PENNING TRAP MASS MEASUREMENTS OF NEUTRON-DEFICIENT Rb AND Sr ISOTOPES

T. Otto, G. Bollen, G. Savard¹⁾, L. Schweikhard, H. Stolzenberg
Institut für Physik, Universität Mainz, D-6500 Mainz, Fed. Rep. Germany

G. Audi
CSNSM, IN2P3-CNRS, Laboratoire René Bernas, Bât 108, F-91405 Orsay Campus,
France

R.B. Moore, G. Rouleau²⁾
Foster Radiation Laboratory, McGill University, Montreal, PQ, H3A 2B2, Canada

J. Szerypo³⁾
Institute of Experimental Physics, Warsaw University, PL-00-681 Warsaw, Poland

Z. Patyk
Soltan Institute for Nuclear Studies, Hoża 69, PL-00-681 Warsaw, Poland

and the ISOLDE Collaboration
CERN, CH-1211 Geneva 23, Switzerland

Abstract

The Penning trap mass spectrometer ISOLTRAP installed at the on-line mass separator ISOLDE-2 at CERN has been used for mass determination of $^{75-87}\text{Rb}$ and $^{78-83,87}\text{Sr}$. Ions are captured in a Penning trap and their cyclotron frequency $\omega_c = \frac{q}{m} \cdot B$ in the trapping field B is measured. Ratios of these frequencies lead to the determination of the atomic mass of these isotopes. A resolving power of typically $m/\Delta m = 10^6$ and an accuracy of $\delta m \approx 10$ keV are obtained. The mass of ^{78}Sr is measured for the first time and, in most cases, the mass values of the other isotopes are significantly improved. The experimental masses are compared with theoretical predictions.

Keywords: ATOMIC MASSES $^{75-87}\text{Rb}$, $^{78-83,87}\text{Sr}$: measured masses. Penning trap mass spectrometer (on-line). Least-squares adjustment of data. Macroscopic-Microscopic mass calculations.

submitted to Nucl. Phys. A

IS 130 / 302

¹⁾ Present Address: AECL Chalk River Laboratories, Chalk River, Ontario, Canada

²⁾ Present Address: Manne Siegbahn Institute, Frescativägen 24, 10014 Stockholm, Sweden

³⁾ Present Address: CERN, CH-1211 Geneva 23, Switzerland

1 Introduction

The mass of a nucleus compared to that of the sum of its constituents gives its total binding energy. Therefore accurate experimental mass values serve as a stringent test of nuclear models, help to improve such models for predictions of nuclear properties of astrophysical interest far from nuclear stability [1], and can reveal nuclear structure. For example, deviations of binding energies from a liquid-drop model were a first sign of nuclear shell structure [2]. Mass differences between odd and even numbered nuclei showed the existence of pairing forces. Departures from a smooth decrease of the two-neutron separation energies, first observed by Barber et al. [3] for the rare earths and later by Thibault et al. [4] for $N=20$ and by Ephner et al. [5] at $N=60$, have all been related to shape transitions in these regions.

Most of the nuclear masses of unstable nuclei were determined from Q -values of nuclear decays or reactions. These methods often yield a wealth of information on nuclear properties but the mass values themselves are often inaccurate due to uncertainties concerning the decay schemes of the nuclei. This is particularly so for nuclei far from stability. Also, the masses of nuclei far from stability will involve a series of Q -value measurements linking the unknown masses to a well known nucleus near stability and statistical and systematic errors in the measurements can add up to large values. Only since the 70's have masses of long isotopic chains become available. Mainly for the alkali elements these were determined using classical magnetic mass spectrometers with resolving powers of up to $m/\Delta m \approx 10\,000$, and a typical accuracy of 20-100 keV [4, 5]. Since the 80's the mass of a large number of relatively light isotopes has been determined by time-of-flight techniques with an accuracy of typically several hundred keV [6, 7]. These techniques take advantage of a direct usage of the recoil ions from target or projectile fragmentation but suffer from the limited resolving power of $m/\Delta m \approx 3000$. In none of these direct mass measurements the resolving power was sufficient to separate isomeric and ground states.

This paper presents the results of an alternative approach, namely mass measurement via a determination of the cyclotron frequency of ions in a Penning trap. The confinement of the ions in the trap allows a long interaction time and therefore high resolution and accuracy. Other advantages of the method are its high sensitivity, allowing measurements to be made on a small number of ions, and its universal applicability to all elements and chemical species.

Recently, mass measurements using this method on a long chain of Cs isotopes were presented [8]. Here we report on measurements on neutron-deficient Rb and Sr isotopes,

an area of interesting nuclear structure effects [9, 10].

Section 2 gives a brief description of the principle of the Penning trap mass spectrometer and the experimental setup. Section 3 deals with the analysis of the data and the extraction of the mass excess, and section 4 contains a comparison of the present results with those of other experiments and with the predictions given by selected nuclear models. The experimental mass values have been used to further develop a specific macroscopic-microscopic model as discussed in the same section.

2 The ISOLTRAP Mass Spectrometer

2.1. PRINCIPLE OF MASS MEASUREMENT IN A PENNING TRAP

In a Penning trap [11] the combined effects of a radially confining magnetic field and an axially trapping electrostatic quadrupole field allow storage of ions. In a pure magnetic field B particles with mass m and charge q will orbit with a cyclotron frequency $\omega_c = \frac{q}{m} B$. In the combined magnetic and electric fields within a Penning trap the ion motion is made up of a simple harmonic axial oscillation at ω_z , a fast circular motion at a frequency ω_+ reduced from ω_c and a slow precession of this circular motion around the trap center at a magnetron frequency ω_- . Both ω_+ and ω_- depend on the trapping voltage, but if the electric field is a pure axially symmetric quadrupole, then their sum is exactly the cyclotron frequency ω_c .

All three characteristic motions can be excited by dipole radio frequency (RF) fields [11]. The amplitudes of the motions increase proportionally to the time of RF application. However, the circular motions can also be excited at the sum frequency $\omega_+ + \omega_-$ by applying an azimuthal quadrupole RF-field [12]. This field couples the reduced cyclotron and the magnetron motion. In resonance, an initially pure magnetron orbit is converted into a pure cyclotron orbit of the same radius. Since in general $\omega_+ \gg \omega_-$, a large increase in rotational kinetic energy accompanies this change from magnetron to cyclotron motion.

The increase in energy at resonance is detected by a time-of-flight (TOF) method [13]. After excitation, the ions are ejected from the trap and allowed to drift through the inhomogeneous fringe field of the solenoid. This inhomogeneous magnetic field gives an axial force due to the magnetic moment of the ion orbit, resulting in an increase in the axial momentum of the ion. In effect, as the magnetic field at the ion's position decreases, the magnetic potential energy of the orbital magnetic moment (which actually is the kinetic energy of the ion revolution) is transformed into axial kinetic energy. Ions in resonance with the RF-field therefore reach a TOF-detector earlier than ions off resonance.

2.2 SETUP AND EXPERIMENTAL PROCEDURE

As shown in Fig.1, the tandem Penning trap mass spectrometer ISOLTRAP consists of two traps connected by an ion optical transfer system. The first is a bunching and cooling trap in the 0.7 Tesla field of an electro-magnet and the second is a high accuracy Penning trap in a 6 Tesla superconducting solenoid. A drift section and a channel plate detector follow the precision trap for detection of the resonance by the TOF-technique.

The on-line mass separator ISOLDE 2 at CERN delivers the radioactive ions as a vertical beam to the bunching trap. Ions are implanted into a rhenium foil located in the lower end electrode of this trap. After collection, the foil is turned to face the inside of the trap and then heated by an electric current pulse. The ions are released, surface-ionized and trapped and cooled to room temperature by collisions with helium buffer gas. Normally the magnetron radius of ions in a Penning trap would increase due to the collisions with buffer gas atoms. This is because the total energy of the magnetron motion decreases with increasing radius. By application of an azimuthal quadrupole RF-field at frequency ω_c this effect can be counteracted. Ions in resonance are then not only cooled but also centered in the trap [14]. This process is mass selective and serves to clean the ion sample from contaminants of different mass number which are present due to the limited resolution of the mass separator. However, with the present bunching-cooling trap the resolution of the method is not sufficient to clean contaminating isobars.

The cooled ions are ejected from the cooling trap as a bunch and guided by the ion optics to the precision trap where they are captured in flight [15] with an initial magnetron radius. Typically 10 - 50 ions are delivered to a potential well of 5.1 V depth. Here isobaric contaminants are removed by application of a dipole RF-field at their reduced cyclotron frequency ω_+ with sufficient power to eject the ions radially from the trap.

Subsequently, the ions under investigation are excited by an azimuthal quadrupole RF-field at frequency ω_c . After application of the RF, the ions are ejected from the trap by pulses applied to the trap electrodes and they start drifting to the microchannel plate detector. Off resonance, the average time of flight is about 500 μ s. In resonance this time is reduced by about 30 %.

The resolving power of this experiment is determined by the interaction time of the quadrupole RF-field with the stored ions. In the present investigation the RF-field was applied for $T_{RF} = 0.9$ s, leading to a Fourier limit of the cyclotron resonance of $\Delta\nu_c(\text{FWHM}) \simeq 1$ Hz. The cyclotron frequency for nuclei with mass numbers of about 85 is $\nu_c \simeq 1$ MHz. Therefore the resolving power in the experiment is $m/\Delta m(\text{FWHM}) = \nu/\Delta\nu(\text{FWHM}) \simeq 10^6$. Expressed in energy, this corresponds to a width of the resonance of $\Delta m(\text{FWHM}) \simeq 85$ keV for these nuclei.

The accuracy in the determination of the cyclotron frequency is in principle limited by magnetic field inhomogeneities and electric field imperfections of the trap [11, 12]. Therefore the precision trap is constructed from materials with very low magnetic susceptibility. It contains two pairs of correction electrodes cancelling electric field multipoles higher than a quadrupole.

A further source of systematic errors is the Coulomb interaction of ions. The effects for ions of the same mass are negligible for the number of ions stored in the trap at any one time in this experiment [12]. However, even for these small numbers of ions the effects for ions of different mass can be significant [16]. This is because the coupling of the eigenmotions of two species by the Coulomb force causes a shift of the cyclotron frequency of each. This is especially important for isotopes with long-lived isomeric states because the mass selective buffer gas cooling in the lower trap has not sufficient resolving power to prepare a clean sample and the ejection by ω_+ -excitation in the high-precision trap may not work in the case of a small energy separation of ground and isomeric state.

In the case where the half-lives of the isomer and the ground state are sufficiently different one can retain the ion sample on the capture foil for a time long enough to allow for the decay of the shorter lived component. However, for two cases in the present work the resolution and sensitivity of the present spectrometer allowed the observation of the cyclotron frequency of both the isomer and the ground state with varying population of each. The results could then be extrapolated to that for a clean sample of either. This is the first time that the resolution of a ground state and an isomer by mass spectrometry has been reported [17].

The demand on the stability of the trapping voltage is not very high, since the cyclotron frequency $\omega_c = q/m \cdot B$ of an ion in a pure magnetic field is detected directly. The primary stability requirements are therefore on the magnetic field. During an on-line run the magnetic field stability of the superconducting solenoid is monitored in short intervals by resonance measurements of a convenient reference isotope. We could observe a field decay at a rate of $\Delta B/(B \cdot \Delta t) \approx 10^{-9}/h$ and a sensitivity to ambient temperature changes of $\Delta B/(B \cdot \Delta T) \approx 10^{-7}/^\circ C$. Systematic errors due to these effects could be minimized by correcting for these changes.

2.3. DATA EVALUATION

A typical resonance curve is shown in Fig. 2. The experimental points are fitted by a Gaussian. The center of the resonance is determined with a statistical accuracy of about 1/20th of the full linewidth at half maximum corresponding to 0.05 Hz or 4 keV. For every isotope 5-10 determinations of the resonance frequency are performed.

The frequency measurements are corrected for the slow drift of the magnetic field as determined from regular measurements of the reference isotope ^{85}Rb . For short intervals between reference measurements this correction gave resonance frequencies for the unknowns which showed no further systematic variations. Therefore, in the average value of these resonance frequencies, only the statistical errors of the frequencies are significant. Frequency ratios are then deduced for each on-line run:

$$R(x) = \frac{\nu_c(^{85}\text{Rb})}{\nu_c(x)} = \frac{m_{\text{ion}}(x)}{m_{\text{ion}}(^{85}\text{Rb})} \quad (1)$$

Finally, the frequency ratios thus obtained in several runs are averaged with weights either from their statistical error ('inner error') or from their dispersion ('outer error'), whatever value is greater.

A possible mass dependent systematic error in the measured resonance frequencies was checked by extensive off-line measurements with ions of ^{39}K , $^{85,87}\text{Rb}$ and ^{133}Cs . The results deviate from values calculated from literature [18] by less than $\Delta\nu_c/\nu_c \approx 10^{-7}$. On-line measurements with ^{85}Rb , ^{133}Cs [8] and ^{226}Ra [19] gave deviations from the mass tables of the order of $4 \cdot 10^{-8}$. It therefore seems reasonable at the present status of the Penning trap experiments to adopt a systematic error of 10^{-7} on the measured frequency ratios. This systematic error contribution of 10^{-7} is quadratically added to the error of the average frequency ratio.

3 Results and Comparison with Previous Experiments

3.1. EXPERIMENTAL RESULTS

The mass measurements were performed in 4 separate runs in which in total 12 rubidium and 8 strontium isotopes were investigated. Table 1 summarizes the experimental results, i.e. the frequency ratios R obtained in this work for the isotopes listed in column 1 together with their half-lives. In all cases ^{85}Rb was used as reference isotope except for ^{83}Sr where ^{83}Rb has been chosen. The uncertainty in the determination of the frequency ratios R is in all cases $\delta R/R < 1.2 \cdot 10^{-7}$ and includes the adopted systematic error of $1 \cdot 10^{-7}$.

As an example for the internal consistency of the data, the histogram in Fig. 3 shows the results of all 34 measurements performed for ^{77}Rb . They have been obtained in two separate on-line runs. Mass excess values were calculated for each resonance frequency determination. All mass values are entered on the histogram with equal statistical weights.

This is possible since the errors in the frequency determinations deviate from each other only by negligible amounts. The Gaussian fitted to this distribution has a standard deviation of $\sigma = 6.7$ keV, or less than 10^{-7} of the central value. This corresponds to a statistical uncertainty of the centroid of ≈ 1 keV.

In order to be treated by the standard weighted least-squares method used in the evaluation of masses [20], the frequency ratios R have to be recast into linear relations between two nuclear masses. They are expressed as a difference MD between the mass-excesses of the unknown ME and of the reference isotope ME_{ref} multiplied by a suitable factor (the three-digit approximation of the ratio of the two mass numbers) $(A/A_{ref})_{trunc.}$.

$$ME - ME_{ref} \cdot (A/A_{ref})_{trunc.} = MD \quad . \quad (2)$$

To stay consistent with former evaluations of masses these equations are expressed in units of 10^{-6} of an atomic mass unit. The equation for ^{77}Rb , for example, is

$$ME(^{77}\text{Rb}) - ME(^{85}\text{Rb}) \cdot 0.906 = 10327(8) \quad \mu\text{u} \quad . \quad (3)$$

Column 4 and 5 of Tab. 1 give the factors $(A/A_{ref})_{trunc.}$ of these relations and the result MD .

The linear equations obtained from the measured frequency ratios are entered into a general adjustment calculation that takes account of all experimental information on nuclear masses. The most recent published result of such an adjustment is the 1986 mass evaluation [18]. In order to include the ISOLTRAP results, a new adjustment was performed.

Table 2 presents for the investigated isotopes the results of this adjustment together with the corresponding values from the 1986 mass table [18], the results from ISOLTRAP, and another recent experiment [21]. For convenience all mass excesses are given in units of keV. The significance S , i.e. the percentage of the influence of the Penning trap data on the values of the new adjustment, is also given. The last column indicates the consistency v/s of the data, defined as the deviation v of the Penning trap data from the mass values of the new adjustment divided by the uncertainty s of the Penning trap results.

The least-squares method used in the mass adjustment implies that information from any datum flows to both nuclei involved, in particular to the 'reference' mass of ^{85}Rb which is therefore subject to a slight change against the last compilation. The ISOLTRAP result given as mass excess in Tab. 2, is obtained by entering the mass of the reference nucleus into the linear equations (2). Note that the uncertainty of these values is also influenced by the uncertainty of the mass excess of the reference, which was taken as $-82164.9(25)$ keV for ^{85}Rb and as $-79070.5(62)$ keV for ^{83}Rb in the case of the measurement of ^{83}Sr .

The comparison between the ISOLTRAP results and the 1986 mass evaluation [18] shows very good agreement for isotopes close to the valley of β -stability. The isotopes $^{84,86,87}\text{Rb}$ and ^{87}Sr can be regarded as test cases for the reliability of the Penning trap data. This is because the masses of these nuclei are determined with very high precision by other experiments. Only in the case of ^{87}Sr the consistency factor v/s exceeds one. However there is agreement within the error bars between the mass excess determined by ISOLTRAP and the value from the new adjustment to which the Penning trap result contributes only 4%.

Far from stability, the results of the present experiment are also in good agreement with the 1986 mass adjustment [18]. Only in the case of ^{77}Rb a disagreement is observed as discussed below. The recent results by Stephans et al. [21] (col. 4) agree with the results of this work.

Figure 4 shows a comparison of the new adjustment, which corresponds to the zero line, with the 1986 mass evaluation [18] and the Penning trap results. For all isotopes far from stability the uncertainties of the new evaluation have been greatly reduced compared to ref. [18], thus completely outweighing older mass data. This is due to the direct comparison of all masses to a well known reference isotope in the case of the ISOLTRAP experiment. Therefore the high accuracy in mass determination is conserved over the whole range of measured isotopes.

3.2. DISCUSSION OF SELECTED CASES

3.2.1. *Rb-Isotopes*

Up to now the most important information on the mass of neutron-deficient Rb-isotopes has come from a series of spectrometric mass triplets. They were obtained from a Mattauch-Herzog-spectrometer set up at the separator ISOLDE 2 [22]. This experiment was limited in that only triplets which span a mass range of up to 10% could be compared. A calculation of the mass of isotopes far from stability only by the use of such triplets suffers from propagation of errors. This was already noticed in [22] and in [23]. At that time it was not possible to account for this possible error, but the authors made the remark that further experiments may show a systematic bias. This was confirmed by recent Penning trap measurements on neutron-deficient Cs-isotopes [8]. Today we are in the position to show that this bias exists also for the case of the Rb-isotopes. Figure 5 shows the deviations of the triplet measurements from the newly adjusted values, normalized to their experimental errors. The histogram is slightly decentered by 0.24 standard deviations. This systematic effect, although negligible and undetectable at that time, is responsible for the build-up of important deviations very far from stability.

The adjusted values for the light Rb isotopes $^{75,76,78}\text{Rb}$ are strongly influenced by the present experiment, the other information coming from the mass spectrometric triplets. Two measurements of the Q_β -values of $^{76,77}\text{Rb}$ [24] are excluded from the present mass adjustment procedure. Careful analysis of the publication shows that the authors underestimated the errors due to uncertainty in the decay scheme at that time, as noted also by the same authors in a later publication [25].

The mass of ^{77}Rb has also been determined in an earlier Penning trap experiment [26]. Only the statistical error of one resonance curve was given. In [27] a complete evaluation resulted in a mass excess $\text{ME}(^{77}\text{Rb}) = -64945(95)$ keV. This value differs from the present result by 1.2 standard deviations. The set-up used for this early experiment was a prototype that has been reconstructed [28] for the recent experiments [8,19 and this work] and in addition new features have been implemented [28, 14]. The result of the present experiment supersedes that from [26, 27].

A slight discrepancy exists for the mass values of ^{79}Rb which has been determined from the nuclear reaction $^{78}\text{Kr}(^3\text{He},d)^{79}\text{Rb}$ [21] with a precision comparable to the present measurement. The result is a binding energy 25 keV less than determined with the present experiment.

The isomer of ^{82m}Rb ($T_{1/2} = 6.3$ h) lives much longer than its ground state ($T_{1/2} = 1.3$ min). A clean sample of ions in the trap could be obtained by letting the ground state ions decay on the collection foil before starting the frequency measurement. The mass of the isomer determined in this way is in good agreement with the mass determinations via the β -decays of the two isomeric states into ^{82}Kr [29] combined with recent direct determination of the excitation energy $\Delta E = 68.3(2)$ keV [30]. The ground state mass excess deduced from the Penning trap data and this excitation energy is $\text{ME}(^{82}\text{Rb}) = -76184(8)$ keV.

As pointed out in section 2, ISOLTRAP is capable of resolving nuclear isomers from the ground state. In the series of measurements performed for this work there were two cases in which the resonances of the ground state and an isomer could be resolved. A detailed description can be found in [17] how to treat frequency shifts due to Coulomb interaction of simultaneously stored ion species and the evaluation of these data. In the case of ^{84}Rb an excitation energy of 464(7) keV was obtained, in agreement with the current adopted value of 463.62(9) keV [31]. Figure 6 shows the resolved cyclotron resonances for $^{84m,84}\text{Rb}$ (top) and the single resonance for the ground state (bottom), obtained by allowing the isomeric state to decay. In ^{78}Rb the excitation energy of the 5.7 min isomer has recently been determined to be 111.2 keV [32]. In this case the required resolving power is close to the limit of the present experiment and thus the data evaluation is more difficult than for

^{84}Rb . The extrapolation procedure gave as lower and upper limits for the mass difference 71 keV and 132 keV [17], in agreement with the adopted value.

The ground state mass values for ^{78}Rb and ^{84}Rb were obtained by retaining the atoms collected from ISOLDE on the collection foil for several half-lives of the isomer.

3.2.2. *Sr-Isotopes*

The mass of ^{78}Sr is determined for the first time experimentally and agrees within the given uncertainties with the value in the 1986 mass tables [18] as estimated from systematic trends. With the precise determination of the mass of ^{79}Sr a strong contradiction between two Q-value determinations [33, 34] can finally be resolved. Both were rejected by the evaluators in [18] and replaced with a 'systematic' value, which agrees with our experiment. With the present result a decision in favor of the value reported in [33] is possible, together with a reduction of the uncertainty by a factor of 10.

Also in $^{80,81}\text{Sr}$ the new adjustment follows exclusively the present experiment, older experimental results [33, 34, 35, 36] having been omitted from the adjustment calculation due to their small statistical weight. Disagreement with older mass adjustments [20, 18] is due to an erroneous Q-value number for the decay of ^{80}Sr [35] in those tables.

4 Comparison with Nuclear Models

4.1. CURRENT MODELS

All nuclear models that are developed to predict or describe quantitatively nuclear properties have to rely on input from experiment. The experimental data serve to check the results of calculations and to adjust the parameters of the models. Figure 7 shows an exemplary comparison of the data presented in this paper with current mass formulae.

In the first case, the difference of experimental and calculated masses for the model of Jänecke and Masson is given [37]. No systematic deviation between theory and experiment is visible. This approach belongs to a class of models based on so-called Garvey-Kelson relations [38]. They are essentially an extreme single-particle picture of the nucleus, in which all interactions between nucleons cancel. By this assumption it is possible to construct a set of equations that includes all experimental mass values as coefficients. By a least-squares procedure several adjustable parameters are determined to render the set of equations solvable. Due to its very strong connection with experimental values this model reproduces successfully the experimental known surface of masses but it has a very limited predictive power for nuclei far from stability [39].

The next two comparisons are made with models derived from a quantum mechanical

description of the nucleus. The second row of Fig. 7 shows the comparison with a model of the macroscopic-microscopic type [40]. These models are a combination of single-particle shell models and collective liquid-drop or droplet models. In the case shown here the single-particle model is based on a folded-Yukawa potential. From the plot in Fig. 7 it can be seen that the deviations of the predicted values from measurement show a clear trend, reflecting physical effects not appropriately accounted for in the model.

The model in the third row [41] follows a more unified physical approach by calculating the nuclear mass from the extended Thomas-Fermi approximations to the system of Hartree-Fock equations of the nucleus. The Thomas-Fermi partial differential equations are based on the Skyrme force. The smoothing involved in the Thomas-Fermi approximation removes shell effects, which have to be reintroduced into the model via a modified Strutinsky-procedure. The model avoids the arbitrary division in a macroscopic and a microscopic part by calculating both gross and single particle effects from the same Skyrme force. The authors of this model admit that it is not yet in its final state, but its approximation to experimental masses is as good as for the macroscopic-microscopic models. In our region of interest it reproduces the experimental values even better. In the figure for strontium, however, one deficiency is clearly visible. The pairing of nuclei is not treated appropriately, leading to a strong odd-even staggering.

The last row shows the differences with a new macroscopic-microscopic parametrization of nuclear masses [42]. It leads to a mass formula with only 12 parameters that can easily be calculated. In spite of its simplicity it gives very satisfying results, comparable to the two quantum mechanical models mentioned above.

Recently a comparison of the predictive power of different nuclear models was performed by comparing their predictions of nuclear masses unknown at the time of calculation with the results obtained in later experiments [39]. Not surprisingly, the models of the Garvey-Kelson type were attested to deliver poor predictions, whereas the models with a more firm physical basis keep their admittedly larger errors constant when extrapolating to more exotic nuclei. Therefore in the following section we develop further on a macroscopic-microscopic model.

4.2. LOCAL ADJUSTMENT OF A MACROSCOPIC-MICROSCOPIC MASS FORMULA

The macroscopic-microscopic models combine a (macroscopic) liquid-drop model [43] and a (microscopic) shell model [2] of the nucleus. While the first one describes successfully the general behaviour of nuclear properties varying smoothly with N and Z , the second one introduces the quantum-mechanical behaviour of nuclear shells with shell corrections.

The characteristic odd-even variations of nuclear properties are accounted for by a pairing correction.

The macroscopic-microscopic approach extracts the good parts of these models, avoiding their respective disadvantages. In this approach, the nuclear mass is equal to the sum of the macroscopic (liquid drop) part and the shell and pairing corrections, which constitute the microscopic part. The shell correction is usually calculated according to the Strutinsky prescription [44] and the pairing correction in the spirit of the BCS theory of superconductivity. The single-particle energies calculated from a given nuclear potential serve as an input to both corrections.

In the calculations presented here, we use for the macroscopic part the Yukawa-plus-exponential model [45] in the specific form of [46]. The microscopic part is based on the deformed Woods-Saxon single-particle potential [47]. We assume only axially-symmetric deformations and describe the nuclear surface (given by the nuclear radius R) in the form

$$R(\vartheta) = R_0(\beta_\lambda)[1 + \sum_{\lambda} \beta_\lambda Y_{\lambda 0}(\vartheta)]. \quad (4)$$

The dependence of R_0 on the deformation parameters β_λ is determined by the volume-conservation condition. The minimum of the total potential energy, leading to the equilibrium deformation of the nucleus, is calculated in the six-dimensional space $\{\beta_\lambda\}$, $\lambda=2,3,4,5,6,7$ [48].

The residual pairing interaction is treated by the Lipkin-Nogami approach [49]. It approximately conserves the number of particles. This is especially important for odd and odd-odd nuclei for which the pairing correlations are weakened by blocking a state by the odd particle and for which the usual BCS approximation is too crude. In this approach two free parameters r and t enter the expression for the smoothed effective pairing gap: $\Delta_G = [rB_s \exp(-tI^2)]/n^{1/3}$ [50]. From this expression the pairing strength G , needed for the solution of the pairing equations, is calculated. n is the number of particles of one kind (neutrons or protons) in a nucleus and $I = (N - Z)/A$ is the relative neutron excess. The relative surface area B_s is taken to be equal 1, as in [50].

Our calculations proceed as follows: for every nucleus considered we determine the equilibrium deformation from the shape-dependent parts of our mass formula, assuming certain values for the pairing parameters r and t . The static equilibrium deformations β_λ^0 for the odd multipolarities $\lambda=3,5,7$ appear to be zero. As consequence, and this is the case for many heavy nuclei [51], the three-dimensional deformation space $\{\beta_\lambda\}$, $\lambda=2,4,6$ is sufficient for the description of Rb and Sr isotopes. However, these nuclei are rather soft to odd deformations. In the case of β_3 this has been observed previously for light Sr

isotopes [52].

As a next step we adjust the parameters of the macroscopic part to obtain the smallest root-mean-square (RMS) deviation between the theoretical and experimental masses for one given isotopic chain where we include all known experimental masses. Due to correlations between the parameters it is sufficient to treat three of them as free: the volume-asymmetry parameter κ_v , the charge-asymmetry parameter c_a and the overall parameter c_0 . The values of two further adjustable macroscopic parameters (the volume-energy constant a_v and the Wigner constant W) were held fixed as well as all parameters which have a fixed value due to their physical meaning. Those were taken from Ref.[46].

The two steps - the search of the equilibrium deformation and the adjustment of the macroscopic parameters - are consecutively repeated for different sets of the parameters r and t . By this way we find the parameter values minimizing the RMS-deviation. The final values of all adjustable parameters, for each isotopic chain separately, are given in Tab. 3 together with the values from the global fit of Möller and Nix [46, 50]. As expected, some of our values differ from those of Möller and Nix, but they are well within the range of physically meaningful parameters.

Figure 8 gives the comparison of the theoretical masses with the newly adjusted ones. Also included in the figure is the prediction of the similar model of Möller et al. [40]. In both models the deviations from experiment exhibit a regular behaviour. The main source of these deviations lies probably in both pairing and shell corrections. The present results are more accurate (as measured by the RMS-deviations listed in Tab. 3), which results partly from the local adjustment restricted to one isotopic chain and partly from the larger deformation space used here.

A characteristic property of nuclei in the investigated region is the energetic closeness of the hypothetical prolate ($\beta_2 > 0$) and oblate ($\beta_2 < 0$) shaped total-energy minima. Figure 9 shows the difference in energy between the minima at prolate and oblate configurations of the nucleus. For most of the studied nuclei this difference does not exceed 0.5 MeV. This has been already observed in Ref.[53], where it was also shown that there exists a rather smooth transition between the two minima via the gamma deformation (see also [54, 55]). This might result in an even lower minimum in energy for a value of $\gamma \neq 0^\circ, 60^\circ$, i.e. triaxially shaped nuclei.

To improve the results of our model, the inclusion of the triaxial deformation degree of freedom is foreseen in order to resolve the problem of the two close lying total-energy minima. It is also planned to achieve a better parametrisation of the pairing force. In addition, the performance of the microscopic-macroscopic model will be checked not only for describing nuclear binding energies but also for reproducing other model-independent

ground-state properties like spins, magnetic and electric moments, and charge radii. Such data are available from laser spectroscopy for Rb and Sr [56, 57] as well as for most of the isotopes [58] on which mass spectrometry can be performed by means of ISOLTRAP. A fit of all ground-state data available for an isotope chain would provide a much more severe test of the model than the fit of the masses alone. This might lead to a better set of model parameters and provide hints to possible improvements of the model which would in turn strengthen the predictive power of the model as heavily requested by nuclear astrophysicists.

5 Conclusions

The ISOLTRAP mass spectrometer set-up at the on-line mass separator ISOLDE 2 has been used for a accurate determination of mass excesses of neutron-deficient Rb and Sr isotopes. The advantages of the method are its constant accuracy even far from stability and its sensitivity to smallest quantities of unstable nuclei. The high accuracy of the data allowed the solution of several disagreements between other independent mass determinations. Beside the determination of so far unknown masses it was possible to greatly reduce the uncertainties of the mass values for isotopes far from stability. A new adjustment of experimental values from different sources is therefore, especially for exotic nuclei, strongly influenced by the Penning trap data.

The analysis of the experimental data in the frame of the macroscopic-microscopic model showed that by adjusting the model parameters locally for the whole isotopic chain one can obtain a better agreement between theory and experiment for the known masses. However, it is generally observed that the disagreement between mass models and experiment exceeds the experimental error by up to two orders of magnitude.

This gap is a challenge for theoreticians to improve the quality of the predictive power of mass models, and one of the conditions to meet this challenge is clearly to extend the set of well established experimental masses even farther from stability.

Acknowledgements

The authors wish to thank especially H.-J. Kluge for his continued support and guidance of this work, and A. Sobiczewski for the valuable comments concerning the theoretical part. We acknowledge financial support by the Bundesministerium für Forschung und

Technologie under Contract Hz188-I and by NSERC of Canada. Travel was also supported by NATO grant no CRG 900675. The work of J. Szerypo was partially supported by KBN contract no. PB 2 0208 91 01. Z. Patyk acknowledges financial support by C.S.N.S.M.

References

- [1] M. Arnoud, Proc. Int. Workshop on the Physics and Techniques of Secondary Nuclear Beams, Dourdan, France, 1992, ed. J. F. Bruandet, B. Fernandez, and M. Bex (Editions Frontieres, Gif-surYvette, 1992) p.175
- [2] M. Goeppert-Mayer, Phys. Rev. **74** (1948) 235
- [3] R.C. Barber, H.E. Duckworth, B.G. Hogg, J.D. Macdougall, W. McLatchie and P. Van Rookhuizen, Phys. Rev. Lett. **12** (1964) 82
- [4] C. Thibault, R. Klapisch, C. Rigaud, A.M. Poskanzer, R. Prieels, L. Lessard and W. Reisdorf, Phys. Rev. C **12** (1975) 644
- [5] M. Epherre, G. Audi, C. Thibault, R. Klapisch, G. Huber, F. Touchard, and H. Wollnik, Phys. Rev. C **19** (1979) 1504
- [6] X.G. Zhou, X.L. Tu, J.M. Wouters, D.J. Vieira, K.E.G. Löbner, H.L. Seifert, Z.Y. Zhou and G.W. Butler, Phys. Lett. B **260** (1991) 285
- [7] N.A. Orr, W. Mittig, L.K. Fifield, M. Lewitowicz, E. Plagnol, Y. Schutz, Zhan Wen Long, L. Bianchi, A. Gillibert, A.V. Belozyrov, S.M. Lukyanov, Yu.E. Penionshkevich, A.C.C. Villari, A. Cunsolo, A. Foti, G. Audi, C. Stephan and L. Tassan-Got, Phys. Lett. B **258** (1991) 29
- [8] H. Stolzenberg, St. Becker, G. Bollen, F. Kern H.-J. Kluge, Th. Otto, G. Savard, L. Schweikhard, G. Audi and R.B. Moore, Phys. Rev. Lett. **65**, (1990) 3104
- [9] R. Bengtsson, P. Möller, J.R. Nix and Jing-ye Zhang, Phys. Scripta **29** (1984) 402
- [10] J. H. Hamilton, P. G. Hansen and E. F. Zganjar, Rep. Prog. Phys. **48** (1985) 631
- [11] R. S. Brown and G. Gabrielse, Rev. Mod. Phys. **58** (1986) 233
- [12] G. Bollen, R. B. Moore, G. Savard and H. Stolzenberg, J. Appl. Phys. **68** (1990) 4355
- [13] G. Gräff, H. Kalinowsky and J. Traut, Z. Phys. **A297** (1980) 135

- [14] G. Savard, St. Becker, G. Bollen, H.-J. Kluge, R. B. Moore, Th. Otto, L. Schweikhard, H. Stolzenberg and U. Wiess, *Phys. Lett.* **A158** (1990) 247
- [15] H. Schnatz, G. Bollen, P. Dabkiewicz, P. Egelhof, F. Kern, H. Kalinowsky, L. Schweikhard, H. Stolzenberg and H.-J. Kluge, *Nucl. Instr. Meth.* **A251** (1986) 17
- [16] E. A. Cornell, K. R. Boyce, D. L. K. Fergusson, and D. E. Pritchard, *Phys. Rev.* **A 45** (1992) 3049
- [17] G. Bollen, H.-J. Kluge, M. König, T. Otto, G. Savard, H. Stolzenberg, R. B. Moore, G. Rouleau and G. Audi, *Phys. Rev.* **C 46** (1992) R2140
- [18] A. H. Wapstra, G. Audi and R. Hoekstra, *At. Data. Nucl. Data Tables* **39** (1988) 281
- [19] G. Bollen, H.-J. Kluge, Th. Otto, G. Savard, L. Schweikhard, H. Stolzenberg, G. Audi, R.B. Moore, G. Rouleau, and the ISOLDE Collaboration, *Jour. Mod. Opt.* **39** (1992) 257
- [20] A. H. Wapstra and G. Audi, *Nucl. Phys.* **A432** (1985) 1
- [21] G. Stephans, H. Fortune, L. Bland, M. Carchidi, R. Gilman, G. Gilfoyle and J. Sweet, *Phys. Rev.* **C 35** (1987) 2033
- [22] G. Audi, M. Epherre, C. Thibault, A. Wapstra and K. Bos, *Nucl. Phys.* **A378** (1982) 443
- [23] G. Audi, A. Coc, M. Epherre-Rey-Campagnolle, G. le Scornet, C. Thibault and F. Touchard, *Nucl. Phys.* **A449** (1986) 491
- [24] D. Moltz, K. Toth, F. Avignone III, H. Noma, B. Ritchie und B. Kern, *Phys. Lett.* **113 B** (1982) 16
- [25] D.M.Moltz, A.C.Betker, J.P.Sullivan, R.H.Burch, C.A.Gagliardi, R.E.Tribble, K.S.Toth, F.T.Avignone III *Phys. Rev. C* **35** (1987) 1275
- [26] G. Bollen, P. Dabkiewicz, P. Egelhof, T. Hilberath, H. Kalinowsky, F. Kern, H.-J. Kluge, R. B. Moore, H. Schnatz, L. Schweikhard, H. Stolzenberg, G. M. Temmer and G. Ulm, *Hyp. Int.* **38** (1987) 793
- [27] G. Bollen, PhD thesis, Univ. Mainz (1989) unpublished, in German

- [28] G. Bollen, H. Hartmann, H.-J. Kluge, M. König, T. Otto, G. Savard and H. Stolzenberg, *Phys. Scripta* **46** (1992) 581 and to be published
- [29] A. Jaffe, G. Bissinger, S. Shafroth, T. White, T. Dzubay, F. Everling, D. Miller and D. Outlaw, *Proc. 4th Int. Conf. Atomic Masses and Fund. Constants*, Teddington (1971) p. 236
- [30] J. Döring, L. Funke, W. Wagner and G. Winter, *Z. Phys. A* **339** (1991)
- [31] H. W. Müller (ed.), *Nuclear Data Sheets* **56** (1989) 551
- [32] J. H. McNeill, Y. A. Akovali, C. R. Bingham, J. Breitenbach, H. K. Carter, J. D. Garrett, J. Kormicki and P. F. Mantica, Oak Ridge National Laboratory Physics Division Progress Report ORNL 6660 (1991) 63
- [33] C. J. Lister, P. E. Haustein, D. E. Alburger and J. W. Olness, *Phys. Rev. C* **24** (1981) 206
- [34] S. DellaNegra, H. Gauvin, D. Jaquet and Y. LeBeyecq, *Z. Phys. A* **307** (1982) 305
- [35] W. Alford, R. Anderson, P. Batay-Csorba, R. Emigh, D. Lind, P. Smith and C. Zafiratos, *Nucl. Phys A* **330** (1979) 77
- [36] R. Broda, A. Hrynkiwicz, J. Styczen and W. Walus, *Nucl. Phys. A* **216** (1973) 493
- [37] Jänecke and Masson, *At. Data Nucl. Data Tables* **39** (1988) 265
- [38] G. T. Garvey and I. Kelson, *Phys. Rev. Lett.* **16** (1966) 197
- [39] C. Borcea and G. Audi, Preprint CSNSM 92.38 and *Proc. 6th Int. Conf. on Atomic Masses and Fund. Const.*, Bernkastel-Kues (1992)
- [40] P. Möller, J.R. Nix, W. D. Myers and W. J. Swiatecki, *Nucl. Phys. A* **536** (1992) 61 and
P. Möller, J.R. Nix, W. D. Myers and W. J. Swiatecki (1992), *At. Data and Nucl. Data Tables*, to be published
- [41] Y. Aboussir, J.M. Pearson, A.K. Dutta, F. Tondeur, *Nucl. Phys.*, to be published (1992) and
J.M. Pearson, Y. Aboussir, A.K. Dutta, R.C. Nayak, M. Farine, *Nucl. Phys A* **528** (1991) 1

- [42] J. Duflo, A.P. Zuker, priv. comm., (1992)
- [43] C.F. v. Weizsäcker, Z. Phys. **96** (1935) 431
- [44] V.M. Strutinsky, Nucl. Phys. **A122** (1968) 1
- [45] H. J. Krappe, R. Nix and A. J. Sierk, Phys. Rev. C **20** (1979) 992
- [46] P. Möller and J.R. Nix, At. Data Nucl. Data Tables **26** (1981) 165
- [47] S. Ćwiok, J. Dudek, W. Nazarewicz, J. Skalski and T. Werner, Comp. Phys. Comm. **46** (1987) 379
- [48] A. Sobiczewski, Z. Patyk, S. Ćwiok and P. Rozmej, Nucl. Phys. **A485** (1988) 16
- [49] H.C. Pradhan, Y. Nogami and J. Law, Nucl. Phys. **A201** (1973) 357
- [50] P. Möller and J.R. Nix, Nucl. Phys. **A536** (1992) 20
- [51] Z. Patyk and A. Sobiczewski, Nucl. Phys. **A533** (1991) 132
- [52] W. Nazarewicz, P. Olanders, I. Ragnarsson, J. Dudek, G. A. Leander, P. Möller and E. Ruchowska, Nucl. Phys. **A429** (1984) 269
- [53] D.A. Arseniev, A. Sobiczewski and V.G. Soloviev, Nucl. Phys. **A139** (1969) 269
- [54] P. Bonche, H. Flocard, P. H. Heenen, S. J. Krieger and M. S. Weiss, Nucl. Phys. **A443** (1985) 39
- [55] W. Nazarewicz, J. Dudek, R. Bengtsson, T. Bengtsson and I. Ragnarsson, Nucl. Phys. **A435** (1985) 397
- [56] C. Thibault, F. Touchard, S. Büttgenbach, R. Klapisch, M. de Saint Simon, H. T. Duong, P. Jacquinet, P. Juncar, S. Liberman, P. Pillet, J. Pinard, J. L. Vialle, A. Pesnelle and G. Huber, Phys. Rev. C **23** (1981) 2720
- [57] F. Buchinger, E. B. Ramsey, E. Arnold, W. Neu, R. Neugart, K. Wendt, R. E. Silverans, P. Lievens, L. Vermeeren, D. Berdichevsky, R. Fleming, D. W. L. Sprung and G. Ulm, Phys. Rev. C **41** (1990) 2883
- [58] E. Otten, Treatise on Heavy-Ion Science, vol. 8, ed. D. Allan Bromley (Plenum Press, New York and London, 1989) p. 516

Table 1: Ratio of cyclotron frequencies for Rb and Sr isotopes as obtained in the present experiment and parameters for the resulting mass relations (eq. (2), see text). The ISOLTRAP data are presented in column 3 as ratios between the cyclotron frequencies of the reference isotope ν_{ref} and the cyclotron frequency ν of the investigated isotope, listed in the first two columns together with their half-lives. ^{85}Rb was used as the reference isotope in all cases except for ^{83}Sr where ^{83}Rb was chosen. Column 4 and 5 give the normalization parameter $(A/A_{ref})_{trunc.}$ of the mass relations and its result MD in micro atomic mass units (see text).

Isotope	$T_{1/2}$	ν_{ref}/ν	$(A/A_{ref})_{trunc.}$	$MD / \mu u$
^{75}Rb	17 s	0.88254535(9)	0.882	16371(8)
^{76}Rb	39 s	0.89428115(9)	0.894	13931(8)
^{77}Rb	3.8 m	0.90600324(9)	0.906	10327(8)
^{78}Rb	17.5 m	0.91775354(10)	0.918	9118(8)
^{79}Rb	23 m	0.92948162(9)	0.929	5934(8)
^{80}Rb	30 s	0.94124138(10)	0.941	5528(8)
^{81}Rb	4.58 h	0.95297689(10)	0.953	3063(8)
^{82m}Rb	6.3 h	0.96474547(10)	0.965	3407(9)
^{83}Rb	86.2 d	0.97648514(10)	0.976	1207(8)
^{84}Rb	33 d	0.98825355(10)	0.988	1536(8)
^{86}Rb	18.6 d	1.01176974(11)	1.012	441(9)
^{87}Rb	stable	1.02352331(11)	1.024	-490(9)
^{78}Sr	?	0.91780111(10)	0.918	13157(8)
^{79}Sr	2.3 m	0.92954900(11)	0.929	11655(9)
^{80}Sr	1.8 h	0.94126496(10)	0.941	7531(8)
^{81}Sr	22.2 m	0.95302652(10)	0.953	7278(8)
^{82}Sr	22.5 d	0.96474676(10)	0.965	3517(8)
^{83}Sr	86.2 d	1.00002951(11)	1.000	2447(9)
^{87}Sr	stable	1.02351988(10)	1.024	-781(9)

Table 2: Comparison of the mass excess from the Penning trap experiment (column 2) with the values from the 1986 mass adjustment ([18], column 3) and a new adjustment (column 5), which takes into account all presently available data. Recent data from [21], which contribute to the new adjustment but not yet to the last are listed in column 4. The significance S , i.e. the percentage of the influence of the Penning trap data on the values of the new adjustment, is given in column 6. The last column indicates the consistency of the data, defined as the ratio of the deviation v of the Penning trap data (column 2) from the mass values of the new adjustment (column 5) divided by the uncertainty s of the values listed in column 2.

Isotope	Mass Excess / keV				S	v/s
	this exp.	1986 adj. [18]	ref. [21]	new adj.		
⁷⁵ Rb	-57220(8)	-57210(100)		-57219 (8)	98%	.2
⁷⁶ Rb	-60479(7)	-60530(60)		-60478 (8)	94%	.1
⁷⁷ Rb	-64822(8)	-64917(30)		-64826 (7)	90%	-.5
⁷⁸ Rb	-66934(8)	-66980(30)		-66934 (8)	94%	.0
⁷⁹ Rb	-70804(8)	-70838(23)	-70779(12)	-70796 (6)	66%	1.0
⁸⁰ Rb	-72168(8)	-72176(18)		-72167 (7)	83%	.1
⁸¹ Rb	-75449(8)	-75459(21)	-75459(11)	-75454 (6)	64%	-.5
^{82m} Rb	-76116(8)	-76122(16)		-76118 (7)	66%	-.3
⁸³ Rb	-79068(8)	-79049(21)	-79079(11)	-79071 (6)	63%	-.3
⁸⁴ Rb	-79748(8)	-79748(3)		-79749 (3)	16%	-.1
⁸⁵ Rb	reference	-82164(3) *		-82165 (2)		
⁸⁶ Rb	-82740(9)	-82744(3) *		-82745 (2)	1%	-.5
⁸⁷ Rb	-84593(9)	-84593(3) *		-84593 (3)	7%	.1
⁷⁸ Sr	-63172(8)	-63450(300)#		-63172 (8)	100%	
⁷⁹ Sr	-65475(9)	-65340(200)#		-65475 (9)	100%	
⁸⁰ Sr	-70302(8)	-70280(30) **		-70302 (8)	100%	
⁸¹ Sr	-71524(8)	-71470(40)		-71524 (8)	100%	
⁸² Sr	-76013(8)	-75998(8)		-76007 (6)	56%	.9
⁸³ Sr	-76791(10)	-76781(21)		-76794 (9)	56%	-.4
⁸⁷ Sr	-84864(9)	-84875(2)		-84876 (3)	4%	-1.4

*: errors corrected for a truncation error in [18].

**: value corrected according to the original paper [35].

#: value from an extrapolation of systematic trends.

Table 3: Adjusted parameters of the microscopic-macroscopic model used in this work. A comparison is made with the macroscopic parameters from [46] and the pairing parameters for the Lipkin-Nogami-approach from [50]. In addition the RMS deviation for both models is given.

This work	κ_v	c_u/MeV	c_0/MeV	r/MeV	t	RMS /keV	
Rb	2.0	0.60	5.1	4.1	0	Rb	825
Sr	2.0	0.56	4.7	4.9	0	Sr	763
Ref. [46,50]	κ_v	c_u/MeV	c_0/MeV	r/MeV	t	RMS /keV	
global	1.927	0.212	4.4	3.3	0	Rb	1119
						Sr	1191

Figure Captions

Fig.1:

The ISOLTRAP mass spectrometer installed at the ISOLDE 2 on-line mass separator at CERN. The ions are collected on a foil, surface-ionized and buffer gas cooled in the lower trap 1. They are ejected as a bunch and guided by ion optics to the precision trap 2. After excitation by an RF field they drift through a time-of-flight section to the ion detector.

Fig.2:

Cyclotron resonance of ^{78}Sr detected by the time-of-flight technique. The resonance curve results from a total of 4713 ions detected. The experimental points are fitted with a Gaussian (full line). The resulting linewidth of $\Delta\nu_c(FWHM) = 1.1\text{ Hz}$ corresponds to a resolving power of 1 million.

Fig.3:

Histogram of results of a sequence of 34 mass determinations for ^{77}Rb . The data are expressed directly as mass excesses. The measurements were performed during two separate runs. The data follow a normal distribution and the standard deviation of the fitted Gaussian is $\sigma = 6.7\text{ keV}$.

Fig.4:

Comparison of mass values for Rb (top) and Sr (bottom) obtained from this experiment (data points) with the newest mass adjustment (solid lines) and the 1986 mass adjustment (dashed lines) [18]. Experimental uncertainties are only indicated where they exceed the symbol size.

Fig.5:

Consistency of the results of the Mattauch-Herzog mass spectrometer [23] with the 1986 mass adjustment (left) and the new adjustment (right). The consistency v/s is defined as the deviation v from the mass adjustment divided by the experimental uncertainties s from [23]. Included for comparison is a standard Gaussian, which would be expected for a perfect experiment with 19 observations. The distribution is slightly uncentered at 0.24σ , thus showing a small systematic bias in that experiment.

Fig.6:

Resonance of isomer and ground state of ^{84}Rb (top) and resonance for the ground state only (bottom), obtained by allowing the isomeric state to decay. The difference in the

cyclotron frequencies of the two states corresponds to 464(7) keV, in excellent agreement with the value reported in ref. [31].

Fig.7:

Comparison of the experimental mass excess (new adjustment) for Rb (left) and Sr (right) with different nuclear mass formulae. The models are from top to bottom: Jänecke and Masson [37], Möller et al. [40], Pearson et al. [41] and Duflo and Zuker [42].

Fig.8:

Comparison of theoretical mass excesses with experimental values (new adjustment). Experimental uncertainties are only indicated in the case they exceed the symbol size. Circles correspond to theoretical values calculated in the present paper, while triangles to those calculated by Möller et al. [40].

Fig.9:

The difference between the total energy minima $E(\text{prolate}) - E(\text{oblate})$ as calculated in the present work for Rb and Sr isotopes, corresponding to the prolate and oblate shapes of the nucleus. The Sr isotopes with $N=48,50,52$ were found to be spherical and are not shown in the figure.

**ION
DETECTOR**

**DRIFT
SECTION**

TRAP 2

**TRANSFER
SECTION**

TRAP 1

ISOLDE BEAM

Fig. 1

Fig. 2

Fig. 3

DEVIATION FROM NEW ADJUSTMENT [keV]

Fig. 4

Fig. 5

Fig. 6

THEORETICAL-EXPERIMENTAL MASS EXCESS [MeV]

Fig. 7

Fig. 8

Fig. 9