EPJ manuscript No.
(will be inserted by the editor)

MISTRAL:

A high precision mass spectrometer for short-lived nuclides

N. VIEIRA[1,4], G. AUDI[1], Z. DJOUADI[1,5], H. DOUBRE[1], C. GAULARD[1,4], S. HENRY[1,4], D. LUNNEY[1], M. DE SAINT SIMON[1], C. THIBAULT[1], G. BOLLEN[2] and the ISOLDE Collaboration[3]

[1] CSNSM, IN2P3-CNRS, UPS, Bâtiment 108, F-91405 ORSAY-Campus, France
[2] NSCL, Michigan State University, East Lansing, Michigan 48824-2321 USA
[3] CERN, CH-1211 Geneva 23, Switzerland
[4] supported by the HPRI Programme
[5] supported by the RTD network EXOTRAPS

Received: date / Revised version: date

Abstract. The MISTRAL experiment (Mass measurements at ISOLDE/CERN with a Transmission RAdiofrequency spectrometer on Line), measures the masses from the cyclotron frequency of an ion in a homogeneous magnetic field. The great advantage of this method is its rapidity, allowing measurements of short-lived nuclides, because the measurement duration corresponds to the time of flight of the ions through the spectrometer ($\sim 50\mu$s). This method is also capable of high resolving power ($\frac{m}{\Delta m} \sim 10^5$) and is accurate to a few 10^{-7}. The magnetic field is stable and comparisons with a reference mass are performed very frequently to eliminate fluctuations. Recently, the $N = Z$ drip-line nuclide ^{74}Rb ($T_{1/2} = 64.9$ ms) was measured. The $N = Z$ nuclei allow the study of the Wigner energy which is an additional term in the binding energy. In order to improve the sensitivity of the apparatus and to access the most exotic (i.e. shortest-lived candidates), a gas-filled radiofrequency quadrupole ion guide is being developed to reduce the injected beam emittance.

1 Introduction

The net result of all interactions in the nucleus are reflected by the total binding energy, which can be derived from the mass. Examination of binding energies over the mass surface [1] gives information about nuclear structure. The mass surface is generally smooth, except near the magic numbers, areas of deformation and at $N = Z$, where a cusp of the binding energy is observed. This cusp can be characterised by an additional term in the semi-empirical mass formula of Bethe-Weizsäcker. This term is called the Wigner energy and is of the form $E_W|N - Z|$. To study the Wigner energy, it is important to measure the masses of the $N = Z$ nuclei with high precision. The radiofrequency spectrometer MISTRAL, whose great advantage is precision and rapidity, has been used to measure the mass of ^{74}Rb ($N = Z = 37$, $T_{1/2} \sim 65$ ms). In section 2, the principle of the spectrometer is described. In section 3, the result of the measurement of the mass of ^{74}Rb is given. In section 4, a study of the Wigner energy is derived. And in section 5, a system which will cool the beam to increase the transmission through the spectrometer, is presented.

2 The principle of MISTRAL

MISTRAL is a radiofrequency, transmission spectrometer based on the principle proposed and realized by Smith [2, 3]. It measures the cyclotron frequency of ions in a magnetic field, which is related to the mass by the formula:

$$f_c = \frac{qB}{2\pi m} \tag{1}$$

As shown in fig 1, the ions make two turns in a homogeneous magnetic field and are extracted and transported to a secondary electron multiplier for counting. At the first and the third half-turn, a radiofrequency modulation (f_{RF}) of the kinetic energy is effected by the modulator [4]. The radiofrequency voltage is applied to the central electrode of the modulator, the two others electrodes being maintained at ground. The modulation of the kinetic energy produces a modulation of the radius of the trajectory of the ions in the magnetic field. The exit slit having the same width as the entrance slit, the ions are transmitted through the spectrometer when the net effect of the two modulations is zero. This is obtained when:

$$f_{RF} = \left(n + \frac{1}{2}\right) f_c \tag{2}$$

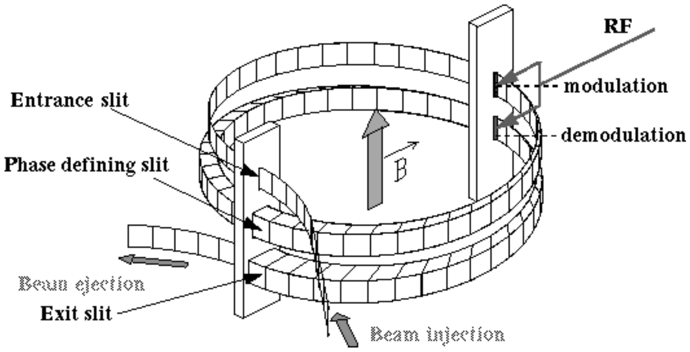

Fig. 1. Trajectory of the ions in the spectrometer MISTRAL: the beams are injected into a homogeneous magnetic field and make two turns along a helicoidal trajectory. At the first and the third half-turn, a radiofrequency modulation of the kinetic energy is effected. At the exit slit, the beam envelope is large when scanning the frequency except when the condition (2) is realized when a most of it is transmitted, forming a peak.

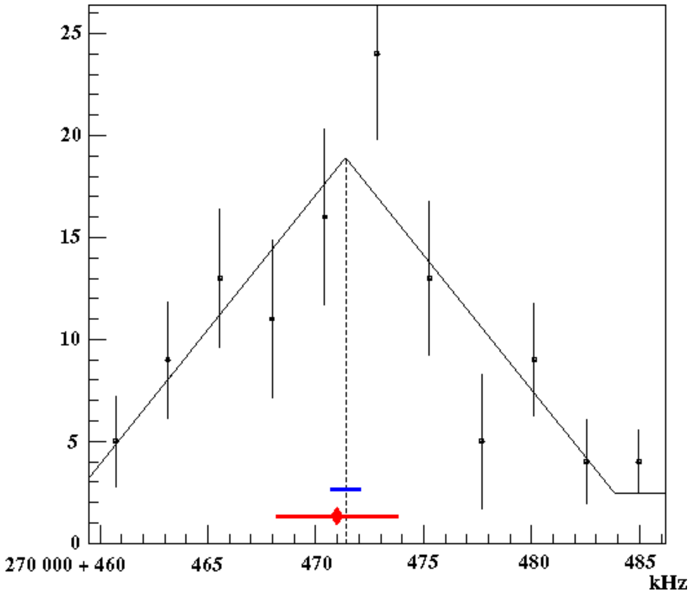

Fig. 2. Transmission peak for ^{74}Rb after summing 67 scans of the radiofrequency and grouping the channels together 5 by 5. The diamond represents the position of the peak calculated with the AME95 value. [1].

where n is an integer (usually a few thousand). The measurement is expected to have a precision of $\frac{\Delta m}{m} \sim 10^{-7}$, but the value of the magnetic field can be determined only with a precision of 10^{-5}. Therefore, the measurement is realized by comparing two masses, one of them being well known, to determine the ratio $\frac{f_c^x}{f_c^{ref}}$. The beam of ISOLDE, containing the nuclei to be measured, and the MISTRAL reference beam, containing the stable nuclei whose mass is known with a sufficient precision, are alternately injected into the spectrometer. This alternation is fast, to compensate eventual drifts of the magnetic field which is kept constant. Since the two beams must have the same trajectory in the magnetic field, the voltages of the electrostatic elements must obey the relation

$$m_{ref} V_{ref} = m_x V_x \qquad (3)$$

And to avoid too large jumps of the voltages, the masses of the unknown nucleus and the reference nucleus must be close. If the jump is large, the power supplies do not have enough time to stabilize and relation (3) is not exactly realized. Then, the two trajectories will not be identical and the magnetic field seen by the ions may be different, causing a shift of the measurement. The best method to reduce this jump is to choose an isobar of the unknown nucleus as reference. For each beam, a transmission curve as in fig 2 is obtained, and a triangular fit [5] is performed to get the value of the frequency f_{RF}.

3 Measurement of the mass of ^{74}Rb

The nucleus ^{74}Rb was measured by comparing its cyclotron frequency to a reference beam of ^{74}Ge, produced by the MISTRAL source. In this source, an oven vaporizes germanium and a plasma ionizes the atoms which are then extracted and accelerated to the desired voltage. In the case of isobars, where the jump is very small, the two beams still may not have exactly the same trajectory because they originate from two different sources. As mentioned is section 2, this induces a shift in the value of the measured mass which is assumed to be the same for all isolde beams. To calibrate this effect, we measured the well known mass of ^{76}Rb by comparing it to ^{76}Ge, also produced by the MISTRAL source. The difference between the measured value and the AME95 value [1] provides the shift. An evaluation of this shift was made before and after each measurement of the mass of ^{74}Rb, introducing a correction of few ten keV. The results are presented in table 1 and figure 3.

Table 1. Difference between the ^{74}Rb measured values and the AME 95 value [1] (in keV): ①, ② and ③ are three measurements of the mass at different times. ④ is the weighted average of these values.

①	−194.1 ± 166.2
②	−72.1 ± 183.5
③	−385.6 ± 170.6
④	−224 ± 100 $\chi^2 = 0.8$

For the nucleus ^{74}Rb, we thus obtain a mass excess

$$\Delta m(^{74}\mathrm{Rb}) = -51949(100)\ \mathrm{keV} \qquad (4)$$

and a mass (in atomic mass unit)

$$m(^{74}\mathrm{Rb}) = 73.944230(107)\ \mathrm{u} \qquad (5)$$

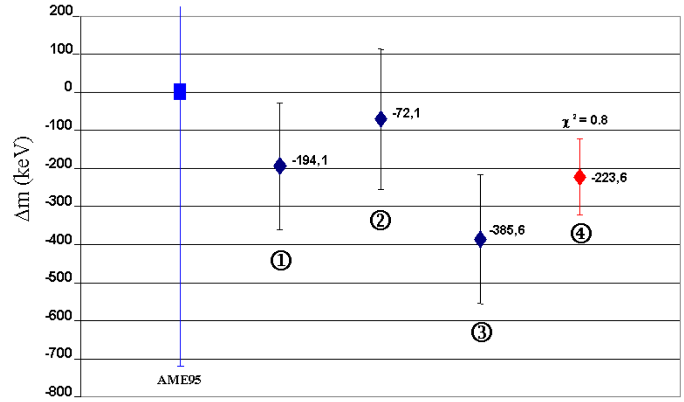

Fig. 3. Difference between the ^{74}Rb measured values and the AME 95 value [1] (in keV): ①, ② and ③ are three measurements of the mass at different times. ④ is the weighted average of these values.

Thus we have improved the AME95 value [1] by more than a factor of seven. Our value is also in complete agreement with that determined by the ISOLTRAP collaboration [6].

4 The Wigner energy

One of the interests of the nuclei $N = Z$ is the Wigner energy, which can be represented by an additional term in the semi-empirical formula of Bethe-Weizsäcker:

$$B = a_v A - a_s A^{2/3} - a_c \frac{Z(Z-1)}{A^{1/3}} - a_a \frac{(N-Z)^2}{A} - E_W |N-Z| + \delta \quad (6)$$

In many studies of the Wigner energy, the term E_W has a dependance on A of the form $1/A$ [7–9]. In those studies, E_W is determined by differences between masses providing second derivatives of the binding energy. Here, E_W is determined by a method applicable in regions where no $N-Z<0$ nuclei exist. After subtraction of the Coulomb and pairing contributions, the experimental binding energies are plotted versus $T_z = (N-Z)/2$ for each A. For $T_z > 0$, these energies can be fitted to a parabola:

$$B = C_1(A) - 2E_W T_z - C_3(A) T_z^2 \quad (7)$$

from which the value of E_W may be extracted (filled diamonds in fig. 4).

In the region where nuclei with $T_z < 0$ exist, another method can be used. This method does not need any assumption for the Coulomb term and can serve to confirm the values of E_W determined by the first method. The experimental binding energies without any correction are plotted versus T_z for each A, and fitted to a parabola for $T_z > 0$. The data are then subtracted from this parabola. On the $T_z > 0$ side, the values obtained are close to zero. But, for $T_z < 0$ the values obtained move away from zero linearly. This can be modelled as a $|T_z|$ term, whose slope is four times E_W. The E_W values obtained by this method are shown as empty diamonds in fig. 4. The two methods give very similar results. This gives confidence for the values of E_W for larger masses. The values obtained show a behavior which corresponds to the shell structure of the nuclei. Maxima for $A = 40, 56, 100$ correspond to the magic numbers $N = Z = 20, 28, 50$. A maximum at $A \sim 80$ corresponds to $N = Z = 40$, the closure of a harmonic oscillator shell.

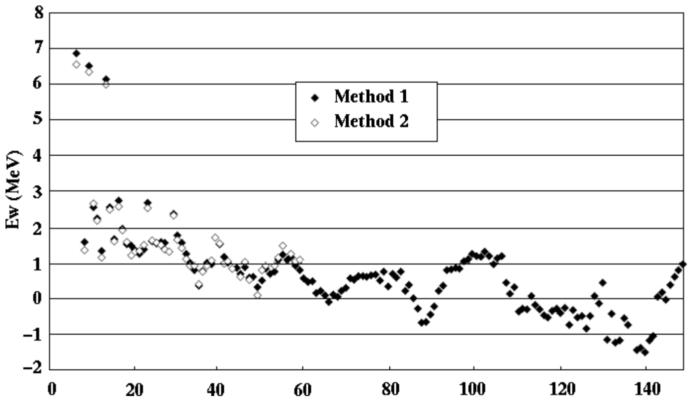

Fig. 4. the Wigner energy E_W obtained by two different methods. Method 1: after correcting the Coulomb interaction. Method 2: by comparing binding energies of $T_z < 0$ isobars with parabola which fits binding energies of $T_z > 0$.

5 A beam cooler to increase the transmission of MISTRAL

Due to the emittances of the beams, and to the size of the four slits of the spectrometer (each slit has a width of 0.4 mm and a height of 5 mm), MISTRAL has a transmission (without radiofrequency) of about 10^{-4} for the ISOLDE beam and a transmission of about 10^{-3} for the reference beam. To explore nuclei which have tiny production rates, the transmission is an important parameter. In order to increase the transmission, the emittance of the beams must be decreased. This is the aim of the study [10,11] described in the PhD thesis of S. Henry [12] who contributes to this conference.

The beam is injected into a system composed of a radiofrequency quadrupole filled with helium gas. Inside the quadrupole, the beam oscillates as shown in fig. 5. These oscillations are quenched by the interactions between the ions and the gas. The system traps the beam along the axis and reduces its emittance. The great advantage of this cooler is to increase the transmission of MISTRAL. Another advantage is to eliminate the problem of the shift when the two beams originate from two different sources. In fact, the cooler forces the beam along the axis and then can be considered as a source. Then, the two beams originate from the same source: the radiofrequency cooler.

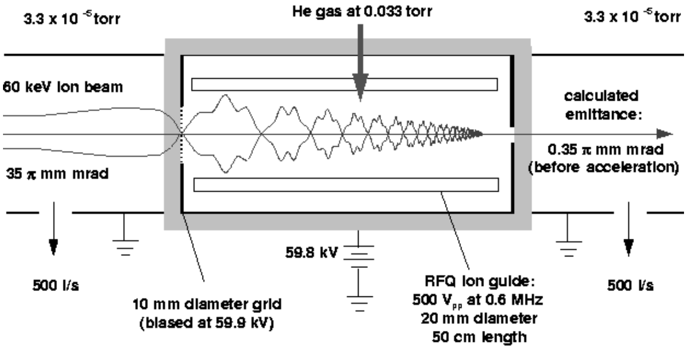

Fig. 5. Principle of the cooler: the beam oscillates in a quadrupole filled with helium gas and is trapped along the axis. Thus, its emittance is reduced.

6 Conclusion

A radiofrequency mass spectrometer which measures masses of very short-lived nuclei has been described and the results of the measurement of the mass of ^{74}Rb have been presented. Methods to extract the Wigner energy, which is one interest of the $N = Z$ nuclei, have also been described and shell effects (including the shell closure of the harmonic oscillator at $N = Z = 40$) have been observed. A similar study must be done with the values of masses predicted by different models. Finally, a system which will reduce the emittance of the beam and increase consequently the transmission of the MISTRAL spectrometer has been mentioned. It will permit to explore nuclei far from the valley of stability produced very weakly.

References

1. G. Audi and A.H. Wapstra, Nucl. Phys. A 595 (1995) 409.
2. L.G. Smith, Proc. Int. Conf. Nuclidic Masses, H. Duckworth, ed. (University of Toronto Press, Canada, 1960) 418.
3. L.G. Smith, Proc. 3rd Int. Conf. Atomic Masses, R. Barber, ed. (University of Manitoba Press, Canada, 1967) 811
4. M. de Saint Simon, C. Thibault, G. Audi, A. Coc, H. Doubre, M. Jacotin, J.F. Képinski, R. Le Gac, G. Le Scornet, D. Lunney, F. Touchard and G. Lebée, Phys. Script. T59 (1995) 406.
5. A. Coc, R. Le Gac, M. de Saint Simon, C. Thibault and F. Touchard, Nucl. Instr. and Meth. A271 (1988) 512.
6. F. Herfurth, A. Kellerbauer and al, these proceedings.
7. W. Satula, D.J. Dean, J. Gary, S. Mizutori, W. Nazarewicz, Phys. Lett. B 407 (1997) 103.
8. K. Kaneko and M. Hasegawa, Phys. Rev. C60 (2000) 024301
9. A.S. Jensen, P.G. Hansen, B. Jonson, Nucl.Phys. A431 (1984) p.393.
10. S. Henry, I. Martel-Bravo, M. de Saint Simon, M. Jacotin, J.-F. Képinski, D. Lunney, Proc. 2nd Int. Conf. Trapped Charged Particles and Related Fundamental Physics, D.H Dubin and D. Schneider eds. (AIP Conf., USA, 1998) p. 120.
11. D. Lunney, R.B. Moore, Int. J. Mass. Spectrom. 190 (1999) 153
12. S. Henry, PhD thesis, University of Strasbourg, 2001 and these proceedings.