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Direct mass measurements of A=80 isobars

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Abstract. Direct mass measurements of A=80 isobars were performed using the second cyclotron of SARA (Système Accélérateur Rhône-Alpes) of the ISN (Institut des Sciences Nucléaires) in Grenoble as a time-of-flight mass spectrometer. Using the 300 MeV ^{58}Ni + ^{27}Al reaction, the isobars ^{80}Rb, ^{80}Sr, ^{80}Y, and ^{80}Zr (only one event!) were measured. For ^{80}Y we found a mass value of 79.934320(180) u, corresponding to a decay energy Q ($^{80}\mathrm{Y} \rightarrow {}^{80}\mathrm{Sr}$) of ($9120 \pm 170$) keV. Comparing this value to the former experiments of Lister et al. and Della Negra et al. results in a difference of about 2.2 MeV. However, it does agree with the recommended value of Audi and Wapstra, which is derived from systematic trends. For ^{80}Zr the single event was identified with a probability of 0.999975 and a mass value of 79.940400(1600) u could be deduced from our experiment.

PACS.

1 Introduction

In the past, most of the atomic masses of unstable nuclei were determined from Q-values of nuclear decays or reactions. Nowadays a wide variety of powerful mass measurement techniques has been developed to obtain the masses directly by measuring the time of flight [1,2], or the cyclotron frequency in a storage ring [3–5], a cyclotron [6,7], or a Penning trap [8].

The masses of ^{80}Y and ^{80}Zr are of great astrophysical interest for rp-process calculations [9]. Up to now the mass of ^{80}Y was deduced from Q-values ($^{80}\mathrm{Y} \rightarrow {}^{80}\mathrm{Sr}$) determined by Lister et al. [10], Della Negra et al. [11], and recently by Shibata et al. [12] by measuring the β^+ endpoint energy in coincidence with γ-rays. Although these values agree very well with each other, there is a 2.2 MeV difference when compared to the recommended value of Audi and Wapstra [13], which is derived from systematic trends (Table 1). It is essential to clarify such discrepancies, since these differences between the extrapolated and the measured mass values may be due to nuclear structure effects, e.g. changes of nuclear deformation, or the experimental values may be wrong. The mass of ^{80}Zr has not been measured before.

Table 1. Q-values ($^{80}\mathrm{Y} \rightarrow {}^{80}\mathrm{Sr}$)

	Q [keV]
Lister et al. [10]	6952 ± 152
Della Negra et al. [11]	6934 ± 242
Shibata et al. [12]	6200 ± 600
Audi & Wapstra, recommended	9140 ± 400

2 Experimental method

In our experiment we used the second cyclotron of SARA (Système Accélérateur Rhône-Alpes – a system of two coupled cyclotrons) as a time-of-flight (TOF) mass spectrometer.

For a constant magnetic field, the relation

$$B\rho = \gamma m v / q, \tag{1}$$

with the magnetic rigidity $B\rho$, the mass m, the velocity v, the charge q of the ion, and the relativistic factor γ, leads to a circular movement with a frequency $\omega = 2\pi f = 2\pi/T = v/\rho$ and then we get

$$T = \frac{2\pi\gamma}{B} \cdot \frac{m}{q} \tag{2}$$

for the time of revolution T in the cyclotron. Due to the large number of turns in the cyclotron, the time-of-flight path in this experiment effectively reaches several kilometers.

The new method used at SARA (Fig. 1) is different from the one applied at GANIL [6]. As in the GANIL method, the primary beam of the first cyclotron bombards a target placed between the two cyclotrons. The reaction products with close charge-over-mass ratios, q/m, are then accelerated in the second cyclotron used as a time-of-flight mass spectrometer. The acceleration mode

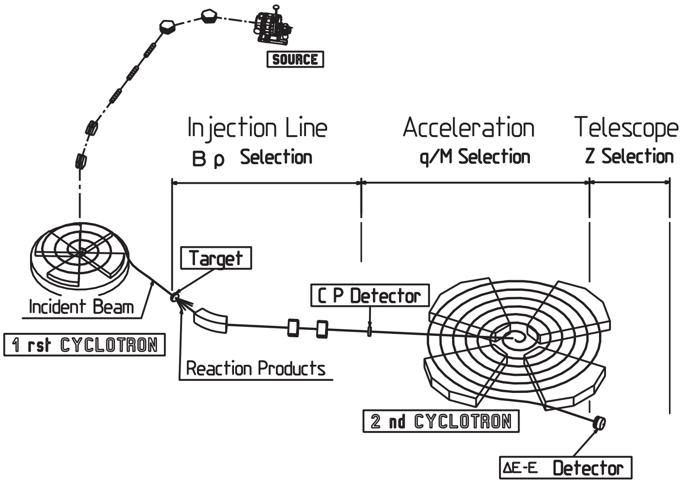

Fig. 1. Experimental set-up for mass measurements at SARA

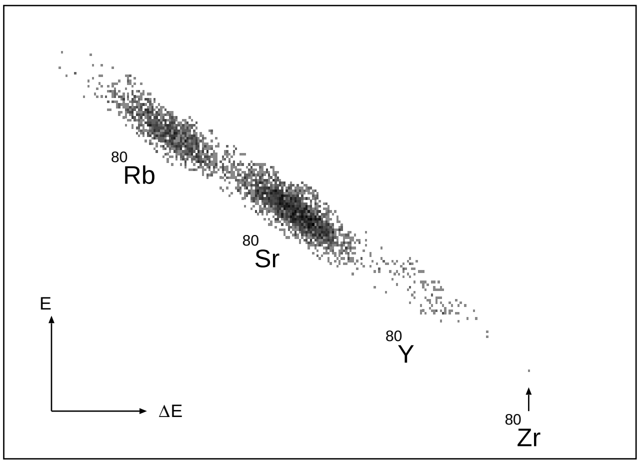

Fig. 2. ΔE-E spectrum showing the single ^{80}Zr event of this A=80 mass measurement

of the second machine is different for the two methods: synchronous at GANIL ($\omega_{\rm RF1} = \omega_{\rm RF2}$), asynchronous at SARA ($\omega_{\rm RF1} \neq \omega_{\rm RF2}$); consequently, ions with only a single q/m ratio can be accelerated at GANIL, while ions of various q/m ratios, within a range of ±5 %, may be accelerated at SARA. In the latter case the change in q/m ratio is obtained by tuning it to a new $\omega_{\rm RF2}$ value. The ions entering the second cyclotron have random phases relative to RF2. The phase acceptance is $\pm 35^o$ and about 20 % of the incoming particles are accelerated. This new procedure greatly simplifies the operations:

- before the mass measurements, the transfer line and the second cyclotron are tuned with a "pilot" beam;
- during the measurements, the magnetic field is held constant (which is essential for reliable measurements) and the radio frequency is fixed at the value $\omega_{RF2} = h_2\ qB/m$ for the selective acceleration of a given q/m ratio.

Isobars are accelerated simultaneously. Their Z-identification is done with a ΔE–E solid state telescope placed in the extraction line of the second cyclotron. The time of flight TOF through the cyclotron is determined with a channel-plate detector placed in front of the second cyclotron and the ΔE–signal of the solid state telescope. In contrast, in the GANIL work the relation between the circulating particle and the RF is measured within the cyclotron [6,7].

3 Signal processing

The time spectrum is measured with a special time-to-digital converter (TDC) built by R. Foglio and J. Pouxe of the ISN, Grenoble. This TDC has a digital resolution of 39.06 ps and a range of approximately $82\mu s$, corresponding to 21 bits ≈ 2 million channels. Thus the total time spectrum for all numbers of turns inside the second cyclotron N (see chapter 4) is recorded.

The main drawback in our previous test measurements was the limited counting rate due to dead time losses in the time measuring electronics, where the TDC was started with the pulses of the channel-plate detector with a typical counting rate of 5000 Hz and stopped with the pulses of the ΔE-detector with a typical counting rate of 2 Hz.

This resulted in the development of a new fixed and stable delay of about $80\mu s$ and with negligible dead time [14]. Applying this delay the TDC is started with the low counting rate of the ΔE-detector and stopped with the delayed channel-plate pulses.

Our delay uses a 17 km long optical fiber cable to delay the high counting rates of the channel-plate detector by $83.4\mu s$ (with a jitter of 170 ps (FWHM) over a few days). To adjust the delay to the time of flight we used a digital delay generator to delay the few counts of the ΔE–detector by $9\mu s$; this unit does not accept any signal during the delay, but this does not have any consequences in this case, because of the very low counting rate of the ΔE-detector.

4 Analysis

The identification of the isobars was done with the ΔE-E spectrum (Fig. 2). For each event this identification was verified by the calculated time of revolution.

The total time of flight (TOF) between the channel-plate and the ΔE-detector can be written as

$$\mathrm{TOF} = T_0 + N \cdot T, \tag{3}$$

where T_0 is the sum of the times of flight in the beamline and in the cyclotron before and after the acceleration, T the time of revolution for one ion (nearly proportional to m/q), and N the integer number of turns inside the second cyclotron.

After calculating the total time of flight from the measured TDC value (considering all used delays), the integer number of turns N can be easily determined from this TOF value. In the case of our A=80 isobars TOF values varying from about 45 to $75\mu s$ and a time of revolution T of approx. $269ns$ lead to N values between 170 and 280 (see Fig. 3).

Table 2. Comparison between well known masses given by Audi & Wapstra [13] and our experiment at SARA

	Audi & Wapstra	present work	
	m_{atom} [u]	m_{atom} [u]	mass excess [keV]
^{48}Sc	47.952235(6)	47.952220(110)	- 44510(110)
^{48}Ti	47.947947(1)	47.947962(51)	- 48473(48)
^{48}V	47.952254(3)	reference	
^{48}Cr	47.954036(8)	47.954003(54)	- 42846(51)
^{80}Rb	79.922519(8)	79.922522(55)	- 72170(52)
^{80}Sr	79.924525(9)	reference	

The time of revolution T for one of the A=80 isobars gives an approximately Gaussian distribution with a FWHM of (12 to 18) ps (depending on the measuring time) corresponding to a resolving power ($T/\Delta T$ (FWHM)) of about 15000 to 22000.

The errors σ_T (used for the calculation of the accuracies given in chapter 5) were calculated by

$$\sigma_T = \frac{\Delta T(\mathrm{FWHM})}{2.35\sqrt{N_E}}, \tag{4}$$

with the number of ions in the peak N_E.

Using the well known mass of one of the isobars as a reference, the masses of the other ions can be calculated from the times of revolution:

$$m_{\mathrm{ion}} = \frac{T_{\mathrm{ion}}}{T_{\mathrm{ref}}} \cdot \frac{\gamma_{\mathrm{ref}}}{\gamma_{\mathrm{ion}}} \cdot m_{\mathrm{ref}} \tag{5}$$

This calculation includes the relativistic corrections considering the different masses of the isobars. The atomic masses given below are calculated from the ion masses [15–18].

Small changes in the magnetic field (or other possible changes affecting all isobars in the same way) do not have an appreciable influence on the calculated mass values because the reference nucleus is measured at the same time. A more detailed discussion of the analysis is given in Ref. [19].

5 Measurements and results

In the previous measurements at SARA the reactions ^{40}Ar + ^{nat}C and ^{40}Ca + ^{nat}C were used to test this method by measuring the well known masses in the A=48 region [20–22]. The mass of ^{48}V was used as a reference and the masses of ^{48}Sc, ^{48}Ti, and ^{48}Cr are determined with an accuracy of the order of 10^{-6}, but the Audi-Wapstra values are reproduced within a few times 10^{-7} (Table 2)

Our measurement was the first use of SARA to determine masses of nuclei far from stability. The secondary ions with m/q = 80/27 were produced by a fusion evaporation reaction, using a 300 MeV ^{58}Ni beam on an ^{27}Al target. The isobars ^{80}Rb, ^{80}Sr, and ^{80}Y were measured at the same time and the well known mass of ^{80}Sr (m_{atom} = 79.924525(9) u) was used as a reference. The well known mass of ^{80}Rb is reproduced with an accuracy of $6.9 \cdot 10^{-7}$ reproducing the known mass within $3.8 \cdot 10^{-8}$ (Table 2).

Table 3. Experimental results for the masses of ^{80}Y and ^{80}Zr compared to the recommended values given by Audi & Wapstra [13] and the former experimental values for the mass of ^{80}Y determined by Lister et al. [10] Della Negra et al. [11] and Shibata et al. [12]

m_{atom} [u]	^{80}Y	^{80}Zr
present work	79.934280(190)	79.940400(1600)
Audi & Wapstra	79.934340(430)	79.940550(320)
Lister et al.	79.931990(170)	–
Della Negra et al.	79.931970(260)	–
Shibata et al.	79.931180(650)	–

^{80}Y

181 events of ^{80}Y were identified and an atomic mass of 79.934320(180) u was obtained.

Very recently two isomeric states of ^{80}Y have been found. The first one with an energy of 228.5(1) keV and a half-life of 4.7(3) seconds was produced by the reaction 190 MeV ^{58}Ni + ^{24}Mg with a ratio of 10 - 20 % [23, 24]. The second one with a half-life of 6 μs [25] could be placed at 312 keV [24].

Due to our experimental time scale of about 50 - 70 μs, we have probably measured the ground state of ^{80}Y and the isomeric state 228.5 keV. Assuming the same relative population of ground state and isomeric state in the 300 MeV ^{58}Ni + ^{27}Al as in the 190 MeV ^{58}Ni + ^{24}Mg reaction, results in a small decrease of the mass value by (25 to 45) keV yielding the atomic mass of ^{80}Y given in Table 3.

Figure 4 compares this value to the mass predictions of Audi and Wapstra [13] (extrapolated from systematic trends) and the model predictions of Möller et al. [26], Jänecke and Masson [27], Aboussir et al. [28], and Duflo and Zuker [29,30]. The experimental value differs from the old experimental value of ^{80}Y [10,11] by 2.2 MeV.

But these beta decay experiments depend on knowing which levels are fed by the beta decay branches. It appears very likely that the ^{80}Y beta decay feeds mainly high lying states in ^{80}Sr which then cascade down through several transitions to the low-lying levels which were used for gating. The present technique is free from such problems, which vastly improves its reliability.

The determined mass of ^{80}Y together with the well known mass of ^{80}Sr yields a Q-value for the decay $^{80}\mathrm{Y} \rightarrow {}^{80}\mathrm{Sr}$ of (9087 ± 177) keV, which is to be compared with the former values and the recomended value of Audi and Wapstra given in Table 1.

^{80}Zr

Due to the small production cross section only 1 event of ^{80}Zr was measured in a real measuring time of about 80 hours. This event is located in the ^{80}Zr area of the ΔE–E spectrum and it has the expected time of revolution. Taking this into account and assuming a ^{80}Y particle instead

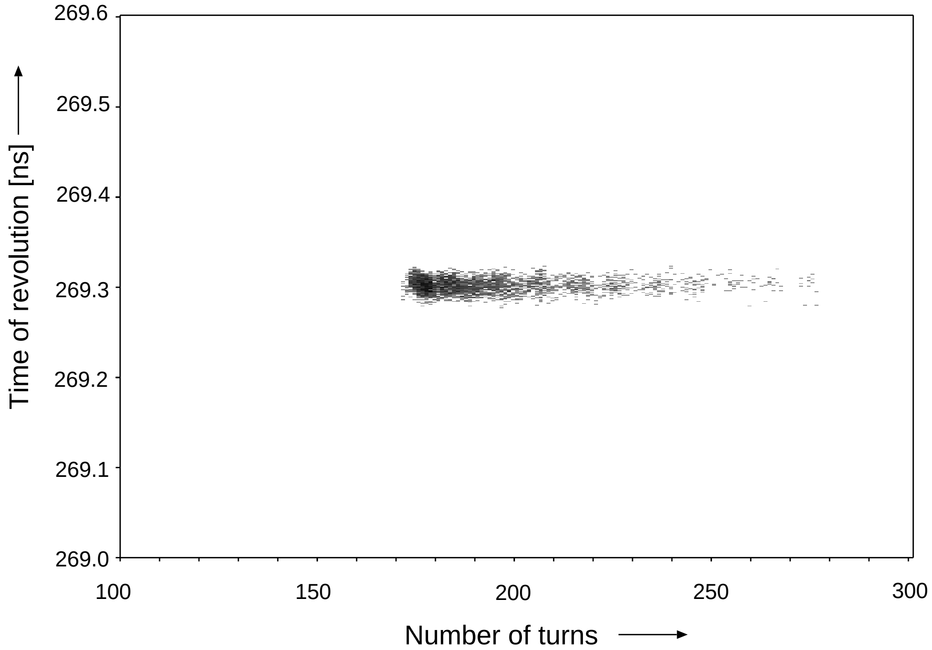

Fig. 3. Time of revolution of ^{80}Sr versus the number of turns N in the second cyclotron. Using the correct value of T_0, the time of revolution is independent of N

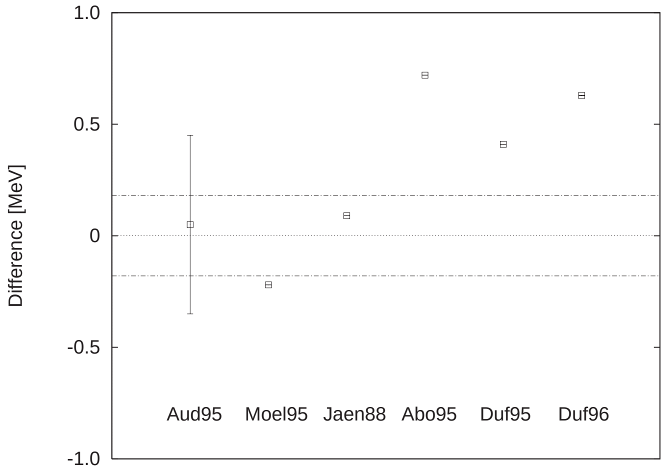

Fig. 4. Comparison between the new ^{80}Y mass value from our experiment and the mass predictions of Audi and Wapstra [13] and the different mass models [26-30]. $\Delta m = m_{\text{pred}} - m_{\text{exp}}$. The experimental error is given as an error band to the zero line

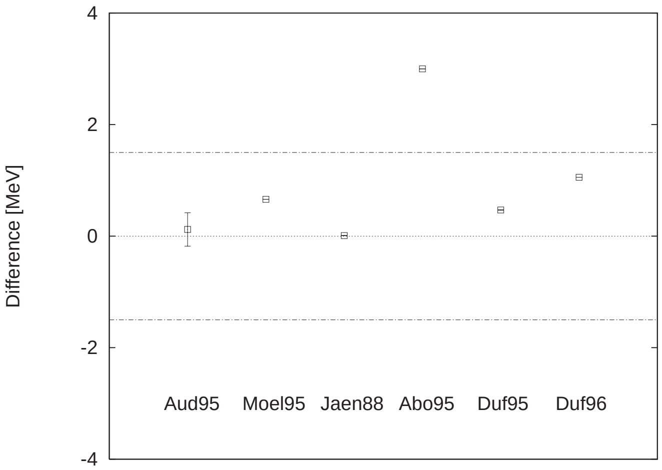

Fig. 5. Comparison between the new ^{80}Zr mass value from our experiment and the mass predictions of Audi and Wapstra [13] and the different mass models [26-30]. $\Delta m = m_{\text{pred}} - m_{\text{exp}}$. The experimental error is given as an error band to the zero line

of ^{80}Zr we estimated a probability of 0.00125 for the location in the ^{80}Zr area of the ΔE–E spectrum and a probability of 0.02 for the determined time of revolution. Combining these probabilities we got a likelihood of 0.000025 for a wrong identified ^{80}Y particle. And this means we have a probability of 0.999975 for the correct identification of this ^{80}Zr event. Assuming the same peak width for ^{80}Zr (in the time-of-revolution spectrum) as measured for ^{80}Sr during this measurement, we got the mass value given in Table 3.

This is the first experimental mass value for ^{80}Zr. Fig. 5 compares it to the mass predictions of Audi and Wapstra [13] (extrapolated from systematic trends) and the different mass models.

6 Conclusions

Our measurements presented here were the first use of SARA to determine masses of nuclei far from stability. Concerning the mass of ^{80}Y, our result agrees with the recommended value of Audi & Wapstra [13], but disagrees with the former experimental value of Lister et al. [10], Della Negra et al. [11], and Shibata et al. [12].

^{80}Zr, whose mass was measured for the first time, is the heaviest N=Z nucleus with a measured mass – except the recently measured ^{100}Sn [7], which was measured with a similar error.

In contrast to many other mass measurement techniques, masses of very short-living isotopes can be obtained using this method, since it takes less than 100μs from the production to the end of the measurement.

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