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Mass measurements of exotic nuclei and their importance for stellar nucleosynthesis

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The masses of nuclides far from stability provide information on decay and reaction energies as well as nuclear structure that is crucial for modeling stellar nucleosynthesis. Low production rates, short half-lives, and the inherent precision required make masses perhaps the most difficult nuclear quantity to measure. The minuteness of the binding energy has also contributed to confounding brave attempts at reliable theoretical mass predictions. In the spirit of previous reviews [Lunney, Pearson, Thibault, Rev. Mod. Phys. 75, 1021, 2003 and Lunney, Eur. Phys. J. A 25, 3, 2005], this paper introduces the role played by masses in astrophysics and and provides an update, comparing the (growing) multitude of mass-measurement programs now active worldwide. The evaluation process that links reaction, decay and binding energies is also described as well as its creation of the mass table: a benchmark for the development of the the mass models required by nucleosynthesis networks.

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1. Introduction

Nuclear astrophysics is much about studying the infinitely small to understand the infinitely large. The properties of atomic nuclei are important ingredients for modeling various astrophysical processes. Here we will concentrate on one: the mass. Like observing a distant star, weighing an exotic nuclide gives us important information due to the binding energy that determines nuclear structure as well as the energy available for decays and reactions.

The landscape of the chart of nuclides is often described as having a valley of stability, formed by the nuclear internal energy (the negative binding energy). Stable nuclides lie along a meandering path that resembles a river running along the bottom of a valley. Each side of the valley rises as nuclides with high neutron-proton (and vice-versa) ratios are less bound, reaching the ridges, or drip lines, at which the internal energy reaches zero; nuclides beyond this precipice are unbound.

This valley was first explored during the 1920's by Francis Aston at Cambridge, who, in taking the art of mass spectroscopy into the realm of precision measurements (10^{-3} at the time), discovered that the mass of helium was less than the total mass of what he thought were its constituents (four protons) [1].[1] Arthur Eddington realized that if the sun could use the energy-equivalent of this mass difference to fuel its combustion, the hotly debated question of the sun's temperature (and hence, age) would be resolved [2]. Thus, the link between mass measurements and stellar nucleosynthesis goes back to the beginning of the field. [2]

Interestingly enough, the relation in question, $E = mc^2$, was quite recently tested using a radiative, neutron-capture reaction where the emitted $\gamma-$ray was measured as well as the mass difference between the initial and final nuclides using a Penning trap [5]. The mass measurement, performed with a relative accuracy of almost 10^{-11}, represents an eight-order-of-magnitude improvement in the 80 years since Aston established the field.

Another interesting application of mass measurements that relates to astrophysics is the determination of fundamental constants, notably *the* kilogram, whose definition continues to be compromised by a variations in cleanliness (and as such, is accompanied by a cleaning recipe) [6]. The reason for worrying about accuracy of fundamental constants comes from astronomical assertions that they may have varied with time [7]. Though much debated, there are definitely implications of such variations in cosmology (see A. Coc, this volume).

Finally, the ultimate in microscopy - particle physics, at the highest energy frontier - seeks to glimpse the beginning of the universe and one key element of that work is in mass measurements of quarks (see [8] for the top quark mass) in order to see if the Higgs boson might be found at CERN with the LHC (see J. Ellis, this volume).

By far the most vigorous mass measurement activity is found in nuclear physics since radioactive nuclides may be as much as 300 times more numerous than the 300 stable ones and we still have no way of predicting their masses with any certainty.

[1] Aston went on to measure the masses of over 200 nuclides, establishing what he termed the "packing fraction" now shown in all nuclear physics textbooks as the binding energy per nucleon [3] and winning the Nobel prize (for Chemistry) in 1922.

[2] The story of "How the sun shines" is brilliantly recounted by John Bahcall [4], whose memory was honored at the NiC-IX conference.

Stellar nucleosynthesis requires a detailed knowledge of the structure of a huge range of nuclides, sometimes to the limits of stability. The mass is particularly important, not only for its decisive effects on nuclear structure (shells, deformation, pairing) but also for energy release. The myriad effects of the binding energy on nuclear structure are discussed in [9, 10, 11] and [12, 13, 14] including references therein. The importance of nuclear data for nucleosynthesis is discussed in [15, 16, 17, 18]. Here, the rapid neutron capture process is recalled along with the reasons it requires us to measure masses of exotic nuclides. Then, the various measurement techniques are introduced and compared, reviewing the numerous (new) measurement programs in the process. Short sections on the Atomic Mass Evaluation and mass models precede the conclusion.

2. The stellar *r* process and why it requires mass measurements

Modeling astrophysical processes is challenging not only because we cannot build a stellar laboratory but also because stellar time scales so greatly eclipse our own. Consequently, there is a great uncertainty regarding astrophysical sites and events, not helped by a lack of nuclear physics data for reaction cross sections at low energy and nuclear properties (like the mass) of exotic nuclei.

The rapid neutron-capture nucleosynthesis process (see Figure 1) is thought to be associated with supernovae when seed nuclei feed on an enormous neutron flux produced in this cataclysmic event. (For details and other contributions to the *r* process, see C. Froehlich, this volume. For the rapid proton capture (*rp*) process and its mass requirements, see H. Schatz, this volume.) The consequence of the *r* process is that a large fraction of the heaviest elements are produced and ejected into the interstellar medium. The general path taken by the *r* process propels it along the steep grade of the nuclear valley where very short-lived, neutron-rich nuclei bathe in this hot broth of neutrons. After the temperature falls and the neutron flood subsides (called *freeze out*) the left-over isotopes β-decay towards stable isotopes - like water trickling down the valley hillside after a rain storm.

To eventually determine the trajectory of the *r* process under given astrophysical conditions (and hence, the abundances produced), we need to know (amongst other things) the neutron-separation energy (S_n, derived from the mass difference of adjacent isotopes) of essentially all neutron-rich nuclides. Gorged on neutrons, the nucleus becomes an easy target for marauding γ-rays that strip off the loosely held neutrons and the S_n tells us how easily that happens. Since we also need to know about neutron-capture cross-sections, we need to know the level densities of all the nuclides in question (as statistical models may not be applicable in this region of small S_n). In addition to mass spectrometry, detailed nuclear spectroscopy is therefore required, including capability for delayed neutrons and fission. And if it wasn't already enough, even more information is needed regarding nuclear potentials and giant dipole resonances. Not only is a huge amount of nuclear data required, there is currently no radioisotope facility on the planet that can even produce most of the isotopes in question! This difficult situation must be remedied by nuclear models of sufficiently microscopic character that can provide the many properties (see [17] and discussion in Sec. 5).

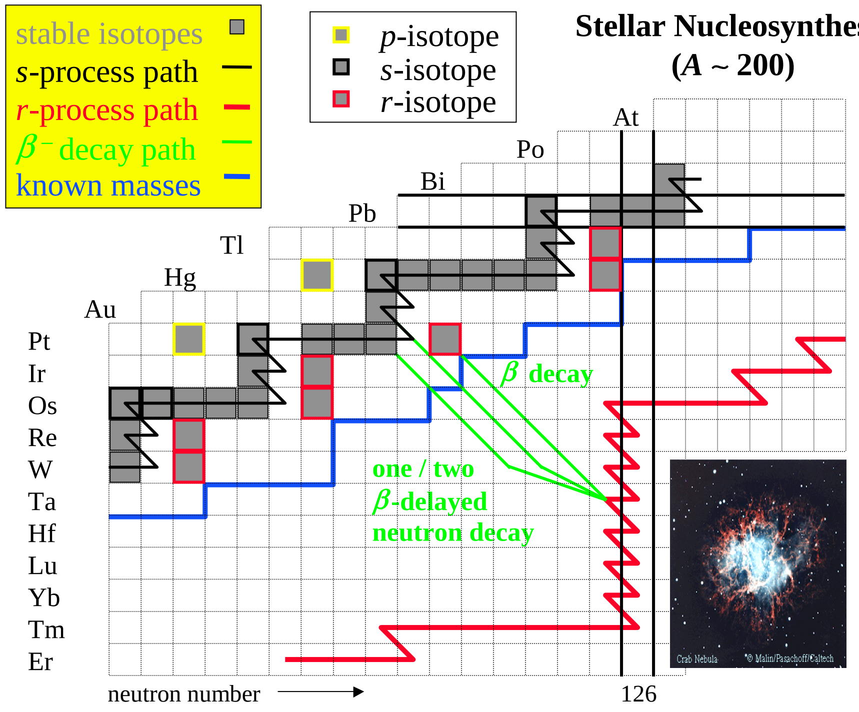

Figure 1: The nuclear chart around $N = 126$ showing possible paths for the slow (s) and rapid (r) neutron capture processes. Also shown is the area delimiting nuclides for which the mass is measured.

3. How exotic nuclides are weighed (and where)

Determining the binding energy of exotic nuclides is easily one of the most difficult challenges of experimental nuclear physics. Masses fall under the class of precision measurements, requiring the exhaustive examination of all possible sources of (systematic) error. This is combined with low production rates (down to a few per second), further compounded by requiring precision apparatus to operate in the harsh environment of accelerator facilities. Such facilities produce radionuclides using two canonical methods [23], fragmentation (or fusion-evaporation) of thin targets with in-flight separation (FIFS) and thick-target, isotope separation on-line (ISOL).

Traditionally, two categories of mass measurements exist: so-called indirect techniques – reactions and decays – that produce Q-values, or energy differences; and direct (or inertial) methods – mass spectrometry – where time-of-flight or cyclotron-frequency measurements of the exotic species are performed with respect to well-known reference masses, ultimately linking them to ^{12}C (with which the mass unit is defined). Aston's measurements (defined with respect to ^{16}O) pioneered the direct scheme, for which he invented the double-focusing technique (see [3]).

Mass measurement programs have been underway for quite some time at GANIL, GSI and ISOLDE.[3] Very recently, ANL, MSU and JYFL have made their first direct mass measurements and realization of new setups are well underway at MAFF and TRIUMF. Fig. 2 shows a global view of (direct) mass measurement program locations. A comprehensive review is given by Lunney,

[3]TOFI at LANL was also active but ceased operation in the 1990's.

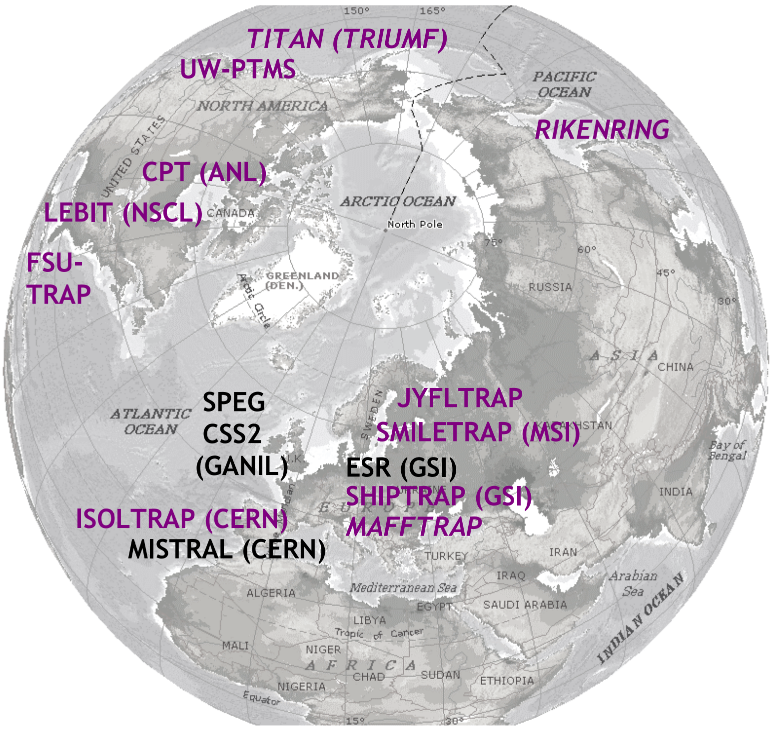

Figure 2: Global view of active mass measurement programs. In light type are programs that use Penning traps. In italic type are facilities that are under construction.

Pearson and Thibault [12], with an update by Lunney [14]. The proceedings of the APAC (Atomic Physics at Accelerators) conference [19] in 2000 provide a comprehensive collection (in a single issue) of the details of the various techniques. Recently, a special issue devoted to H.-J. Kluge [20] has appeared which is a valuable (and needed) update. See also Scheidenberger [21] and Blaum [22] for recent reviews.

It might be argued that there is no need for the masses themselves of nuclei very far from stability since what is important for nuclear structure are $Q-$values or proton/neutron-separation energies (especially in the case of unbound nuclides, for example). While this is indeed true, there are other considerations that make the (direct) determination of a mass important, for example a strong constraint on a theoretical shell-correction term (especially in the case of doubly-magic nuclei). This point is of particular interest for mean-field-based mass formulas under development (see [62, 63]). An illustrative view of the different mass measurement programs worldwide is shown in Fig. 2. Below, is a summary of the direct measurement programs only. The reader is referred to the [12, 19, 20] for information on indirect techniques.

With TOFI gone, SPEG at GANIL is now the grand-daddy of mass programs. Using fragmented projectiles, measurements of time-of-flight and rigidity are combined to determine the mass. Although the resolving power is modest, the tremendous sensitivity of their method allows them to reach the drip line for many light species (see Savajols *et al.* in [24]).

At GANIL, attempts were made to improve time-of-flight measurements by lengthening the flight path using the many turns that result from injection of fusion-evaporation products into the

CSS2 cyclotron [26]. Some difficulties were experienced initially but recently the technique has been improved and the newly-measured results and revised errors now provide good agreement in all cases [27]. The same technique has been used with the new cyclotron CIME, which offers more flexibility regarding acceleration frequency. The first tests are quite promising [28]

The same idea of lengthening the time of flight can be realized by storing the ions in a ring, as with the Experimental Storage Ring (ESR) at GSI [29]. Relativistic fragments are filtered through a mass separator and injected into the ring operated with a given rigidity where their masses can be measured two ways. One is by detecting the so-called Schottky signal of a charged particle each time it passes an electrode and obtaining the evolution frequency from the Fourier transform. To do this, however, the ions must be cooled since the fragmented beam has a relatively large velocity spread. This is done with an electron cooler but the process requires several seconds [30]. The second method, used to measure short-lived species, requires operating the ring in isochronous mode where the revolution frequency is (to first order) independent of the velocity spread. In this case the ions are monitored in-beam with a thin-foil detector the the revolution frequency is derived from matching successive time signals [34]. An enormous volume of mass data has now been produced by the ESR, spanning a sizeable portion of the nuclear chart [30]. Recently, a experiment using the fragmentation of ^{152}Sm was performed which should provide a large harvest of proton-rich masses in the medium-mass range [31]. For a recent status report on ESR work see [32, 33].

No place on earth operates more storage rings than CERN, site of this conference. Though used for the primary beams, CERN storage rings were instrumental in the very first on-line mass measurements using a spectrometer [36]. These were done using 24-GeV protons from the PS (synchrotron) ring. The PS also serves as injector for the AD, SPS and LHC (see [37]). More recently, 1.4-GeV protons from the PS Booster ring have been used to create exotic nuclides at the world's premier ISOL facility ISOLDE (see Fig. 3) [38].[4]

Perhaps the most distinguishing difference between ISOL and In-flight Fragmentation facilities is the the low energy and superior optical properties of the resultant beam of exotic nuclides. ISOLDE, the mother of all ISOL facilities possesses two permanent experiments dedicated to mass measurements: MISTRAL and ISOLTRAP, both of which rely on the particular optical characteristics of ISOL beams.

MISTRAL is a good example of a technique that combines good accuracy and sensitivity. As a transmission, time-of-flight spectrometer using a radiofrequency "clock", its measurement technique is very fast allowing access to the shortest-lived nuclides produced at ISOLDE [39]. In 2003 MISTRAL measured the mass of ^{11}Li (a "superlarge" nuclide - see [40]) with an accuracy of 5 keV (see Bachelet *et al.* in [24] and Lunney *et al.* in [20]). MISTRAL is located at the mother of all ISOL facilities: ISOLDE, where a few meters of beamline separate it from ISOLTRAP, the mother of all on-line Penning-trap installations .

ISOLTRAP (see Herfurth *et al.* in [24], Delahaye [44] and Herlert, this volume) has pioneered most of the trap-based methods now being used for measuring masses of radioactive species (al-

[4]According to the original ISOLDE Users' Guide, edited by H.-J. Kluge (1986), "The first four letters of the acronym ISOLDE have a rational explanation: they stand for Isotope Separator On-Line. It is left to the imagination of the reader to complete the interpretation, if necessary."

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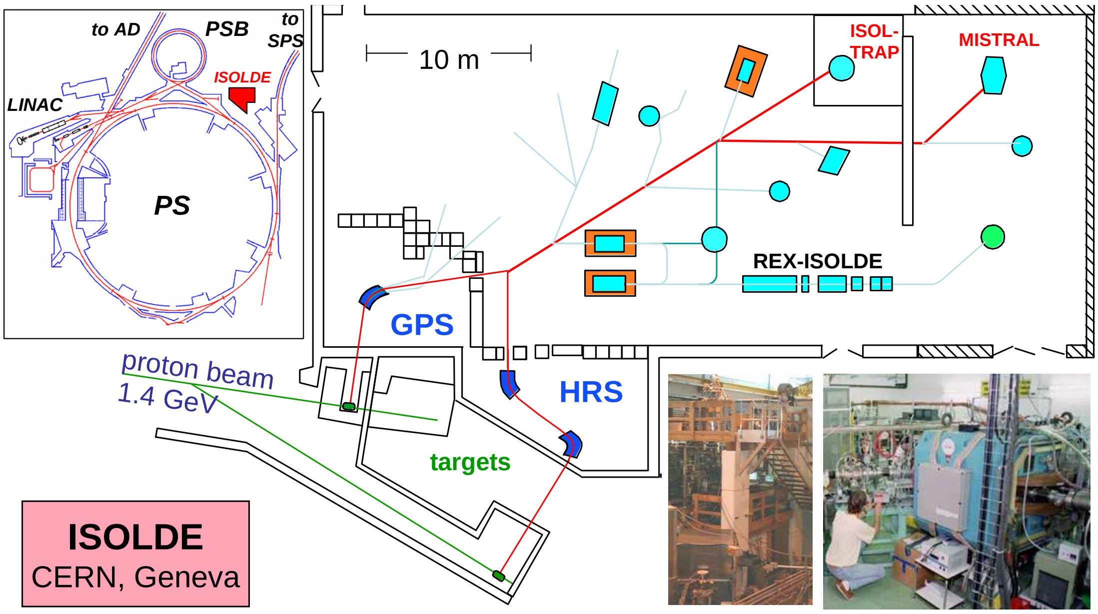

Figure 3: The ISOLDE facility at CERN. Shown are the two target stations, one feeding the General Purpose Separator and the other, the High Resolution Separator, followed by the merging switchyard, central beam line and experiments. Inset upper left shows the 200-meter diameter PS ring complex, including the Linac and PS Booster ring that alternately sends the 1.4-GeV protons to ISOLDE and the PS (which was used for the pioneering on-line mass measurements in the 1970's). Also shown are photographs of the permanent mass measurement experiments ISOLTRAP and MISTRAL currently at ISOLDE.

most) everywhere else.[5] Starting with a gas-filled, linear RFQ trap, low-energy ion bunches are injected into a large-volume, cylindrical Penning trap for isobaric purification. The isobar of interest is retained and sent to the precision Penning trap where its cyclotron frequency is excited and measured by time of flight after ejection. By bringing an enormous reserve of resolving power to bear (requiring storage times of over one second), ISOLTRAP is able to weigh even *isomeric* states, resulting in unambiguous identification, otherwise impossible by nuclear spectroscopy (see, for example, C. Weber *et al.* [42]). Another interesting application of traps is obtaining different chemical species (sometimes not available as ISOLDE beams) by waiting for a trapped radioactive ion to decay to its daughter [43].

The superior performance of the versatile Penning trap has naturally triggered new experimental programs. The first "clone" of ISOLTRAP was SMILETRAP, located at the Manne Siegbahn Laboratory in Stockholm [49, 50], generally dedicated to stable species produced with high charge states. The next project was the Canadian Penning Trap (CPT) which, after a difficult early life and excommunication from Canada, is now in full-fledged operation at ANL (see Clark *et al.* in [24], [25] as well as Clark, this volume). It is the first instrument of its kind making use of "the best of both worlds"; the advantages of high-energy production reactions and low-energy precision apparatus - linked by a gas cell (see Savard in [24]).

Now starting to produce results (and brought to you by the makers of ISOLTRAP) is SHIP-

[5]The invention of the Penning trap for precision measurements earned H. Dehmelt a share of the 1989 Nobel prize.

TRAP at GSI (see Block *et al.* in [24], [53] and Vorobyev, this volume), a new-generation instrument reaching for the best of both worlds by trapping trans-uranium elements created by fusion-evaporation residues that issue forth from a gas cell.

JYFLTRAP in Jyvaskyla was built almost essentially as a twin to SHIPTRAP using a two-in-one design where the isobaric separator trap and precision hyperbolic trap – separated in the case of ISOLTRAP – are located in the same magnet. One great advantage of JYFLTRAP is the host of neutron-rich refractory elements that can be fed to it by the IGISOL facility, greatly complementing the elements produced at ISOLDE. The initial production of this young experiment is truly impressive (see Jokinen *et al.* in [24], [54, 55, 56, 57] and Hager, this volume).

The newest arrival is LEBIT at MSU, the first Penning trap to be filled with products of a fragmentation reaction (see Schury *et al.*, Ringle *et al.* and Sun *et al.* in [24]). Overcoming great difficulties with contamination from the rather violent stopping of the fragmented beam in a gas cell, LEBIT has now produced its first result, on ^{38}Ca [58]. Further results, on stable species, have validated LEBIT's accuracy to a few parts in 10^{-8} [59]. LEBIT has reached a great milestone in opening the world of fragmentation to the Penning trap and will be of great importance for the future.

Not content at MSU only measuring masses with a Penning trap, a new experiment has been commissioned, inspired by SPEG at GANIL, coupling time-of-flight and rigidity measurements of fragmented beams (see Matos [35] with promising results recorded on very neutron-rich species produced by fragmentation of a Kr beam (see Estrade, this volume).

Another interesting (non-Penning-trap!) development was made at ORNL where masses of neutron-rich species produced by an ISOL fission target were measured as position differences between known and unknown-mass isobars, dispersed at the image of the energy-analyzing magnet following the 25 MV tandem post-accelerator, and identified by an energy-loss measurement [61].

Two other Penning traps are being commissioned. One is MAFFTRAP which will enjoy the copious production rates of neutron-rich species offered by thermal neutron-induced fission using the FRM-2 reactor, now operating near Garching (see Habs *et al.* in [24]). Also under test is TITAN, a Penning trap at TRIUMF in Vancouver, which will be the first installation to use high-charge states of radioactive species (bred in an EBIT) to achieve higher accuracy (i.e., higher cyclotron frequencies) with shorter trapping times (see [60] and Dilling *et al.* and Rykov *et al.* in [24]).

In addition to SMILETRAP, two other Penning trap spectrometers continue in the pursuit of the ultimate precision (currently approaching 10^{-11}) of the masses of stable nuclides: the "Tallahassee Trap" (at Florida State University [47, 48], formerly at MIT [46]) and the University of Washington Penning trap (UWPTMS) [45].

Figure 4 shows an interesting comparison of the different techniques devoted to radioactive species: the obtained measurement uncertainty (for some recent results) as a function of the isobaric distance from stability of the measured nuclide (see [12] for description). The most striking feature (compared to the 2003 version of the figure [12] and the 2005 version [14] is the amount of new data and new programs. All in all, the different techniques are quite complementary. Without going into details (see Lunney in [24] for those), it is clear to see that achieving good accuracy is difficult to very short-lived nuclides. However, great progress is being made in the case of traps for accessing more exotic nuclides.

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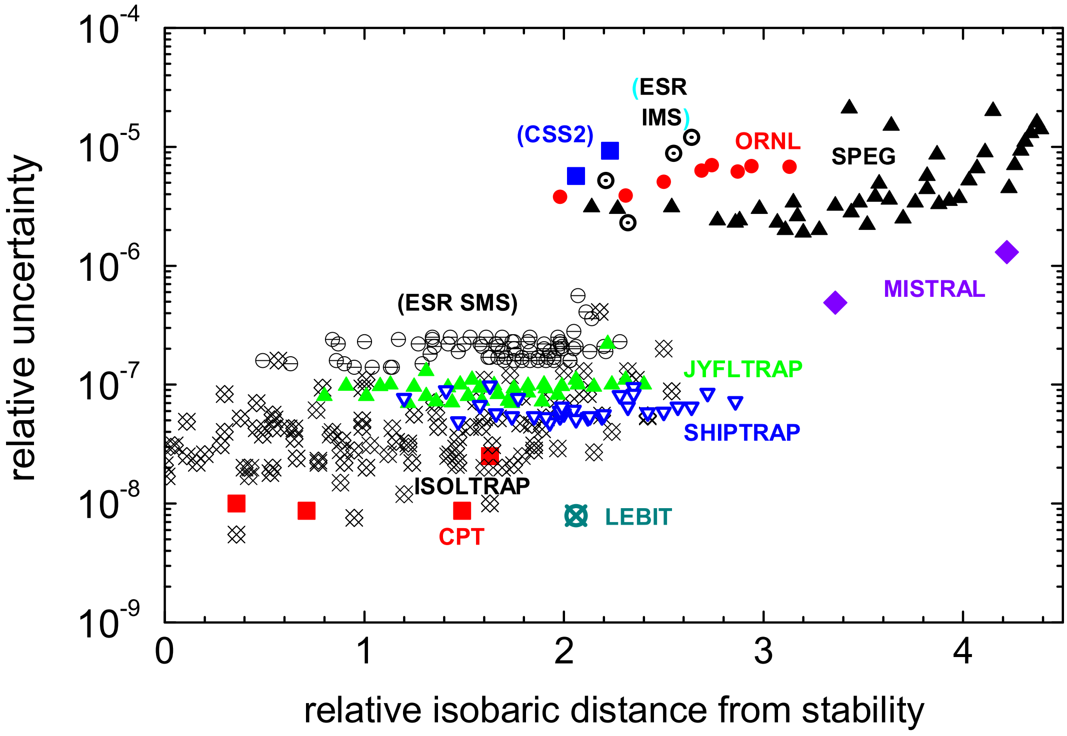

Figure 4: Experimental uncertainty of mass results (published in only the last 3-4 years) versus isobaric distance from stability for each nuclide (see [12] for description where a 2003 version is shown - note that the programs in brackets correspond to older data shown for comparison). Data from SPEG: Savajols *et al.* in [24]; CSS2: [27]; ESR-IMS: [34]; ESR-SMS: [30]; MISTRAL: Bachelet *et al.* in [24]; CPT: [52, 25]; ISOLTRAP: Herfurth *et al.* and Guénaut *et al.* in [24]; JYFLTRAP: [54, 55, 56, 57]; SHIPTRAP: [53] and Vorobyev, this volume; LEBIT: [58]; ORNL: [61].

4. The Atomic-Mass Evaluation: not just a mass table

It is important to distinguish the AME from a simple compilation of data. Since the atomic mass unit has been defined as one twelfth the mass of the ^{12}C atom, the mass of every other nuclide is ultimately linked. Due to the inherent difficulty of measuring magnetic fields with sufficient accuracy, the masses measured by direct (inertial) methods are always given with respect to a well-known reference measured the same way. In the case of indirect (energy) methods, an absolute mass is not usually given but a decay or reaction $Q-$value. Thus, the ensemble of all reaction, decay and spectrometry data possesses many cross links. In order to produce a mass table from this data, a detailed evaluation must be performed. Note that this is unlike any other physical quantity (e.g., the half life) that can be directly inserted into a compilation.

For many years now, we have been privileged to have two grand inquisitors for atomic masses (G. Audi and A.H. Wapstra) whose careful evaluation of the various input data produced the atomic mass table. The evaluation ensures that the mass determined in any one way is coherent when determined independently. The most recent atomic mass evaluation [10] contains 2228 experimental masses and another 951 estimated from systematic trends. These masses are the result of the combination of 7773 experimental data (of which 374 are rejected as a result of careful evaluation), solving 1381 equations with 847 parameters in order to produce the mass table. The mass table is a unique case of providing a global starting point - and benchmark - for the development of mass models.

5. Mass models (and chaos)

Despite the impressive developments in mass spectrometry, and those with associated radioactive beam production and handling techniques, it is still not yet possible to reach many of the nuclides involved in the *r* process, leaving no choice but to resort to theory.

Attempts at (and needs for) the prediction of the nuclear mass date from not so long after the very discovery of the binding energy. The first mass formula was that of Von Weizsaecker [64]. The same formula is still used today with various refinements – sometimes in (dubious) attempts at mass predictions but mostly for illustrating the effects of shell closures that were not included. It is instructive to consider that Von Weizsaecker initially formulated his model using only four parameters (volume, surface, symmetry, and Coulomb) which he fit to the 200 or so mass values known at the time. The same exercise today, using the 2228 masses now known, achieves an rms error of only 4.25 MeV. Given the absence of shell effects (unknown in Von Weizsaecker's time), this is a remarkable achievement.[6]

For the last 60 years, mass formulas have been based on this type of liquid-drop formula with "modern" refinements from microscopic effects such as shell closures and deformation (see general description in [12]). This class of models is known as microscopic-macroscopic due their hybrid nature. Such models are widely used since they provide extended data sets for masses and sometimes, other nuclear properties. The most well-known microscopic-macroscopic approach is the Finite-Range Droplet Model (FRDM) of Moeller, Nix *et al.* [65]. The FRDM has pushed the mic-mac approach to its limit and is exemplary for the generalized data sets and availability. The microscopic part, though somewhat uncoupled from the liquid-drop part, is constructed using a single-particle, folded Yukawa potential which can also be used to generate beta-decay half-lives, strength functions, fission barriers and nuclear deformation parameters in addition to the mass.

Some handy algebraic relations exist that have been formulated from the symmetry of the nuclear charge and (taking into account the easily-determined Coulomb component) allow reasonable calculation of locally-unknown masses surrounded by known ones. Examples are, the Isospin Mass Multiplet Equation (IMME) with which the mass of a nuclide forming an isobaric analog multiplet can be remarkably reproduced using only a quadratic function. Another scheme, the Garvey-Kelson relation, uses a similar idea but by constructing a sort of finite-difference grid in which unknown masses are determined iteratively using the neighboring known masses as boundary values. Such relations, broadly classified as local, can be useful where specific, locally-unknown masses are required (for example, near the proton drip line) but generally show gross systematic deviations in

[6] The formula also gives a prediction for the location of the drip lines in astonishing concordance with that of a microscopic mean-field model (see Fig.2 by J.M. Pearson in [19]).

distant, unknown territory (see discussion in [12]). Moreover, no auxiliary nuclear properties can be computed.

A microscopically-rooted approach worth mentioning is an evolution by Duflo and Zuker, inspired by the Shell-Model Hamiltonian [66]. Though still a parametrization, (in order to empirically bypass the problematic monopole term which is responsible for nuclear saturation), it involves solving the Schroedinger equation that produces wave functions from which other nuclear properties may be consistently derived in addition to a full mass table.

Mass tables have – at last – been constructed using a nucleon-nucleon interaction: the Skyrme-Hartree-Fock-Bogoliubov appraoch (see detailed discussion in [12]). Due to the availability of copious computing power, systematic variations of Skyrme-force parameters can now be performed, using the experimental mass data as a diagnostic. The sensitivity of the interaction parameters has been systematically studied through the elaboration of a total of 13 mass tables, one of which, HFB9, was tailored to satisfy constraints of neutron matter. These tables now provide residual fits to the ensemble of known nuclides that rival all other approaches. Goriely, Samyn, Pearson, (*et al.*, sometimes) discuss the HFB-13 in [63] where references to the previous mass tables can be found.

The question that we obviously need to ask is: What is the best mass model? Alas, it will be impossible to answer given the apparent failure of theory and the need for experiment to confirm reality. However, the problem is that experiment is in no position to determine the location of the drip line and we are forced, in a vicious circle, to rely on theory. Let us examine some criteria that might help us judge the different approaches.

One benchmark of importance is the *rms* error of model predictions compared to experimental data. This quantity is a first indication since the models are all adjusted to the same data. Indeed, this is one of the fundamental contributions that the Atomic Mass Evaluation makes to nuclear theory, by providing common starting point and benchmark data for meaningful comparison.

Fig. 5 shows the *rms* error of various models. On the left are the global models. On the right are local models for which essentially all calculated masses are adjustable. For more details on these models and their (number of) parameters, see [12].

The local models generally provide a better fit, simply because they have a very large parameter space and as such, more *souplesse* for incorporating different effects. This causes disaster for extrapolations, however. In the case of the Garvey-Kelson relations (GK in Fig. 5) only 60% of the experimental masses could be reproduced, since going farther caused instability in the algorithm. With the exception of Duflo-Zuker (DZ in Fig. 5), who show an impressive fit of only 375 keV, the global models all give practically the same fit of about 700 keV. This observation prompted Bohigas and Leboeuf [67] to suggest that perhaps the idea of chaos, or fluctuations in the periodic orbits of particles in the nuclear potential, contrive to limit the possibilities in calculation of the nuclear binding energy. This interesting idea has been taken up by others, notably Hirsch et al. in [24] who have exploited the non-physics of the Garvey-Kelson relations to lower this limit to about 80 keV.

The *rms* error can be viewed as a scalar indication. Perhaps more important, due to the fact that we develop models in order to extrapolate, is a vector approach. For this we can calculate the rms error for new data, which have not been used in the adjustment procedure. This study was performed in [12] and the reader is referred there for the results and discussion. It is interesting to note that there is no consensus amongst the different models concerning extrapolation. The

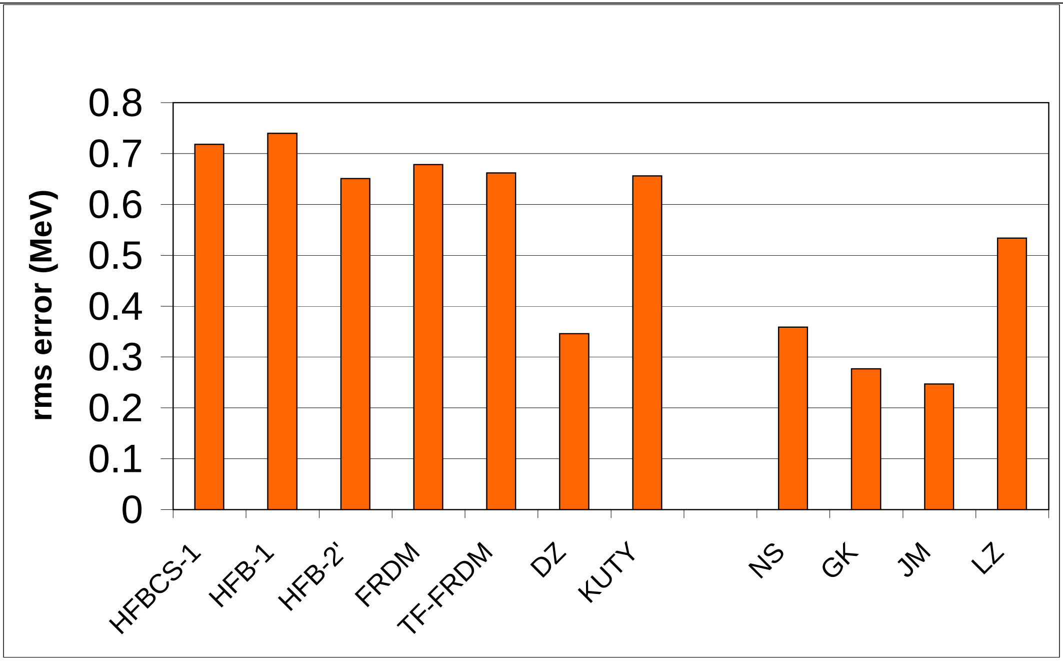

Figure 5: The root-mean-square difference between experimental masses (of the AME1995) and different mass models (global approaches on the left and local, on the right). See [12] for model descriptions.

question indeed becomes existential, invoking the idea expressed by Kierkegaard: "...a truth that is true for me."

6. Epilog

We have seen that CERN, *Lord of the Rings* and site of NiC-IX, is not only a place where the deepest cosmological questions are probed (at the LHC) but also where the very first mass measurements of exotic nuclei were performed (at the PS) and where that fine tradition continues (at ISOLDE), producing the most accurate results of the age.

Nuclear Astrophysics, or Astronuclear physics, as some refer to it [68], will continue to struggle due to considerable uncertainties (and impossibilities) regarding observations. Whatever the role that exotic nuclides will play, the impressive feats and progress in the field of mass measurements will not be to blame!

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