2^{nd} *International Wokshop on Nuclear Fission and Fission-Product Spectroscopy*
Château de la Baume, Seyssins, 22-25 April 1998

Present status of the MISTRAL mass measurement experiment

C. Monsanglant [a], G. Audi [a], C. Borcea [b], H. Doubre [a], M. Duma [b], M. Jacotin [a], J.-F. Képinski [a], G. Lebée [c], G. Le Scornet [a], M.D. Lunney [a, c], M. de Saint Simon [a], C. Thibault [a], C. Toader [a, b], the MISTRAL and the ISOLDE collaborations

[a] *CSNSM, IN2P3-CNRS, Bâtiment 104–108, F-91405 Orsay Campus, France*
[b] *IAP, Bucharest, Romania*
[c] *EP division, CERN, Geneva, Switzerland*

Abstract

The MISTRAL experiment for measuring masses of very short-lived nuclides at ISOLDE has been installed during the summer of 1997 and has had its first radioactive beam in November 1997. Tests are presently been carried out to study all possible systematic effects. This paper recalls the basic principles of the Smith-type radio-frequency spectrometer, gives its present characteristics and limitations, and describes the methods used to improve its performances.

1 Introduction

Accurate knowledge of atomic masses, more specially those far from stability, is important for nuclear physics and nuclear astrophysics. Comparison of calculated and measured values is essential to adjust and to test nuclear models. They allow to define the predictive power of the different models and to select among them the best suited for predicting masses far from stability [1]. In the present situation almost all models agree in the narrow area where masses are known, but diverge drastically out of that region (Figure 1). Deviation from mass surface regularity indicates shell, and sub-shell closures, or nuclear deformation, shape transitions or special structures like halo nuclides. Another important subject is the description of the nucleosynthesis paths in stars - involving nuclides which will probably never be produced in laboratories - and, more precisely, rapid neutron capture process (the r-process). This topic does not address the interest in stable nuclides and those lying close to the stability line which are of interest in metrology, atomic physics, weak interaction physics (e.g. neutrino mass, test of the standard model).

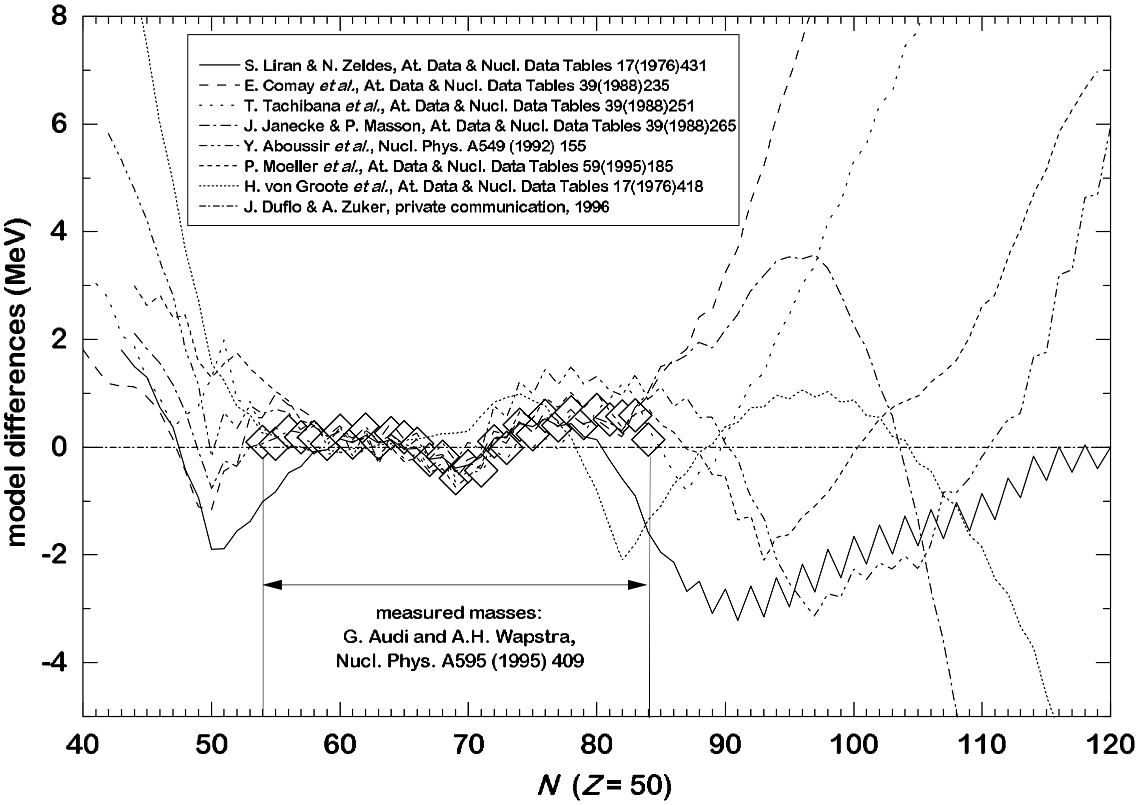

Figure 1: Differences between the mass predictions of selected models [1] for the series of the Cs isotopes. One model has been chosen arbitrarily to lie on the zero axis. The experimentally known masses are represented by diamonds. MISTRAL will allow to extend each of such isotopic chain by several units in N, putting thus important constraints on the models.

2 Principle

With these goals in mind, the MISTRAL project (Mass measurements at ISOLDE using a Transmission RAdiofrequency spectrometer on Line) has been designed for the ISOLDE PS Booster facility at CERN in order to complement the ISOLTRAP experiment by concentrating on the very short-lived nuclei. The spectrometer MISTRAL has been installed in the summer 1997 in the new beamhall extension of ISOLDE.

MISTRAL is a Smith-type radiofrequency spectrometer [2]. The principle is to measure the cyclotron frequency of an ion in an homogenous magnetic field. An ion injected in the spectrometer follows a helicoidal trajectory with a diameter of 1 m. It makes two turns in the magnet (Figure 2). At the end of the first and third half-turn, the ion undergoes a modulation of its kinetic energy (and so, of

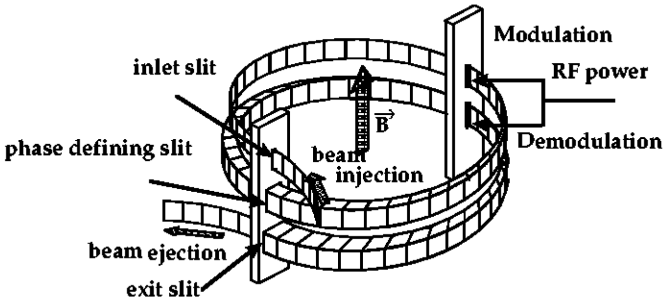

Figure 2: Envelope of the beam inside the MISTRAL magnet. After the first and the third half-turns the ions undergo a kinetic energy modulation. If these two modulations are exactly opposite the ion will recover the nominal diameter and exit the spectrometer through a slit.

the radius of its trajectory) depending on the phase of the radiofrequency in the modulator, at the time it passes through it. Only ions which verify the relation:

$$f_{RF} = (n + \frac{1}{2}) \times f_c \quad \text{with} \quad f_c = \frac{q \times B}{2 \times \pi \times m} \tag{1}$$

where n is an integer harmonic number of the order of 2000, f_c is the cyclotron frequency of an ion of mass m and charge q in the magnetic field B, will be transmitted through the exit slit of the spectrometer and detected by an electron-multiplier. As a result, in a frequency scan we get a series of peaks of transmission corresponding to successive harmonic numbers n, and separated by f_c. To determine the resonance frequency f_{RF}, we scan a narrow range of radiofrequencies and determine the center of the obtained peak. Provided the harmonic number is known (it has to be determined with an accuracy better than 0.1 units), one gets then the cyclotron frequency.

The ions of interest are produced by ISOLDE which accelerates them at 60 keV. They are directly accepted by MISTRAL. The reference ions are produced by an auxiliary source which also serves for setting up the whole apparatus. We use these reference ions for making a relative measurement: $f_A \times m_A = f_B \times m_B$. The mass is thus obtained by comparison of the cyclotron frequency of the unknown mass(B) in the homogeneous magnetic field to that of a reference mass(A).

The only limitation on half-life is the ISOLDE target release time (the flight time through the apparatus is about $50 \mu s$). Then, about one hundred candidates with yields greater than 10 atoms/s and half-lives shorter than one second could be measured (50 for which no measured mass values exist and 50 for which the mass values can be significantly improved). The achieved spectrometer resolution of 10^5 provides a potential measurement accuracy of some 10^{-7}. Thus the MISTRAL experiment complements nicely the ISOLTRAP penning trap which has a higher accuracy (better than 10^{-7}) but is limited to longer half-lives.

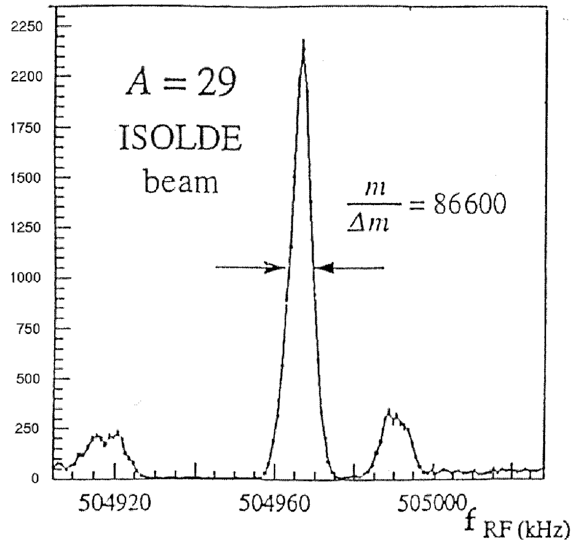

Figure 3: Experimental spectrum at mass A=29, obtained during the November test. Three isobars are clearly separated. The resolving power is 86 600.

3 On-line experimental test

In November 1997, MISTRAL has had its first radioactive beam. Data taking was focused on the mass range $A = 27 - 30$. The ISOLDE source was a plasma ionization type which provides many isobars at each mass number, including unwanted stable molecules. Due to a resolving power around 100 000 (Figure 3), very close to the value expected from a multi-particle simulation, MISTRAL could separate very distinctly these isobars. Unfortunately, at this stage at least, the overall transmission was found to be far from the one observed with our reference source. One of the reasons might be an off-axis injection of the ISOLDE beam in the spectrometer. Additional deflectors have been added to cure this problem.

The next runs are planned in July 1998 with a surface-ionizer source to measure masses around mass $A = 30$, and in November 1998 for medium-A masses.

4 Improving the set-up

To improve the transmission, we more particularly need to know better the beam envelope inside the spectrometer. We have added beam shape multi-wire diagnostics. The RF modulator which is the most crucial part in the spectrometer for obtaining a high resolving power was specially designed [3] for the mass measurement program at ISOLDE. This last point is developed further in the present section.

The mass spectra from which the masses will be derived, result from the two

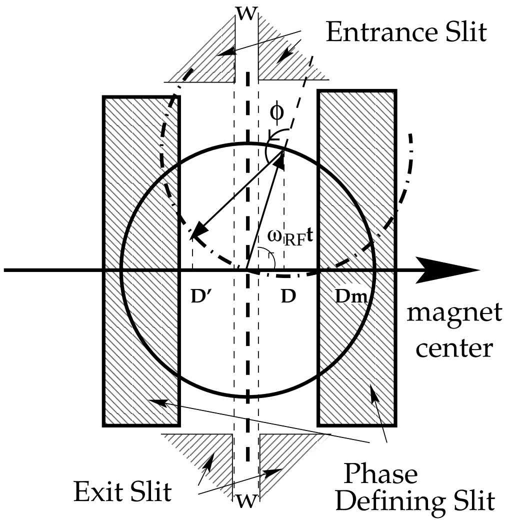

Figure 4: Fresnel's diagram for the two modulations with the same amplitude D_m. Each of them is represented by a vector rotating with the same angular frequency ω_{RF}. The first one has a projection D, the combined first and second vector, D'. In the present case, D' falls out of the exit slit and the ions will not be transmitted. ϕ is the phase difference between the two modulations. w is the width of the entrance and of the exit slits.

actions of the modulator and from the cuts by the slits. These combined effects can be best explained with a Fresnel diagram (Figure 4) where D and D' are the projections of two rotating vectors. The phase difference ϕ between the two modulations is $2 \times \pi \times \frac{f_{RF}}{f_c}$. The exit slit defines an acceptance in phase, thus in f_{RF}, which is a function of the position of the first rotating vector. A "phase defining slit" (PDS) is used to cut the positions of this first vector, for which the frequency admittance is too large, and thus to get a null signal between the resonance peaks (see figure 3 and also ref [4]). The actual modulator has a non-zero thickness, as represented on Figure 5. It is composed by a set of three parallel plates: a central electrode connected to the radiofrequency voltage surrounded by two grounded plates. Two openings let the beam through: the upper one is for the first modulation and the lower one for the second modulation (slits size: 0.4mm×5mm).

In order to describe the ion trajectory inside the spectrometer, and particularly the modulator, multi-particle ion simulations have been performed. We focus here on the first modulation and compare in Figure 6 the observed beam profil obtained at the location of the PDS (after one full turn) with the result of the simulation. Scanning the PDS with a narrow slit, we have obtained modulation amplitude profiles at the two frequencies (260 MHz and 505 MHz) which were used in the on-line experimental test described above (Figure 6a for 505 MHz). The simulation program was run under the same conditions and yielded the same type of figures

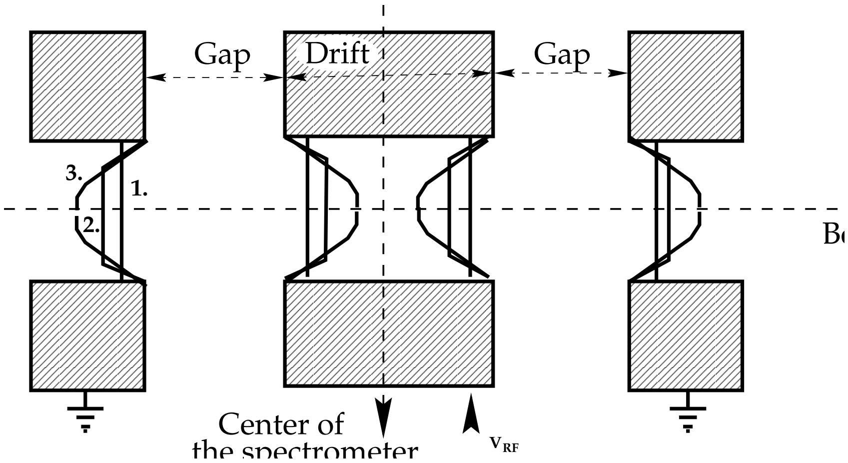

Figure 5: Top view of the upper part of the modulator. The ions go through two accelerating gaps with a drift between them. As a result the modulation will be effective only if the phase has changed by π (or an odd multiple of π) during the transit time between the two accelerating gaps. The lower part of the modulator is identically the same. Represented are the 3 steps, in the evolution of the simulation program, for describing the distribution of the electric equipotential surfaces inside the modulator. Step 1 is the first level of the approximation: plane equipotentials. Step 2 describes better the continuity conditions near the edge of the slit that was cut in the electrode. We are now in the process of describing (step 3) the voltages as given by the Simion program (see text).

(Figure 6b). The experimental figures exhibits a flatter external slope of the modulation profile. The measurement method can explain this in part: the slit used for scanning the PDS has a finite width (about 0.4 mm) in order to have enough statistics. But this does not explain all the differences. Therefore we decided to improve the simulation program. The most important part of the simulation program is the calculation of the ion trajectory in the electric field of the modulator. To recreate as exactly as possible the experimental reality (step 3 on Figure 5), we made use of the simulation program Simion [5] which determines the potentials by solving the Laplace equation and yields the equipotential lines of the electric field inside the modulator. We are in the process of integrating these results into the modulator simulation program.

Experimentally we also have a limitation in the modulation amplitude at 505 MHz due to the reflected power which is not well absorbed above 480 MHz. At 260 MHz we could go to much higher voltages, but found a limitation due to electrical discharges in the modulator gaps. Fortunately these limitations will not prevent measurements to be performed with the expected precision.

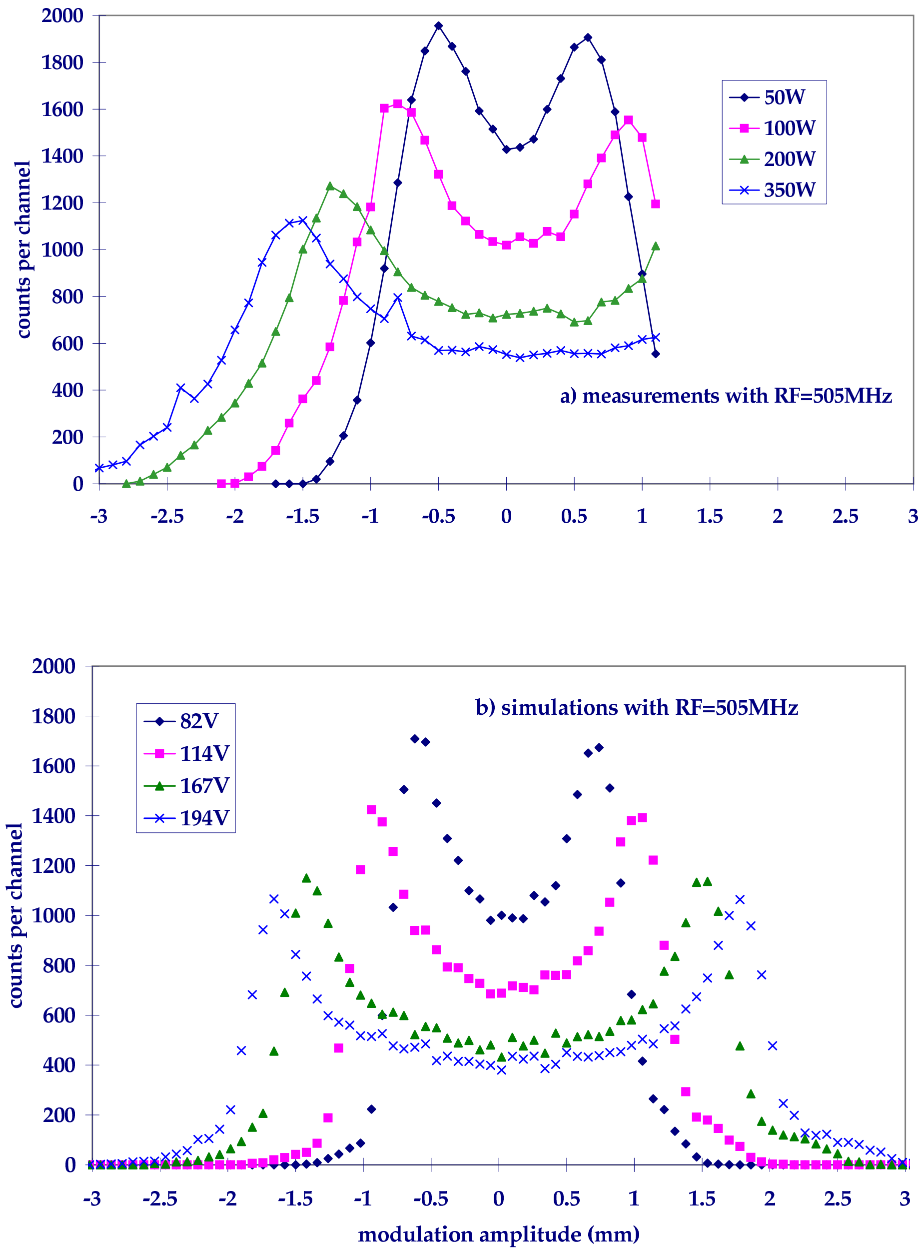

Figure 6: Measured (a) and simulated (b) beam profiles at the level of the "Phase Defining Slit" (PDS), i.e. after one full turn inside the MISTRAL magnet. The experimental profiles have a cut on the right side of the figure due to a mechanical limitation.

5 Future improvement

We are working on a beam cooling system that would allow to reduce the emittance of the beam entering the spectrometer by one order of magnitude or better. Presently the emittance of the ISOLDE beam is much larger than the acceptance of the MISTRAL spectrometer. Among the existing schemes - stochastic cooling, electron cooling, laser cooling and buffer gas cooling - we have chosen the last one because of its rapidity and its relative simplicity [6]. Currently experimental tests are being conducted on a bench coupled to a conventional mass spectrometer at Orsay.

6 Conclusion

First measurements and simulations show that MISTRAL keeps its promises. We can inject the ISOLDE beam, separate isobaric masses and, in a near future, measure them with good precision. Two runs in July and in November 1998 in the region of light nuclides around $A = 30$ and heavier A should establish the actual possibilities of the spectrometer.

Acknowledgements

We wish to thank S. Henry for providing us with the electric potentials inside the modulator, calculated with the Simion program.

References

[1] C. Borcea and G. Audi, Rev. Roum. Phys. **38** (1993) 455-467.

[2] L.G. Smith, Proc. Int. Conf. on Nuclidic Masses (Edited by H.E. Duckworth) (Univ. of Toronto Press, Canada 1960), p. 418.

[3] 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 and F. Touchard, Phys. Scr. **T59** (1995) 406-410.

[4] A. Coc, R. Le Gac, M. de Saint Simon, C. Thibault and F. Touchard, Nucl. Instrum. Meth. **A271** (1988) 512-517.

[5] David A. Dahl, "Simion 3D", Report **INEL-95/0403**, August 1995.

[6] M.D. Lunney, B. Simmons, A. Maniscalco, R.M. Moore, T. Kim and P. Varfalvy, Report **CSNSM 97-02**, February 1997.