Extending and refining the nuclear mass surface with ISOLTRAP and MISTRAL

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Abstract

Through the nuclear binding energy, the atomic mass gives us important information about nuclear structure. Viewing the ensemble of mass data over the nuclear chart, we can examine the hills and valleys that form this surface and make hypotheses about the effects of certain nuclear configurations. To unveil these effects, mass measurements of very high precision ($< 10^{-6}$) are required. Two experiments at ISOLDE pursue this effort of nuclear cartography: the tandem Penning trap spectrometer ISOLTRAP and the radiofrequency transmission spectrometer MISTRAL. Between them, the masses of almost 150 nuclides have been measured from stable isotopes to those with half-lives as short as 30 ms. Both experiments rely on good optical properties of a low energy ion beam and are thus well suited to the ISOLDE facility.

1 Introduction

Mass spectrometry plays an enormous role in science in general and at ISOLDE in particular. The GPS (general purpose separator), the very heart of ISOLDE, exploits the fact that ions created and accelerated from the target-ion source are transported, sorted and selected by using the magnetic field corresponding to their mass. In many domains of science, this very same principle is used to separate and measure isotopic components of an ionized sample, for example in radioactive carbon dating applications that determine the ratio of $^{14}C/^{12}C$.

However it is the absolute determination of the mass that is of importance for nuclear physics since the total mass contains a binding energy that reflects the

net results of all forces at work within the nucleus. If we look at the binding energy along an isobaric chain (Fig.1), we perceive an inverted parabolic effect with the stable isotope in the middle (^{100}Ru) having the strongest binding energy while those further away from stability are less bound and consequently have higher masses. This shows in a qualitative way how nuclides that are further from stability have shorter half-lives against radioactive decay. In fig.1 we can also perceive a zig-zag effect which is due to a phenomenon of nuclear structure called pairing: nuclides with even numbers of protons and neutrons are more bound than those with odd numbers.

If we now examine the mass surface in fig.2 defined by the two-neutron separation energy $S_{2n} = BE(Z,N) - BE(Z,N-2)$ (where BE is the binding energy) we observe a series of lines where this pairing effect is avoided. The general trend is that S_{2n} decreases as we add neutrons and deviations from this behavior point us to manifestations of microscopic nuclear structure effects. For example, at N = 50 we see a sharp decrease of S_{2n} which indicates a neutron shell closure and the region above $N = 60$ indicates that nuclear deformation is at work. This illustrates how masses give us a first glimpse of nuclear structure.

From fig.2 we can see that these various nuclear effects have an energy scale of about 1 MeV. When we compare this to the total mass (of about 100 GeV in this region of $A = 100$) we see that just to evidence these phenomena requires a precision of one part in 100,000 and in order to probe these effects and extract information of interest requires at least a factor of ten times more. Thus mass measurements are part of the class of precision measurements with a component of metrology. The atomic mass evaluation [1] not only ensures that masses determined via different reactions, decays and mass spectrometry methods all agree but also provides an excellent accompanying review of the various motivations for measuring masses.

There are special cases where mass measurement precision must go even further. In atomic physics, when the atomic binding energy of hydrogen-like ions is compared to that of the fully stripped ion, a very important test of the relativistic corrections to quantum electrodynamics is possible - the most precise theory in existence. This type of physics requires precision of 10^{-10} or better, difficult to achieve in the case of unstable isotopes due to measurement time restrictions that are limited by radioactive decay.

Where precisions of 10^{-8} or so are possible, nuclear mass measurements can play an important role in testing the standard model because of its unitarity requirement of the Cabibbo-Kobayashi-Maskawa quark mixing matrix. The V_{ud} matrix element is determined by certain special cases of nuclides that β-decay by so- called super-allowed transitions. Precise mass measurements of the parent and daughter nuclides of such transitions give stringent β-endpoint

values and complement nuclear spectroscopy measurements (Ed: see contributions of such experiments at ISOLDE e.g., Dessagne et al. and Jokinen et al.).

Finally, knowledge of the nuclear binding energy is extremely important for nucleosynthesis, in particular the rapid neutron capture, or r-process, thought to occur in supernovae. Since this process occurs on the very neutron-rich side of the valley of stability, the properties of most nuclides involved have not been measured (let alone, produced!). We must therefore rely on models to generate the required data, most of which are derived from calculations of masses [3]. The problem, illustrated by fig.3, is that the various mass models that are proposed, none are in agreement beyond what is measured! Measurements of masses very far from stability are therefore important for constraining these models. There has long been considerable activity at ISOLDE concerning the r-process in the form of nuclear spectroscopy, notably for measuring β-decay half-lives which are important to determine the upward branching points that condition the abundances [4].

There are several experimental programs wholly dedicated to mass measurements, each using a different (and complementary) technique. Often the choice of technique is strongly conditioned by the method of production of radionuclides (see review of [5]). ISOLDE is an excellent facility for performing precision measurements. Not only is high intensity of the radioactive beam important but it is especially good beam quality that allows controlled and efficient injection into very sensitive apparatus. Two experiments at ISOLDE are dedicated to precision mass measurements in order to further map and refine the nuclear mass surface: the tandem Penning trap spectrometer ISOLTRAP and the radiofrequency, transmission spectrometer MISTRAL. ISOLTRAP attains measurement precision of better than 0.1 ppm while MISTRAL, dedicated to the more short-lived isotopes, has achieved 0.4 ppm. Both instruments perform measurements of the cyclotron frequency of a ion in a homogeneous magnetic field as described in the following sections. Cyclotron frequency and time-of-flight methods now dominate mass measurement programs [6].

The first criteria for a precision measurement is having a signal with a narrow lineshape i.e., high resolution. Both ISOLTRAP and MISTRAL are high resolution spectrometers. ISOLTRAP can reach a resolving power of over ten million! MISTRAL, while more modest at one hundred thousand, can achieve this resolution within the time it takes to scan over the frequency range as the ions transit the spectrometer whereas ISOLTRAP must confine the ions for over 10 seconds per frequency point in this case. For comparison, the GPS mass resolution is 1000-2000, sufficient for the separation of adjacent isotopes while the HRS (high resolution separator), designed for separation of isobaric contaminants has so far reached a resolving power of over 15,000. In this sense, MISTRAL could be thought of as a Very-HRS and ISOLTRAP, the first mass

spectrometer to demonstrate resolution of isomeric states, an Ultra-HRS.

2 ISOLTRAP

The tandem Penning trap spectrometer ISOLTRAP has existed at ISOLDE for many years. Well over 100 masses have now been measured and while the essential technique of trapped-ion cyclotron motion excitation coupled with time-of-flight detection has not changed, the spectrometer has considerably evolved in its methods of stopping the radioactive ion beam and introducing the ions into the trap systems.

2.1 The ISOLTRAP Spectrometer

The basic principle of mass measurements with ISOLTRAP is the determination of the cyclotron frequency $\omega_c = qB/m$ of ions with a charge-over-mass ratio q/m stored in a Penning trap with known magnetic field B. Fig. 4 shows the present layout of the ISOLTRAP spectrometer [7,13]. The first section of the spectrometer has the task to stop the 60 keV ISOLDE beam and to prepare it for efficient transfer into the cooler trap. In the past a stopping/re-ionization technique was applied which limited the applicability of ISOLTRAP to surface ionizable elements. Recently the system was considerably improved by the implementation of RFQ trap ion beam buncher systems [30], which allow to capture the continuous ISOLDE beam in flight. The lower Penning trap [9] has the task to accumulate, cool, and mass separate the ions delivered from the ion preparation section and to bunch them for an efficient delivery to a second Penning trap. This precision trap is the actual mass spectrometer where the cyclotron frequency of the captured ions is determined. Important aspects of the performance of ISOLTRAP will be discussed in the following.

2.2 ISOLDE Beam preparation

An essential ingredient for Penning trap mass measurements at ISOLDE is an efficient deceleration and bunching of the 60-keV ion beam prior to its transfer into the tandem Penning trap system of ISOLTRAP. An important step towards an extension of the applicability of ISOLTRAP to essentially all isotopes delivered at ISOLDE was the use of a scheme that allows a direct stopping, cooling and bunching of the approximately continuous ISOLDE beam. The basic principle is the use of a gas-filled radiofrequency quadrupole (RFQ) ion trap which is on a potential close to that corresponding to the ISOLDE beam

energy. By this the ISOLDE ions are electrostatically retarded and after entering the trap are captured by energy loss due to buffer gas collisions. After a certain accumulation time the ions are ejected as an ion bunch and accelerated towards a long drift tube with a potential typically 2 keV lower than the trap potential. The drift tube is switched to ground potential after the 2 keV ion bunch has entered it and by this a low energy ion bunch is now available for transfer into the tandem Penning trap system. In its first version a RFQ trap with cylindrical symmetry was used. This system was used very successfully for a series of measurements in particular in the $Z = 82$ mass region. However, due to a mismatch between the ISOLDE beam emittance and the acceptance of the cooler/buncher only a low efficiency was obtained. Therefore a new system was developed which is based on a linear quadrupole rf-trap. The system, which has some similarity with the ion beam cooler planned for MISTRAL (see below), is presently under test.

2.3 Isobar and isomer separation

Penning trap mass measurements require rather clean beams in order to avoid systematic errors in the mass determination arising from Coulomb interaction of different ion species in the trap. The resolving power of the ISOLDE general-purpose separator is by far not high enough to deliver such isobarically pure beams. A mass selective cooling technique [10–12], based on the simultaneous application of a buffer gas cooling and radio frequency excitation of the ion motion, is employed in the first "cooler" Penning trap. This cylindrical trap system has been optimized for a mass selectivity high enough to resolve isobars and for the delivery of clean and cooled ion bunches to the precision trap, an essential ingredient for highly accurate mass measurements. As an example, Fig. 5 shows a "mass scan" performed with the cooler trap for an $A = 138$ ion beam delivered by ISOLDE from a Ta-foil target. Shown is the number of ions extracted from the trap as a function of the applied radio frequency. The mass resolving power achieved here is about $R = 10^5$, which is sufficient to resolve and separate isobars even close to stability.

The precision trap in which the cyclotron frequency determination of the ions takes place is in operation without major modification since several years and performs excellently [13]. This trap is normally operated with a resolving power R close to one million, corresponding to rf excitation times of $T_{rf} = 1s$ for $A = 100$ ions. If required, the resolving power can be considerably increased by increasing T_{rf}. The maximum resolving power that has been realized in off-line tests with ^{133}Cs ions is $R = 8$ million using $T_{rf} = 12s$. This corresponds to a mass resolution of $\delta m_{fwhm} = 15keV$.

For the investigation of trends in nuclear binding energies an accuracy of

$\delta m/m \approx 10^{-7}$ is normally sufficient and is already achieved with modest resolving powers ($R < 10^6$). Higher resolving powers become important in the case of long-lived isomers produced simultaneously with isotopes in their ground state. Over the nuclide chart nearly one third of the isotopes have long-lived isomeric states with (in many cases unknown) excitation energies. Only in a few cases information about the production ratio exists which may vary drastically depending on the spins and on the half-lives and release time from the targets. Therefore, the resolution of isotopes in their ground or isomeric state is essential for an unambiguous determination of the mass of the isotope in one or the other state. That this can be achieved with ISOLTRAP has now been demonstrated several times. Two recent examples are shown in Fig. 6 for ^{141}Sm and ^{185}Hg.

2.4 Recent Results

In total 76 isotopes and states have been investigated since 1995, and are listed in table 1. An accuracy in the mass determination of $\delta m/m = 10^{-7}$ was achieved for most of these isotopes. The measurements concentrated on rare earth isotopes, isotopes of mercury and of heavier elements, which became only possible by the recent improvements of the spectrometer.

2.4.1 Rare earth isotopes

So far direct mass measurements in this region were hampered by the fact that many isobars are delivered simultaneously by ISOLDE. Since the cooler trap can be operated as an isobar separator, clean ion samples can be prepared and sent to the precision trap. In several beam times it was possible to investigate more than 50 isotopes in the vicinity of ^{146}Gd, most of them with $N \leq 82$ and $Z < 64$. For most of the isotopes the detailed analysis of the data is completed [14] and an atomic mass evaluation similar to the work of Audi and Wapstra [1] has been performed. The evaluation shows that the ISOLTRAP measurements have a large impact on this mass region. This is illustrated in Fig. 7, which shows the trend of the two neutron separation energies. The upper and lower part of the figure show the situation before and after the ISOLTRAP data have been included.

Prior to the ISOLTRAP measurements strong discontinuities were observed in the S_{2n} trends derived from experimental mass values as can be seen in the upper figure. Above the $N = 82$ shell closure, for $Z = 67$ and $Z = 68$, these discontinuities are now removed and the separation energies follow the regular trend observed in the neighboring isotopic chains. The trends in the region $N < 82$ and $Z < 64$ are also now more clearly established. Systematic

deviations from a linear trend for $Z > 56$ around N=76 and N=77 are now visible up to Z=60. They might be related to the eradication of the proton sub-shell gap at $Z \approx 64$ as one departs from N=82 and be accompanied by a change in nuclear deformation.

Since mass values of many isotopes are linked via known Q-values to other isotopes, accurate mass measurements of a few key isotopes can have a large impact on the knowledge of masses over a whole mass region. The case of ^{150}Ho will be discussed as an example. Mass differences between 19 isotopes linked to ^{150}Ho, some of them beyond the proton drip-line around $Z = 80$, are already known via experimental Q-values. No link existed between these nuclei and the backbone of stability, since a doubtful experimental Q-value for ^{150}Ho was rejected in the 1995 atomic mass evaluation [1]. This unsatisfactory situation is now resolved by the ISOLTRAP measurement on ^{150}Ho, which justifies the early rejection of the old experimental datum, which is 810 keV away from the ISOLTRAP value. The ISOLTRAP measurement therefore not only gives an accurate experimental mass value for ^{150}Ho but also anchors the masses for all 19 isotopes linked to it.

2.4.2 Neutron-deficient mercury isotopes

The interest for nuclear structure investigations and mass measurements in this region arises from the appearance of shape coexistence at low excitation energies in the region around the shell closure at Z=82. The onset of rotational bands built on low-lying 0^+ states has been found [15] in even-even Pt, Hg, Pb and Po isotopes mid-shell between N = 82 and N = 126. A large staggering in the $\delta < r^2 >$ values determined from isotopic shift measurements was observed for $A \leq 185$ for the ground- states of the light Hg isotopes, a jump from small to strong deformation in the neighboring Au isotopes at $A \leq 186$ and a smooth transition in the Pt isotopes [16–18]. However, until recently no mass values were known in this mass region. Today, precise information is still lacking for $A \leq 185$, where the strongest structural changes occur.

The neutron-deficient isotopes of elements around Z = 82 are all members of long α-decay chains with well-known Q-values. Therefore, an accurate determination of such isotopes allows to fix these chains, making a large impact on a whole mass area starting at the upper part of the rare earth region and reaching to the border of known proton-rich isotopes.

With ISOLTRAP, a first series of mass measurements on the neutron-deficient mercury isotopes $^{185-197}Hg$ was carried out in December 1996 after the installation of the RFQ trap ion beam buncher. In the case of the even isotopes where no isomeric states exist, the evaluation was straightforward and an accuracy of $\delta m \approx 20keV$ can be assigned to all mass values. However, in the case

of the odd isotopes long-lived isomers exist and are produced at ISOLDE. The excitation energies of typically 100 - 150 keV of these isotopes are very low. In the first measurements in December 1996 the spectrometer was operated with a resolving power of $R \approx 500000$, which corresponds to a mass resolution of 300 keV in this mass range. Therefore it was not possible to resolve isomeric and ground states.

Therefore, in a second run the attempt was made to verify the production of the isomers and to resolve them and the corresponding ground states. For this purpose the spectrometer was operated with resolving powers up to R = 5 million with which a mass resolution of $\delta m \approx 30keV$ was achieved. Using such a scenario it was possible to resolve isomeric and ground state in the cases of ^{185}Hg (see Fig. 6) and ^{193}Hg. Furthermore, it was verified that the ground state is dominantly produced in the case of ^{197}Hg, while for ^{195}Hg only the isomeric state has been seen, for which the excitation energy is known. Therefore for all these isotopes the ground state masses are now identified and determined with an accuracy of 20 keV. In addition, during this run it was possible to extend the measurements in the mercury chain out to ^{184}Hg.

The evaluation of the data is completed and it is presently investigated if a non-linearity in the trend of the two-neutron separation energies observed both in the mercury isotopes and in the neighboring chain of platinum isotopes (linked to the mercury isotopes via known Q- values) can be connected to the appearance and disappearance of low-lying deformed states in these isotopes as one approaches and departs the midshell region. In this context it would be helpful if the experimental information on nuclear binding energy could be significantly extended towards more neutron-deficient isotopes.

2.4.3 Isotopes with Z = 82 - 85

Using the Paul trap ion beam buncher, the investigation of a new region of isotopes with $Z \geq 82$ was started very recently. In a first experiment isotopes were selected which are members of long α-decay chains, those either not linked to an isotope with known mass or to one with a large mass uncertainty. Fig. 8 shows the decay chains and the isotopes investigated by ISOLTRAP. Due to the high accuracy of the ISOLTRAP data together with the availability of the Q_α- values accurate information on nuclear binding energies is now available even for very heavy proton-rich isotopes like ^{210}Th, ^{213}Pa, or ^{218}U, situated at the borderline of known nuclei.

The expected increase of the efficiency of ISOLTRAP will allow to extend the on-going studies even farther from stability. The mercury mass measurements will be extended beyond midshell as discussed above and some still unknown excitation energies of isomeric states will be measured. One example of planned studies in new mass regions are those on neutron-rich isotopes at and above the magic proton number Z = 82. This "terra incognita" is of importance in the context of nuclear astrophysics modeling of element synthesis but also very sensitive for the adjustment of parameters of theoretical models used for the prediction of properties of super-heavy elements.

The high accuracy of ISOLTRAP is planned to be employed in a mass determination of ^{32}Ar and ^{33}Ar. The positron-neutrino correlation in the β- decay of ^{32}Ar was recently studied at ISOLDE [19] and the result sets presently the best constraint on scalar weak interactions. In order to make this result fully experimental a more precise mass determination ($\delta m = 3keV$) of ^{32}Ar is still required since it is not the available mass value ($\delta m = 50keV$) that is used but an estimate obtained via a mass formula: the Isospin Multiplet Mass Equation (IMME). As discussed in more detail in [19] the ^{32}Ar and ^{33}Ar correlations can, if combined with other precise experimental information including binding energies, also be used to test isospin impurities in these superallowed decays.

3 MISTRAL

The MISTRAL spectrometer is a relative newcomer to ISOLDE. Installed in 1997, the first results were already achieved in July 1998 with a second successful run in November of the same year and a further one in May 1999. MISTRAL employs a rather special technique of radiofrequency excitation of the cyclotron motion at the full beam transport energy that allows very rapid measurements of high accuracy thus rendering it particularly suitable for short-lived isotopes. Thus, MISTRAL complements ISOLTRAP which must store ions for longer periods in order to make a very accurate measurement. For a full description of MISTRAL see [20,21].

3.1 Description of apparatus

A schematic diagram of the MISTRAL spectrometer with its nominal trajectory is shown in fig.9. Ions injected at the full ISOLDE beam energy (60

keV) follow a two-turn helicoidal trajectory inside the annular, homogeneous magnetic field (fig.9, inset center) and are counted using a secondary electron multiplier. With an injection slit size of 0.4 mm and orbit radius of 0.5 m, a mass resolution of 2500 is obtained using no radiofrequency. In order to make a measurement, a longitudinal kinetic energy modulation is effected using two symmetric electrode structures (fig.9, inset right) located at the one-half and three-half turn positions inside the magnetic field. This way the ions make one cyclotron orbit between the two modulators. A radiofrequency voltage is applied to the central modulator electrodes. Depending on the phase of this voltage when the ions cross the gaps, the resulting longitudinal acceleration produces a larger or smaller cyclotron radius than that of the nominal trajectory (all the trajectories are isochronous). The ions are transmitted through the 0.4 mm exit slit when the net effect of the two modulations is zero. This happens when the radiofrequency voltage is an integer-plus-one-half multiple of the cyclotron frequency which means that during the second modulation the ions feel exactly the opposite of what they felt during the first. For high harmonic numbers (e.g. larger than 1000) and a radiofrequency voltage of about 200 V, the ion signal over a radiofrequency scan shows narrow transmission peaks evenly spaced at the cyclotron frequency, having resolutions of more than 100,000 (fig.9, inset left).

A mass measurement is made when an unknown mass is alternately injected with a reference mass - without changing the magnetic field. Comparing masses in this way requires changing not only the transport energy of the reference beam but the voltages of all electrostatic elements in the spectrometer (two quadrupole triplets, eight pairs of steering plates, and two cylindrical benders plus the injection switchyard bender). These comparisons are done in rapid succession (seconds) in order to eliminate short-term drift in the magnetic field.

In the case of short-lived isotopes (as well as elements with very rapid release times from the target matrix, such as Na) it is impossible to scan the entire required frequency range in time after the impact of the proton pulse. In this case, a special acquisition mode is used (called, appropriately: point-by-point). For each radioactive beam pulse, the ion transmission signal is recorded for only one radiofrequency point (determined randomly) and the resonance peak is reconstructed at the end. This mode not only allows us to increase statistics in the peak but for each point, the ion signal can be recorded with the radiofrequency switched off so that not just the intensity but the true transmission is measured in order to correctly normalize the peak. This offers an excellent way of identifying isobars. An example is given in fig.10 (center) for the isobaric doublet $^{27}Na - ^{27}Al$. Since we count the ions in the beam that have been separated with very high resolution, we can produce very clean release curves as shown in fig.10 (left). The stable Al peak is easily recognised by its constant release in fig.10 (right).

A first test run using radioactive isotopes around A = 27 took place in November 1997 using a UC_2 target coupled with a plasma ion source. The spectrometer was able to cleanly separate the isobaric components with relatively good sensitivity and very encouraging indications for measurement precision. At present some 35 isotopes have been measured by MISTRAL (see table 2) with the analysis completed for the series $^{23-30}Na$ [23]. This element is interesting for nuclear physics due to the so called "island of inversion" around the $N = 20$ shell closure [24,27] which also includes ^{32}Mg, measured during the May 1999 run and currently under analysis.

Shown in fig.11 is a recorded peak for ^{30}Na from the July 1998 run. This measurement corresponds to a sum of 25 series of 64 (random) frequency steps, corresponding to almost two hours of measurement time. The center frequency is derived from a triangular fit which is the theoretically expected lineshape[22]. In this case, the frequency corresponds to harmonic number 2421 of the cyclotron frequency of ^{30}Na in the 0.38679 T field at a beam energy of 60 keV. The mass resolution in this case is about 50,000 (reduced on purpose in order to favor transmission) but has been measured at over 1.2×10^5. The sensitivity of MISTRAL was evaluated at $2000 s^{-1}$ which is worse than that evaluated from ISOLDE beam emittance measurements. This is due to the very difficult beam transport conditions which we hope to improve in the future.

When we compare our preliminary values to those in the mass table we perceive an offset (proportional to ΔM, the mass-doublet difference) of about $7 \times 10^{-7} \times \Delta M$. When we correct this linear offset, the residual differences scatter randomly about zero within a value of about 25 keV, an uncertainty already better than the present one for $^{28,29,30}Na$ (80, 90, 90 keV) [1]. This systematic error is due to a lack of congruency between the reference ion trajectory and that of the mass being measured and ions of differing trajectories do not experience exactly the same integrated magnetic field because of residual gradients ($\approx 10^{-5}/cm$).

Between the two runs in 1998 we upgraded the high voltage system of the spectrometer. This allows us to operate the reference source at 80 kV and to use a reference mass which is lighter than the unknown mass. This was crucial for using both ^{23}Na and ^{39}K as references for the precise determination of the systematic error. We plan to reduce these field gradients through the use of current shim coils [28] which are now installed and under test.

Though preliminary, the sodium masses seem to indicate that the N = 20 shell effect may be washed out. This question was raised originally by Thibault et

al. [24] but later measurements made with both the TOFI spectrometer [25] and SPEG [26] found the effect to be attenuated. The new MISTRAL measurements would appear to revive this interesting question. Detailed analysis is now underway. In fig.12, the result of our measurement of ^{30}Na is plotted with respect to all measured values that constitute the mass value in the table [1]. The MISTRAL value is in agreement with all values except for the TOFI91 result [25] and represents a great improvement in measurement uncertainty. There is a considerable offset of over 200 keV from the mass table value due to heavy weight carried by the TOFI91 datum.

3.3 Near Future Measurement and Development Programme of MISTRAL

The immediate measurement program of MISTRAL will concentrate on neutron-rich Ne isotopes and Ar and K isotopes across the N = 28 shell closure. The interesting case of ^{74}Rb is also a near-term future concern. This N=Z isotope is of great interest since it is a super-allowed β emitter and can bring constraints to bear on the standard model [2].

Technical developments are currently underway to increase the magnetic field homogeneity using shim coils to correct both the axial and radial residual field gradients [28] in hope of reducing the frequency shift and its contribution to the experimental uncertainty. Also underway is the design of a new, wide-band radiofrequency modulator system that will allow greater flexibility of operation.

The high resolution of MISTRAL offers excellent possibilities for isobarically purifying the ISOLDE beam i.e., providing isobaric separation with no limitation in dynamic range. It is well known that isobaric contamination is perhaps the most important problem for nuclear spectroscopy so this prospect is a very interesting one. Of course resolution always comes with a price in transmission and for the moment it is necessary to improve the transmission through the spectrometer to make this possibility viable.

For the longer term, this crucial question of sensitivity is being addressed by the development of a beam cooling device at the entrance of the spectrometer. By reducing the emittance of the incoming beams, the transmission through the many slits inside the spectrometer will be improved as well as the overlap of the two trajectories through the spectrometer. We plan to install a gas-filled ion guide that will use the alternate focusing of a radiofrequency quadrupole field to continually refocus the ion beam onto the axis while it loses kinetic energy from collisions with the gas [29,30]. The prototype is now under test in Orsay with a targeted installation in 2000. We are also collaborating with ISOLTRAP on the development of a similar device with an additional

bunching capacity for transfer to the first Penning trap. Both experiments are members of the EXOTRAPS European Research (TMR/LSF) Network with beam cooling being one of its principle themes [31].

4 Conclusion and Outlook

Both of these modern approaches to high accuracy mass measurements of exotic isotopes are very successful and further, complementary. In many cases it is important that the masses of isotopes of critical importance be checked using different methods. ISOLTRAP focuses on heavier isotopes where high resolving power is a must but will also study medium short-lived isotopes of special interest, for example ^{32}Ar, where very high accuracy is required. MISTRAL focuses mainly on light isotopes but will also be employed for measurements of heavier isotopes in cases of very short-lived isotopes that can not be studied with ISOLTRAP.

Important technical developments for both projects are the cooling of the ISOLDE beam, as pursued in the framework of the EXOTRAPS research network, and the development of an absolute mass calibration via carbon cluster ions.

Finally, both ISOLTRAP and MISTRAL are designed based on the availability of low-energy radioactive beams of high quality and are thus, perfectly adapted for the ISOLDE facility.

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List of figures

envelope of modulated cyclotron diameters), the second modulator at three-half turns and finally the exit slit. Inset (left) shows the transmitted ^{39}K ion signal as a function of radiofrequency spanning three harmonic numbers (around 3400). The mass resolution is greater than 100,000.

FIGURE 10. (center) a frequency scan at mass $A = 27$ showing two nicely resolved isobaric components. When the time profile of these peaks is plotted, we can easily identify each one as (left) short-lived Na from its release time correlated to its production at the arrival of the proton pulse and (right) stable Al from its constant release.

FIGURE 11. A recorded (reconstructed) peak for ^{30}Na ($T_{1/2} = 48ms$). This measurement corresponds to 64 (random) frequency steps of 320 ms each and is a sum of about 25 scans. The center frequency is derived from a triangular fit and corresponds to harmonic number 2421 of the cyclotron frequency in the 0.38679 T field at an energy of 60 keV. The mass resolution is about 50,000 (reduced to favor transmission).

FIGURE 12. Comparison of the MISTRAL mass value for ^{30}Na with the four values used in the mass evaluation [1].

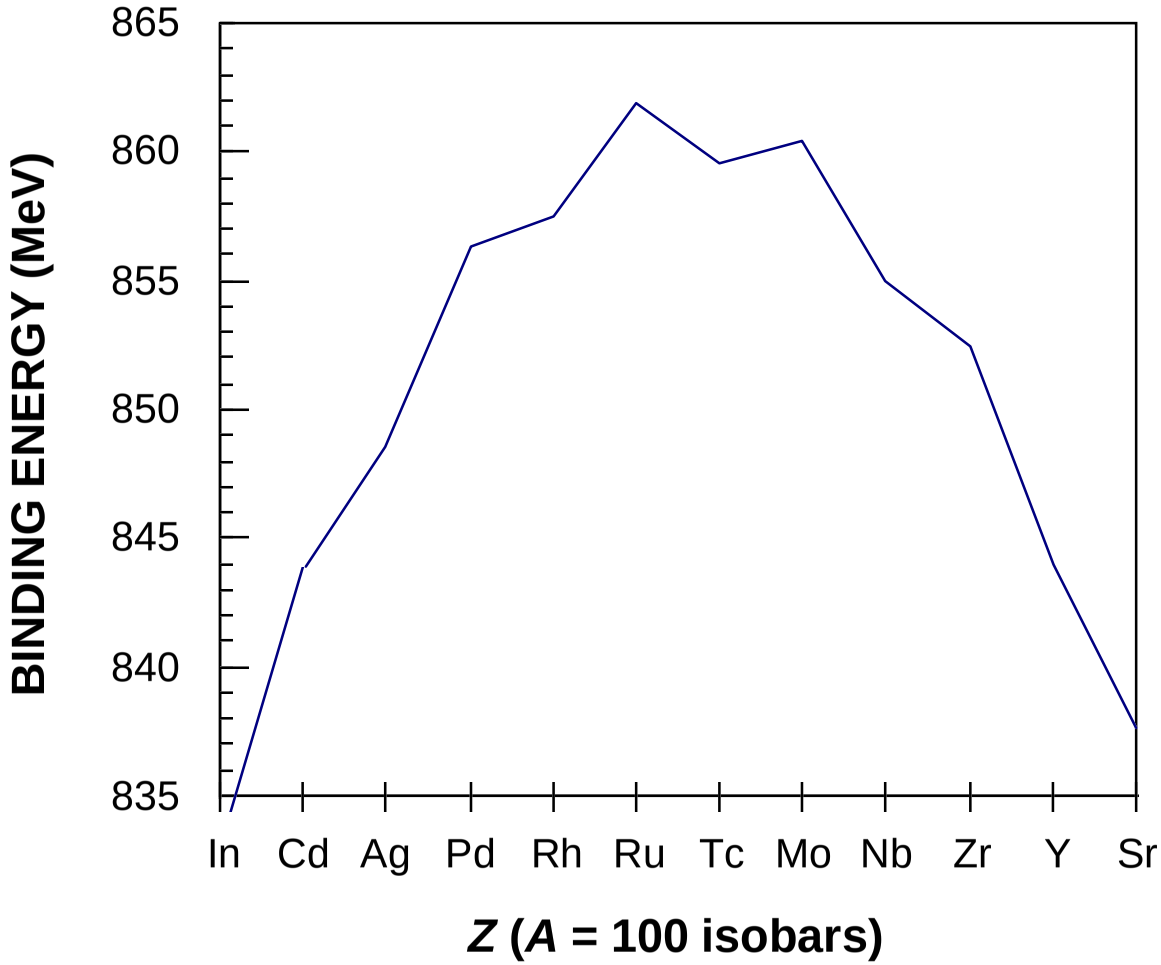
List of tables

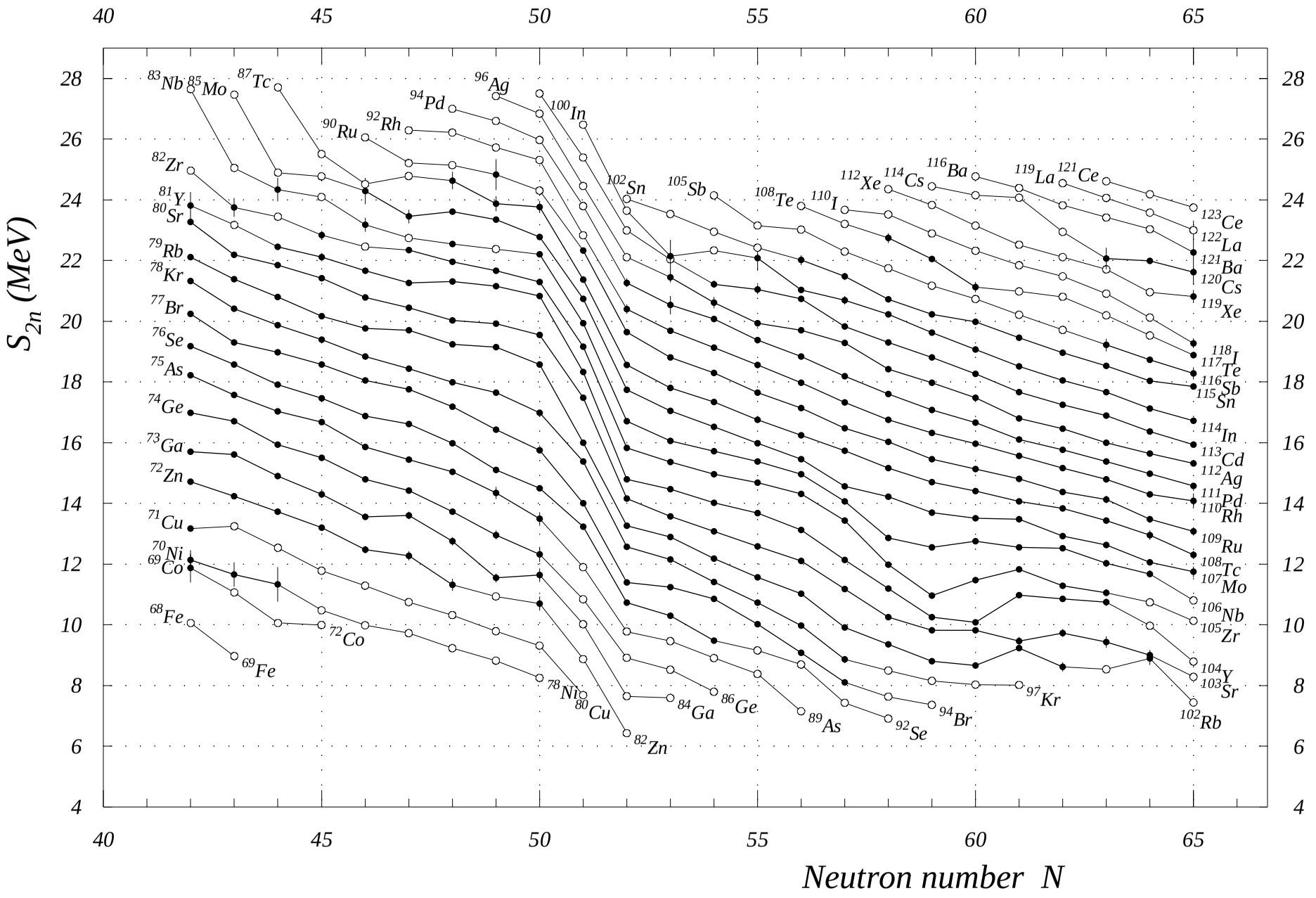
TABLE 1. List of isotopes investigated with ISOLTRAP from 1995 until end of 1998.

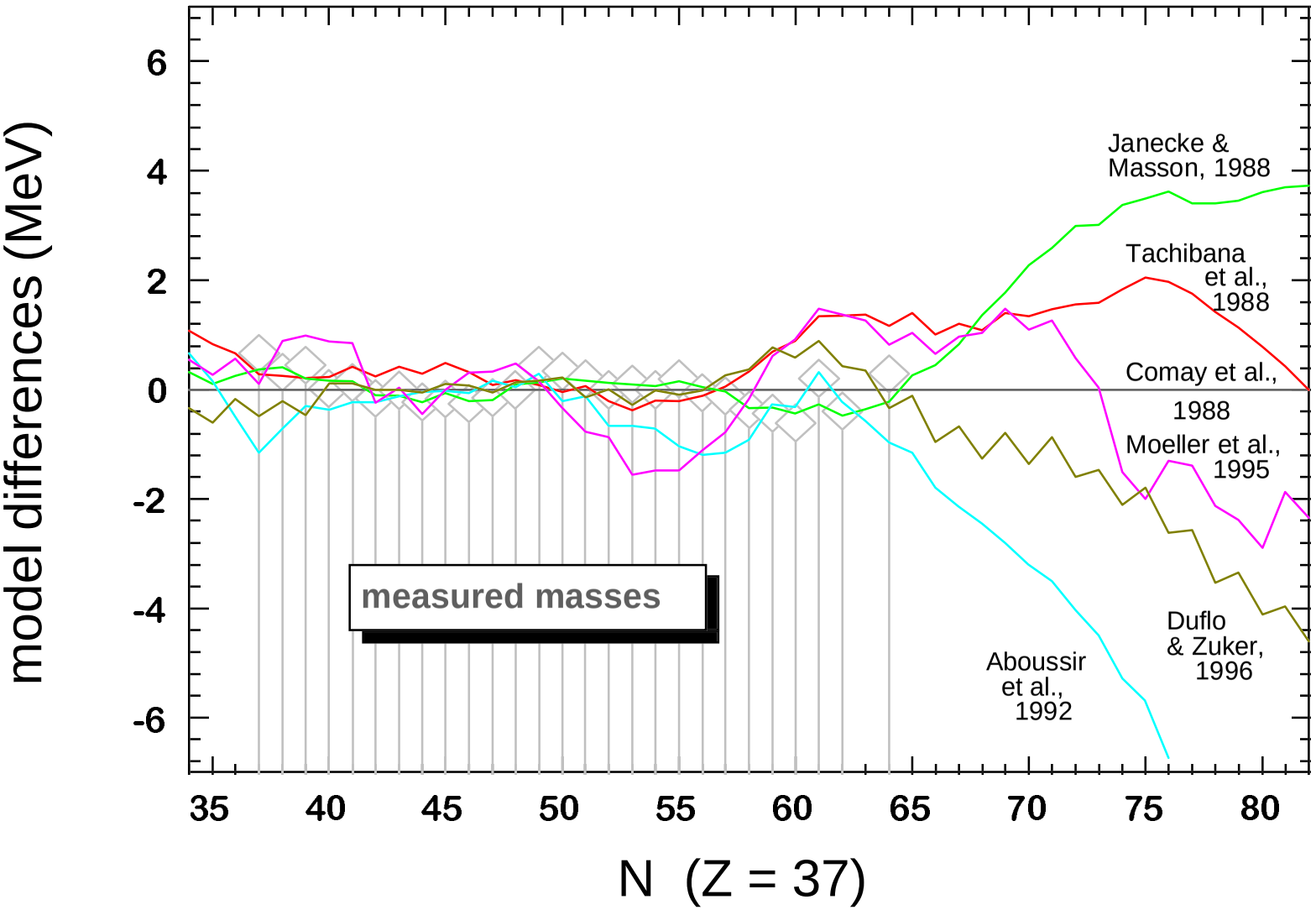
Element	Mass Number	Element	Mass Number
Ba	123, 125, 127, 131	Ho	150
Cs	133 (reference isotope)	Tm	165
Ce	132, 133, 134	Yb	158, 159, 160, 161, 162, 163, 164
Pr	133-137	Hg	184, 185g+m, 186-190, 191m
Nd	130, 132, 134-138		192, 193g+m, 194-196, 197g
Pm	136-141, 143	Pb	196,198, 208 (reference isotope)
Sm	136-140, 141g+m, 142, 143	Bi	197
Eu	139, 141-149, 151, 153	Po	198
Dy	148, 149, 154	At	203

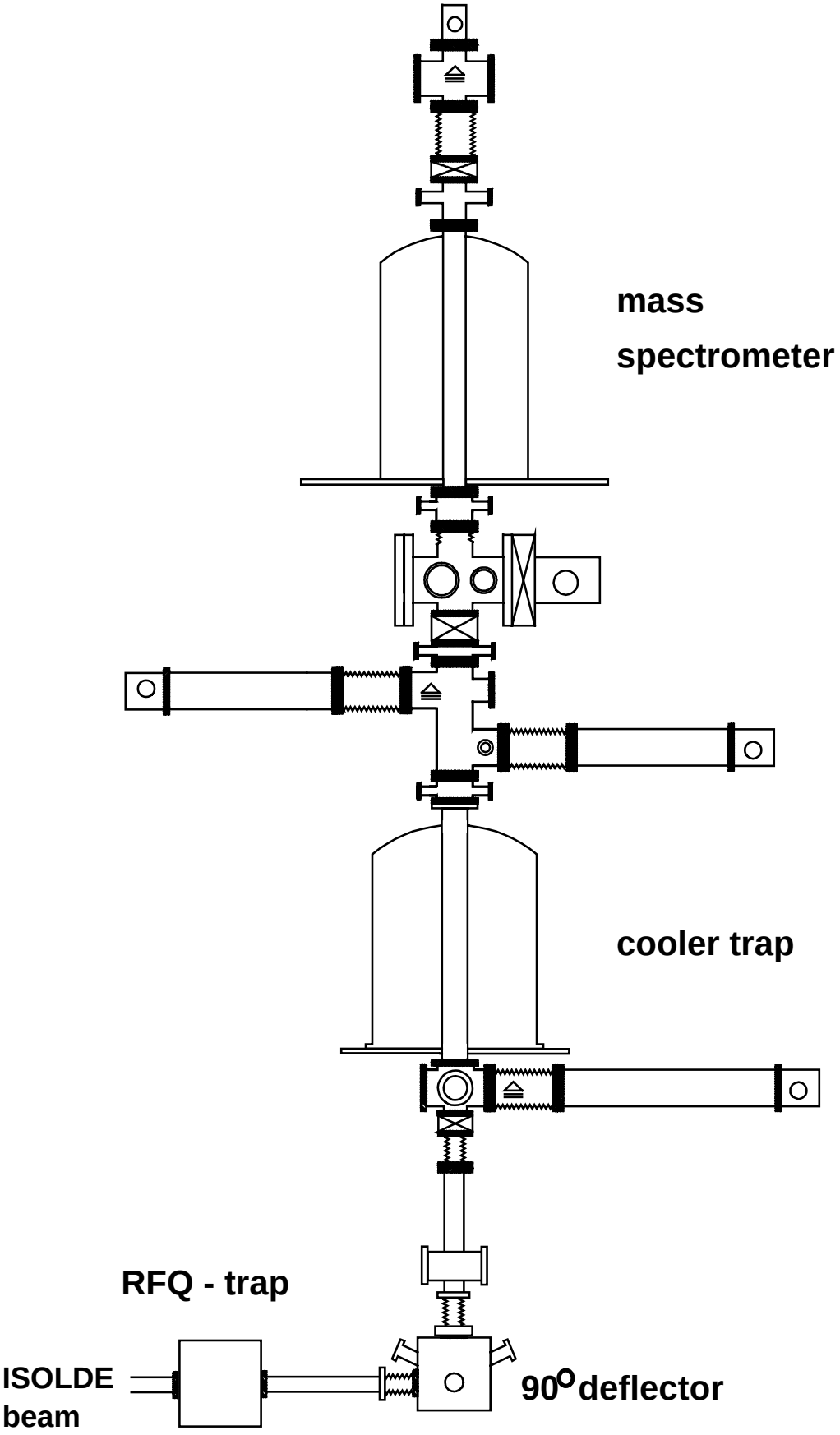
TABLE 2. List of isotopes whose masses have been measured by MISTRAL, so far.

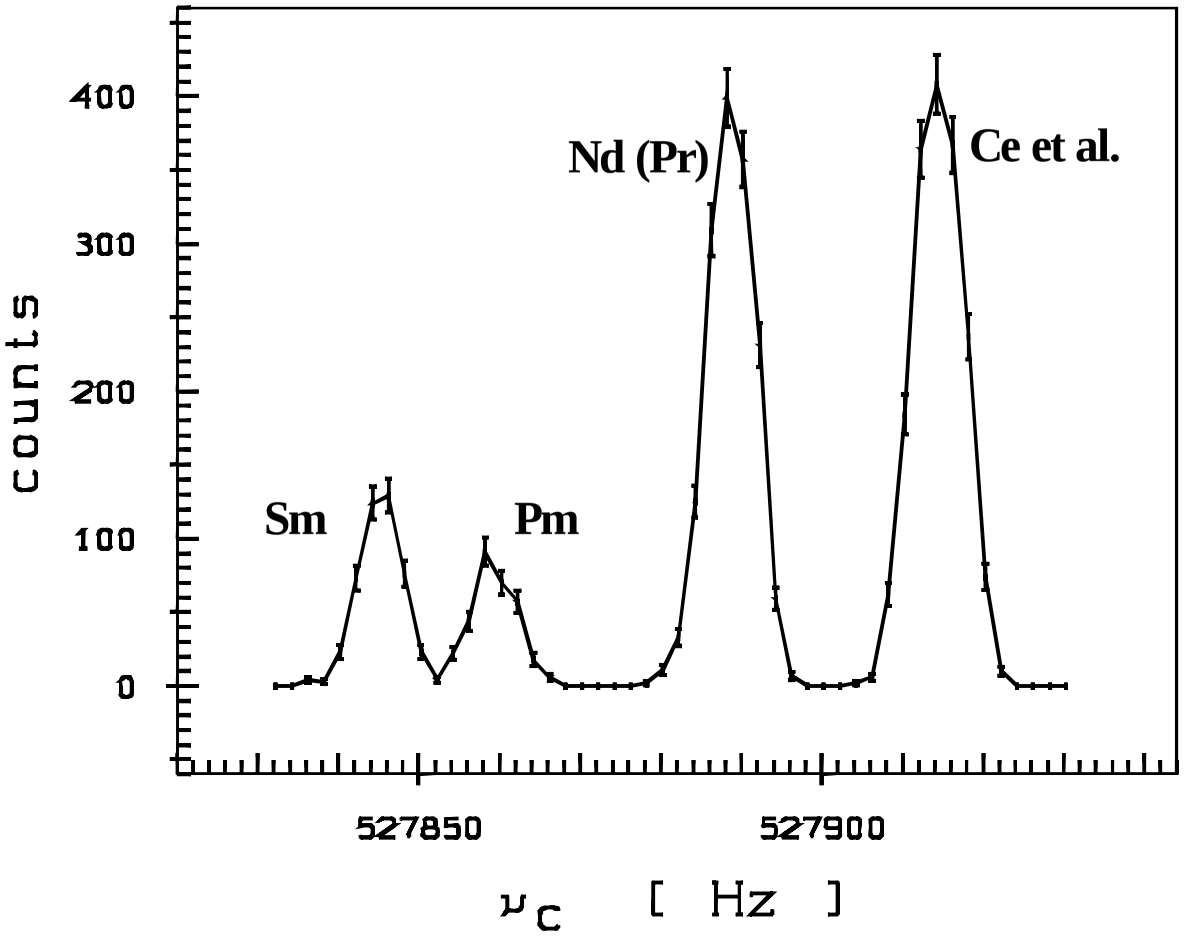
Element	Mass Number
Ne	23, 25, 26
Na	23, 24, 25, 26, 27, 28, 29, 30
Mg	24, 25, 26, 27, 28, 29, 30, 31, 32
Al	27, 29
K	39, 41, 42, 43, 44, 45, 46, 47
Ca	46, 47, 48
Ti	47, 48

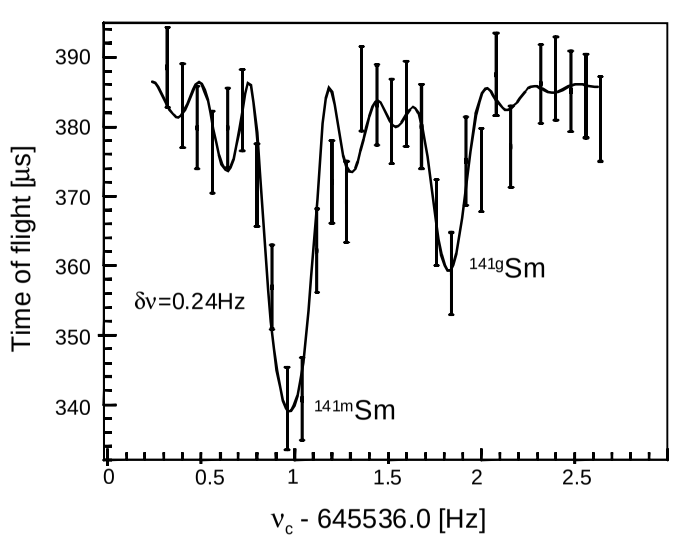

BINDING ENERGY (MeV)
865
860
855
850
845
840
835
In
Cd
Ag
Pd
Rh
Ru
Tc
Mo
Nb
Zr
Y
Sr
Z (A = 100 isobars)

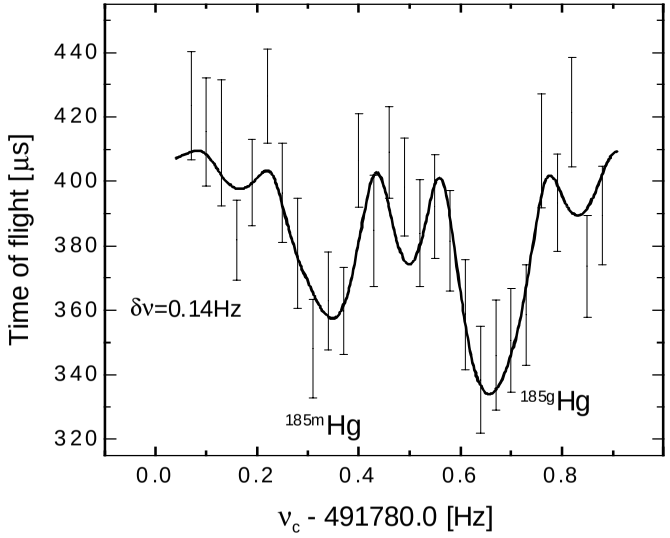

S_{2n} (MeV)
Neutron number N
40
45
50
55
60
65
4
6
8
10
12
14
16
18
20
22
24
26
28
^{83}Nb
^{85}Mo
^{87}Tc
^{90}Ru
^{92}Rh
^{94}Pd
^{96}Ag
^{100}In
^{102}Sn
^{105}Sb
^{108}Te
^{110}I
^{112}Xe
^{114}Cs
^{116}Ba
^{119}La
^{121}Ce
^{123}Ce
^{122}La
^{121}Ba
^{120}Cs
^{119}Xe
^{118}I
^{117}Te
^{116}Sb
^{115}Sn
^{114}In
^{113}Cd
^{112}Ag
^{111}Pd
^{110}Rh
^{109}Ru
^{108}Tc
^{107}Mo
^{106}Nb
^{105}Zr
^{104}Y
^{103}Sr
^{102}Rb
^{97}Kr
^{94}Br
^{92}Se
^{89}As
^{86}Ge
^{84}Ga
^{82}Zn
^{82}Zr
^{81}Y
^{80}Sr
^{79}Rb
^{78}Kr
^{77}Br
^{76}Se
^{75}As
^{74}Ge
^{73}Ga
^{72}Zn
^{71}Cu
^{70}Ni
^{69}Co
^{68}Fe
^{69}Fe
^{72}Co
^{78}Ni
^{80}Cu

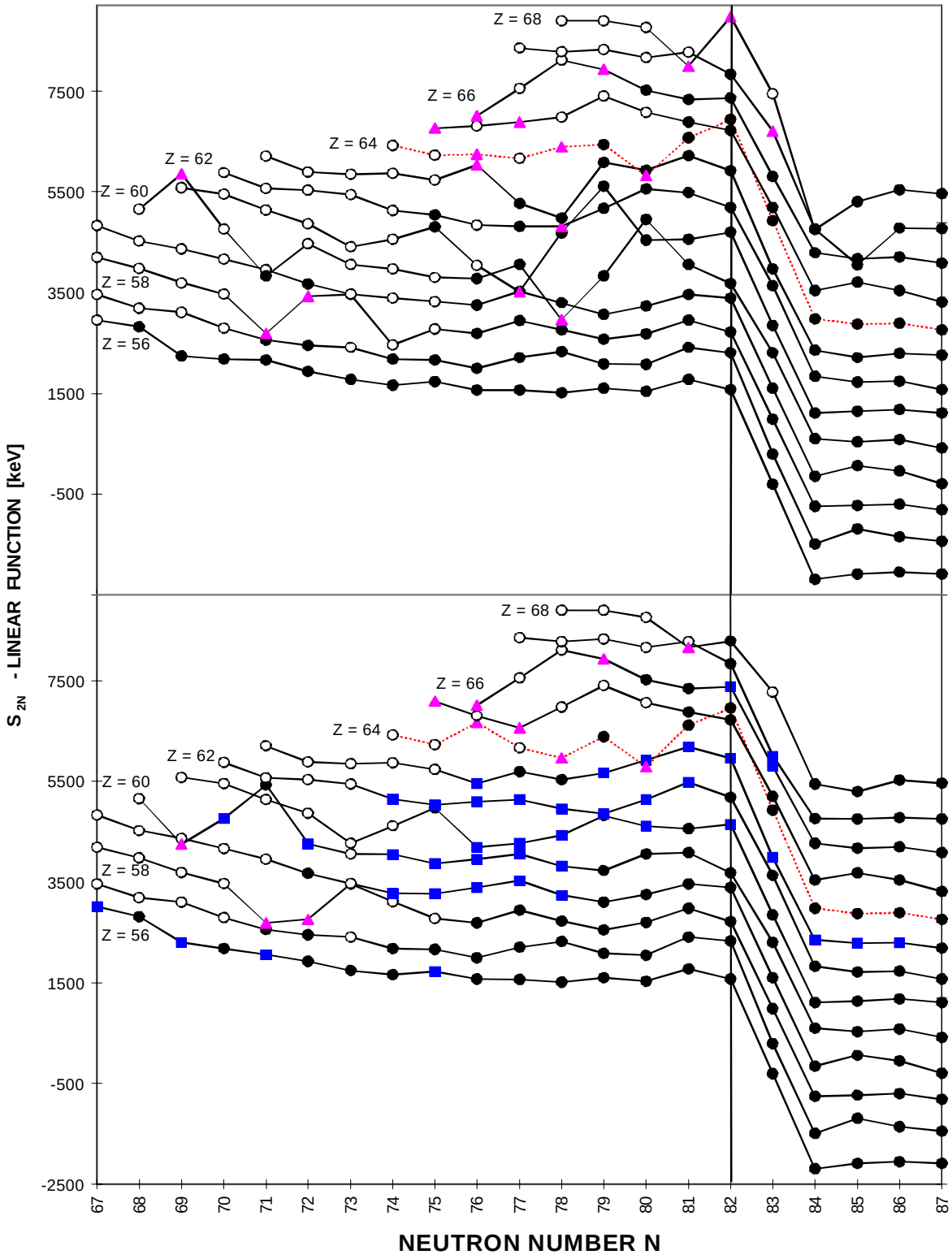

model differences (MeV)
6
4
2
0
-2
-4
-6
35
40
45
50
55
60
65
70
75
80
N (Z = 37)
measured masses
Janecke &
Masson, 1988
Tachibana
et al.,
1988
Comay et al.,
1988
Moeller et al.,
1995
Duflo
& Zuker,
1996
Aboussir
et al.,
1992

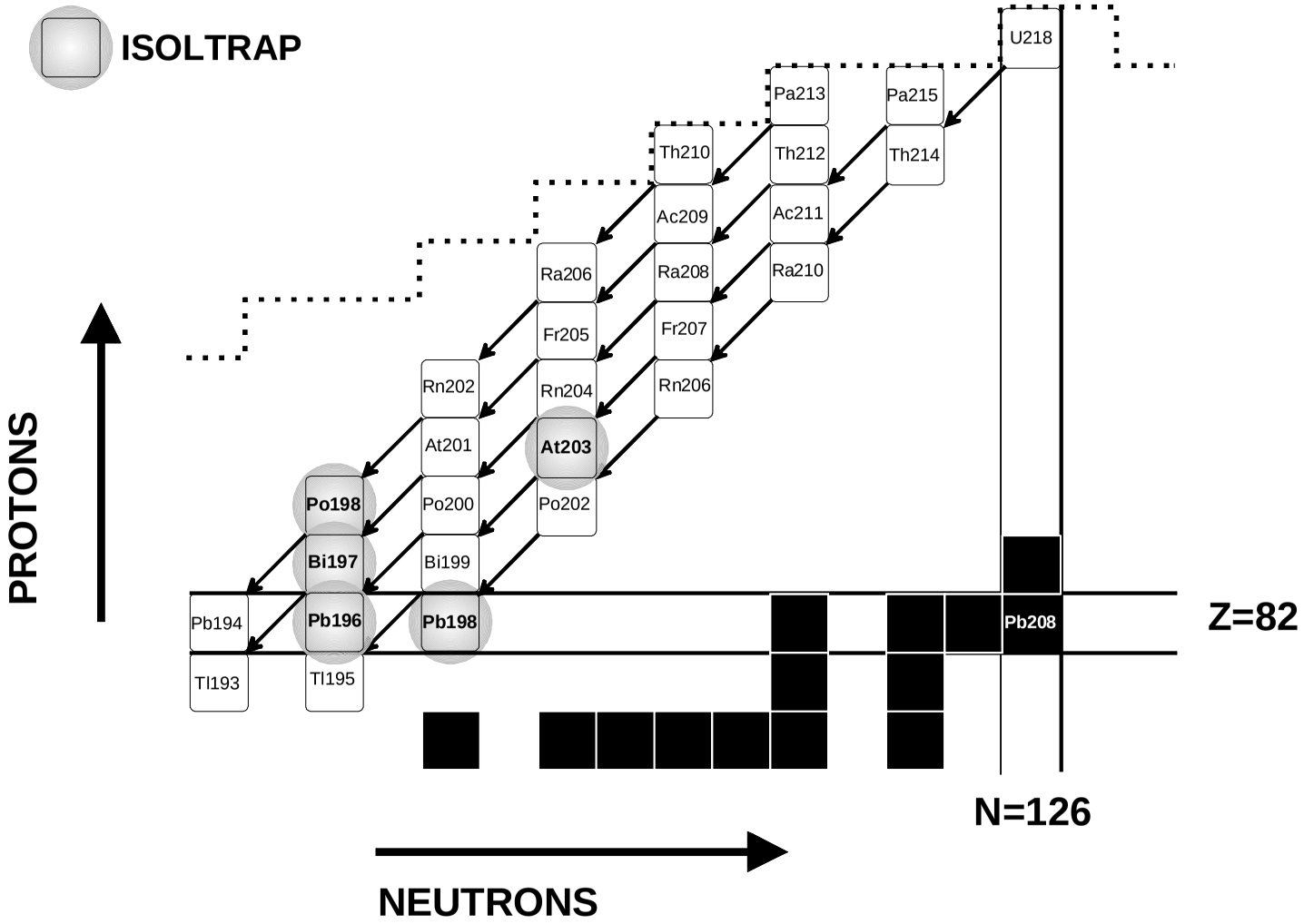

mass
spectrometer
cooler trap
RFQ - trap
ISOLDE
beam
90° deflector


400
300
200
100
0
counts
Sm
Pm
Nd (Pr)
Ce et al.
527850
527900
ν_C [Hz]

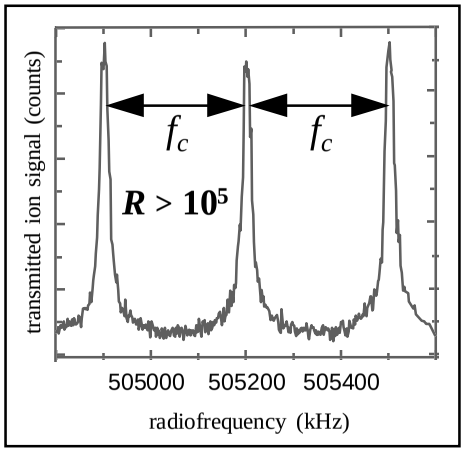

Time of flight [µs]
390
380
370
360
350
340
δν=0.24Hz
141g Sm
141m Sm
0
0.5
1
1.5
2
2.5
νc - 645536.0 [Hz]

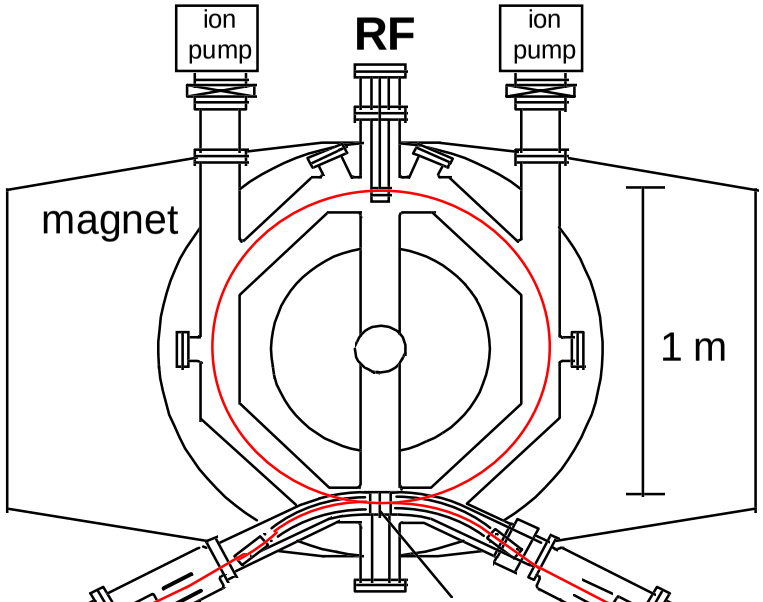

Time of flight [µs]
440
420
400
380
360
340
320
δν=0.14Hz
185m Hg
185g Hg
0.0
0.2
0.4
0.6
0.8
νc - 491780.0 [Hz]

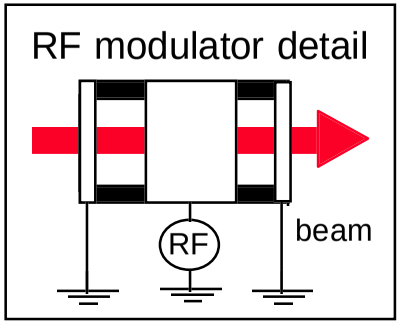

Z = 68
Z = 66
Z = 64
Z = 62
Z = 60
Z = 58
Z = 56
7500
5500
3500
1500
-500
-2500
67
68
69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
86
87
S 2N - LINEAR FUNCTION [keV]
NEUTRON NUMBER N


ISOLTRAP
U218
Pa213
Pa215
Th210
Th212
Th214
Ac209
Ac211
Ra206
Ra208
Ra210
Fr205
Fr207
Rn202
Rn204
Rn206
At201
At203
Po198
Po200
Po202
Bi197
Bi199
Pb194
Pb196
Pb198
Pb208
Tl193
Tl195
PROTONS
NEUTRONS
Z=82
N=126

$f_{RF} = (n + ½)\, f_c$

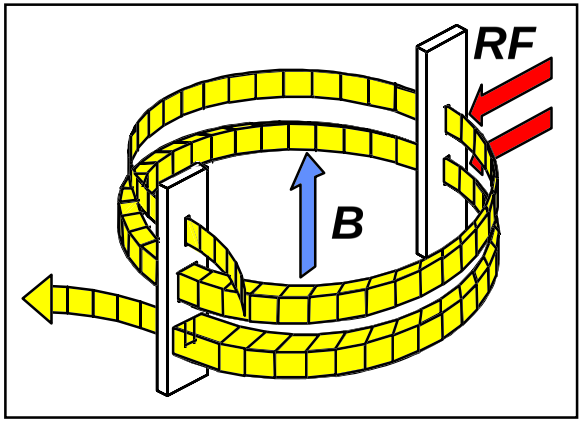




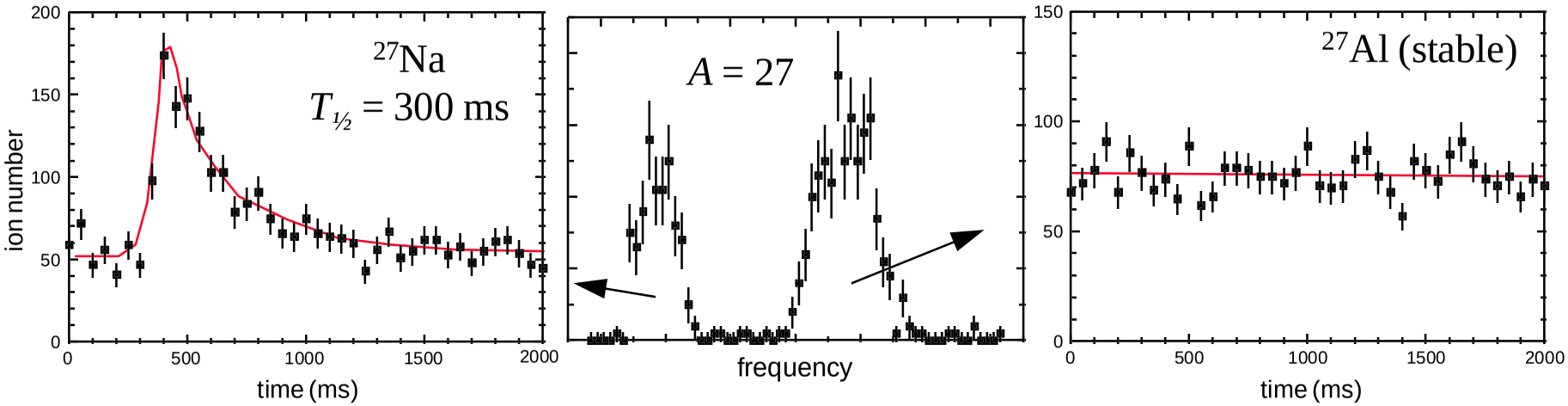


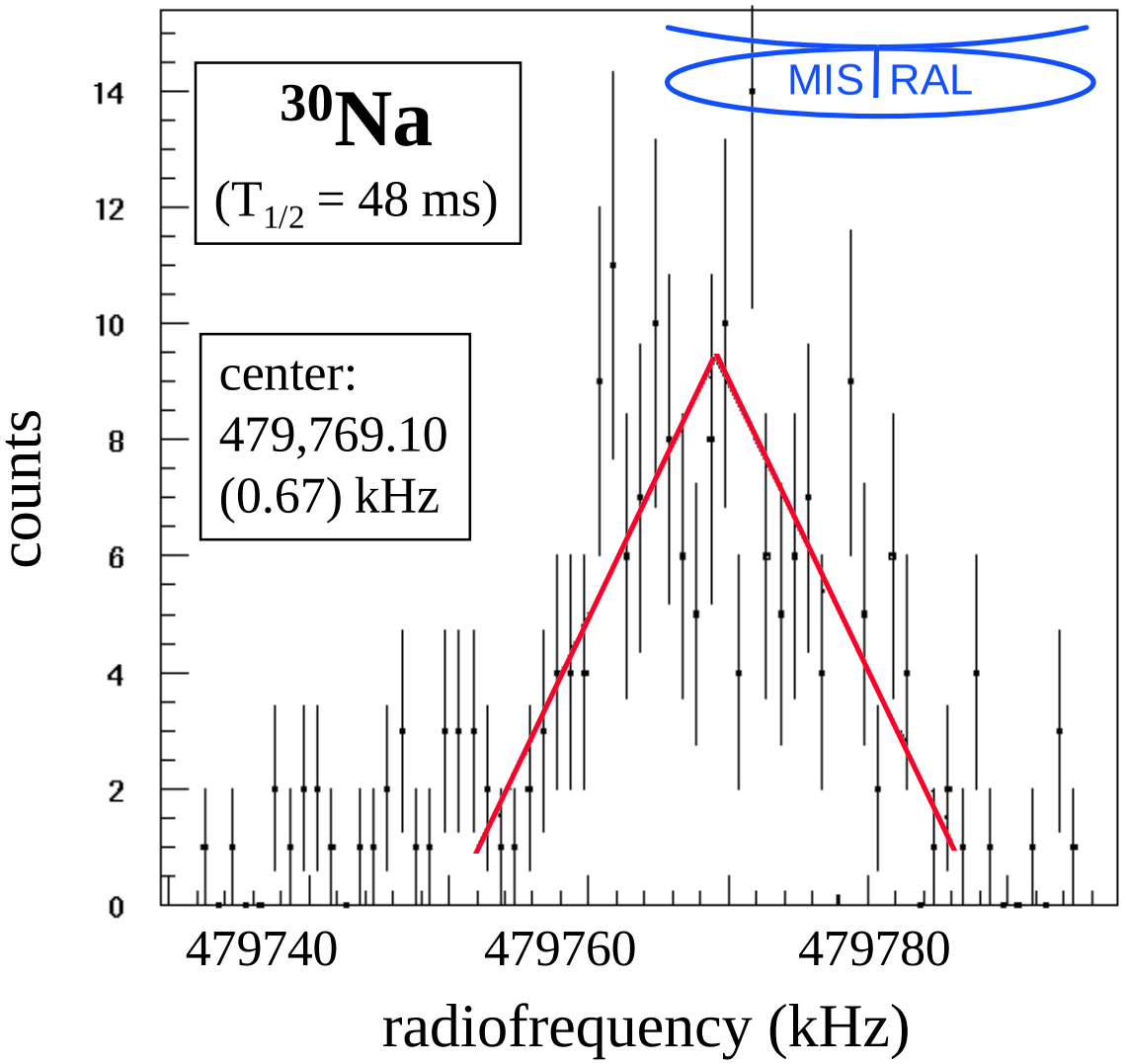
60 kV ISOLDE beam

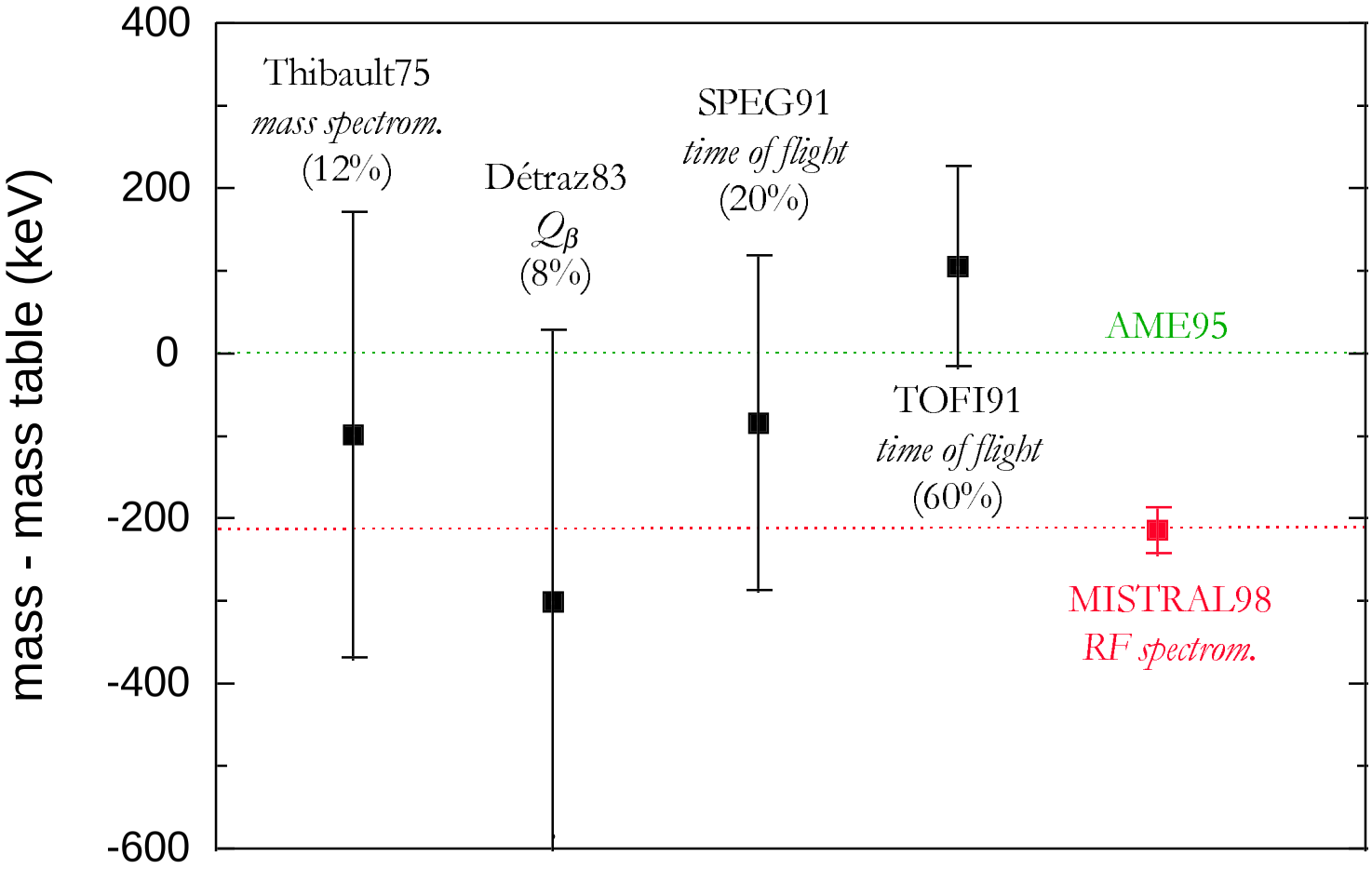
detection region: ion counting and nuclear spectroscopy



reference ion source


^{27}Na
$T_{½}$ = 300 ms
ion number
time (ms)
A = 27
frequency
^{27}Al (stable)
time (ms)


^{30}Na
($T_{1/2}$ = 48 ms)
center:
479,769.10
(0.67) kHz
MIS RAL
counts
radiofrequency (kHz)
0
2
4
6
8
10
12
14
479740
479760
479780


400
200
0
-200
-400
-600
mass - mass table (keV)
Thibault75
mass spectrom.
(12%)
Détraz83
Q_β
(8%)
SPEG91
time of flight
(20%)
TOFI91
time of flight
(60%)
AME95
MISTRAL98
RF spectrom.