

This is a self-archived version of an original article. This version may differ from the original in pagination and typographic details.

Author(s): Kankainen, Anu; Kolhinen, Veli; Elomaa, Viki-Veikko; Eronen, Tommi; Hakala, Jani; Jokinen, Ari; Saastamoinen, Antti; Äystö, Juha

Title: Penning-trap mass measurements on 92, 94-98, 100Mo with JYFLTRAP

Year: 2012

Version: Accepted version (Final draft)

Copyright: © SIF, Springer-Verlag Berlin Heidelberg 2012

Rights: In Copyright

Rights url: <http://rightsstatements.org/page/InC/1.0/?language=en>

Please cite the original version:

Kankainen, A., Kolhinen, V., Elomaa, V.-V., Eronen, T., Hakala, J., Jokinen, A., Saastamoinen, A., & Äystö, J. (2012). Penning-trap mass measurements on 92, 94-98, 100Mo with JYFLTRAP. In J. Äystö, T. Eronen, A. Jokinen, A. Kankainen, I. Moore, & H. Penttilä (Eds.), *Topical collection: An IGISOL Portrait - Selected contributions* (48, pp. 47). Springer. *European Physical Journal A*.
<https://doi.org/10.1140/epja/i2012-12047-0>

Penning-trap mass measurements on $^{92,94-98,100}\text{Mo}$ with JYFLTRAP

A. Kankainen^{1a}, V.S. Kolhinen¹, V.-V. Elomaa^{1b}, T. Eronen^{1c}, J. Hakala¹, A. Jokinen¹, A. Saastamoinen¹, and J. Äystö¹

Department of Physics, P. O. Box 35(YFL), FI-40014 University of Jyväskylä, Finland

Received: date / Revised version: date

Abstract. Penning-trap measurements on stable $^{92,94-98,100}\text{Mo}$ isotopes have been performed with relative accuracy of $1 \cdot 10^{-8}$ with the JYFLTRAP Penning trap mass spectrometer by using ^{85}Rb as a reference. The Mo isotopes have been found to be about 3 keV more bound than given in the Atomic Mass Evaluation 2003 (AME03). The results confirm that the discrepancy between the ISOLTRAP and JYFLTRAP data for $^{101-105}\text{Cd}$ isotopes was due to an erroneous value in the AME03 for ^{96}Mo used as a reference at JYFLTRAP. The measured frequency ratios of Mo isotopes have been used to update mass-excess values of 30 neutron-deficient nuclides measured at JYFLTRAP.

PACS. 07.75.+h Mass spectrometers – 32.10.Bi Atomic masses, mass spectra, abundances, and isotopes

1 Introduction

Recently, a discrepancy was found between cadmium mass measurements performed at JYFLTRAP, where $^{96}\text{Mo}^+$ was used as a reference [1], and SHIPTRAP [2] and ISOLTRAP results, where $^{85}\text{Rb}^+$ was used as a reference ion [3]. Earlier JYFLTRAP has shown to be capable of performing very accurate mass measurements. Therefore, it was assumed that the ^{96}Mo mass-excess value would be about 3 keV off in the Atomic Mass Evaluation 2003 (AME03) [4]. The mass evaluation done in Ref. [3] showed that there is a -3.2 keV shift between the AME03 value and the evaluated value for ^{96}Mo . In this work, we wanted to confirm this evaluation result by a direct mass measurement of ^{96}Mo . If the mass of ^{96}Mo is off by 3 keV, also the neighbouring isotopes connected by (n, γ) reactions in the AME03 are likely to be off. Thus, we decided to check the mass-excess values of all stable molybdenum isotopes and investigate where the possible 3-keV offset could come from. These measurements have a direct effect on previous JYFLTRAP results since stable molybdenum isotopes ($^{94,96,97,98}\text{Mo}$) have been used as references for 30 neutron-deficient nuclides at JYFLTRAP.

2 Mass measurements

JYFLTRAP [5] is a double cylindrical Penning trap mass spectrometer for accurate mass measurements at the Ion-Guide Isotope Separator On-Line (IGISOL) facility [6, 7] in Jyväskylä, Finland. The setup consists of a Radio-Frequency Quadrupole (RFQ) cooler and buncher [8] and a double Penning-trap [9] spectrometer (see Fig. 1). In this experiment, we used an offline electric discharge ion-source at IGISOL to create singly-charged $^{85}\text{Rb}^+$ and $^{92,94-98,100}\text{Mo}^+$ ions.

The first trap of JYFLTRAP (purification trap) is used for the isobaric purification of the injected ion bunches by using the buffer-gas cooling technique [10]. The mass measurement is carried out in the second Penning trap (precision trap). The measurement is based on the determination of the sideband frequency of the ions of interest $\nu_+ + \nu_-$, where ν_+ and ν_- are the reduced cyclotron frequency and the magnetron frequency, respectively. In an ideal Penning trap this sideband frequency matches with the true cyclotron frequency $\nu_c = \frac{1}{2\pi} \frac{q}{m} B$ of ions with charge state q and mass m in the magnetic field B [11]. The frequency determination was done by using the time-of-flight ion-cyclotron-resonance (TOF-ICR) technique [12]. In this method, the ion's radial energy is increased in the trap by using an azimuthal quadrupole radio-frequency (RF) field with the cyclotron frequency of the ions. Since the radial energy of the ions is converted to axial energy in the gradient of the magnetic field when extracted from the trap, the increased energy leads to a shorter flight time to the micro-channel plate (MCP) detector. In this experiment, a Ramsey-type ion motion excitation was used [13,14] with two 25 ms long fringes

^a Email: anu.k.kankainen@jyu.fi

^b Present address: Turku PET Centre, Accelerator Laboratory, Åbo Akademi University, FI-20500 Turku, Finland

^c Present address: Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg, Germany

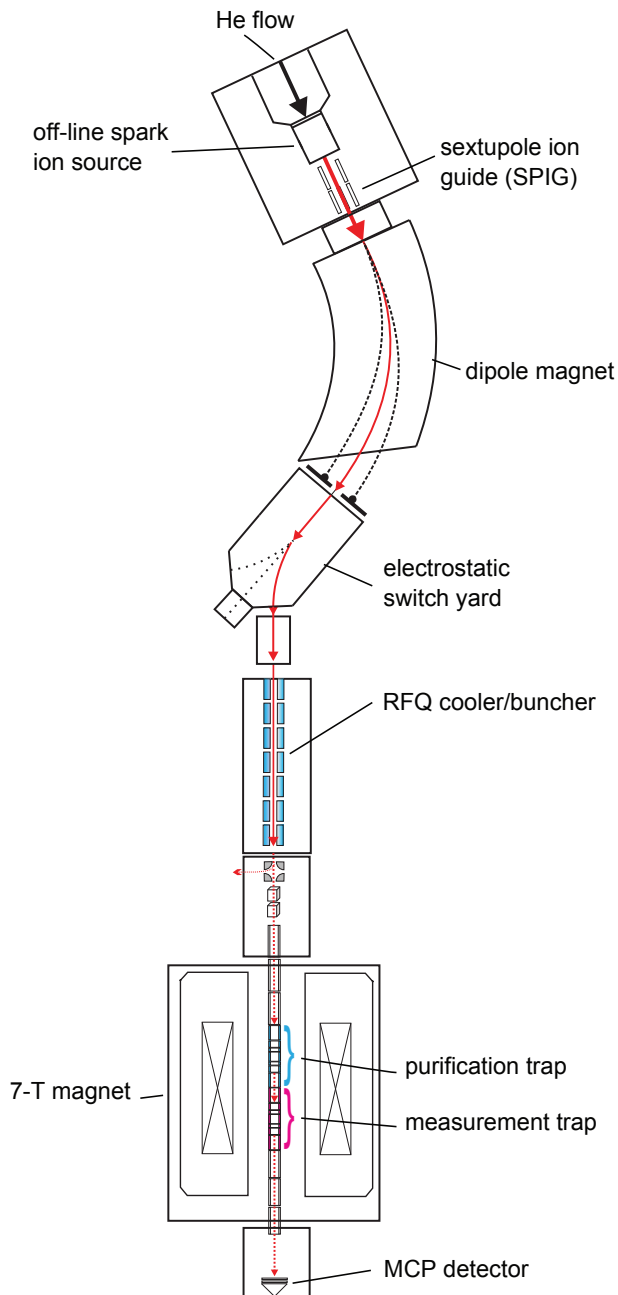


Fig. 1. Schematic illustration of the JYFLTRAP beam line for offline experiments.

separated by a 750 ms long waiting time. Fig. 2 shows two examples of Ramsey TOF-resonances for $^{85}\text{Rb}^+$ and $^{96}\text{Mo}^+$. The cyclotron frequency of an ion and its uncertainty are obtained from the experimental TOF data by fitting the theoretical fit function.

The mass measurement in a Penning trap is based on the measurement of the frequency ratio r between a reference ion with a well-known mass and an ion of interest:

$$r = \frac{\nu_{c,ref}}{\nu_c}. \quad (1)$$

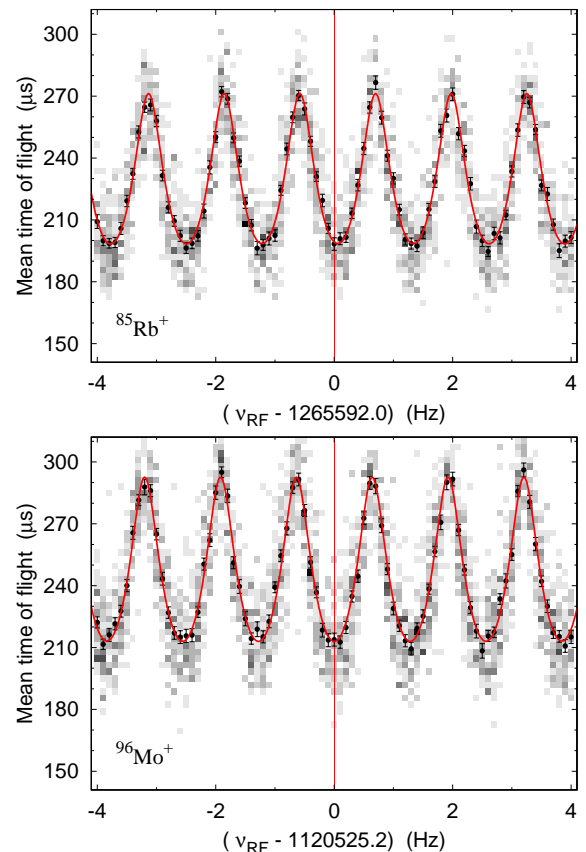


Fig. 2. Ramsey TOF resonances of ^{85}Rb and ^{96}Mo with 25 – 750 – 25 ms timing containing 15 scan cycles (≈ 22 min). Shaded boxes show the density of detected ions, black dots are the average time-of-flights with the uncertainty limits and solid line is the theoretical fitted line shape.

This frequency ratio and its uncertainty are used to deduce the mass of the ion of interest by using equation

$$m_{meas} = r(m_{ref} - m_e) + m_e, \quad (2)$$

where m_{meas} is the mass of the atom of interest, m_{ref} is the mass of the reference atom and m_e is the mass of the electron. Thus, the uncertainty in the mass of the reference atom contributes to the final mass value, and it can be re-evaluated by using the most accurate knowledge for the mass of the reference atom.

3 Data analysis and results

To minimize frequency shifts coming from the drifting magnetic field, the measurements were performed by running 2 scan cycles of the ion of interest (Mo^+) and then 2 scan cycles of the reference ion ($^{85}\text{Rb}^+$) and repeating this pattern. The measured data were divided into 15-cycles-long runs. A count-rate class analysis [15], where the data were divided into classes according to the number of detected ions, was applied. The frequency was extrapolated to 0.6 ions in the trap due to the 60 % detection efficiency.

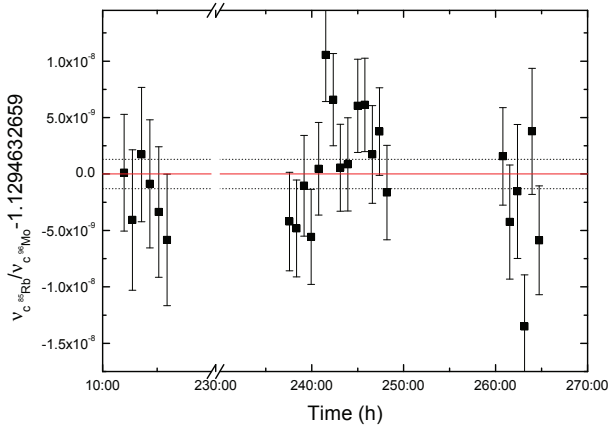


Fig. 3. Measured frequency ratios between $^{85}\text{Rb}^+$ and $^{96}\text{Mo}^+$ obtained by using 25 – 750 – 25 ms Ramsey excitation. Each data point contains 15 scan cycles (≈ 22 min) of both masses. Solid line is the weighted average of these points and the dotted lines show one standard deviation limits.

The average frequency ratios were calculated by using the weighted means. The internal errors (σ_{int} , statistical uncertainties of the weighted means) were compared to external errors (σ_{ext} , weighted standard deviations) and so-called Birge ratios $R = \sigma_{ext}/\sigma_{int}$ were determined [16]. In the ideal case, the ratio should be close to 1. For the uncertainty of r we took always the larger one of the internal and external uncertainties. For this value σ_r , a mass-dependent uncertainty $\sigma_m(r) = (7.5 \cdot 10^{-10}/u) \cdot \Delta m \cdot r$ [17] and a residual uncertainty $\sigma_{res}(r) = (7.9 \cdot 10^{-9}) \cdot r$ [17] were added quadratically.

Measured frequency ratios and their uncertainties are shown in Table 1. Birge ratios were close to 1 in each mass measurement set. This means that the deviations in the data are statistical. The used atomic mass unit is $u = 931\,494.009\,0(71)$ keV [18], the electron mass $m_e = 510.998910(13)$ keV [19], and the value for ^{85}Rb mass excess $\text{ME} = -82167.331(11)$ keV [4]. An example of the measured frequency ratios is shown in Fig. 3.

4 Comparison to previous measurements

In the Atomic Mass Evaluation 2003 (AME03) the molybdenum masses had three main sources. Masses 92-93, 94-95, 95-96, 96-97, 97-98 were linked together with (n, γ) reaction measurements [20, 21]. Masses 92, 94, 95, 96, 98 were measured with a mass spectrometer by using different CH-molecules as references [22]. Masses 92-94 and 98-100 were measured by comparing mass differences of molybdenum oxide chlorides [23]. Actually, also other molybdenum pairs were measured in Ref. [23] but only two links were left in the AME03 sheets. Moreover, there have been several β decay measurements from both sides [24–31]. Different reaction studies, such as (p, n) [32–34], (p, d) [35], $(d, ^3\text{He})$ [36], $(^3\text{He}, p)$ [37], $(^3\text{He}, d)$ [38, 39], $(^3\text{He}, ^6\text{He})$ [40], (t, p) [41], (t, α) [42], and (n, α) [43], have also yielded information on molybdenum isotopes.

In Fig. 4 all the links influencing the Mo mass-excess values in the AME03 are shown. Since the JYFLTRAP values disagreed with the AME03 values (except for ^{92}Mo), a thorough comparison to earlier measurements was carried out and all possible links from and to the Mo isotopes in the AME03 were checked out in this work. The results are given below nuclide by nuclide.

The main result is that the values from Bishop *et al.* [23] disagree with the JYFLTRAP values and explain most of the difference between the JYFLTRAP results and the AME03 values. Deviations were also found to $\text{C}_7\text{H}_{10} - ^{94}\text{Mo}$ [22], $^{95}\text{Nb}(\beta^-)^{95}\text{Mo}$ [24], $^{98}\text{Mo}(n, \gamma)^{99}\text{Mo}$ [20, 21], and $^{100}\text{Mo}(^3\text{He}, p)^{102}\text{Tc}$ [37]. The (n, γ) results between ^{94}Mo and ^{98}Mo agree nicely with the JYFLTRAP values. JYFLTRAP mass-excess values for Mo isotopes suggest that these Mo isotopes are systematically too weakly bound in the AME03. This will also have an effect on the nuclides which have main influences coming from these isotopes, such as for neighbouring Nb and Tc nuclides or ^{101}Mo .

^{92}Mo

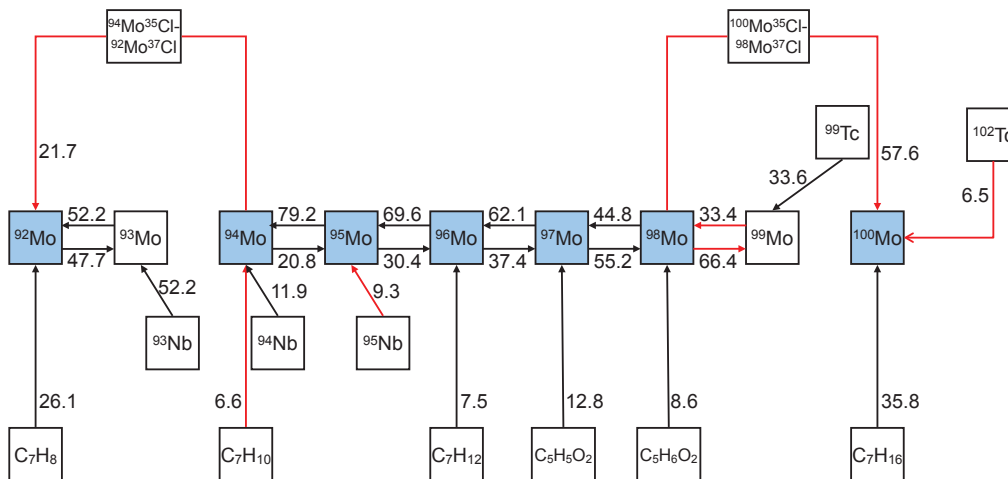
The JYFLTRAP mass value for ^{92}Mo agrees with the values from $\text{C}_7\text{H}_8 - ^{92}\text{Mo}$ [22] and $^{92}\text{Mo}(n, \gamma)^{93}\text{Mo}$ [20] experiments, which have altogether a 78.3 % influence on the ^{92}Mo value in the AME03. The JYFLTRAP value for ^{92}Mo agrees with the AME03 value and other experimental data except with the data from Ref. [23]. The JYFLTRAP mass value for ^{92}Mo is 6.3(22) keV higher than the value obtained from the mass difference of $^{94}\text{Mo}^{35}\text{Cl}^{16}\text{O} - ^{92}\text{Mo}^{37}\text{Cl}^{16}\text{O}$ [23] employing the JYFLTRAP mass value of ^{94}Mo (see Fig. 5). For ^{92}Mo , some (p, n) , $(^3\text{He}, t)$, (p, α) and $(\alpha, ^8\text{He})$ experiments having uncertainties bigger than 20 keV have been omitted from Fig. 5, where the deviation from different experiments (ME_{LIT}) to the JYFLTRAP mass-excess value (ME_{JYFL}) is shown.

^{94}Mo

The mass value measured for ^{94}Mo at JYFLTRAP disagrees with the AME03 value by $-3.0(21)$ keV. Similarly to ^{92}Mo , there is a 6.3(22) keV difference between the JYFLTRAP value and the value obtained from the mass difference of $^{94}\text{Mo}^{35}\text{Cl}^{16}\text{O} - ^{92}\text{Mo}^{37}\text{Cl}^{16}\text{O}$ [23] employing the JYFLTRAP value for ^{92}Mo (see Fig. 6). Actually, even bigger disagreement is found when the AME03 value for ^{92}Mo is used. In addition, the value from $\text{C}_7\text{H}_{10} - ^{94}\text{Mo}$ [22] gives a 5.3(31) keV higher mass-excess value for ^{94}Mo than measured at JYFLTRAP. The beta-decay experiments [26–28] agree with the JYFLTRAP value but the value from (p, n) reactions [32] disagrees with it. The $^{94}\text{Mo}(n, \gamma)^{95}\text{Mo}$ [20] agrees nicely with the JYFLTRAP results for ^{94}Mo and ^{95}Mo . A shift of about 3 keV is found when the AME03 value for ^{95}Mo is used instead of the JYFLTRAP value.

Table 1. Isotope, number of measurements, frequency ratio r , mass excess and the literature value [4] for the mass excess. Each measurement contains 15 scan cycles. The reference ion was $^{85}\text{Rb}^+$.

Isotope	#	r	ME(keV)	AME03(keV)	JYFL-AME03(keV)
^{92}Mo	16	1.082380355(10)	-86807.8(8)	-86805(4)	-2.8(39)
^{94}Mo	21	1.105914072(12)	-88412.7(9)	-88410(2)	-3.0(21)
^{95}Mo	17	1.117699950(12)	-87710.8(1.0)	-87707(2)	-3.3(21)
^{96}Mo	26	1.129463266(13)	-88793.4(1.0)	-88790(2)	-2.9(22)
^{97}Mo	23	1.141256082(14)	-87542.8(1.1)	-87540(2)	-2.3(22)
^{98}Mo	16	1.153025857(15)	-88114.5(1.2)	-88112(2)	-2.7(23)
^{100}Mo	11	1.176604185(16)	-86190.9(1.3)	-86184(6)	-6.6(60)

**Fig. 4.** Influences (%) of different reactions on the molybdenum mass-excess values in the AME03 [4]. The red arrows show the reactions which disagree with the results of this work. The masses of highlighted Mo isotopes were measured in this work.

^{95}Mo

The JYFLTRAP mass value for ^{95}Mo is 3.3(21) keV lower than the AME03 value. The AME03 value is mainly based on the $^{94}\text{Mo}(n,\gamma)^{95}\text{Mo}$ [20] and $^{95}\text{Mo}(n,\gamma)^{96}\text{Mo}$ [20] values, which agree well with the JYFLTRAP results for ^{94}Mo , ^{95}Mo , and ^{96}Mo . A shift is observed when the AME03 value is applied for ^{94}Mo and ^{96}Mo , again indicating that these Mo isotopes are systematically less bound in the AME03 (see Fig. 7). Also the value based on the beta decay $^{95}\text{Nb}(\beta^-)^{95}\text{Mo}$ [24] disagreeing with the JYFLTRAP value has an influence on the ^{95}Mo value in the AME03.

^{96}Mo

The JYFLTRAP mass-excess value for ^{96}Mo is 2.9(22) keV lower than the AME03 value. All reaction links in the AME03 agree with the JYFLTRAP value when JYFLTRAP mass-excess values for ^{95}Mo and ^{97}Mo are used (see Fig. 8). The disagreement between the AME03 value and the JYFLTRAP value comes from the erroneous mass values of ^{95}Mo and ^{97}Mo in the AME03.

^{97}Mo

The JYFLTRAP mass-excess value for ^{97}Mo is 2.3(22) keV lower than the AME03 value. The JYFLTRAP value agrees with all the reaction links in the AME03 except with the values from $^{97}\text{Nb}(\beta^-)^{97}\text{Mo}$ [31], $^{96}\text{Mo}(n,\gamma)^{97}\text{Mo}$ and $^{97}\text{Mo}(n,\gamma)^{98}\text{Mo}$ when AME03 values for ^{96}Mo and ^{98}Mo are applied (see Fig. 9). The ^{97}Nb beta decay does not have an influence on the ^{97}Mo mass value in the AME03.

^{98}Mo

The JYFLTRAP value for the mass excess of ^{98}Mo disagrees with the AME03 value by 2.7(22) keV. The JYFLTRAP mass-excess result is in agreement with the results from $\text{C}_5\text{H}_6\text{O}_2-^{98}\text{Mo}$ [22] and $^{97}\text{Mo}(n,\gamma)^{98}\text{Mo}$ [20], when JYFLTRAP value for ^{97}Mo is applied (see Fig. 10). Here, again a disagreement is found when the AME03 values of ^{97}Mo and ^{99}Mo are used for the $^{97}\text{Mo}(n,\gamma)^{98}\text{Mo}$ and $^{98}\text{Mo}(n,\gamma)^{99}\text{Mo}$ reactions, indicating that the Mo isotopes have generally too high mass-excess values in the AME03.

^{100}Mo

The JYFLTRAP mass-excess value slightly disagrees with the AME03 value for ^{100}Mo . An almost perfect agreement is found with the value based on $\text{C}_7\text{H}_{16}-^{100}\text{Mo}$ [22],

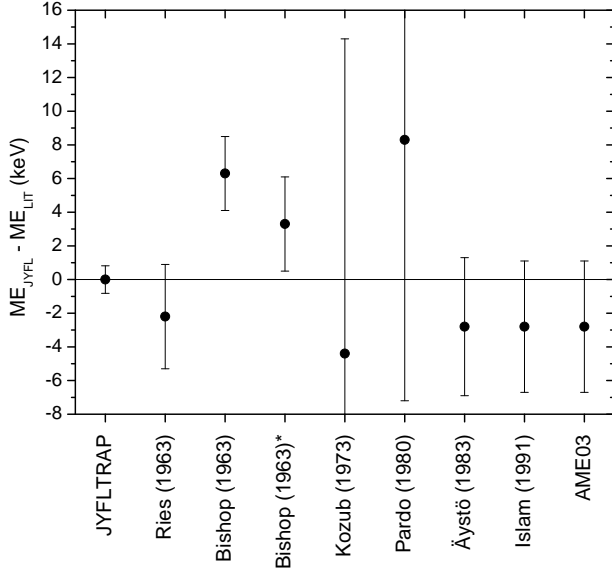


Fig. 5. Mass excess of ^{92}Mo measured at JYFLTRAP compared to earlier experiments of $\text{C}_7\text{H}_8-^{92}\text{Mo}$ (Ries *et al.* [22]), $^{94}\text{Mo}^{35}\text{Cl}^{16}\text{O}-^{92}\text{Mo}^{37}\text{Cl}^{16}\text{O}$ (Bishop *et al.* [23]), $^{92}\text{Mo}(p,d)^{91}\text{Mo}$ (Kozub & Youngblood [35]), $^{92}\text{Mo}(^3\text{He},^6\text{He})^{89}\text{Mo}$ (Pardo *et al.* [40]), ^{93}Tc S_p value (Åystö *et al.* [25]), $^{92}\text{Mo}(n,\gamma)^{93}\text{Mo}$ (Islam *et al.* [20]) and AME03 [4]. Bishop (1963)* employs the AME03 mass value [4] for ^{94}Mo instead of the value from this work.

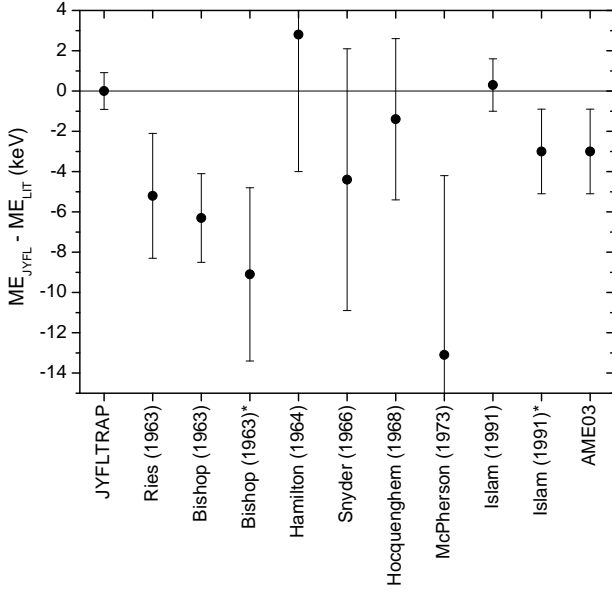


Fig. 6. Mass excess of ^{94}Mo measured at JYFLTRAP compared to earlier experiments of $\text{C}_7\text{H}_{10}-^{94}\text{Mo}$ (Ries *et al.* [22]), $^{94}\text{Mo}^{35}\text{Cl}^{16}\text{O}-^{92}\text{Mo}^{37}\text{Cl}^{16}\text{O}$ (Bishop *et al.* [23]), $^{94}\text{Tc}(\beta^+)^{94}\text{Mo}$ (Hamilton *et al.* [26]), $^{94}\text{Nb}(\beta^-)^{94}\text{Mo}$ (Snyder *et al.* [27], Hocquenghem *et al.* [28]), $^{94}\text{Mo}(p,n)^{94}\text{Tc}$ (McPherson & Gabbard [32]), $^{94}\text{Mo}(n,\gamma)^{95}\text{Mo}$ (Islam *et al.* [20]) and AME03 [4]. The values marked with * are based on the AME03 [4] mass values of ^{92}Mo and ^{95}Mo .

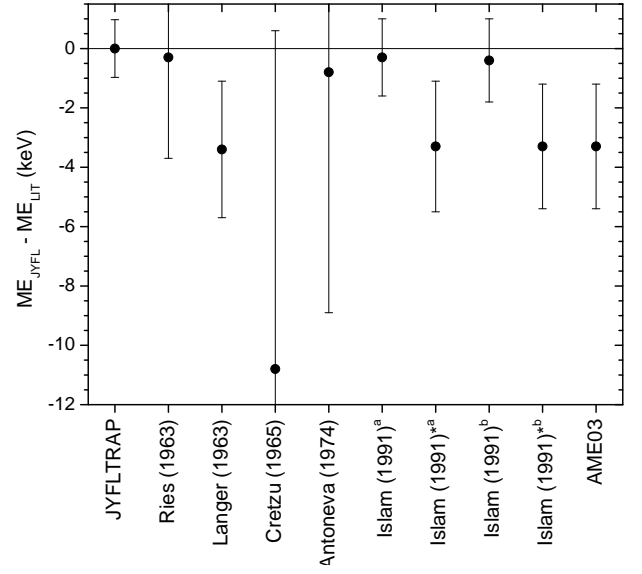


Fig. 7. Mass excess of ^{95}Mo measured at JYFLTRAP compared to earlier experiments of $\text{C}_7\text{H}_{11}-^{95}\text{Mo}$ (Ries *et al.* [22]), $^{95}\text{Nb}(\beta^-)^{95}\text{Mo}$ (Langer & Wortman [24]), $^{95}\text{Tc}(\beta^+)^{95}\text{Mo}$ (Cretzu *et al.* [29], Antoneva *et al.* [30]), $^{94}\text{Mo}(n,\gamma)^{95}\text{Mo}$ (Islam *et al.* [20]), $^{95}\text{Mo}(n,\gamma)^{96}\text{Mo}$ (Islam *et al.* [20]), and AME03 [4]. The values marked with * are based on the AME03 [4] mass values of ^{94}Mo and ^{96}Mo . Islam (1991)^a refers to $^{94}\text{Mo}(n,\gamma)^{95}\text{Mo}$ value and ^b to the $^{95}\text{Mo}(n,\gamma)^{96}\text{Mo}$ value.

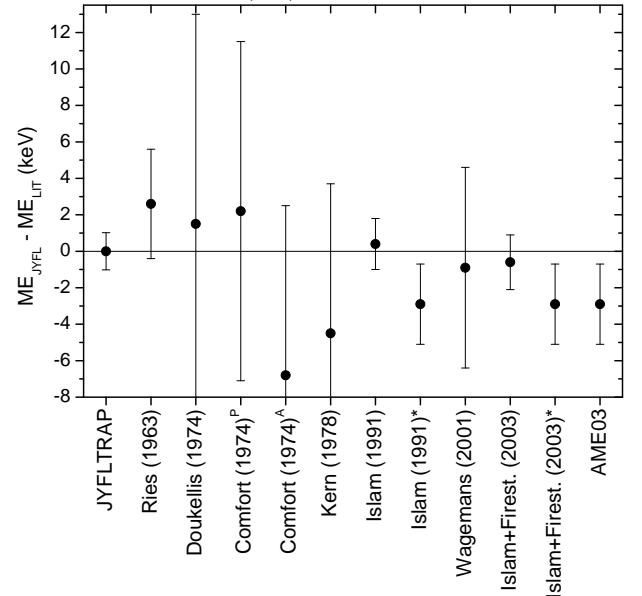


Fig. 8. Mass excess of ^{96}Mo measured at JYFLTRAP compared to earlier experiments of $\text{C}_7\text{H}_{12}-^{96}\text{Mo}$ (Ries *et al.* [22]), $^{96}\text{Mo}(p,n)^{96}\text{Tc}$ (Doukellis *et al.* [33], Kern *et al.* [34]), $^{96}\text{Mo}(^3\text{He},d)^{97}\text{Tc}$ (Comfort *et al.* [38]) measured at Pittsburgh (P) and at Argonne (A), $^{95}\text{Mo}(n,\gamma)^{96}\text{Mo}$ (Islam *et al.* [20]), $^{99}\text{Ru}(n,\alpha)^{96}\text{Mo}$ (Wagemans *et al.* [43]), $^{96}\text{Mo}(n,\gamma)^{97}\text{Mo}$ (Islam *et al.* [20], Firestone *et al.* [21]), and AME03 [4]. The values marked with * are based on the AME03 [4] mass values of ^{95}Mo and ^{97}Mo . The value from $^{96}\text{Nb}(\beta^-)^{96}\text{Mo}$ having an uncertainty of 20 keV has been left out.

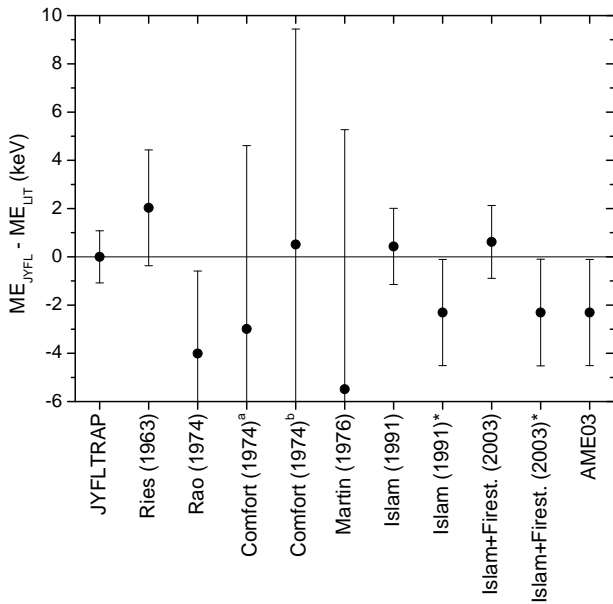


Fig. 9. Mass excess of ^{97}Mo measured at JYFLTRAP compared to earlier experiments of $\text{C}_5\text{H}_5\text{O}_2-^{97}\text{Mo}$ (Ries *et al.* [22]), $^{97}\text{Nb}(\beta^-)^{97}\text{Mo}$ (Rao *et al.* [31]), $^{97}\text{Mo}(\text{p,n})^{97}\text{Tc}$ (Comfort *et al.* [38]), $^{97}\text{Mo}({}^3\text{He,d})^{98}\text{Tc}$ (Comfort *et al.* [38], Martin & Macphail *et al.* [39]), $^{97}\text{Mo}(\text{n},\gamma)^{98}\text{Mo}$ (Islam *et al.* [20]), $^{96}\text{Mo}(\text{n},\gamma)^{97}\text{Mo}$ (Islam *et al.* [20], Firestone *et al.* [21]), and AME03 [4]. Comfort (1974)^a refers to $^{97}\text{Mo}(\text{p,n})^{97}\text{Tc}$ and ^b to $^{97}\text{Mo}({}^3\text{He,d})^{98}\text{Tc}$. The values marked with * are based on the AME03 [4] mass values of ^{96}Mo and ^{98}Mo .

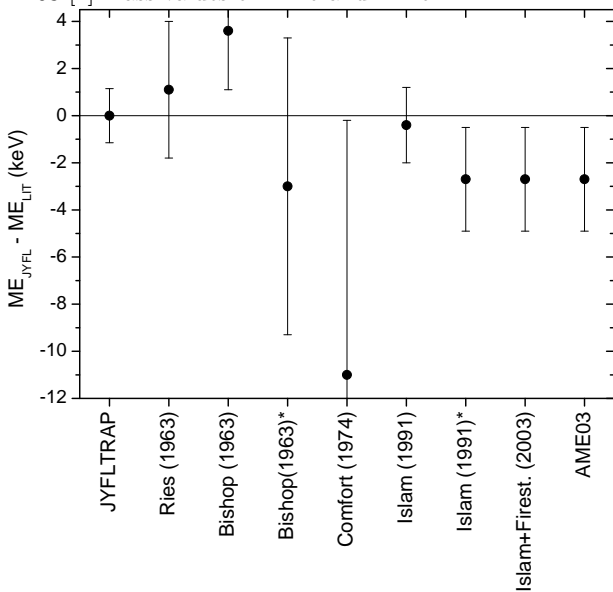


Fig. 10. Mass excess of ^{98}Mo measured at JYFLTRAP compared to earlier experiments of $\text{C}_5\text{H}_6\text{O}_2-^{98}\text{Mo}$ (Ries *et al.* [22]), $^{100}\text{Mo}^{35}\text{Cl}^{16}\text{O}-^{98}\text{Mo}^{37}\text{Cl}^{16}\text{O}$ (Bishop *et al.* [23]), $^{98}\text{Mo}(\text{p,n})^{98}\text{Tc}$ (Comfort *et al.* [38]), $^{97}\text{Mo}(\text{n},\gamma)^{98}\text{Mo}$ (Islam *et al.* [20]), $^{98}\text{Mo}(\text{n},\gamma)^{99}\text{Mo}$ (Islam *et al.* [20], Firestone *et al.* [21]), and AME03 [4]. The values marked with * are based on AME03 [4] mass values of ^{100}Mo and ^{97}Mo .

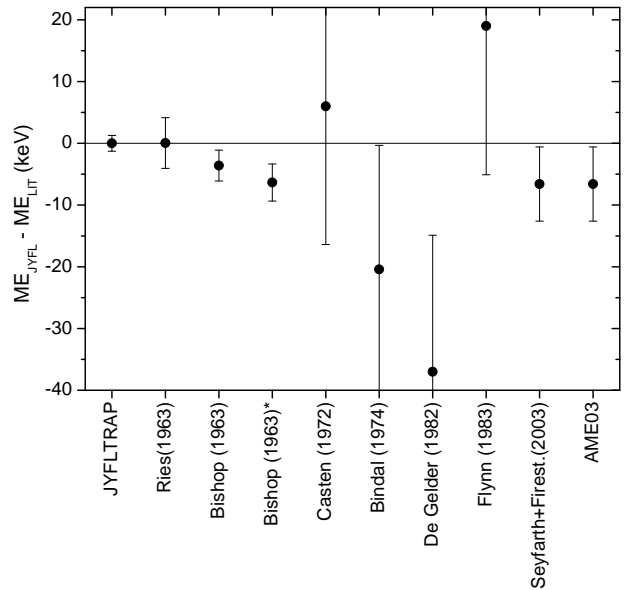


Fig. 11. Mass excess of ^{100}Mo measured at JYFLTRAP compared to earlier experiments of $\text{C}_7\text{H}_{16}-^{100}\text{Mo}$ (Ries *et al.* [22]), $^{100}\text{Mo}^{35}\text{Cl}^{16}\text{O}-^{98}\text{Mo}^{37}\text{Cl}^{16}\text{O}$ (Bishop *et al.* [23]), $^{100}\text{Mo}(\text{t,p})^{102}\text{Mo}$ (Casten *et al.* [41]), $^{100}\text{Mo}(\text{d},{}^3\text{He})^{99}\text{Nb}$ (Bindal *et al.* [36]), $^{100}\text{Mo}({}^3\text{He,p})^{102}\text{Tc}$ (De Gelder *et al.* [37]), $^{100}\text{Mo}(\text{t},\alpha)^{99}\text{Nb}$ (Flynn *et al.* [42]), $^{100}\text{Mo}(\text{n},\gamma)^{101}\text{Mo}$ (Seyfarth *et al.* [44], Firestone *et al.* [21]), and AME03 [4]. The value marked with * is based on the AME03 [4] mass value of ^{98}Mo . The values from (t, ${}^3\text{He}$) and β^- experiments have been left out due to large uncertainties.

but the values from $^{100}\text{Mo}^{35}\text{Cl}^{16}\text{O}-^{98}\text{Mo}^{37}\text{Cl}^{16}\text{O}$ [23] and $^{100}\text{Mo}({}^3\text{He,p})^{102}\text{Tc}$ [37] influencing the AME03 value of ^{100}Mo , deviate from our Penning trap mass measurement. In addition, the value derived from the $^{100}\text{Mo}(\text{n},\gamma)^{101}\text{Mo}$ [44] reaction gives a similar deviation as the AME03 value. This suggests that the AME03 value for ^{101}Mo should be about 6.6 keV lower in order to agree with the (n, γ) data.

5 Updated mass values of the nuclides measured at JYFLTRAP using Mo references

Up to date, 30 neutron-deficient nuclides have been measured with respect to molybdenum reference ions at JYFLTRAP (see Refs. [1, 45, 46]). Thus, the results of this paper have an effect on these mass-excess values. The values can be easily updated by multiplying the old frequency ratio measured against a molybdenum isotope (r_{old}) by the frequency ratio of the corresponding molybdenum ion to $^{85}\text{Rb}^+$ measured in this work ($r_{\text{Mo-Rb}}$):

$$m_{\text{new}} = r_{\text{old}} r_{\text{Mo-Rb}} \cdot [m(^{85}\text{Rb}^+) - m_e] + m_e \quad (3)$$

The updated values are collected in Table 2. The Y, Zr, and Nb isotopes were measured as oxides. The uncertainties due to the isomers $^{83}\text{Y}^{\text{m}}$ ($E_x = 61.98(11)$ keV [47]), $^{84}\text{Y}^{\text{m}}$ ($E_x = 67$ keV [48]), $^{85}\text{Nb}^{\text{m}}$ ($E_x \geq 69$ keV

[49]), $^{87}\text{Nb}^m$ ($E_x = 3.84(14)$ keV [47]), $^{88}\text{Nb}^m$ ($E_x = 40(140)$ keV [47]) have been taken into account according to Eq. (14) of Ref. [50] and added quadratically to the experimental uncertainties. No correction due to the isomer in ^{86}Nb ($E_x = 250(160)\#$ keV [47]) has been done since this isomer is considered as uncertain. It should also be noted that for ^{85}Nb , the energy of the isomer is only a lower limit [49]. The previous values for ^{91}Tc and ^{91}Ru were published in Ref. [46], which was a joint publication of JYFLTRAP and SHIPTRAP. Here, the JYFLTRAP values measured against ^{94}Mo have been updated and new weighted means of JYFLTRAP and SHIPTRAP values have been calculated for ^{91}Tc and ^{91}Ru . As can be seen from Table 2, the updated values are on the average about 2.8 keV lower than the old values. This is well within the error bars.

Although the 3-keV shift in the mass excesses of Mo isotopes is less than 1σ , it is important to take it into account. For example, the Cd isotopes have been measured at SHIPTRAP [2] and ISOLTRAP [3] by using ^{85}Rb as a reference. The mass-excess values determined with JYFLTRAP for Cd isotopes employing ^{96}Mo as a reference [1] disagreed in some cases with ISOLTRAP and SHIPTRAP (see Fig. 12). The shift from the AME03 value in the mass of ^{96}Mo was already observed in the mass evaluation performed in Ref. [3]. In this work, we have experimentally determined this mass value. The updated Cd values (see Table 2) agree within one standard deviation with the ISOLTRAP data. However, the SHIPTRAP values for $^{101,102,104}\text{Cd}$ still deviate from the ISOLTRAP and JYFLTRAP data.

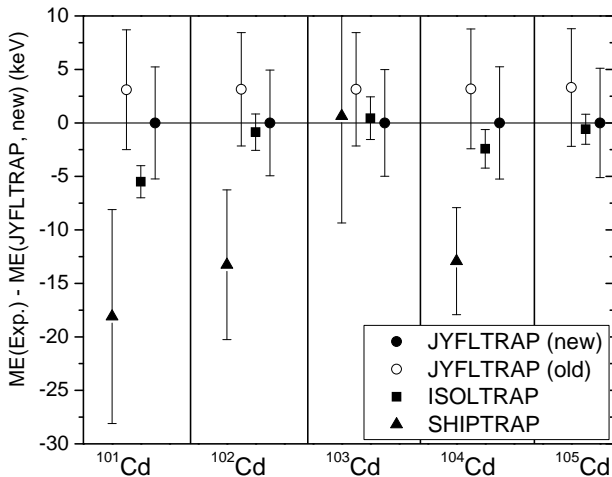


Fig. 12. Comparison of different Penning-trap measurements for $^{101-105}\text{Cd}$ with respect to the new JYFLTRAP value. After adjusting the old mass-excess values measured against ^{96}Mo at JYFLTRAP with the ^{96}Mo value measured in this work, a new JYFLTRAP value is obtained. The new value agrees with the values from ISOLTRAP [3]. The SHIPTRAP values for $^{101,102,104}\text{Cd}$ still disagree with JYFLTRAP but the value for ^{103}Cd agrees well with JYFLTRAP and ISOLTRAP.

6 Conclusions

In this paper, we have reported frequency ratios between $^{92,94-98,100}\text{Mo}$ and ^{85}Rb measured with the JYFLTRAP setup. The mass-excess values of the Mo isotopes have been determined with about 1-keV precision, which is at least by a factor of 2 more precise than in the AME03. In addition, all measured stable Mo isotopes have been found to be more bound than given in the AME03. This will also have an effect on the nuclides which have main influences coming from these Mo isotopes in the AME03, such as for neighbouring Nb, Mo and Tc nuclides.

$^{94,96,97,98}\text{Mo}$ have been used as references for 30 neutron-deficient nuclides measured at JYFLTRAP, and thus, these values have been updated with the new molybdenum values. Although the difference to the previous values is less than 1σ , it is worthwhile to take it into account for example when comparing to results from other facilities. In addition, proton-capture rates relevant for astrophysical rp [51,52] and νp [53,54] processes depend exponentially on proton separation energies, and already a small change will have an effect on the rate. In any case, the stable molybdenum isotopes are now more accurate references for future mass measurements of neutron-deficient nuclides.

This measurement was motivated by the discrepancy in the cadmium mass-excess values between JYFLTRAP, ISOLTRAP and SHIPTRAP. An inaccurate mass-excess value of ^{96}Mo in the literature has now been confirmed to be the reason for the deviation. This gives a perfect example why the main result from a Penning-trap measurement should be rather the frequency ratio between the reference ion and the ion of interest and its uncertainty rather than the mass-excess value itself. This way one can always use the most accurate value for the mass of the reference ion and recalculate the mass values of ions of interest.

This work has been supported by the EU 6th Framework programme “Integrating Infrastructure Initiative - Transnational Access”, Contract Number: 506065 (EURONS) and by the Academy of Finland under the Finnish Centre of Excellence Programme 2006-2011 (Nuclear and Accelerator Based Physics Programme at JYFL).

References

1. V. Elomaa *et al.*, Eur. Phys. J. A **40**, 1 (2009).
2. A. Martín *et al.*, Eur. Phys. J. A **34**, 341 (2007).
3. M. Breitenfeldt *et al.*, Phys. Rev. C **80**, 035805 (2009).
4. G. Audi, A. H. Wapstra, and C. Thibault, Nucl. Phys. A **729**, 337 (2003).
5. A. Jokinen *et al.*, Int. J. Mass Spectrom. **251**, 204 (2006).
6. J. Äystö, Nucl. Phys. A **693**, 477 (2001).
7. H. Penttilä *et al.*, Eur. Phys. J. A **25**, 745 (2005).
8. A. Nieminen *et al.*, Nucl. Instrum. Methods Phys. Res. A **469**, 244 (2001).
9. V. S. Kolhinen *et al.*, Nucl. Instrum. Methods Phys. Res. A **528**, 776 (2004).
10. G. Savard *et al.*, Phys. Lett. A **158**, 247 (1991).
11. L. S. Brown and G. Gabrielse, Rev. Mod. Phys. **58**, 233 (1986).

Table 2. Old mass-excess values for several neutron-deficient nuclides measured at JYFLTRAP employing Mo isotopes as references and the new values updated with the frequency ratios measured in this work. The difference between the old and new values is also tabulated. The isomer contribution has been taken into account for $^{83,84}\text{Y}$ and $^{85,87,88}\text{Nb}$.

Isotope	Ref.	ME _{old} (keV)	ME _{new} (keV)	ME _{new} – ME _{old} (keV)
^{80}Y	^{96}Mo	–61144(7) [45]	–61146.8(6.1)	–2.8
^{81}Y	^{97}Mo	–65709(6) [45]	–65711.4(5.5)	–2.4
^{82}Y	^{98}Mo	–68060(6) [45]	–68062.8(5.5)	–2.8
^{83}Y	^{98}Mo	–72201(19) ¹ [45]	–72204(19) ¹	–3.2
^{84}Y	^{97}Mo	–73922(20) ² [46]	–73925(20) ²	–2.4
^{83}Zr	^{98}Mo	–65908(7) [45]	–65910.6(6.1)	–2.6
^{84}Zr	^{98}Mo	–71418(6) [45]	–71420.3(5.6)	–2.3
^{85}Zr	^{98}Mo	–73170(6) [45]	–73173.3(5.8)	–3.3
^{86}Zr	^{98}Mo	–77958(7) [45]	–77961.0(5.9)	–3.0
^{87}Zr	^{97}Mo	–79341.4(5.3) [46]	–79343.9(5.0)	–2.5
^{88}Zr	^{98}Mo	–83624(7) [45]	–83627.2(6.2)	–3.2
^{85}Nb	^{98}Mo	–66308(21) ³ [45]	–66310(21) ³	–2.4
^{86}Nb	^{98}Mo	–69129(6) ⁴ [45]	–69132.2(5.6) ⁴	–3.2
^{87}Nb	^{98}Mo	–73870(7) ⁵ [45]	–73873.0(6.5) ⁵	–3.1
^{88}Nb	^{98}Mo	–76169(14) ⁶ [45]	–76172(13) ⁶	–2.5
^{96}Mo	^{97}Mo	–88789(6) [45]	–88791.3(5.5)	–2.3
^{98}Mo	^{97}Mo	–88111(6) [45]	–88113.0(5.6)	–2.0
^{91}Tc	$^{94}\text{Mo}/^{85}\text{Rb}$	–75984.8(3.3) ⁷ [46]	–75986.4(3.2) ⁷	–1.6
^{91}Ru	$^{94}\text{Mo}/^{85}\text{Rb}$	–68237.1(2.9) ⁸ [46]	–68238.2(2.8) ⁸	–1.1
^{94}Pd	^{94}Mo	–66097.9(4.7) [46]	–66100.9(4.4)	–3.0
^{95}Pd	^{94}Mo	–69961.6(4.8) [46]	–69964.6(4.5)	–3.0
^{96}Pd	^{94}Mo	–76179.0(4.7) [46]	–76182.0(4.3)	–3.0
^{99}Pd	^{96}Mo	–82178.9(5.1) [1]	–82181.9(4.8)	–3.0
^{101}Pd	^{96}Mo	–85427.1(5.2) [1]	–85430.2(4.9)	–3.1
^{101}Cd	^{96}Mo	–75827.8(5.6) [1]	–75830.9(5.2)	–3.1
^{102}Cd	^{96}Mo	–79655.6(5.3) [1]	–79658.7(4.9)	–3.1
^{103}Cd	^{96}Mo	–80648.5(5.3) [1]	–80651.6(5.0)	–3.1
^{104}Cd	^{96}Mo	–83962.9(5.6) [1]	–83966.1(5.2)	–3.2
^{105}Cd	^{96}Mo	–84330.1(5.5) [1]	–84333.4(5.1)	–3.3
^{102}In	^{96}Mo	–70690.4(5.4) [1]	–70693.5(5.1)	–3.1

¹ The original values of –72170(6) keV (old) and –72173.2(5.6) keV (new) were modified for an unknown mixture of isomeric states ($^{83}\text{Y}^m$ at 61.98(11) keV [47]).

² The original values of –73888.8(5.2) keV (old) and –73891.2(4.9) keV (new) were modified for an unknown mixture of isomeric states ($^{84}\text{Y}^m$ at 67 keV [48]).

³ The original values of –66273(7) keV (old) and –66275.4(6.0) keV (new) were modified for an unknown mixture of isomeric states ($^{85}\text{Nb}^m$ at $E_x \geq 69$ keV [49]).

⁴ Possible contribution from an isomer at 250(160)# keV [47] has not been taken into account.

⁵ The original values of –73868(7) keV (old) and –73871.1(6.4) keV (new) were modified for an unknown mixture of isomeric states ($^{87}\text{Nb}^m$ at 3.84(14) keV [47]).

⁶ The original values of –76149(7) keV (old) and –76151.5(6.1) keV (new) were modified for an unknown mixture of isomeric states ($^{88}\text{Nb}^m$ at 40(140) keV [47]).

⁷ A weighted mean of JYFLTRAP and SHIPTRAP values (see Ref. [46]). The JYFLTRAP values with ^{94}Mo reference are –75983.4(45) keV (old) and –75986.3(4.2) keV (new).

⁸ A weighted mean of JYFLTRAP and SHIPTRAP values (see Ref. [46]). The JYFLTRAP values with ^{94}Mo reference are –68235.3(48) keV (old) and –68238.2(4.5) keV (new).

12. M. König *et al.*, Int. J. Mass Spectrom. Ion Processes **142**, 95 (1995).
13. S. George *et al.*, Int. J. Mass Spectrom. **264**, 110 (2007).
14. M. Kretzschmar, Int. J. Mass Spectrom. **264**, 122 (2007).
15. A. Kellerbauer *et al.*, Eur. Phys. J. D **22**, 53 (2003).
16. R. T. Birge, Phys. Rev. **40**, 207 (1932).
17. V.-V. Elomaa *et al.*, Nucl. Instrum. Methods Phys. Res. A **612**, 97 (2009).
18. G. Audi, Hyperfine Interact. **132**, 7 (2001).
19. P. D. Group, Phys. Lett. B **667**, 103 (2008), review of Particle Physics.
20. M. A. Islam, T. J. Kennett, and W. V. Prestwich, Can. J. Phys. **69**, 658 (1991).
21. R. Firestone *et al.*, *Database of prompt gamma rays from slow neutron capture for elemental analysis*, Lawrence Berkeley National Laboratory, 2004, LBNL Paper LBNL-55199.

22. R. R. Ries, R. A. Damerow, and W. H. Johnson, *Phys. Rev.* **132**, 1662 (1963).
23. R. Bishop *et al.*, *Can. J. Phys.* **41**, 1532 (1963).
24. L. M. Langer and D. E. Wortman, *Phys. Rev.* **132**, 324 (1963).
25. J. Äystö *et al.*, *Nucl. Phys. A* **404**, 1 (1983).
26. J. Hamilton, K. Löbner, A. Sattler, and R. V. Lieshout, *Physica* **30**, 1802 (1964).
27. R. E. Snyder and G. B. Beard, *Phys. Rev.* **147**, 867 (1966).
28. J. C. Hocquenghem, S. André, and P. Liaud, *J. Phys. France* **29**, 138 (1968).
29. T. Cretzu, K. Hohmuth, and J. Schintlmeister, *Nucl. Phys.* **70**, 129 (1965).
30. N. Antoneva *et al.*, *Izv. Akad. Nauk SSSR, Ser. Fiz.* **38**, 48 (1974).
31. C. N. Rao, B. M. Rao, P. M. Rao, and K. V. Reddy, *Proc. of the 17. Nucl. Phys. and Solid State Phys. Symposium, Bombay, 1974*, p. 10.
32. M. R. McPherson and F. Gabbard, *Phys. Rev. C* **7**, 2097 (1973).
33. G. Doukellis *et al.*, *Nucl. Phys. A* **229**, 47 (1974).
34. B. D. Kern *et al.*, *Phys. Rev. C* **18**, 1938 (1978).
35. R. L. Kozub and D. H. Youngblood, *Phys. Rev. C* **7**, 404 (1973).
36. P. K. Bindal, D. H. Youngblood, and R. L. Kozub, *Phys. Rev. C* **10**, 729 (1974).
37. P. De Gelder *et al.*, *Phys. Rev. C* **25**, 146 (1982).
38. J. R. Comfort, R. W. Finlay, C. M. McKenna, and P. T. Debevec, *Phys. Rev. C* **10**, 1236 (1974).
39. D. J. Martin and M. R. Macphail, *Phys. Rev. C* **13**, 1117 (1976).
40. R. C. Pardo *et al.*, *Phys. Rev. C* **21**, 462 (1980).
41. R. F. Casten, E. R. Flynn, O. Hansen, and T. J. Mulligan, *Nucl. Phys. A* **184**, 357 (1972).
42. E. R. Flynn, R. E. Brown, F. Ajzenberg-Selove, and J. A. Cizewski, *Phys. Rev. C* **28**, 575 (1983).
43. C. Wagemans, J. Wagemans, and G. Goeminne, *Hyperfine Interact.* **132**, 323 (2001).
44. H. Seyfarth *et al.*, *Fizika (Croatia)* **22**, 183 (1990).
45. A. Kankainen *et al.*, *Eur. Phys. J. A* **29**, 271 (2006).
46. C. Weber *et al.*, *Phys. Rev. C* **78**, 054310 (2008).
47. G. Audi, O. Bersillon, J. Blachot, and A. H. Wapstra, *Nucl. Phys. A* **729**, 3 (2003).
48. J. Döring, A. Aprahamian, and M. Wiescher, *J. Res. Natl. Inst. Stand. Technol.* **105**, 43 (2000).
49. A. Kankainen *et al.*, *Eur. Phys. J. A* **25**, 355 (2005).
50. A. H. Wapstra, G. Audi, and C. Thibault, *Nucl. Phys. A* **729**, 129 (2003).
51. H. Schatz *et al.*, *Phys. Rep.* **294**, 167 (1998).
52. H. Schatz, *Int. J. Mass Spectrom.* **251**, 293 (2006).
53. C. Fröhlich *et al.*, *Phys. Rev. Lett.* **96**, 142502 (2006).
54. J. Pruet *et al.*, *Astrophys. J.* **644**, 1028 (2006).