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Developments in laser spectroscopy at the Jyväskylä IGISOL

J. Billowes[a]

Schuster Laboratory, University of Manchester, Manchester M13 9PL, UK

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Abstract. This paper describes the programme of work on laser spectroscopy of radioactive atoms being carried out at the IGISOL facility by a Birmingham-Jyväskylä-Manchester collaboration. The advantageous features of the ion guide ion source, combined with an ion beam cooler-buncher allows a broad range of studies to be pursued. Highlighted in this presentation are collinear beams laser spectroscopic measurements on Zr and Y isotopes, and charge radii determinations for two 8^- isomers in ^{130}Ba and ^{176}Yb. A laser ion source capability called FURIOS is being developed for the IGISOL which will not only provide isobarically pure beams for experiments, but also allow in-source laser spectroscopy of short-lived isomers of heavy elements.

PACS. 21.10.Ft Charge distribution – 21.10.Ky Electromagnetic moments – 32.10.Fn Fine and hyperfine structure

1 Introduction

The finite spread of the nuclear charge distribution, and the static nuclear magnetic and electric moments affect the energy levels of the valence electrons at the part per million level. A range of methods of laser spectroscopy can measure the atomic perturbations with such precision that high quality information may be deduced about nuclear properties [1,2,3]. The hyperfine structure of an optical transition provides the nuclear spin, magnetic dipole and electric quadrupole moments. The change in the mean square charge radius of two isotopes may be deduced from the frequency shift of the transition (the isotope shift) between the two isotopes. Although it is sometimes difficult to get an exact calibration of the size of the radial change, the comparisons of charge radii changes from isotope to isotope are very sensitive to even small structural changes. For example, the change in the proton distribution due to the removal of a single neutron is clearly evident, and a shape change between to isotopes is very obvious.

The high sensitivity of the laser techniques allows these studies to be extended to radioactive ions lying an appreciable distance from the region of nuclear stability and to short-lived nuclear state and isomers with half-lives in the millisecond, and even microsecond region. The present status of optical measurements is shown in fig. 1. The standard technique, that has been adapted for use at the IGISOL (Ion Guide Isotope Separator, On-Line) facility, is the collinear beams method which makes efficient use of the radioactive sample and compresses the Doppler broadening of the optical transitions to a point where it is comparable to the natural linewidth which sets the ultimate limit on the precision of the measurement.

A Birmingham-Manchester group have been collaborating with the IGISOL group at the Cyclotron Laboratory, University of Jyväskylä (JYFL) for a decade. The facility provides low-energy radioactive ion beams from an ion guide ion source [4] for mass determinations, and nuclear and laser spectroscopy measurements. The ion source consists of a chamber through which helium gas flows. Nuclear reaction products recoil and stop in the flowing gas which carries them out through a 1 mm diameter nozzle. Those products which have not neutralized are drawn through an aperture in a gas "skimmer" plate and enter a conventional mass separator which delivers them to experiments at a beam energy of typically 40 keV. The ion guide has two particularly beneficial features for nuclear research: i) the extraction from the ion source is relatively fast (1 millisecond) compared with conventional thermal-release ion sources, and ii) ions of any element can be extracted with comparable efficiency, almost independent of their chemistry [4]. Of course, for some experiments this can also be a drawback since the extracted beam will be a cocktail of isobars of different elements. Other drawbacks of the ion guide method are the poor overall efficiency of the source, and the energy spread of the extracted ion beam, which simultaneously increases the Doppler width and reduces the sensitivity of the collinear beams laser spectroscopy method. The solution at JYFL was to insert an "ion beam cooler" in the mass separated beam line [5].

[a] e-mail: j.billowes@manchester.ac.uk

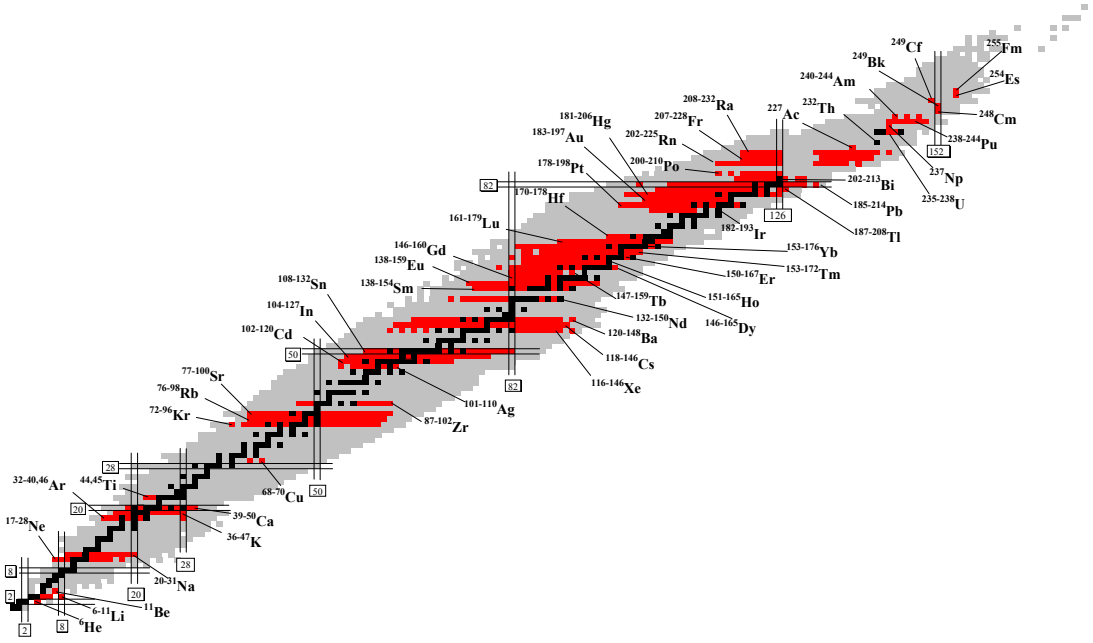

Fig. 1. Present status of optical measurements. The black squares indicate stable isotopes. The dark shade indicates measured isotopes. The figure is taken from ref. [3] and revised by one of the authors (WN).

This also had the ability to accumulate and bunch the ion beam —a feature that led to a new and general technique for background reduction in the subsequent laser measurements.

2 Laser spectroscopy with the ion beam cooler-buncher

The cooler-buncher is gas-filled linear Paul trap held on a high-voltage platform a hundred volts or so below the ion source voltage. The IGISOL ion beam is thus decelerated as it enters the gas-filled RFQ structure. The ions are thermalised by viscous collisions with the helium before being carefully extracted and reaccelerated at the far end for delivery to the experiment. The energy-spread of the beam is reduced to less than 1 eV. A small electric potential gradient of about 5 V over the length of the trap draws the ions through the cooler, resulting in a transit time of the order of 1 ms. Alternatively, the exit can be closed by applying a positive voltage to the end plate, creating a potential well just inside the cooler where the ions may be allowed to accumulate for up to a second. Lowering the plate voltage releases these ions in a bunch with a time-spread of 15–20 μs with little effect on the energy spread of the ions.

In the laser measurements a CW laser beam overlaps the ion beam collinearly and resonantly scattered photons are observed when the laser frequency is brought to resonance with the atomic or ionic transition. There is a continuous background in the photon signal from scattered laser light and photon detector dark counts. This background is at least two orders of magnitude higher than the signal from a radioactive isotope beam. If the ion beam is bunched and the photon signal is gated for just the 20 μs period when the ions are present in the laser beam, then the background can be suppressed by more than four orders of magnitude, resulting in a very sensitive method of spectroscopy that can be generally applied to any isotope or element provided the life-time is longer than about 50 ms.

3 Charge radii of Zr and Y isotopes

The bunched-beam method of laser spectroscopy has been applied to the neutron-rich [6] Zr isotopes from proton-induced fission of uranium, and the neutron-deficient [7] isotopes produced in ^{89}Y(p, xn) reactions. The charge radii systematics of this chain [8] are very similar to zirconium's nearest even-Z neighbour, strontium [9]. The smallest r.m.s. radius occurs in stable ^{90}Zr at the $N = 50$ shell closure, and the radii increase steadily with neutron number for both the lighter and heavier isotopes, as seen in fig. 2. A marked increase in deformation is seen at $N = 60$ which is consistent with nuclear spectroscopic studies in the region [10].

The mean square charge radius dependence on nuclear deformation may be expressed by

$$\langle r^2\rangle_{\text{deformed}} = \langle r^2\rangle_{\text{spherical}}\left[1 + \frac{5}{4\pi}(\beta_2^2 + \beta_3^2 + \ldots)\right].$$

The dashed lines in fig. 2 show the changes in mean square charge radii with neutron number as predicted by the droplet model [11] corrected for quadrupole deformation

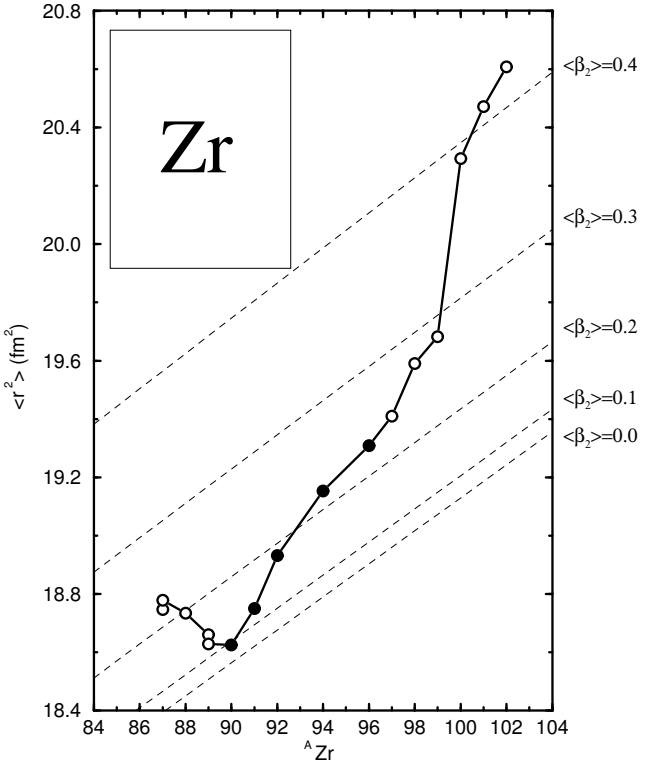

Fig. 2. Changes in mean square charge radii for the zirconium isotopes. Filled circles are stable isotopes; open circles are radioactive isotopes. The isodeformation lines are predictions of the droplet model [11].

according to the above formula. The charge radii data thus suggest that there is a slow but steady increase in deformation from the spherical nucleus ^{90}Zr at $N = 50$ up to $N = 59$. This is contrary to nuclear spectroscopic information where the the low $B(E2; 2_1^+ \rightarrow 0^+_{\text{g.s.}})$ values [12] suggest the ground state stays spherical for all the stable even isotopes. Unfortunately there is no quadrupole moment information for ^{93,95}Zr which might shed some light on this contradictory situation. The available $B(E3)$ data suggest it is unlikely that octupole vibrations are responsible for the increase in charge radii [6,13]. The $B(E2)$ strength to all higher 2^+ states should be included to get the correct β_2^2 estimate for the droplet model correction. Including the missing strength may resolve the apparent inconsistency between the $B(E2)$ and charge radii data.

In order to pursue the problem, a programme of measurements on the yttrium isotope chain has started. This is the odd-Z neighbour between Sr and Zr. The yttrium isotopes are rich in low-lying isomers which will be accessible to laser measurement and a comprehensive study of quadrupole shape evolutions should be possible in this neutron number region.

Off-line testing on a number of transitions from the Y^+ ionic ground state (224 nm, 311 nm, 363 nm) have been carried out. The strongest transition is the 363 nm $(s^2)\ ^1S_0 \rightarrow (dp)\ ^1P_1$ due to (p^2) and (d^2) admixtures in the ground state and an (sp) admixture in the $^1P_1$ state. New laser optics and a Brewster-cut intra-cavity doubling crystal have been installed and on-line measurements have begun on the neutron-deficient isotopes. Measurements on the neutron-rich produced as fission fragments will begin next year.

4 Isomer shifts of multi-quasiparticle isomers

There are two instances in the literature where an excited nuclear state has a smaller r.m.s. charge radius that the nuclear ground state despite being no less deformed. The most well-known is the ^{178m2}Hf(16^+) 4 quasiparticle 31-year isomer [14]. The second example is a 3 quasiparticle isomer in the isotone ^{177}Lu [15]. A possible explanation is that the blocking of orbitals near the Fermi surface by the quasiparticles leads to a reduction of the paring which then reduces the diffuseness of the nuclear surface and thus reduces the mean square charge radius.

At JYFL it has been possible to measure two 8^- isomers in ^{176}Yb and ^{130}Ba which are related to the 2-neutron and 2-proton configurations of the 16^+ state in ^{178}Hf. There are a number of experimental problems in these isomer shift measurements. Both $K = 8$ isomers are two-neutron configurations with small magnetic moments. Consequently, the hyperfine structure is bunched up around the much more intense nuclear ground state resonance peak. Furthermore, the quadrupole interaction can change the order of the hyperfine levels and assignments of the peaks are difficult when some components may be hidden under the ground state peak. Nevertheless, an unambiguous analysis for ^{130}Ba(8^-) was possible [16] and, like the ^{178}Hf isomer, the state was found to have a smaller r.m.s. charge radius despite a similar deformation to the ground state.

The ^{176}Yb(8^-) isomer was populated in the ^{176}Yb(d, pn) reaction at 13 MeV with a deuteron beam current of 5.5 μA. The isomer flux of the $A = 176$ beam was determined by gamma-ray spectroscopy to be 200 isomers/sec out of a total flux of 8,400 ions/s. The analysis has now been completed [17]. The results are compared with the measured $N = 106$ isomers in the neighbouring chains of Lu and Hf in fig. 3. For display purposes the data have been normalised to the ground states at $N = 99$ and 106 (although this is not quite consistent with the atomic factor evaluations used for the extraction of the change in mean square charge radii). It is evident from the figure that all isomers are smaller than their nuclear ground state. A comparison of the β_2 deformation parameters derived for the ground states and isomers indicate that none of the isomer shifts can be attributed to a reduction in deformation of the isomer. The reduction in r.m.s. charge radius is greatest for the 4 quasi-particle 16^+ state. The ^{176}Yb(8^-) and ^{177}Lu$(23/2^-)$ states are both 2 quasi-particle effects compared to their respective ground states, and are about twice the size of the normal odd-even staggering of isotope shifts which might be thought of as a 1 quasi-particle effect. As yet there is no published quantitative theoretical explanation.

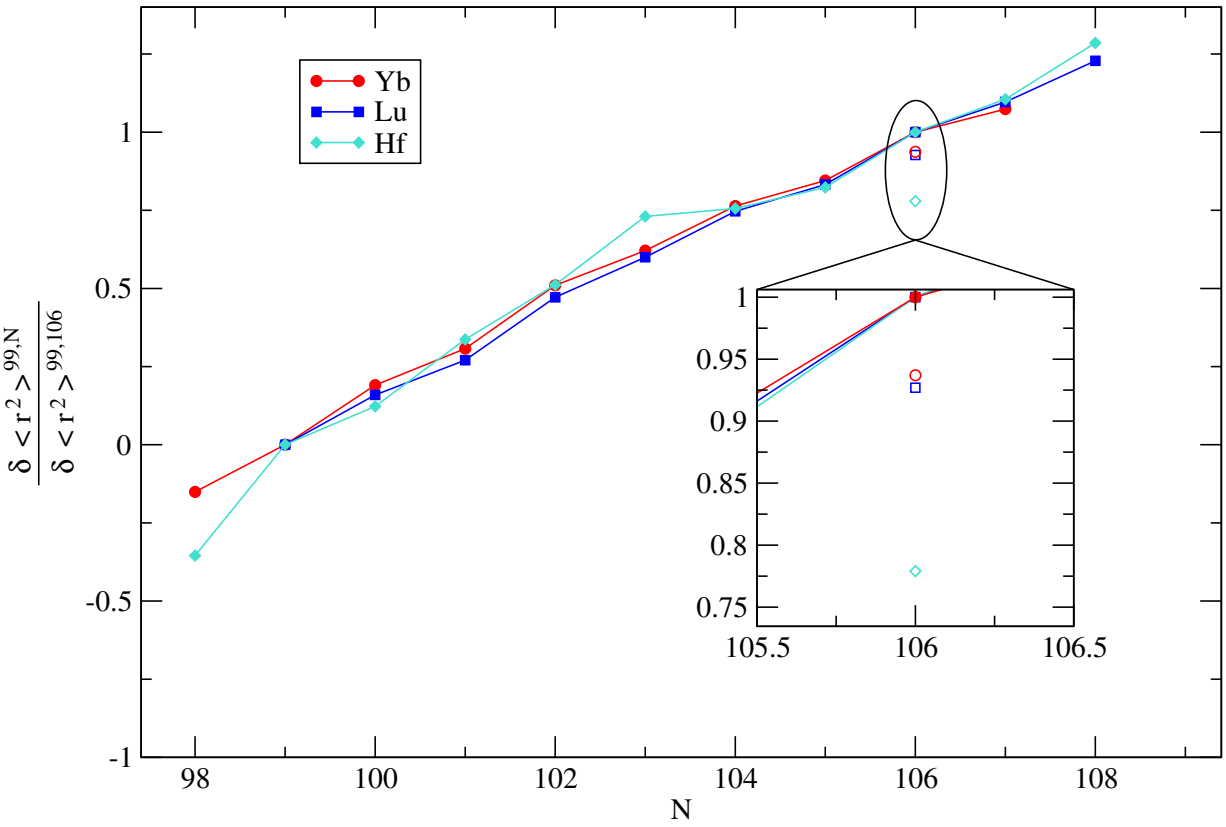

Fig. 3. Relative changes in mean square charge radii for the $N = 106$ isomers of Yb [17], Lu [15] and Hf [14]. The isomers are shown in the panel as open symbols. ^{178}Hf(16^+): diamond; ^{177}Lu($23/2^-$): square; ^{176}Yb(8^-): circle.

5 Development of the FURIOS laser ion source facility at JYFL

The insensitivity of the ion guide to an element's chemistry has been essential to many of the laser spectroscopic studies made at JYFL. However, this property can become a disadvantage when working on isotopes very far from the stability line, because the mass-separated beam may contain isobars of other elements produced with much higher fluxes. Considerable work on improving the selectivity of gas-catcher ion sources has been done by the Leuven group [18] who developed the laser resonance ionization ion guide, IGLIS.

In order to improve and extend the studies on exotic isotopes at the IGISOL facility a laser ion source project has started at JYFL which will provide improved isobaric purity and higher efficiency without compromising the universality and fast release of the IGISOL system. Several techniques will be developed. One will be similar to the IGLIS concept where pulsed lasers produce ions within the gas cell volume. A second method will use lasers to ionize atoms after they have flowed out of the gas volume.

The element selectivity is provided by the laser resonance ionization process whereby a neutral atom is stepwise excited by two or three pulsed laser beams separately tuned to each step of the ionization scheme. Only pulsed lasers can produce the high power densities required to saturate the transitions in the scheme. To avoid duty cycle losses in some of the laser techniques proposed for the facility, the laser repetition rate rate must be of the order of 10 kHz. In order to cover as broad a range of elements as possible two sets of pulsed lasers will be available, one using well-known dye laser technology, the other using solid state pump and titanium sapphire lasers. The laser facility has been named FURIOS (Fast Universal Resonance laser Ion Source). A schematic layout of FURIOS is shown in fig. 4.

All of the lasers have been bought and are being installed and commissioned. A pulsed dye laser and dye amplifier will be pumped by an Oxford Lasers 45 W copper vapour laser with a 1–15 kHz repetition rate. The dye amplifier will be seeded by a CW Spectra Physics 380 ring dye laser. This will provide a Fourier-limited linewidth for the amplified light of less than 100 MHz. The three Ti:Sapphire Z-cavity lasers have been designed and built by Dr K. Wendt's group at Mainz University. These are pumped at 532 nm by a 100 W Nd:YAG laser with a repetition rate of 1–50 kHz supplied by Lee Lasers.

Figure 4 also shows one of the techniques to be developed at JYFL. Atoms flowing out of the helium chamber nozzle will be laser-ionized inside an RF trap. Ionic species from the gas chamber can be completely suppressed and the ion beam extracted from the RF trap will have exceptionally high purity.

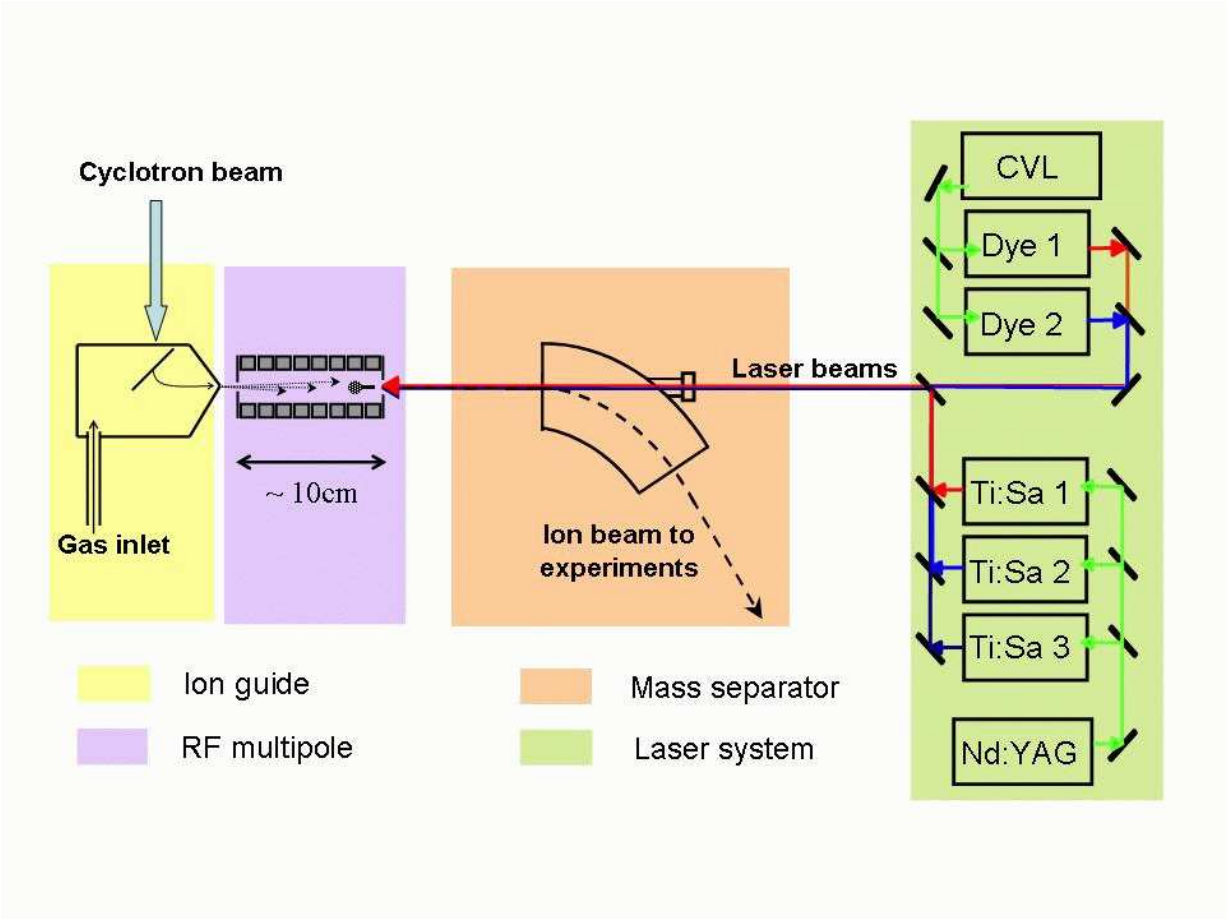

Fig. 4. The planned FURIOS laser ion source facility at JYFL.

An application using the narrow-bandwidth pulsed dye laser light is in-source resonance ionization spectroscopy on sub-millisecond isomers. The laser beams can be introduced through a window at the back of the chamber for illumination of the larger volume. Full operation of this facility is keenly awaited.

The on-going work described in this paper is being carried out by a collaboration involving the Universities of Birmingham (G. Tungate, D.H. Forest, B. Cheal, M.D. Gardener, M. Bissel), Jyväskylä (J. Äystö, H. Penttilä, A. Jokinen, I.D. Moore, J. Huikari, S. Rinta-Antila) and Manchester (J. Billowes, P. Campbell, A. Nieminen, K. Flanagan, A. Ezwam, M. Avgoulea, B.A. Marsh and B.W. Tordoff). The ^{130m}Ba measurement was done in collaboration with Dr A. Bruce (University of Brighton), and the ^{176m}Yb work was in collaboration with Professor G. Dracoulis (Australian National University). The FURIOS Collaboration also involves the University of Mainz (K.D.A. Wendt, Ch. Geppert and T. Kessler). The chart in fig. 1 has been kindly supplied by Wilfried Nörtershäuser.

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