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TESTING ATOMIC MASS MODELS WITH RADIOACTIVE BEAMS*

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ABSTRACT

Significantly increased yields of new or poorly characterized exotic isotopes that lie far from beta-decay stability can be expected when radioactive beams are used to produce these nuclides. Measurements of the masses of these new species are very important. Such measurements are motivated by the general tendency of mass models to diverge from one another upon excursions from the line of beta-stability. Therefore in these regions (where atomic mass data are presently nonexistent or sparse) the models can be tested rigorously to highlight the features that affect the quality of their short-range and long-range extrapolation properties. Selection of systems to study can be guided, in part, by a desire to probe those mass regions where distinctions among mass models are most apparent and where yields of exotic isotopes, produced via radioactive beams, can be optimized. Identification of models in such regions that have good predictive properties will aid materially in guiding the selection of additional experiments which ultimately will provide expansion of the atomic mass database for further refinement of the mass models.

INTRODUCTION

A number of features of nuclear structure and nuclear dynamics have been investigated by studies of nuclei far from stability. In addition to characterization of the mass surface, these have included mapping the variation of single particle energies with proton and neutron number, following evolution of nuclear deformation between shell closures, observing the onset of fissility and examining fission decay modes, characterizing beta-delayed particle emission and direct proton radioactivity, and elucidating aspects of nuclear structure that are important in *r*- and *rp*-process nucleosynthesis.

New accelerator facilities that will provide radioactive beams will allow even greater excursions to be made from the valley of beta stability. As a consequence of increased available decay energy of the produced nuclides, more exotic decay channels will be opened, many of which will provide the opportunity to expand studies of the type

enumerated above and to discover entirely new features of nuclear structure. In anticipation of the construction of one or more large radioactive beams facilities it is instructive to prepare some preliminary plans for the study of the masses of new nuclei that could be prepared and characterized at such facilities. This contribution to the Proceedings is a summary of the motivations and methods that underlie such activities.

DIVERGENCES IN MASS MODEL PREDICTIONS

Calculation and Analysis Methods

It is useful to examine the predictions of atomic mass models in regions beyond the body of measured masses, since these regions will be the ones where exploratory studies with radioactive beams will begin. Previous experience has shown[1] that mass model predictions (as well as predictions of other nuclear properties) diverge from one another in regions far from stability and that this divergence frequently becomes large and occurs rapidly on excursions from the valley of beta stability. *Where these divergences occur and how fast they occur are useful pieces of information.* They can point to specific mass regions where selected projectile/target combinations can be employed to produce optimal yields of new isotopes for broad ranging studies of nuclear structure and masses at those places where distinctions among models are most apparent.

Using the recently published 1986 - 1987 Atomic Mass Predictions[2], root-mean-square (rms) divergences in the mass predictions were computed in the following way: 1) mass predictions for any measured isotopes or any isotopic masses predicted by systematics were excluded; 2) any isotope which had been predicted by any model to be on or beyond the proton or neutron drip line was excluded; and 3) at least six predictions (of the available ten sets) had to exist for the remaining cases (approximately 1,100 nuclides). Average mass predictions at each isotope and the rms deviation of the average where then computed. These were then binned according to size and plotted (figures 1 - 5) in the format of the Chart of the Nuclides. Isotopes excluded by the first criterion represent the blank areas between the very proton-rich and very neutron-rich clusters of points. The widths of the energy bins and the symbols used to denote these energy ranges are summarized in the lower part of each figure.

Analyses of these summary plots were made in two steps. In the first step, the plots were inspected to identify trends, i.e., the size and rate of spread of the mass predictions. Two classes were identified, class-1 being where divergences tended to be

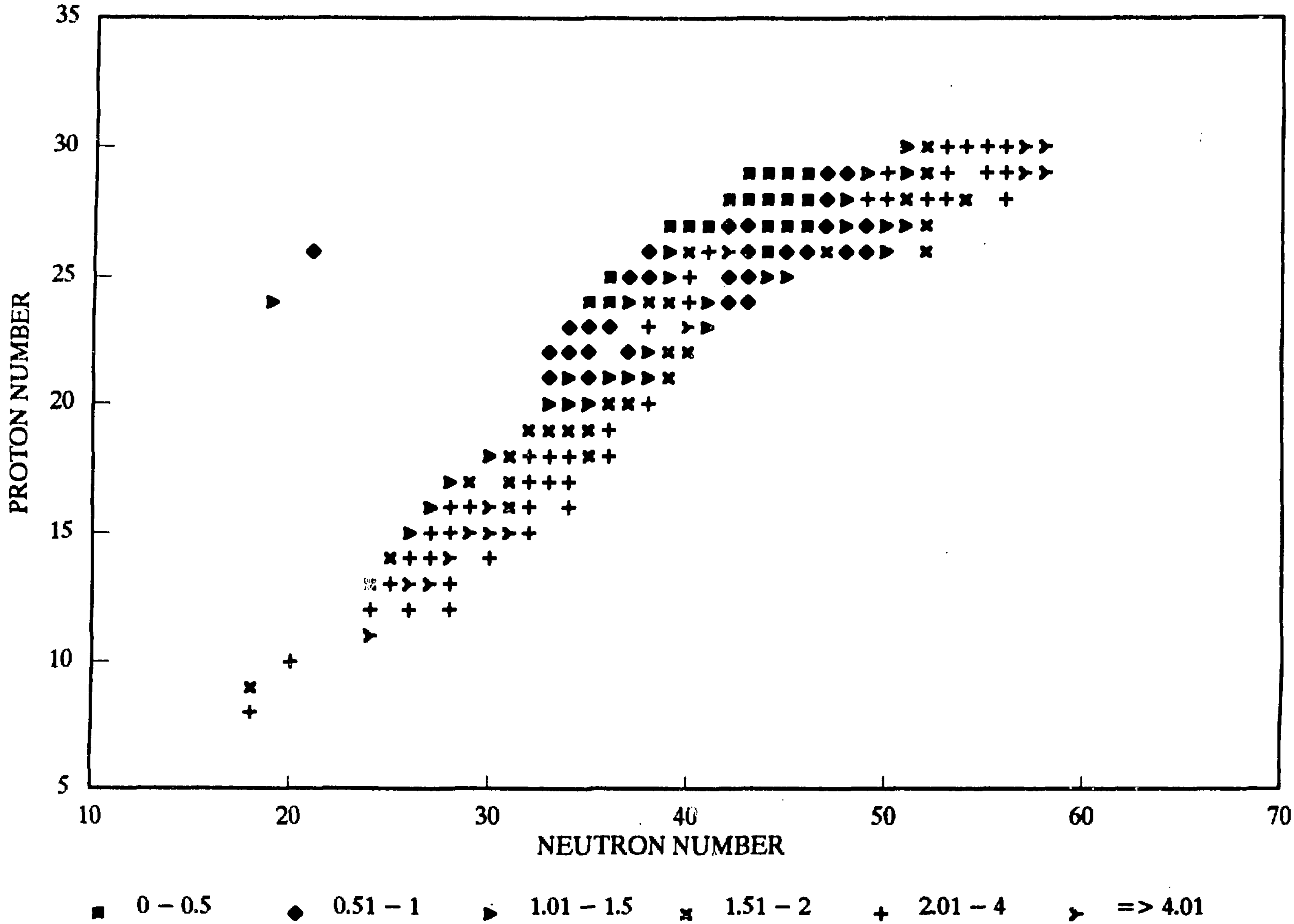

Figure 1. Root-mean-square (rms) divergences of atomic mass predictions, plotted for Z = 8 to 30 in the format of the Chart of Nuclides. The rms deviations (in MeV) are binned by energy. Symbols at the bottom of the figure indicate the ranges of the energy bins.

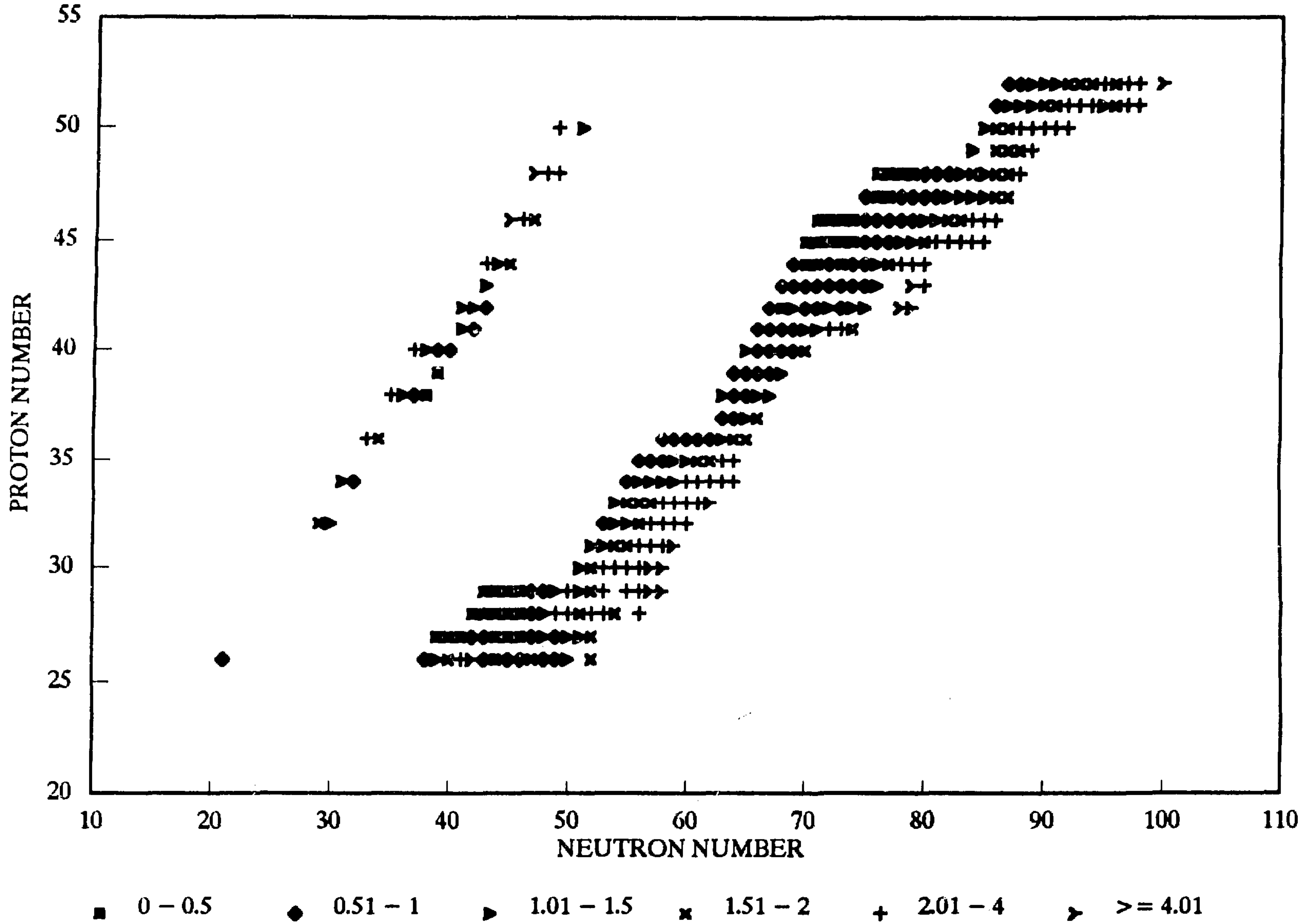

Figure 2. Root-mean-square (rms) divergences of atomic mass predictions, plotted for Z = 26 to 52 in the format of the Chart of Nuclides. See figure 1 for symbol definitions.

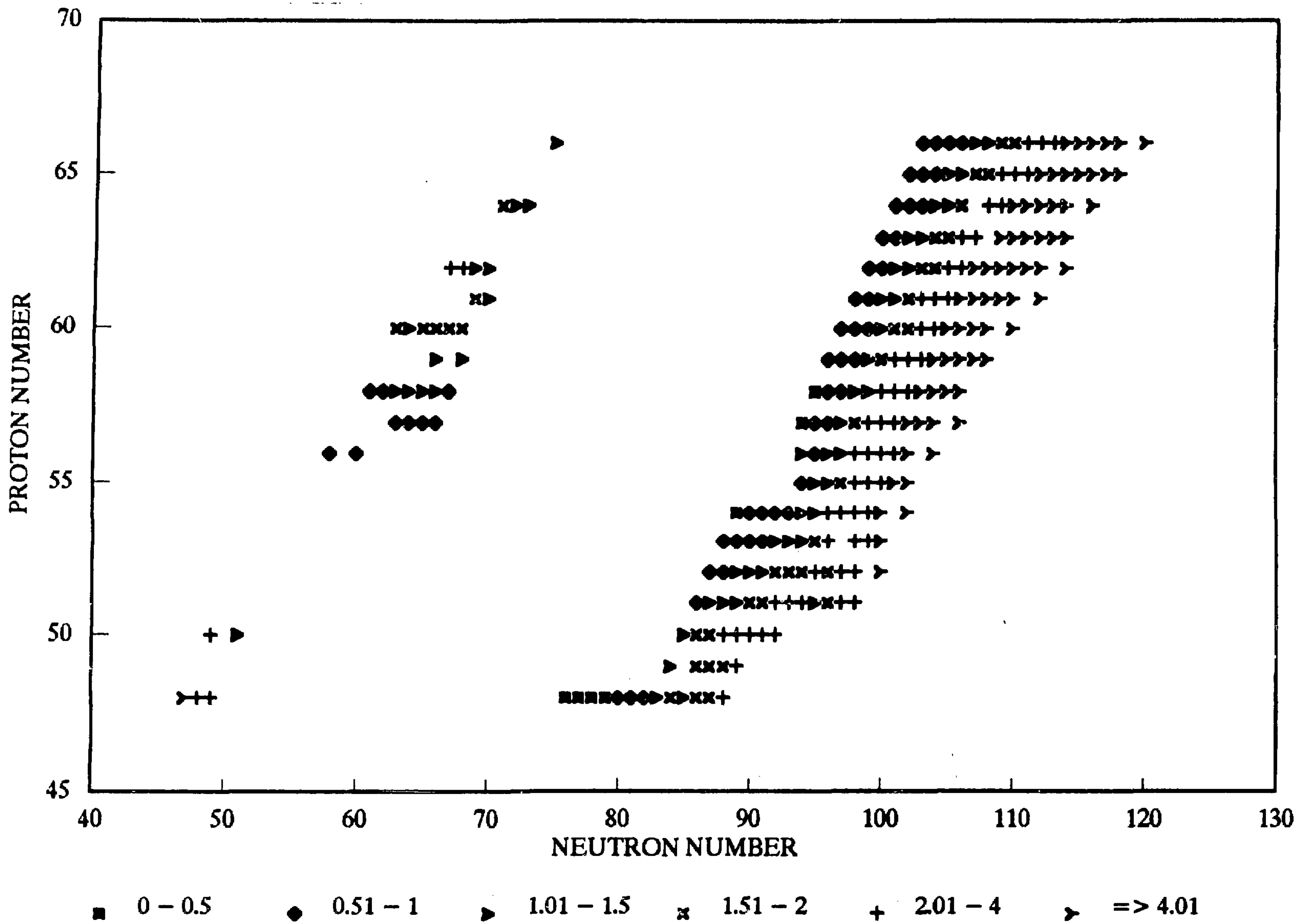

Figure 3. Root-mean-square (rms) divergences of atomic mass predictions, plotted for Z = 48 to 66 in the format of the Chart of Nuclides. See figure 1 for symbol definitions.

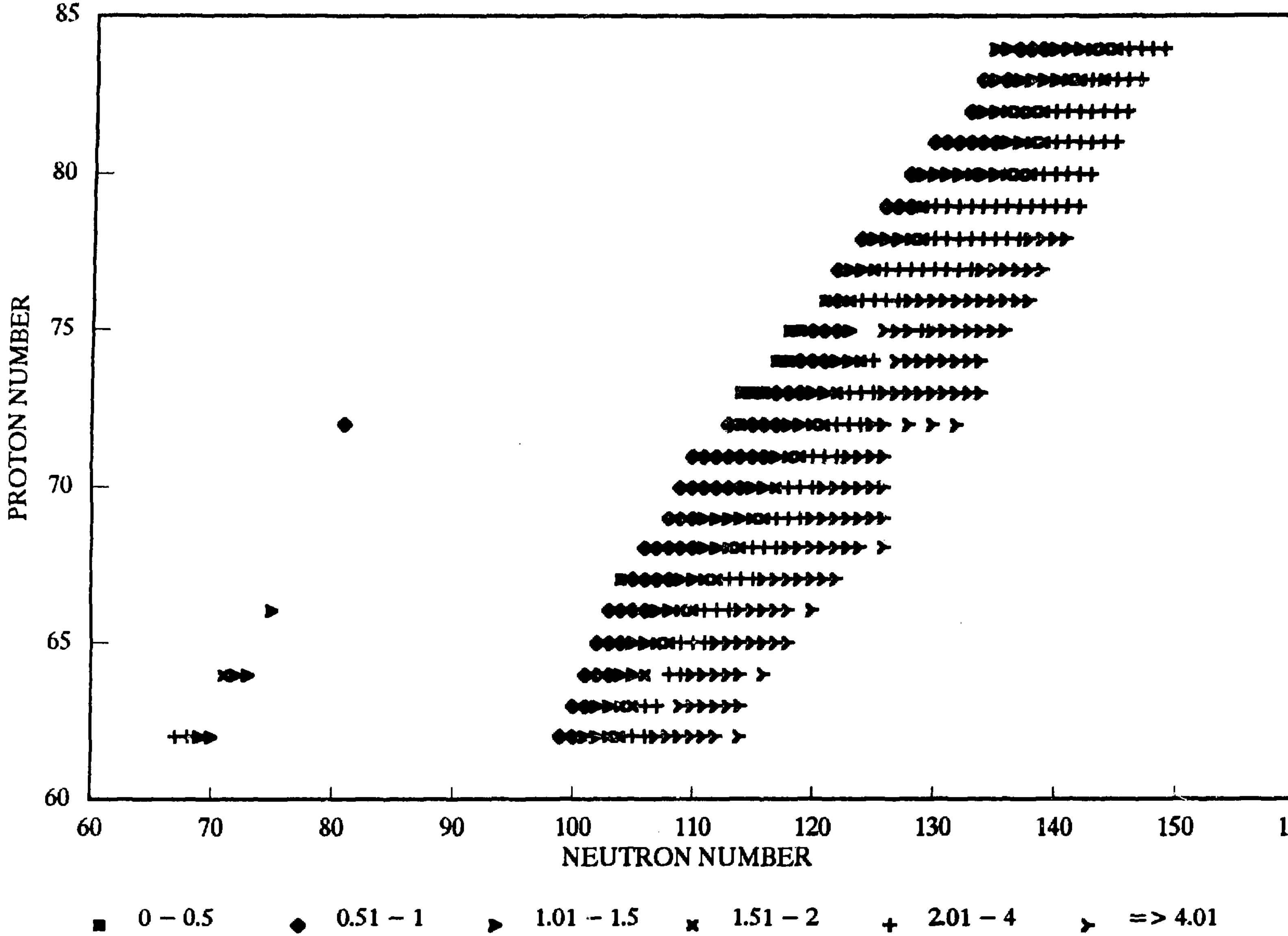

Figure 4. Root-mean-square (rms) divergences of atomic mass predictions, plotted for Z = 62 to 84 in the format of the Chart of Nuclides. See figure 1 for symbol definitions.

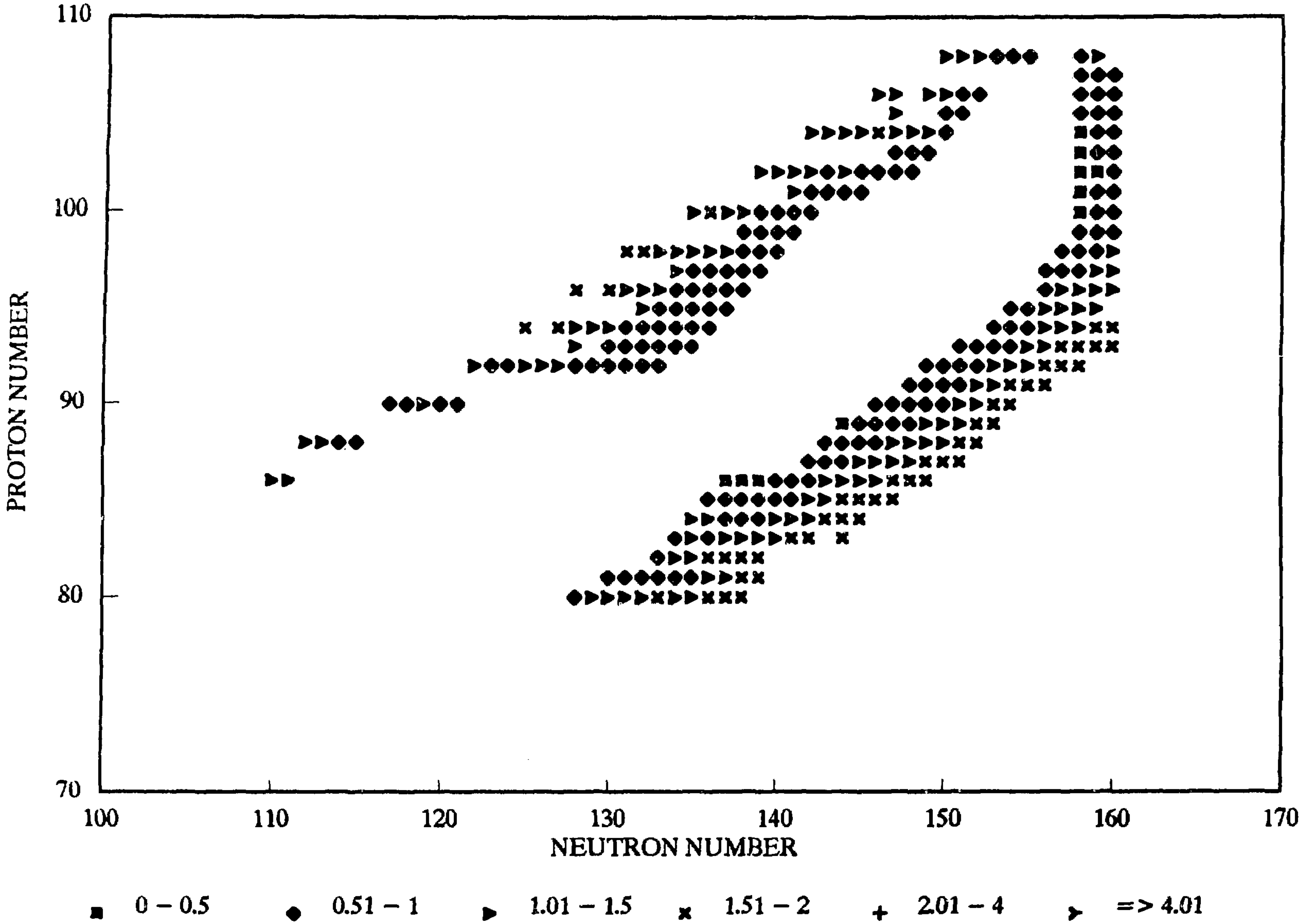

Figure 5. Root-mean-square (rms) divergences of atomic mass predictions, plotted for Z = 80 to 108 in the format of the Chart of Nuclides. See figure 1 for symbol definitions.

small and to grow slowly and class-2 consisting of mass regions with large and/or rapidly growing divergences. In general the first class represents several mass regions closely adjacent to the body of measured masses; the second class also includes a few such mass regions but it also includes several other mass regions significantly further removed from stability. Radioactive beams will facilitate production of isotopic species in class-1 relative to smaller yields obtainable with stable beams. In class-2 (where careful mass measurements will provide greater insight) radioactive beams will be *essential*. In the second analysis step radioactive projectile / (radioactive) target combinations were considered to identify appropriate reaction pathways to reach the class-2 mass regions.

Regions with small divergences in mass model predictions

Several regions where divergences in mass model predictions are small have been identified and listed below in order of increasing mass:

Z = 27 to 29, neutron rich, and extending about 6 to 9 neutrons,
Z = 44 to 48, neutron rich, and extending 5 to 10 neutrons,
Z = 37 to 43, proton rich, along the N = Z line,
Z = 73 to 76, neutron rich, and extending about 5 neutrons,
Z = 81, starting near N = 126, and extending about 5 neutrons,
Z = 86, neutron rich, and extending about 5 neutrons,
Z = 100 - 104, along N = 156 & 157.

Each of these regions can be identified in the figures by clusters or groupings of symbols that correspond to the smallest rms deviations, i.e. squares (0 - 0.5 MeV) or diamonds (0.51 - 1 MeV). In most of these regions an analysis has been presented elsewhere[3)] concerning the probable origins of these consensus predictions. In general it is related to the availability of numerous mass measurements and other spectroscopic data in immediately adjacent isotopes. Mass measurements of new isotopes in each of these regions can be performed with modest extensions of existing experimental methodologies that can be additionally enhanced by use of radioactive beams.

Regions with large divergences in mass model predictions

Regions where divergences in mass predictions are either large or grow rapidly are now summarized. In almost all cases radioactive beams or radioactive targets will have to be used to reach these regions.

Z = 10 to 20, neutron rich: In these light neutron-rich nuclei rms deviations of the mass predictions range in some cases to more than 4 MeV. Any well measured masses in this region will clearly be of great interest. Indirect evidence of failures of several mass models has recently been obtained at GANIL, where the particle instability of ^{24}O has been demonstrated[4)] in studies of projectile fragments from a beam of ^{48}Ca. Several mass models predicted that ^{24}O would be stable against two-neutron emission. A program of mass measurements in this region with similar aims is also underway at the TOFI facility at Los Alamos[5)]. Radioactive beam facilities that could produce, capture, store, and momentum-cool light neutron-rich projectile fragments such as ^{40}S or ^{36}Si would provide additional means to study nuclei in this region. Inverse reactions of such beams on lighter targets are indicated for both mass measurements and other spectroscopic studies.

Z = 28 to 36, neutron-rich, especially beyond N = 50: The clusters of symbols in figure 2 (▶, ✕, etc.) signal large divergences in mass predictions for N > 50 in elements with Z between 28 and 34. This signals the influence of the N = 50 shell closure and how it is treated in the various models. It also suggests that these nuclei, which are intimately involved in *r*-process nucleosynthesis starting in lighter seed nuclei are rather poorly predicted. Radioactive beams produced from fragmentation of relatively neutron-rich stable species, e.g. ^{96}Zr , ^{100}Mo, ^{104}Ru, or even fission product 369-day ^{106}Ru appear to be the best way to reach new isotopes in this region.

Z = 44 to 50, along the N = Z line: The small divergences in mass model predictions that were characteristic of nuclei on or near the N = Z line with Z between 37 to 43 change to much larger ones for elements up to tin (Z = 50). Since the heaviest compound nucleus with N = Z that can be made with stable isotopes is ^{80}Zr (via ^{40}Ca + ^{40}Ca), further studies of heavier nuclides along the N = Z line should employ radioactive beams and/or targets. Several candidate radioactive species with N = Z to consider are ^{44}Ti, ^{48}Cr, and ^{56}Ni; each has long lifetime so that conventional methods could be employed in acceleration of these isotopes or in their fabrication as targets.

Z = 52 to 95, very neutron rich: For nuclides of medium mass and up to the light actinides, figures 3 - 5 show a consistent pattern wherein the rms divergences of mass model predictions are small at the edge of the known neutron-rich mass surface but they grow steadily with increasing neutron number, reaching more than 4 MeV in many cases. The cutoff of points on the right hand side in each figure at each Z is determined by the predicted location of the neutron drip line in the various models and the plotting requirement that at least six mass predictions exist as each isotopic position. The predicted location of the neutron drip line varies considerably from model to model and is a reflection of the generally divergent sets of predictions for very neutron-rich isotopes. Previous analysis[6)] of older sets of atomic mass predictions quantified, in detail, this aspect and its consequences. Many of the extremely neutron-rich isotopes plotted in figures 3 - 5 will be inaccessible even with the availability of radioactive beams or targets. The ones which can be reached, however, are well worth studying. If enough of them are characterized a pattern may develop that will identify the more successful models. To reach these areas present methods will have to be significantly extended, e.g., performing very fast on-line identification of fission products into the high-mass, low-yield wings of the fission product distribution. Projectile fragmentation of heavy stable nuclides that yield very neutron-rich beams would provide an alternative method to achieve adequate isotopic yields in these regions. Reactions of these beams with very neutron-rich radioactive targets should also be considered, since such combinations yield the compound nuclei with maximal neutron richness.

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