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HIGH ACCURACY MASS MEASUREMENT OF THE VERY SHORT-LIVED HALO NUCLIDE ^{11}Li

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Abstract. A critical input parameter for state-of-the art three-body nuclear models for halo nuclides such as ^{11}Li is the binding energy of the two neutrons forming the halo. To reduce the uncertainty of this quantity, a high accuracy mass determination of ^{11}Li was performed at ISOLDE in April 2002 using the MISTRAL spectrometer. Due to beam transport complications with the HRS and a discharge in the MISTRAL RF system, the measurement was only a partial success. Although the obtained mass precision of 25 keV is an improvement on previous measurements and as such, an important result, we request a further nine shifts in order to achieve our projected goal of 5 keV.

1. Introduction and Motivation

The physics case on which our experiment for measuring the mass of ^{11}Li was accorded by the INTC (and CERN research board), is detailed in the original proposal [LUN01]. We retain one essential element concerning the present state of the halo models from Hansen and Sherrill [HAN01]: "it has become customary to calculate the radial wave functions in potential-well models that are adjusted to the experimental separation energy."

Since the original proposal, further theoretical work concerning ^{11}Li has also appeared. Forssén, Efros and Zhukov [FEZ02] used a recently developed analytical model to study the electromagnetic dissociation (EMD) energy spectra. Broglia et al., [BRO02] extended the three-body halo description to allow for core polarization in terms of a particle-vibration coupling formalism. Though they did not yet treat ^{11}Li, Bertulani, Hammer and van Kolck [BHK02] have developed an effective field theory which is interesting since it casts halo nuclei within the same framework used to describe light systems consistently with QCD.

2. *MISTRAL*[1]

The reader is referred to the extended literature for the detailed operation of the MISTRAL spectrometer [LU01A, LU01B, STS95]. Three essential points are retained here for the discussion: the ion beam kinetic energy *modulator*, the resulting mass *resolution*, and the *calibration* required to make a measurement.

A schematic diagram of the *MISTRAL* spectrometer with its nominal trajectory is shown in Fig. 1. Ions injected at the full *ISOLDE* beam energy (60 keV) follow a two-turn helicoidal, isochronous trajectory inside the homogeneous magnetic field (Fig. 1, inset center) and are counted. To obtain high mass resolving power, a longitudinal kinetic energy modulation is effected using two symmetric electrode structures (Fig. 1, 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 and the ions are transmitted through the 0.4 mm exit slit only 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. When scanned over a large radiofrequency range, the ion signal shows transmission peaks evenly spaced at the cyclotron frequency (Fig. 1 inset left).

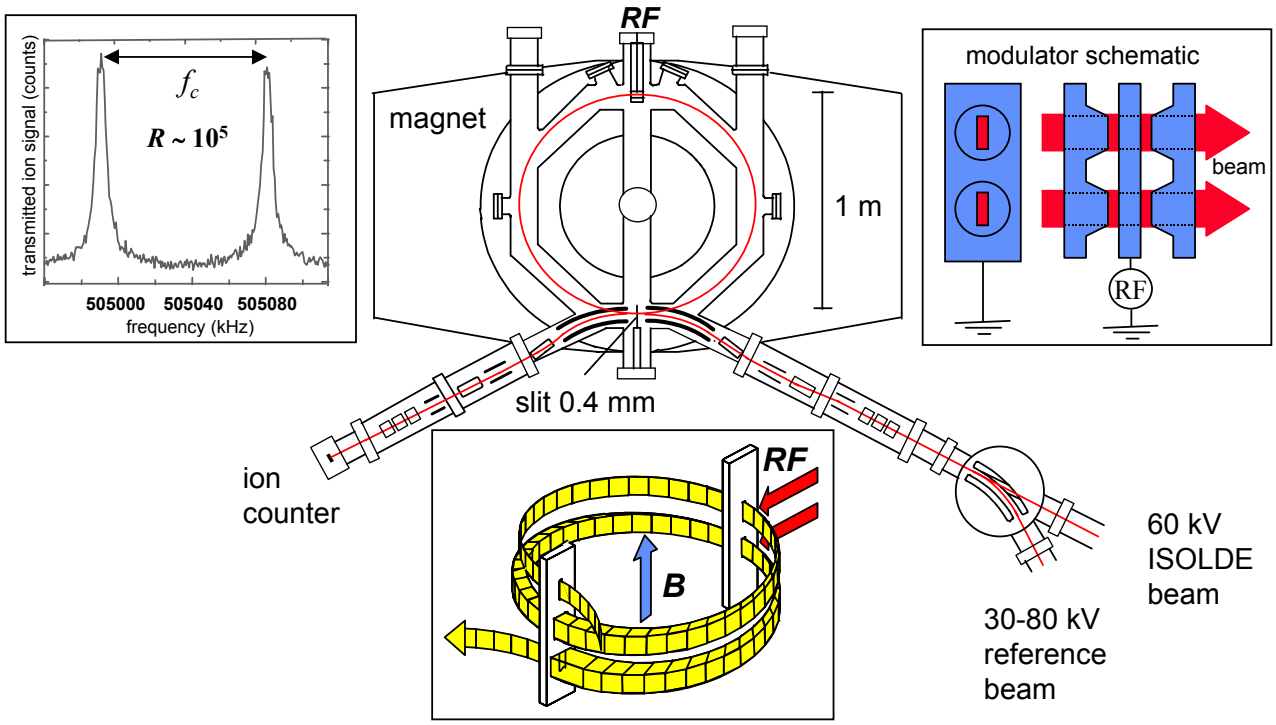

FIGURE 1. Layout of the *MISTRAL* spectrometer showing the nominal ion trajectory. Ions are injected from the *ISOLDE* beam line at the full transport voltage of 60 kV while the reference mass is alternately injected (without changing the magnetic field) at its corresponding energy. Inset (center) shows an isometric view of the trajectory envelope with the 0.4 mm injection slit followed by the first modulator at one-half turn, the second modulator at three-half turns and finally the exit slit. Inset (right) shows front and side views of the modulator geometry (see Fig.3 for a photo). Electric fields are formed in two 0.5 mm gaps. Inset (left) shows a transmitted ^{39}K ion signal frequency scan spanning two harmonic numbers (around 3400). The mass resolution here is about 50,000 but can easily exceed 100,000.

[1] A brief report of the MISTRAL experimental program was published in the last ISOLDE newsletter [ISN02].

2.A. Resolving Power

The resolving power of the spectrometer is determined by the FWHM of these peaks - and the applied frequency. The choice of frequency depends on the response of an impedance network that matches the modulator load to the RF amplifier. The FWHM of the peak varies as a function of modulation amplitude, determined by the voltage applied to the modulator. Under the right kinematic conditions, the resolving power is increased as this voltage is increased. Depending on the frequency (and selected amplifier power), a large voltage can be applied (inadvertently) to the modulator electrode. With a gap of only 0.5 mm, sparks are readily created and worse, a sustained discharge. Before the run, the peak shape was recorded as a function of RF power (Fig. 2) and a distortion is evident after 10 W which was attributed to a discharge. After the run, as part of the installation of a completely new RF system, the modulator was dismounted and examined: the photograph shown in Fig. 3 is testimony to the fact that a discharge did indeed inflict damage on the electrode, limiting the attainable resolution (to the very modest value of about 14000).

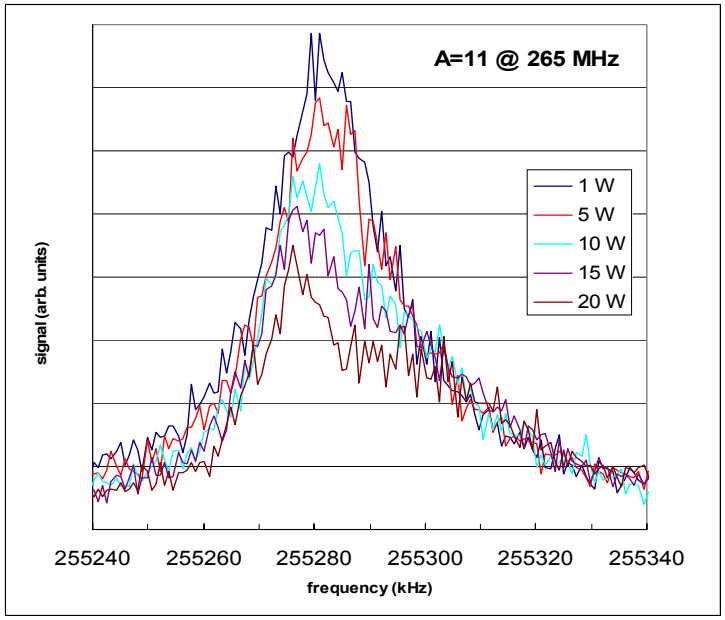

Figure 2: The transmission peak for ^{11}B versus modulation frequency for increasing RF power, measured just before the ^{11}Li run. The FWHM of the peak should be reduced as the power is increased. Not only is the resolution unchanged but the peak shape is distorted. This is indirect evidence of a problem with the electric field in the modulator (see Fig. 3).

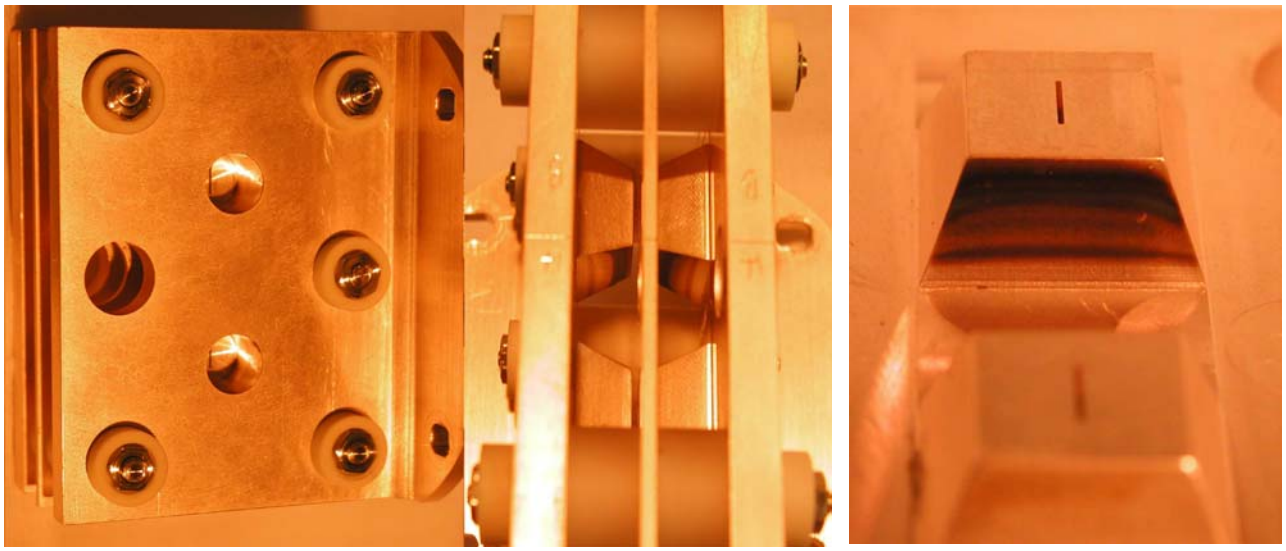

Figure 3: (left) The modulator assembly as seen by the beam. (center) Side view of modulator assembly showing the central electrode and gaps. (right) One of the ground plates of the modulator, autopsied after the ^{11}Li run, on which the sinister shadow of a discharge can clearly be seen.

For each radioactive beam pulse, the ion transmission signal is recorded for only one radiofrequency point (determined randomly) and the transmission peak is reconstructed at the end. This point-by-point mode not only allows us to increase statistics in the peak (shown in Fig. 4-left) of which a total of 430 counts were accumulated, but also to produce very clean release curves (see Fig. 4-right). A time window is used to reconstruct the transmission peak with reduced background.

The poor resolving power and limited statistics contribute 1.5×10^{-6} to the total relative error of 2.2×10^{-6}, or 25 keV absolute error.

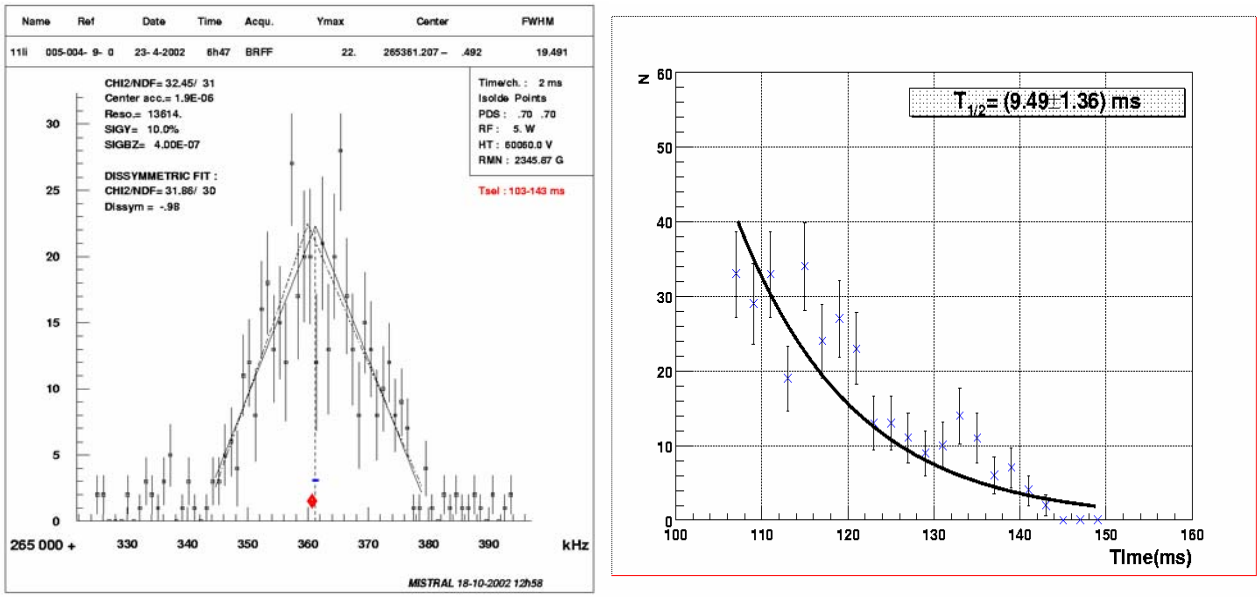

Figure 4. (left) The accumulated transmission peak for ^{11}Li, recorded over two shifts of beam time (at a miserable rate of about 0.01 atoms/s). (right) The target release curve corresponding to the recorded ^{11}Li events. A fit to this curve gives a value in excellent agreement with the 8.6 ms half-life that completely dominates its decay.

2.B. Mass Calibration

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. These comparisons are done once every PS supercycle in order to eliminate short-term drift in the magnetic field.

Our previous measurements have revealed that a calibration is necessary due to the slightly differing trajectories of the measured and reference ions. This is accomplished by first measuring masses known to sufficient accuracy (using isobaric doublets wherever possible). In the 2002 measurement, the masses $^{6\text{-}9}$Li from ISOLDE were compared to $^{10\text{-}11}$B for this purpose. The results, shown in Fig. 5, were surprising: in the past, these comparisons were found to vary linearly as a function of the compared mass difference whereas the lithium measurements revealed a quadratic dependence. For the moment we have not established the exact cause of this phenomenon but it would seem to be evidenced only for very light masses where the mass difference is a sizable percentage. Three such calibrations were performed during the run. An average value for the offset correction was used to determine the mass of ^{11}Li, however the error brought by this procedure adds 1.64×10^{-6} to the statistical error and represents more than half of the overall experimental uncertainty.

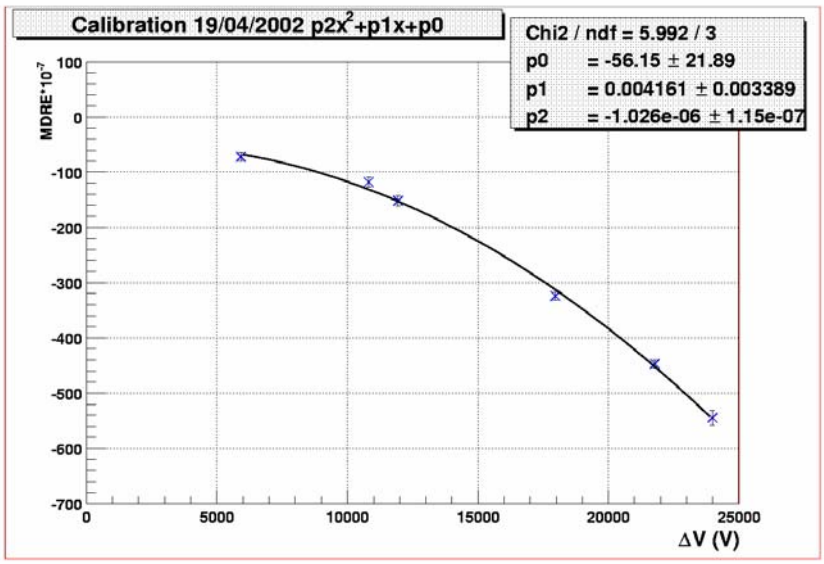

FIGURE 5. Difference between mass value determined by MISTRAL and the value in the atomic mass evaluation for a calibrant (i.e., sufficiently well known) mass as a function of ion kinetic energy difference through the magnetic field of the spectrometer (from right to left: ^{9}Li-^{10}B, ^{9}Li-^{11}B, ^{8}Li-^{10}B, ^{7}Li-^{10}B, ^{7}Li-^{11}B, ^{6}Li-^{10}B). The curve is extrapolated to (near) zero, corresponding to the mass difference between ^{11}Li and ^{11}B, in order to correct for the offset. Beam transport problems increased the uncertainty of this offset correction.

3. The ^{11}Li result

The new MISTRAL result is shown in figure 6 in the form of the S_{2n} (since the mass of ^{9}Li is known to within 2 keV, the error is dominated by that of ^{11}Li). There are four values more or less in agreement but only one of which has an uncertainty approaching what could be termed "high precision". The earliest measurement was made using a mass spectrometer [THI75]. Later results followed from TOFI at Los Alamos [WOU88] and two reactions: an unpublished result from a double pion exchange reaction *Q*-value [KOB91] and a more recent *Q*-value of the ^{14}C(^{11}B,^{11}Li)^{14}O reaction from MSU [YOU93] which had, until now, reported the smallest error bar of 35 keV.

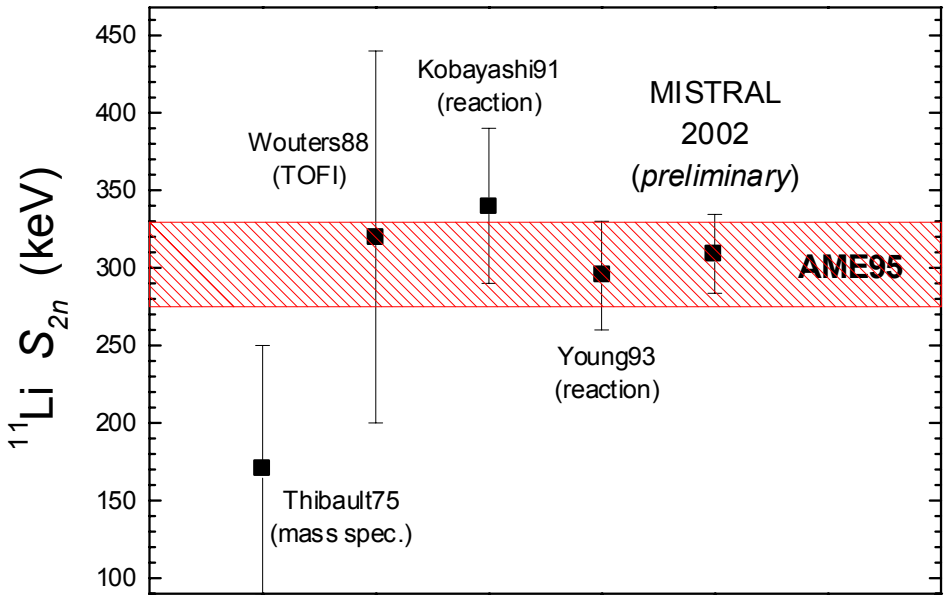

FIGURE 6. Two-neutron separation energy for ^{11}Li determined from the recent MISTRAL measurement, compared to results from previous experiments. From left to right: Thibault et al. [THI75] using a mass spectrometer, Wouters et al. [WOU88] using a fragmentation-time-of-flight technique; Kobayashi et al. [KOB91] from the ^{11}Be(π^{+},π^{-})^{11}Li reaction (unpublished) and Young et al. [YOU93] using the ^{14}C(^{11}B,^{11}Li)^{14}O reaction. The hatched area is from the 1995 atomic mass evaluation [AME95] and corresponds to the weighted error of 27 keV.

The MISTRAL value, accompanied by a reduced uncertainty of 25 keV, is in complete agreement with the MSU value. This is an important result since the two techniques are completely different, ensuring that any undetected measurement effects would not be similar and as such, bias the result in any systematic way.

The S_{2n} value including the MISTRAL result and its weighted average gives 302(18) keV, a whole 1 keV less than the 1995 Atomic mass evaluation result [AUD95], but 33% more accurate.

4. A new ^{11}Li mass measurement

Due to problems encountered with the MISTRAL spectrometer (presented in section 2), as well as grave difficulties with beam transport due to the HRS (discussed below), we ask the committee for extra beam time in order to achieve the best possible result.

4.A. ISOLDE High-Resolution-Separator

In the original proposal it was stated that the experiment could be performed with either the GPS or the HRS and events conspired to schedule the run on the HRS. A enormous amount of money and (especially) manpower has been invested in the HRS which is a very sensitive piece of equipment. At the time of our measurement, new control software had been written for the HRS but was not yet in a sufficiently robust state of operation. As it involves two magnets, mass changes are quite delicate and even small deviations will have grave consequences at the end of the long journey to the MISTRAL spectrometer, itself, an instrument that is tremendously sensitive to the incoming beam position (and, contrary to most experiments, beam direction). At the start of the experiment, the calibration of the two magnets was probably not exact: while the beams of $^{6\text{-}9}$Li were transported through MISTRAL with nominal transmission, ^{11}Li was not. An independent measurement of the ^{11}Li (using a neutron detector on LA1), confirmed that it was indeed the transmission (through CB0, CC0, RA0, RA2 and RA4) and not the target production that was causing the problem. A later experiment on ^{11}Li performed by the COLAPS collaboration using the HRS encountered *exactly the same problem*: normal transport of the ^{9}Li beam and almost a complete loss of transmission for ^{11}Li [BLA02]. Though COLAPS managed to see some ^{11}Li, it was not possible to optimize the magnet and beam line setting to recover the full yield. MISTRAL, located much further downstream, saw absolutely nothing forcing us (to use the French expression) *à faire la pêche à la ligne*. (In the end the beam was "optimised" using a count rate of less than 0.01 ^{11}Li ions/s - an absurd situation. It did, however, permit a measurement!)

The ideal situation (in addition to simplifying the experiment by using the GPS) would be to have an isobaric beam available, not only to optimize the transmission, but especially to minimize the mass calibration error. The best choice would be to produce a ^{11}Be beam with the RILIS installation. The published ^{11}Be yield of 3×10^{6} /μC would be largely sufficient and eliminate most of the calibration error component.

4.B. Potential uncertainty

The overall uncertainty will depend on three quantities: the calibration error, the mass resolving power, and the accumulated statistics. Figure 7 illustrates the interplay of these quantities and the result that was achieved. It was impossible to increase the resolving power due to the discharge in the modulator and the problems with the HRS not only limited statistics but also rendered the mass calibration more uncertain. This calibration error is decisive. In order to reach an overall experimental uncertainty of 5 keV, it is necessary to reduce the calibration error to at most 3×10^{-7}. By using the RILIS beams of $^{10\text{-}11}$Be in conjunction with our reference beams of $^{10\text{-}11}$B, an excellent

mass calibration could be made over a very restrained mass range, with no need for extrapolation. Once this is achieved, increasing the resolving power can be used to compensate statistics. Tests with the new RF system have demonstrated that a resolving power of more than 50000 is now easily achievable with modest RF power. This would require statistics in the range of about 1000 ions, easily obtainable at nominal transmission within one shift.

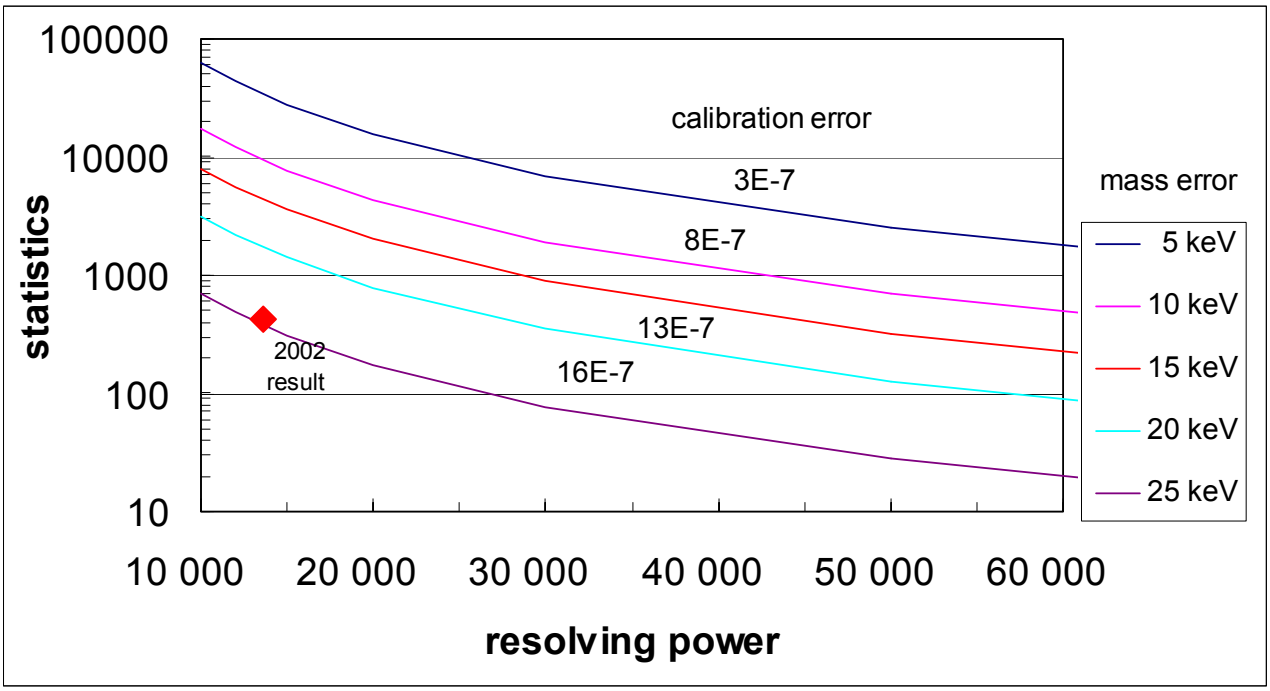

Figure 7: The relative mass uncertainty for ^{11}Li achievable by MISTRAL plotted as a function of statistics, resolving power and calibration error. The result achieved in 2002 is shown. In order to reach the target uncertainty of 5 keV, it is necessary to reduce the calibration error to at most 3×10^{-7}. Resolving powers of over 50000 around mass range $A = 11$ are now possible requiring only modest RF power.

4.C. Beam time request

Given a ^{11}Li yield of 2000/pulse, one independent measurement with sufficient statistics could be performed in one shift of beam time. We would require a minimum of five independent measurements, each of which accompanied by a calibrating mass measurements of $^{10\text{-}11}$Be requiring a few hours. We therefore ask for a complement of 9 consecutive shifts of beam time using a thin (2 micron) foil Ta target together with Be RILIS on the GPS in order to provide a ^{11}Li mass measurement of highest possible accuracy with this experiment.

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