tests,* Phys. Rev. Lett. 91 (2003) 260801.

[5] D. Rodriguez *et al.*, *Mass measurements on the rp-process waiting point ^{72}Kr*, Phys. Rev. Lett., in print (2004).

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Beam time request 2005:

We ask for the second 2-years period of our originally submitted proposal P160. In particular, we ask for a total number of 25 radioactive beam shifts for next year. The beam time request is given in detail in Table 3.

Table 3: Beam time request for 2005.

Nuclides	Field of interest	No. of shifts	Ion Source	Target
^{14}O	CVC, CKM	3	Hot plasma	SiC
$^{17-19}$N	halo, IMME	6	Hot plasma	CaO
^{26m}Al	CVC, CKM	3	Hot plasma	SiC
$^{70-71}$Ni	mass surface	5	WSI	UC
$^{125-131}$Cd	Astrophysics	5	RILIS	UC
$^{131-134}$Sn	Astrophysics	3	RILIS	UC
25 radioactive beam shifts				

List of publications 2003/2004:

2003

1. **From direct to absolute mass measurements: A study of the accuracy of ISOLTRAP**
A. Kellerbauer, K. Blaum, G. Bollen, F. Herfurth, H.-J. Kluge, M. Kuckein, E. Sauvan, C. Scheidenberger, and L. Schweikhard
Eur. Phys. J. D 22, 53 (2003)

2. **Mass measurements and nuclear physics – recent results using ISOLTRAP**
F. Herfurth, F. Ames, G. Audi, D. Beck, K. Blaum, G. Bollen, A. Kellerbauer, H.-J. Kluge, M. Kuckein, D. Lunney, R.B. Moore, M. Oinonen, D. Rodríguez, E. Sauvan, C. Scheidenberger, S. Schwarz, G. Sikler, C. Weber, and the ISOLDE Collaboration
J. Phys. B 36, 931 (2003)

3. **Resent developments at ISOLTRAP: towards a relative mass accuracy of exotic nuclei below 10^{-8}**
K. Blaum, G. Bollen, F. Herfurth, A. Kellerbauer, H.-J. Kluge, M. Kuckein, S. Heinz, P. Schmidt, L. Schweikhard
J. Phys. B 36, 921 (2003)

4. **Pushing the relative mass accuracy limit of ISOLTRAP on exotic nuclei below 10 ppb**
K. Blaum, D. Beck, G. Bollen, F. Herfurth, A. Kellerbauer, H.-J. Kluge, R.B. Moore, E. Sauvan, C. Scheidenberger, S. Schwarz, and L. Schweikhard
Nucl. Instrum. Methods B 204, 478-481 (2003)

5. **Carbon cluster ions for a study of the accuracy of ISOLTRAP**
A. Kellerbauer, F. Herfurth, E. Sauvan, K. Blaum, H.-J. Kluge, C. Scheidenberger, G. Bollen, M. Kuckein, and L. Schweikhard
Hyperfine Interact. 146/147, 307 (2003)

6. **Laser Desorption/Ionization Cluster Studies for Calibration in Mass Spectrometry**
K. Blaum, G. Huber, H.-J. Kluge, and L. Schweikhard
Eur. Phys. J. D 24, 145 (2003)

7. **Atomic and Nuclear Physics with Stored Particles in Ion Traps**
H.-J. Kluge, K. Blaum, F. Herfurth, W. Quint
Physica Scripta T104, 167 (2003)

8. **Recent improvements of ISOLTRAP: Absolute mass measurements of exotic nuclides at 10^{-8} precision**
A. Kellerbauer for the ISOLTRAP Collaboration
Int. J. Mass Spectrom. 229, 107 (2003)

9. **Cluster Calibration in Mass Spectrometry: Laser Desorption/Ionization Studies of Atomic Clusters and an Application in Precision Mass Spectrometry**
K. Blaum, A. Herlert, G. Huber, H.-J. Kluge, J. Maul, L. Schweikhard
Anal. Bioanal. Chem., 377, 1133 (2003)

10. **Masses of ^{32}Ar and ^{33}Ar for Fundamental Tests**
K. Blaum, G. Audi, D. Beck, G. Bollen, F. Herfurth, A. Kellerbauer, H.-J. Kluge, E. Sauvan, S. Schwarz
Phys. Rev. Lett. 91, 260801 (2003)

2004

11. **Unambiguous identification of three β-decaying isomers in ^{70}Cu**
J. Van Roosbroeck, C. Guénaut, G. Audi, D. Beck, K. Blaum, G. Bollen, J. Cederkall, P. Delahaye, H. De Witte, D. Fedorov, V.N. Fedoseyev, S. Franchoo, H. Fynbo, M. Gorska, F. Herfurth, K. Heyde, M. Huyse, A. Kellerbauer, H.-J. Kluge, U. Köster, K. Kruglov, D. Lunney, A. De Maesschalck, V.I. Mishin, W.F. Müller, S. Nagy, S. Schwarz, L. Schweikhard, N.A. Smirnova, K. Van de Vel, P. Van Duppen, A. Van Dyck, W.B. Walters, L. Weissmann, C. Yazidjian
Phys. Rev. Lett. 92, 112501 (2004)

12. **Direct mass measurements on the superallowed emitter ^{74}Rb and its daughter ^{74}Kr: Isospin-symmetry-breaking correction for Standard-Model tests**
A. Kellerbauer, G. Audi, D. Beck, K. Blaum, G. Bollen, B.A. Brown, P. Delahaye, C. Guénaut, F. Herfurth, H.-J. Kluge, D. Lunney, S. Schwarz, L. Schweikhard, C. Yazidjian
Phys. Rev. Lett. 93, 072502 (2004)

13. **Population inversion of nuclear states by a Penning trap mass spectrometer**
K. Blaum, D. Beck, G. Bollen, P. Delahaye, C. Guénaut, F. Herfurth, A. Kellerbauer, H.-J. Kluge, D. Lunney, S. Schwarz, L. Schweikhard, C. Yazidjian
Europhys. Lett. 67, 586 (2004)

14. **A new control system for ISOLTRAP**
D. Beck, K. Blaum, H. Brand, F. Herfurth, and S. Schwarz
Nucl. Instrum. Methods A 527, 567-579 (2004)

15. **Mass measurement of radioactive isotopes**
H.-J. Kluge, K. Blaum, C. Scheidenberger
Nucl. Instrum. Methods A 532, 48-55 (2004)

Submitted or in print

16. **Recent results from the Penning trap mass spectrometer ISOLTRAP**
K. Blaum, G. Audi, D. Beck, G. Bollen, P. Delahaye, C. Guénaut, F. Herfurth, A. Kellerbauer, H.-J. Kluge, D. Lunney, D. Rodrígez, S. Schwarz, L. Schweikhard, C. Weber, C. Yazidjian
Nucl. Phys. A, in print (2004)

17. **Masses along the rp-process path and large scale surveys on Cu, Ni and Ga with ISOLTRAP**
F. Herfurth, G. Audi, D. Beck, K. Blaum, G. Bollen, P. Delahaye, C. Guénaut, A. Kellerbauer, H.-J. Kluge, D. Lunney, D. Rodrígez, S. Schwarz, L. Schweikhard, G. Sikler, C. Yazidjian
Nucl. Phys. A, in print (2004)

18. **Towards high-precision mass measurements on 74Rb fo a test of the CVC hypothesis and the unitarity of the CKM matrix**
A. Kellerbauer, G. Audi, D. Beck, K. Blaum, G. Bollen, P. Delahaye, F. Herfurth, H.-J. Kluge, V. Kolhinen, M. Mukherjee, D. Rodrígez, S. Schwarz
Nucl. Phys. A, in print (2004)

19. **Trapping Radioactive Ions**
H.-J. Kluge, K. Blaum
Nucl. Phys. A, in print (2004)

20. **Direct mass measurements of neutron-deficient xenon isotopes using the ISOLTRAP mass spectrometer**
J. Dilling, F. Herfurth, A. Kellerbauer, G. Audi, D. Beck, G. Bollen, H.-J. Kluge, D. Lunney, R.B. Moore, C. Scheidenberger, S. Schwarz, G. Sikler, J. Szerypo, and the ISOLDE Collaboration
Eur. Phys. J. A, in print (2004)

21. **The Mass of ^{22}Mg**
M. Mukherjee, A. Kellerbauer, D. Beck, K. Blaum, G. Bollen, F. Carrel, P. Delahaye, J. Dilling, S. George, C. Guénaut, F. Herfurth, A. Herlert, H.-J. Kluge, U. Köster, D. Lunney, S. Schwarz, L. Schweikhard, C. Yazidjian
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22. **Mass measurement on the rp-process waiting point ^{72}Kr**
D. Rodríguez, V.S. Kolhinen, G. Audi, J. Äystö, D. Beck, K. Blaum, G. Bollen, F. Herfurth, A. Jokinen, A. Kellerbauer, H.-J. Kluge, M. Oinonen, H. Schatz, E. Sauvan, S. Schwarz
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23. **Atomic Clusters and Ion Cyclotron Resonance Mass Spectrometry - a Fruitful Combination**
L. Schweikhard, K. Blaum, A. Herlert, G. Marx
Eur. J. Mass. Spectrom., submitted (2004)

24. **ISOLTRAP mass measurements of exotic nuclides at $\delta m/m=10^{-8}$**
K. Blaum, G. Audi, D. Beck, G. Bollen, P. Delahaye, S. George, C. Guénaut, F. Herfurth, A. Herlert, A. Kellerbauer, H.-J. Kluge, D. Lunney, M. Mukherjee, S. Schwarz, L. Schweikhard, C. Yazidjian
Nucl. Phys. A, submitted (2004)