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TITLE MASSES AND DECAY PROPERTIES OF NUCLEI FAR FROM STABILITY

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Masses and Decay Properties of Nuclei Far from Stability[1]

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In 1981 a macroscopic-microscopic calculation of 28 fission barriers and 4023 nuclear masses throughout the periodic system was performed with a folded-Yukawa single-particle potential and a Finite-Range microscopic model[1,2]. A detailed analysis of the results showed that the model described well nuclear masses far from stability[1] as well as other nuclear properties, for example the onset and magnitude of nuclear deformation[3].

The above model has recently been applied to a study of the stability of elements in the heavy and superheavy regions[4,5]. We show two results from this calculation. In fig. 1 we show calculated neutron

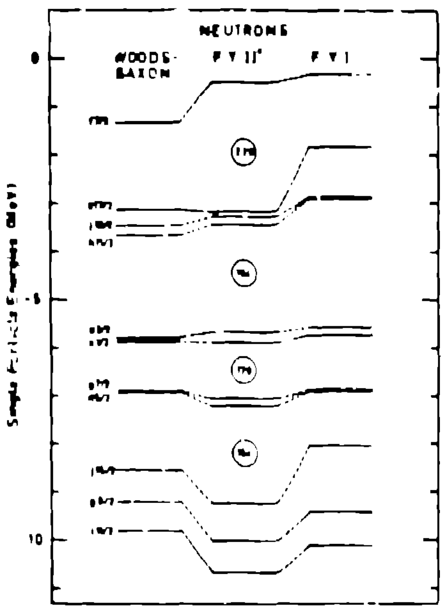

Figure 1

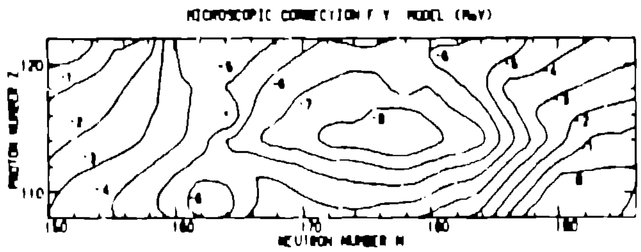

Figure 2

single-particle levels for the spherical nucleus $^{298}_{114}X$ (middle), compared to results from an earlier version of the folded-Yukawa single-particle potential[6,7] (right) and to the results of a Woods-Saxon model[8]. Calculated ground-state shell corrections are shown in fig. 2. For each nucleus the energy has been minimised with respect to the deformation coordinates ϵ_2 and ϵ_4. We note in fig. 2 that the largest shell correction occurs at Z=114 and N=178, although the largest gap in the middle set of levels in fig. 1 is at N=184. The reason is that the set of highly degenerate levels above the N=184 gap pushes the minimum of the shell correction to the lower neutron number N=178. Relative to the calculations with the earlier model[7], whose level predictions are seen in the right part of fig. 1 we get considerable

[1] Work supported by the U.S. Department of Energy.

changes for the predicted properties of the elements in the superheavy region. In particular we now predict $^{288}_{110}X$ and $^{290}_{110}X$ to be the most stable elements in this region, both with a half-life of 200 days.

Another interesting feature in fig. 2 is the small local minimum around Z=110 and N=162. This minimum corresponds to deformed shapes and to an N=162 gap in the deformed neutron single-particle level spectrum. The half-life of $^{272}_{110}X$ is predicted to be 40 milliseconds. In analogy with the characterisation of the region around $^{298}_{114}X$ as the superheavy island the region around $^{272}_{110}X$ has been baptised the "rock". It has been suggested that the rock has been thrown out by God from the superheavy island for man to step on, in his quest to reach that bigger but more distant island of stability.

One may ask about the reliability of the half-life predictions made above. This is primarily a question about the reliability of the mass model itself. With the measure

$$\sigma^2 = \frac{1}{N}\sum_{i=1}^{N}(M^i_{\rm calc} - M^i_{\rm exp})^2 \tag{1}$$

for the error of the mass formula one obtained[1] σ=0.835 MeV for the 1323 masses in the known region to which the model parameters were adjusted. Later, Haustein[9] has studied the ability of various mass models to predict masses in regions to which its parameters were not adjusted. For the above models he obtained σ=0.97 MeV, for a set of 213 new masses, suggesting a divergence in the results far from stability. However, one may observe that in this set the element $^{34}_{11}$Na has an experimental error of 3.5 MeV, and its measured mass differs from our prediction by 7 MeV. If this single nucleus is removed from the set of 213 masses a σ of 0.825 MeV is obtained for the remaining set of 212 masses. To avoid such arbitrariness in the determination of σ, one may proceed as follows. We introduce

$$\xi = \sum_{i=1}^{N} w_i(M^i_{\rm calc} - M^i_{\rm exp})^2 \ , \tag{2}$$

where

$$w_i = \frac{1}{{\sigma_{\rm th}}^2 + {\sigma^i_{\rm exp}}^2} \ . \tag{3}$$

If all the M^i are independent and $M^i_{\rm calc}$ and $M^i_{\rm exp}$ are Gaussian with the same mean value, so that the mean of $M^i_{\rm calc} - M^i_{\rm exp}$ is zero, and with standard deviations $\sigma_{\rm th}$ and $\sigma^i_{\rm exp}$ then ξ is distributed according to the χ^2 distribution with n degrees of freedom. We shall assume that the above assumptions hold. It then follows that the mean and the variance of ξ are given by

$$m = \mathbf{E}(\chi^2(n)) = n \ \text{ and } \ \sigma^2 = \mathbf{D}^2(\chi^2(n)) = 2n \ . \tag{4}$$

Here we have for the number of degrees of freedom for the χ^2 distribution that $n = N - p$ where p is the number of linear dependencies introduced through adjustment of the model coefficients to the data points $M^i_{\rm exp}$ occuring in Eq.(2). There is one unknown parameter $\sigma_{\rm th}$ in our expressions. One general method for determining an unknown parameter of a distribution function is the *maximum – likelihood* method. Here we proceed slightly differently. The average of $\frac{1}{N-p}\chi^2$ is 1 and we determine $\sigma_{\rm th}$ by assuming we have observed this average value and solve

$$1 = \frac{1}{N-p}\sum_{i=1}^{N}\frac{1}{{\sigma_{\rm th}}^2 + {\sigma^i_{\rm exp}}^2}(M^i_{\rm calc} - M^i_{\rm exp})^2 \ . \tag{5}$$

The precise procedure is to minimise Eq.(2) with an initial guess for ${\sigma_{\rm th}}^{(0)}$ to find initial values of the model parameters, then to keep the model parameters fixed and find ${\sigma_{\rm th}}^{(1)}$ from Eq.(5) and perform this iteration until convergence. Only two iterations are required if the initial guess of $\sigma_{\rm th}$ is correct to within 30%. For comparison we also define two other quantities, namely

$${\sigma_{\rm conv}}^2 = \frac{1}{N}\sum_{i=1}^{N}(M^i_{\rm calc} - M^i_{\rm exp})^2 \tag{6}$$

and

$$\sigma_{wt}{}^2 = \frac{1}{\sum_{i=1}^{N} w_i} \sum_{i=1}^{N} w_i (M^i_{calc} - M^i_{exp})^2 \quad . \tag{7}$$

Here conv stands for conventional, wt for weighted and w_i is given by Eq.(3). We also determine error limits by observing that the standard deviation of $\frac{1}{n}\chi^2$ is $\sqrt{2/n}$. Thus by solving Eq.(5) for $1 \pm \sqrt{2/n}$ in the left member, we determine error limits for σ_{th}.

For the model discussed here[1,2] with its original set of constants we find from solving Eq.(5) with p=5 that $\sigma_{th}=0.8325^{+0.0168}_{-0.0160}$ MeV, and by evaluating Eqs.(6,7) that σ_{wt}=0.8346 MeV and σ_{conv}=0.8348 MeV. We now study the ability of the model to predict new masses by considering the new masses in the Wapstra and Audi 1983 mass evaluation[10]. Precisely, we do the following. Only masses with Z and N equal to or greater than 8 are considered. The new masses are the masses in ref.[10] that are not in ref.[11]. The latter is the data set considered by refs.[1,2]. There are 219 such new masses. In addition there are two masses in the 1977 evaluation with an error larger than 1 MeV, which were excluded in the 1981 adjustment. These two masses are in the 1983 evaluation, still with an error larger than 1 MeV, like one additional mass, namely $^{34}_{11}$Na. These cause no difficulty when σ_{th} is calculated by solving Eq.(5), and are included in our new set of masses giving a total of 221 masses, a slightly different set from the one considered by Haustein[9]. With the original set of constants and with p=0 in this case, we find from Eqs.(5,6,7) that $\sigma_{th}=0.8096^{+0.0408}_{-0.0403}$ MeV, σ_{wt}=0.8272 MeV and σ_{conv}=1.0064 MeV.

These results show the inadequacy of using Eq.(6) as a measure of the error in mass formulae. In addition we observe that σ_{th} is the same in the region where the parameters were determined and in the new region, within the error limits. Our interpretation is that the errors are random. We cannot calculate masses exactly, so some terms or some other features are missing from the model, but the effect of their absence is random on the errors in the predictions of the model. In particular the terms that are present in the model have not been forced to reproduce the effect of the missing terms by a spurious choice of values for the adjustable parameters. However, this is obviously the case for some of the multiparameter models as is shown in the survey by Haustein[9], since for those models the errors are much larger for new masses outside the region to which the model parameters were adjusted than for the region of adjustment.

We are currently investigating the possibilities for improving further both the macroscopic and microscopic parts of the models. In the earlier calculation[1,2] levels were determined only for single particle wells corresponding to a set of 15 nuclei on the line of β stability. The microscopic corrections were then calculated by filling up levels to the appropriate N and Z values and by using an interpolation procedure. In fig. 3 we show the result of calculating the microscopic correction for single-particle wells appropriate to each individual nucleus. This means that a diagonalisation has to be done for each nucleus. In addition we have in fig. 3 adjusted to the 1983[10] mass table and changed the reference point for the odd-particle corections from odd-even to even-even nuclei. We see that this has increased σ_{th} to 0.882 MeV. However, compared to the earlier[1,2] results the errors are more bunched together and even more correlated to the positions of the magic numbers in the sense that the errors are largest coming in and going out of magic nuclei, that is the errors are largest for soft, transitional nuclei. This suggests that some new feature is required in the model to describe this class of nuclei better.

The last figure, fig. 4, shows results obtained with the identical microscopic corrections as used in fig. 3, but with the Finite-Range Droplet model (FRDM) for the macroscopic energy. The FRDM is discussed in ref.[12]. In the FRDM the folding model for the surface energy has been incorporated into the Droplet model. In addition the calculation of the Coulomb energy has been improved, and a new term affecting the compressibility of light nuclei has been added. The error is now σ_{th}=0.764 MeV, considerably better than for the Finite-Range (Yukawa-plus-exponential) model used in fig. 3.

We are at present assessing the significance these new features we have discussed here have for more reliable predictions by mass formulae of masses out to the proton and neutron drip lines and masses in the superheavy region.

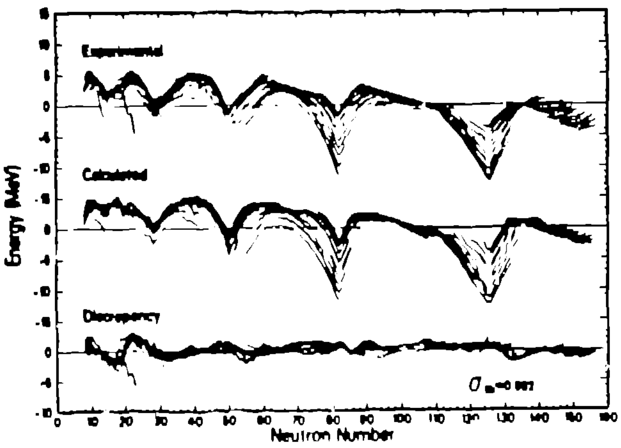

Figure 3

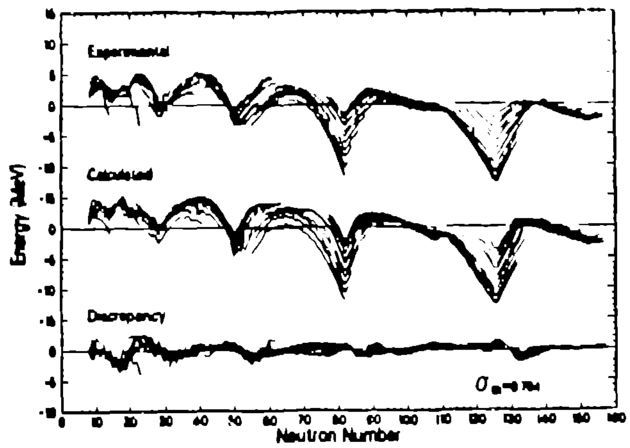

Figure 4

References

[1] P. Möller and J. R. Nix, Nucl. Phys. **A361** (1981) 117.

[2] P. Möller and J. R. Nix, Atomic Data Nucl. Data Tables, **26** (1981) 165.

[3] R. Bengtsson, P. Möller, J. R. Nix and Jing-ye Zhang, Phys. Scr. **29** (1984) 402.

[4] G. A. Leander, P. Möller, J. R. Nix and W. M. Howard, Proc. 7th Int. Conf. on Nuclear Masses and Fundamental Constants (AMCO-7), Darmstadt-Seeheim, 1984 (Lehrdruckerei, THD Darmstadt, 1984) p. 466.

[5] P. Möller, G. A. Leander and J. R. Nix, Z. Phys., to appear.

[6] M. Bolsterli, E. O. Fiset, J. R. Nix and J. L. Norton, Phys. Rev. **C5** (1972) 1050.

[7] E. O. Fiset and J. R. Nix, Nucl. Phys. **A193** (1972) 647.

[8] J. Dudek and W. Nazarewicz, private communication (1984).

[9] P. Haustein, Proc. 7th Int. Conf. on Nuclear Masses and Fundamental Constants (AMCO-7), Darmstadt-Seeheim, 1984 (Lehrdruckerei. THD Darmstadt, 1984) p. 413.

[10] A. H. Wapstra and G. Audi, Nucl. Phys. **A432** (1985) 1.

[11] A. H Wapstra and K. Bos, Atomic Data Nucl. Data Tables, **19** (1977) 177; **20** (1977) 1.

[12] P. Möller, W. D. Myers, W. J. Swiatecki and J. Treiner, Proc. 7th Int. Conf. on Nuclear Masses and Fundamental Constants (AMCO-7), Darmstadt-Seeheim, 1984 (Lehrdruckerei, THD Darmstadt, 1984) p. 457.