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Comments on Primordial Superheavy Elements*

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A Woods-Saxon potential which reproduces the single particle levels in the lead region provides the basis for a discussion of the stability properties of nuclei in the superheavy region. A closed $N = 228$ neutron shell is associated with the recent observation of nuclei with $Z = 124$ and 126.

Strong evidence has recently been obtained[1] for the existence of naturally occurring superheavy elements. In particular, proton-induced x-ray analysis of monazite inclusions in biotite mica, characterized by giant halos,[2] indicates the presence of at least three superheavy elements with $Z = 116$, 124, and 126. It is the main purpose of this note to show that a qualitative description of the major features of the observations can be obtained within the framework of conventional theory. Specifically, (a) we give arguments for the existence of adequately stable nuclei ($\tau_{1/2} \sim 10^6$–10^9 yr) with $Z \sim 114$, $Z \sim 126$, and $Z \sim 164$; (b) we speculate that the 10–15-MeV α radiation, presumably responsible for the formation of the giant halos,[2] may be due to the decay of elements with $Z \sim 164$; and (c) we discuss the chemical compatibility of these elements with the host material. A few suggestions are also given for the further study of elements in the superheavy region.

The stabilities of nuclei with respect to α decay, β decay, and fission can be discussed by standard methods. We consider first the single particle spectrum generated by a Woods-Saxon potential with parameters optimized for extrapolation into the region of superheavy nuclei. The parameters of our potential were obtained from a fit to the particle levels in ^{209}Pb and ^{209}Bi carried out by Rost.[3] The potential has a standard form[3] with depth given by (upper sign for protons)

$$V_0 = 51.6[1 \pm 0.73(N - Z)/A] \text{ MeV}. \qquad (1)$$

The remaining parameters were held constant and are as given by Rost, namely $r_0 = 1.262$ fm, $r_{so} = 0.908$ fm, $a = 0.70$ fm, $\lambda = 17.5$ for protons; $r_0 = 1.295$ fm, $r_{so} = 1.194$ fm, $a = 0.70$ fm, $\lambda = 28.2$ for neutrons. Our approach differs from that of Rost in that Eq. (1) is used for scaling the potential depths into the superheavy region. This scaling procedure is consistent with the hypothesis of charge independence and also yields reasonable fits to observed particle levels in ^{120}Sn and ^{138}Ba. We also use a pairing correction term similar to that introduced by Blomqvist and Wahlborn[4] which improves the predicted energies of occupied levels in ^{208}Pb, ^{120}Sn, and ^{138}Ba.

We have calculated single particle levels for a variety of nuclei in the region $Z = 108$–168 and $N = 127$–312 using the above prescription. Strong shell closures are obtained for $N = 184$, 228, and 308. Weaker proton shell closures occur in approximate correspondence with these neutron closures for $Z = 114$, 126, and 164, respectively. Results for these particular cases are shown in Fig. 1. Other authors[5-7] have observed some of these same features but they have not discussed the important combination $Z = 126$ and $N = 228$. In

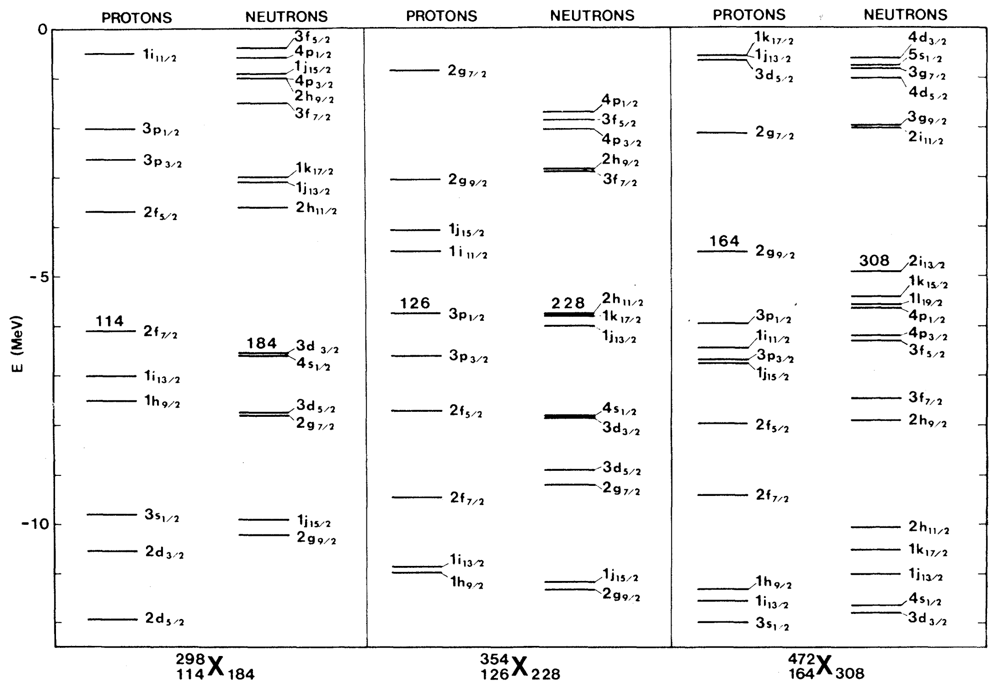

FIG. 1. Calculated single particle levels for β-stable doubly closed shell nuclei in the superheavy region.

the vicinity of each of the neutron closed shells, we find both even and odd β stable isotones. Estimates of the α energies and α lifetimes for some even nuclei of interest are given in Table I. All are β stable except for $Z=124$ and $N=228$ which can decay by the first forbidden $2h_{11/2} \rightarrow 1i_{11/2}$ transition with an energy of 0.3 MeV. The estimated lifetime for this decay is 10^{-2} yr.

Detailed calculations of the fission half-lives of

TABLE I. Calculated α energies and half-lives for various nuclei. The decay energies were estimated as $Q_\alpha = 28.3\ \text{MeV} - 2S_n - 2S_p + \Delta$ where S_n and S_p are the binding energies of the uppermost occupied neutron and proton orbits, respectively, and Δ is a correction for shell breaking effects estimated to lie between 0 (for nuclei with two nucleons beyond the shell closure) and $300/A^{0.86}$ (for nuclei with closed shells or two neutron or proton holes). The α lifetimes were estimated from Q_α by means of a standard formula quoted in Ref. 6.

Nucleus	Q_α (MeV)	$\ln[\tau_{1/2}^{\alpha}\ (\text{yr})]$
$^{298}_{114}X^{184}$	5.5	10
$^{300}_{116}X^{184}$	7.8	−1.1
$^{352}_{124}X^{228}$	5.1	18
$^{354}_{126}X^{228}$	7.4	4.3
$^{472}_{164}X^{308}$	11.0	1.9

these nuclei have not been attempted. However, we have made estimates of the spherical shell corrections to the droplet energy[8] for level groupings like those in Fig. 1 using the Strutinsky method.[9] We find the shell corrections for $Z=114$, $N=184$ (fissility $x=0.935$), and $Z=126$, $N=228$ ($x=1.02$) to be of the order of 7–11 MeV with most of the effect coming from the neutron shell in the latter case. Corrections of this size are typically associated with fission half-lives in excess of 10^9 yr for nuclei with fissility $x \sim 1$.[5] The shell correction for $Z=164$, $N=308$ ($x=1.32$) is about 18 MeV in agreement with the results of Lukasiak and Sobiczewski,[6] who estimate the fission half-life for this nucleus to be about 10^{60} yr. The single particle levels used in the calculations of Refs. 5 and 6 have no proton gap at $Z=126$ and a neutron shell at $N=228$ which is somewhat weaker than found here.

The lifetimes given above were obtained directly from the potential calculations with no attempt at optimization of the results. For all nuclei considered, a factor of 10^3–10^4 yr is gained in the α half-life by increasing the depth of the neutron potential by only 0.5 MeV. This same change also removes the β-decay problem associated with $^{352}_{124}X_{228}$ and brings the total half-lives for nuclei in the $N=228$ region to around 10^9 yr. The element $^{300}_{116}X_{184}$ is anomalous in that somewhat larger, but perhaps still reasonable, changes are re-

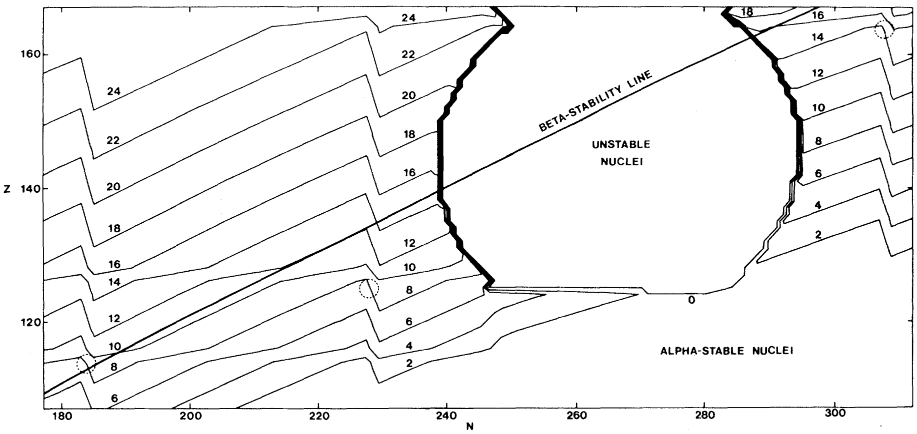

FIG. 2. Contours of constant α energy for the superheavy region. Circles indicate doubly closed shell regions of interest. The correspondence with the shell-model results is only approximate.

quired to produce adequate stability. This may be an indication that $Z=116$ is not spherical.[10] The important point is that stability appears to be well within reach of the calculations in these regions.

To provide a rough summary of some of the systematics in the superheavy region, Fig. 2 has been prepared from the Myers-Swiatecki mass formula[8] with shell closures at $Z=82$, 114, 126, 164 and $N=126$, 184, 228, and 308. The plot shows the contours of constant α energy and the extrapolated β-stability line.[11] Fission stability is expected only near doubly closed shells. It is clear from the figure that elements in the circled $Z=114$, 116, and 124, 126 regions cannot be the source of 10–15-MeV α activity associated with giant halos. One possible explanation might be a radioactive decay chain which begins in the region $Z\sim164$ and $N\sim308$. This radioactive chain presumably would follow a line in the N, Z plane just below the line of β stability until spontaneous fission becomes dominant. The fission products from this region should contain unusual amounts of radiogenic lead, thus providing a possible explanation for the extreme reverse discordance[12] observed for certain monazite materials. Of course, other explanations[2] of the 10–14-MeV α activity may yet prove adequate.

Theoretical calculations[13] of the electronic structures of superheavy elements show that elements 124 and 126 are members of the superactinide series. The chemical affinity of the monazite crystal for lanthanides and actinides is thus consistent[2] with the observation of these elements in this material. The element $Z=116$ for which evidence has also been reported[1] is chemically described[13] as eka-polonium which apparently does not show chemical affinity for monazite. Its presence can possibly be explained if it is formed as a product of radioactive decay from the $Z=124$ and 126 region. If this explanation is correct, inclusions which contain $Z=116$ together with $Z=124$ or 126 would be expected to exhibit a slight enhancement of α decays with energies between 6 and 8 MeV. Element 114 is described as eka-lead and presumably could be formed in a similar manner. However, $Z=114$ is difficult to observe in the proton induced x-ray experiments.[1] The affinity of monazite for element 164 is less clear. This element has been variously described[12] as chemically similar to lead or platinum, but long extrapolations are involved. If the observed giant halos are indeed produced as a result of the decay of element 164, measurable amounts of this element may yet remain.

The major result obtained here has been to provide a qualitative explanation for the important features of the recent observations.[1] In view of the fact that the main input for our extrapolations comes almost entirely from nuclei with $Z\leq82$, it would not be surprising if many of the details obtained here prove to be quantitatively incorrect. Nevertheless, the qualitative results, including the predictions of the N, Z combinations with maximum stability, are expected to be reliable. We hope that the above work will stimulate more sophisticated investigations of these regions.

The next generation of experiments will presumably involve nuclear scattering. Two good initial candidates appear to be (i) deuteron elastic scattering with kinematic separation and

(ii) polarized and unpolarized proton elastic scattering via isobaric analog resonances. The former experiment is capable of yielding some measure of Z and $N+Z$ with the presently available targets, provided that certain experimental difficulties can be overcome. The latter experiment requires an appropriately enriched target. Calculations to predict the form of the proton resonances from our single particle spectra are in progress. An important consequence of the existence of naturally occurring superheavy nuclei is the possibility of investigating superheavy electromagnetic effects[14] by bombardment with medium mass projectiles such as Ag.

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Reflectivity of Liquid ^{4}He Surfaces to ^{4}He Atoms

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We explain recent results on the reflectivity of liquid ^{4}He surfaces to externally incident ^{4}He atoms in terms of a Van der Waals interaction and strong coupling to quantized surface-tension waves which suppresses all other influences on the reflectivity. The model gives numerical agreement with experiment and it is found that a proper treatment of density variation at the liquid ^{4}He surface is essential.

In a recent experiment Edwards *et al.*[1] measured the reflection coefficient for ^{4}He atoms incident on the surface of liquid ^{4}He, the liquid being at 30 mK and the range of incident energies lying between 0.1 and 3.0 K relative to vacuum (or 7.26 and 10.16 K relative to the binding energy of ^{4}He in the liquid). It might be expected that a finite elastic, specular, reflection coefficient would be seen, less than unity because many of the incident atoms will lose energy to elementary excitations of the liquid, but rising to unity at low energies as the wavelength becomes long compared with the onset of the surface potential. At higher energies, in particular at the roton threshold,[2] a drop in the elastic reflectivity should be seen associated with the new channel for inelastic decay.