Nuclear Masses: Experimental Programs, Theoretical Models and Astrophysical Interest

David Lunney

[1] *Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse*
CSNSM-IN2P3-CNRS, Batiment 108, F–91405 Orsay, France

Abstract. Knowledge of the mass plays a key role in understanding the nuclear physics of interest to astrophysics. Some nucleosynthesis scenarios, for example, involve isotopes that may never be produced in the laboratory. In these cases mass models must be used, however there are none in agreement beyond what is measured. A brief review of the various models available and the numerous experimental programs dedicated to mass measurements is given along with an outline of the astrophysical motivation.

1 Introduction

The atomic mass is a particular quantity. It embodies the net result of all the interactions present in the atom and gives us indications of all of these when we can make a very accurate mass measurement. This is due to the fact that the mass of an atom, and especially of a nucleus, is not merely the sum of the masses of its constituents but is accompanied by a binding energy. Thus, the mass is sought after by scientists in many different domains. Chemists and biologists, though not requiring absolute mass determinations, depend heavily on mass spectrometry of large molecular fragments in order to study reaction dynamics. In atomic physics, accurate mass measurements of highly charged atoms reveal relativistic effects and other contributions to atomic binding energies beyond what is accounted for by quantum electrodynamics. Particle physics can be dramatically affected by the results of high precision mass measurements. One example is the case of super-allowed $(0^+ \rightarrow 0^+)$ β-decay that can constrain the up quark-down quark element of the Cabibbo-Kobayashi-Maskawa mixing matrix. This quantity dominates the unitarity tests that must be satisfied by a three-generation standard model. Masses have a great influence on nuclear physics as the binding energy reveals a host of nuclear structure effects: "magic" configuration number effects (known as shell, and sub-shell closures), shape and deformation effects, and also nucleon pairing. Finally, as the binding energy determines how much energy is available for a given nuclear reaction, the impact of masses in astrophysics is far reaching. A host of quantities derived from the mass are in play, notably neutron and proton separation energies.

The mass is particular in another way: it is the only fundamental quantity whose standard measure is defined by an object. *The* kilogram resides in Sèvres, near Paris. So near to smoggy Paris, in fact, that part of its definition includes a cleaning recipe! Metrological efforts are underway to redefine this standard by counting the number of Si atoms in a pure crystal lattice and redefining the Avogadro constant. Obviously such an effort requires a superlative mass measurement of ^{28}Si.

Since we have defined the atomic mass unit as one twelfth the mass of the ^{12}C atom, every other mass is ultimately linked. Since masses can be measured by a variety of techniques or even reactions (section 4) we are privileged to have two grand inquisitors of atomic masses, evaluators who take care to check that the mass determined one way jibes with the same mass determined via a different reaction or technique. Thus this exercise is far from a mere compilation and the results are sometimes surprising. This atomic mass evaluation, currently containing almost 2000 harmoniously adjusted values, is published every few years and is now available electronically via the WWW [1].

2 Masses and the r-process

Modeling astrophysical processes is challenging (to say the least!) not only because we cannot build a stellar laboratory but also stellar time scales 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. Astrophysicists would like to be sure of the starting points for their models in order to have better leeway mapping out their cosmic scenarios.

The rapid neutron-capture nucleosynthesis process is thought to be associated with exploding supernovae when seed nuclei feed on an enormous neutron flux produced in this cataclysmic environment. The consequence of this reaction is that a large fraction of our heavist elements are produced and ejected into the interstellar medium. The various paths followed by this reaction course through an exotic landscape of very short-lived neutron-rich nuclei as they 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 a hillside after a rain storm.

In a perfect world, we would like to follow these r-process paths with our mass spectrometer (in itself a lifetime of work and for many people) but several problems prevent that at present, not the least of which is that there is currently no radioisotope facility on the planet that can even produce most of the isotopes in question! Exceptions occur at the so- called "waiting points" near "magic" neutron numbers where the isotopes pause to digest their neutrons, prefering to suffer several β-decays that bring the flow back towards stability.

In order to eventually determine the trajectory of the r-process under given astrophysical conditions, we must start by determining the neutron separation energy (S_n, derived from the mass difference of adjacent isotopes) of essentially every single isotope on the neutron-rich side of stability. While gorging on neutrons, a given isotope along the r-process path becomes an easy target for marauding γ-rays that can strip off these loosely held neutrons. 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 (statistical models may not be applicable in this region of small S_n). Thus you find yourself having to collaborate with a group of nuclear spectroscopists who not only have to worry about good old-fashioned β-decay but also β-delayed-neutron decay. And if it wasn't already enough, even more information is needed regarding nuclear potentials and giant dipole resonances [2].

Viewed in this way, it seems to be a hopeless situation. However, to pursue these fascinating questions further, we can turn to nuclear mass models.

3 A brief history of mass models

Mass models started out as empirical formulas but have now evolved into more or less full scale nuclear models, many capable of predicting a whole host of nuclear properties besides the mass.

Some handy relations exist that depend on the symmetry of the nuclear charge and (taking into account the easily determined Coulomb component) allow calculation of masses of unknown n-rich nuclei from known p-rich ones opposite the $N = Z$ line. This is generally know as the Isospin Mass Multiplet Equation (IMME)[3]. Another, the Garvey-Kelson relation, uses a similar idea but by contructing a sort of finite-difference grid using the known masses as boundary values [4]. These types of algebraic relations, broadly classified as *local*, have limited use and generally show gross systematic deviations in far, unknown territory. They represent a somehow unpalatable empirical approach.

Efforts at "modern" mass models try to build in fundamental physics. It seems easy to believe that this is the best strategy for expeditions into the far unknown. Enjoying reasonable success and relative ease of use are the class of mesoscopic models where a gross, *macroscopic* component simply dependent on the number of nucleons, is finely sculpted using *microscopic* corrections for shell behavior, deformation, nuclear compressibility, nucleon pairing, *etc.* This approach finds its orgins in the famous Bethe-Weizsaecker mass formula. These corrections are parametrized and the parameters fixed by minimizing a fit to all known masses. Some questions arise about what can be called a parameter and there exist models with quite a large number, always presenting a danger of potentially unstable extrapolation.

Probably the best known of this class of models is the Finite Range Droplet Model (FRDM)[5]. Containing a relatively modest number of parameters, it not only fits the known masses with a good residual error, but generates a huge range of auxiliary data of interest to nuclear physics and astrophysics. Indeed, the FRDM has been used extensively for modeling the very r-process itself. [6]

The third category of models is classified as fully microscopic. These models are ostensibly built on first principles, namely an effective two-body (nucleon-nucleon) interaction or a relativistic mean field (RMF). The former are called Hartree-Fock (HF) and if pairing is included then they are Hartree-Fock-Bogoliubov (HFB) [7] HFB calculations and can employ a variety of different interaction recipes, the best-known being either a zero-range (Skyrme) or finite-range (Gogny) interaction. The latter describes the nuclear interaction by an exchange of mesons and photons using a parametrized Lagrangian [8]. In reality there are some empirical parameters in these HFB and RMF potentials since we still do not know the exact nature of the nuclear force. These approaches permit the calculation of any nuclear property one might desire (in a fully self-consistent manner) but they pay for their fundamentalness in computation time and consequently there does not yet exist an HFB or RMF mass table as such. Strangely enough, these microscopic models do a somewhat disappointing job reproducing known mass values but then again they have no free parameters either. A further problem is that aside from restrictions to undeformed nuclei, they generally do not succeed in calculating odd nuclei - something of an inconvenience for astrophysics. Here, a mesoscopic model, while perhaps less reliable in its calculations of auxiliary quantities, can at least produce the data needed to set the astrophysicist to work.

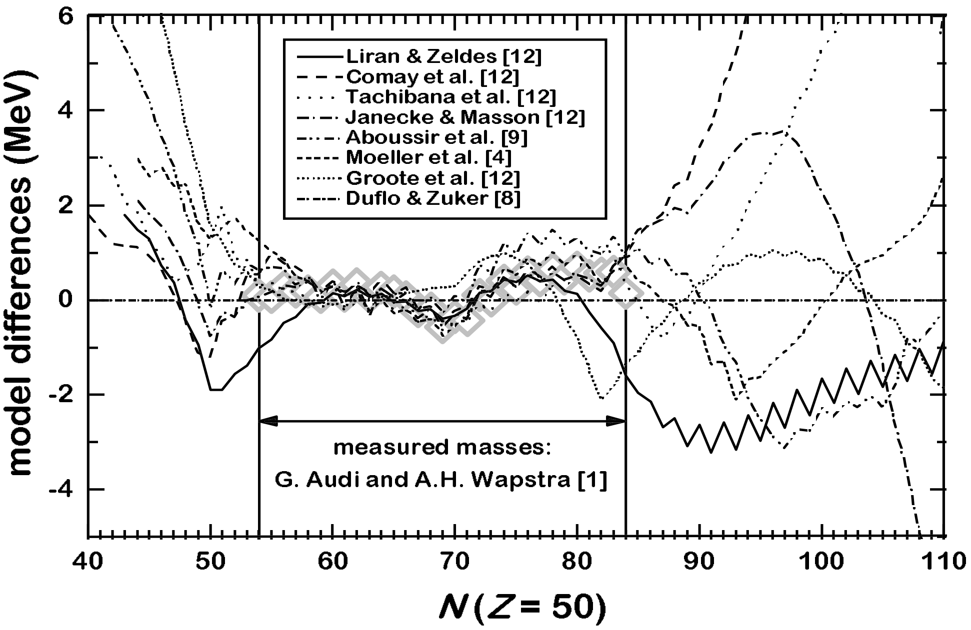

Figure 1: Relative differences in mass predictions between several mass models together with experimental results from [1]. Where masses are known, agreement between the various models is seen whereas outside this region the predictions diverge.

Another microscopically rooted approach worth mentioning is an evolution by Duflo and Zuker [9] of the famous shell model. Though still a parametrization, it employs only seven terms and by using wave functions, produces masses, radii and excited states. This approach holds some promise for the future because of its self-consistency coupled with ease of computation.

In a compromise between a fully microscopic description and a complete generation of nuclear data, the Extended Thomas-Fermi Strutinski Integral (ETFSI) model was born [10]. It is mesoscopic, using the Strutinski shell correction and other microscopic sculpturings of a macroscopic nuclear blob but in this case the blob is the Thomas-Fermi approximation to the microscopic HF approach. The Strutinski shell correction is also made using the very same force as in the macroscopic part. This model consequently enjoys success in mass prediction and extension to r-process calculations [11, 2].

In an attempt to analyse what these various models tell us, figure 1 shows us the differences between a host of models (either mesoscopic or local) for a particular element. (Patyk *et al.* [12] have produced a nice review of these various approaches including comparisons with microscopic models.) One can easily see that in areas of known nuclei (where the parameters are fit) there is excellent agreement but outside this region - an almost immediately outside - the divergence is striking. Aside from the problem of generating auxiliary physical quantities, the very question of which model to choose just for mass values is a perplexing one.

4 Mass measurement programs

In the eternal quest for the truth, we again must turn to experiment in order to test the diverging opinions of these various models. There are in fact, several experiments dedicated to the measurement of masses both on-line and off. Off- line experiments will generally refine the mass surface closer to stability, improving the fit of a given model. Such measurements are also of great use for calibration masses. Only on-line experiments will allow us to get to short-lived nuclei to really test the various model predictions (perhaps elucidating new nuclear structure in the process) on the condition that the result is of sufficient accuracy.

On-line mass measurements in nuclear physics can be divided into two broad categories: direct and indirect. Though all measurements are indirect in the sense that we must ultimately compare them to the standard of ^{12}C, the question is whether we mesure one mass with respect to another (direct) or the difference between two masses (indirect). The latter type usually result from reaction or nuclear decay measurements. When doing nuclear spectroscopy, for example, the endpoint of a β-spectrum will give the difference between the parent and daughter nuclide. Problems arise however in accurately determining this endpoint since it will depend somewhat on the nuclear levels feeding the ground state. It often happens that masses determined from spectroscopy have mistaken the ground state for an excited (isomeric) state. This error can be compounded as the differences are measured further and further from known mass values. Direct, mass spectrometry measurements are needed to anchor these floating chains of relative measurements. As described below, direct measurements rely either on time-of-flight or frequency determinations (in the past voltage measurements were used but are now much less common).

Nuclear physics can be broadly divided into experiments using *thick* targets and *thin* targets to produce the radioisotopes for study. The production technique has a great influence on what type of mass measurement is possible. Thin targets are bombarded generally at high energy, fragmenting the projectile and producing easily identifiable exotic nuclei but in very small quantities and with inferior beam properties. Thick targets, on the other hand, tend to produce less chemically selective but more intense radioactive beams that are of higher optical quality. Spallation or fission of these targets by a primary projectile produces the radioactive species that diffuse from the (heated) target matrix. Once ionized, the isotopes are accelerated to produce good quality beams of modest energy (*e.g.,* 60 keV at the ISOLDE facility at CERN [14]). Such beams can be more easily used for precision measurements rather than the more rudimentary counting and coincidence measurements using higher energy beams from thin targets.

A recent example using a thin target is the mass measurement of ^{100}Sn at GANIL [15] - a veritable exploit but unfortunately, of not sufficient enough accuracy to pick a real model winner. The measurement technique is original, using two phase-locked cyclotrons to accelerate the isotope in question (produced by fragmentation after the first cyclotron, CSS1) and determine its mass by time-of-flight inside the second cyclotron, CSS2. A similar technique is being used at SARA in Grenoble where their cyclotrons are uncoupled [16].

Also at GANIL, the energy-loss spectrometer SPEG has been frequently used in conjunction with time-of-flight for exotic mass measurements.[17] A similar technique was, for a long-time used at Los Alamos with the TOFI spectrometer [18]. While the masses produced are quite far from stability, the accuracy of these measurement, about 1 ppm, is just barely sufficient to distinguish between mass models.

Penning traps deserve special mention as they hold the current records for mass measurements of the highest accuracy. Inside the serene environment of a high magnetic field and quadrupole electric field, trapped ions readily subject themselves to various judicious couplings of their eigenfrequencies that allows the measurement of their cyclotron frequency and hence, their mass. This frequency is compared to that of a reference mass measured in the same way (at nearly the same time). These record measurements (better than 10^{-10}) are performed on stable isotopes that are generally created inside a cryogenically sealed trap, well away from polluting particle accelerators [19].

Using a Penning trap to measure radioactive ions is a different story however. Getting ions from a mass separator, with relatively high kinetic energies, into a trap compromises somewhat the trap's performance. Nonetheless, the ISOLTRAP spectrometer at CERN manages to make very accurate measurements (better than 10^{-7}) on quite short- lived nuclei [20]. One of the key successes is using a first Penning trap to clean unwanted isobars and cool the ion of interest before sending it into a precision trap for measurement. Over 100 masses have now been measured by ISOLTRAP [21]. ISOLTRAP's cousin, CPT (which now stands for Chicago Penning Trap but originally stood for the *Canadian* Penning Trap, developed at Chalk River National Laboratory and moved after the sad and untimely closure of the TASCC facility there) is presently under test at Argonne National Laboratory [22].

Two experiments dedicated to mass measurements are permanent residents of ISOLDE: ISOLTRAP and more recently, MISTRAL [23]. MISTRAL complements ISOLTRAP by aiming for very short-lived nuclides that become difficult with the Penning trap due to the simple fact that the ions must be stored for some time in order to measure their mass. While not as accurate as the Penning trap, MISTRAL, a radio-frequency, Smith-type spectrometer, achieves very good accuracy with no limit on life-time. (Note: one week after this *NiC* conference, MISTRAL had its first data taking run, successfully measuring masses of $^{23-30}$Na with good accuracy. The lifetimes of the last three isotopes are all less than 50 ms.)

One technique that uses the best of both situations is the Experimental Storage Ring (ESR) at GSI, Darmstadt [24]. The isotopes under study are produced at high energy with a thin target and then injected into the ring where they are cooled. As the circulating ions pass through a set of metal plates, they induce a so-called Schottky signal and the frequency of this signal can determine the mass. A great advantage of this technique is that many measurements are made simulaneously and furthermore, the decay of the signal height with time gives additional information about the radioactive half-life [25].

These various experimental approaches are all complementary. and so many programs dedicated to masses is a good sign of the interest in the various physics problems evoked in section 1. For constraining mass models, it is important that masses of exotic isotopes are correct by different types of measurements. For more details concerning the various measurement techniques, the reader is refered to two recent reviews [26, 27].

5 Conclusion

The need for accurate mass measurements is important for nucleosynthesis in order to place serious constraints of the wide variety of theoretical possiblities. Several experiments dedicated to on-line mass measurements now exist at radioisotope facilities. All complementary, it is also important that we compare measurements of the same isotopes from all these experiments wherever possible in order to ensure consistency.

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