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Abstract: The nuclear properties of superheavy nuclei are described. The problems in the laboratory synthesis of these elements are reviewed.

I. Introduction

Since prehistory, attempts have been made to discover the basic building blocks of nature. In recent decades that quest has taken the form of attempts to extend the periodic table beyond the last naturally occurring element, element 92, uranium. In the forty plus years since the discovery of the first of the transuranium elements, neptunium and plutonium, scientists have synthesized (or "discovered") fourteen new transuranium elements ranging in atomic number from 95 to 108. Along with neptunium and plutonium, these sixteen elements represent an addition of more than 15% to the elemental building blocks of nature.

The question naturally arises whether there is a limit to the periodic table and what it might be. One might expect that when the number of protons in the nucleus becomes large enough, the Coulomb repulsion between these protons will cause the nucleus to spontaneously fission. A simple calculation should suffice to illustrate when this might occur (Huizenga,1978). The liquid drop model of the nucleus predicts that a nucleus will fission almost instantaneously when

$$E_c = 2\ E_s$$

where E_c and E_s are the repulsive Coulomb and attractive surface energy of the nucleus, respectively. The quantities E_c and E_s are given by

$$E_c = (3/5)(Ze)^2/R = k_c Z^2/A^{1/3}$$

$$E_s = 4\pi R^2 \gamma = k_s A^{2/3}$$

where γ is the nuclear surface tension (~1 MeV/fm^2), Z is the atomic number and R is the nuclear radius (which is proportional to $A^{1/3}$ where A is the nuclear mass number). The limiting value of the atomic number,

Z_{limit}, is then

$$Z^2_{limit} = 2\ (k_s/k_c)\ A_{limit}$$

The neutron/proton ratio in heavy nuclei is ~1.5/1, (A_{limit} ~2.5 Z_{limit}), thus

$$Z_{limit} = 5\ (k_s/k_c)$$

Thus the upper bound to the periodic table is proportional to the ratio of two fundamental constants related to the strength of the nuclear (surface) and electromagnetic forces. The ratio (k_s/k_c) is about 20-25 and thus, on the basis of this estimate, we might expect 100-125 chemical elements.

As of 1970, the experimental data on the stability of the transuranium elements seemed to indicate that a practical limit to the periodic table would be reached at approximately element 108. (Figure 1) By extrapolation of the experimental data existing at that time, one would have concluded that at about element 108, the halflives of the longest lived isotopes of the elements would become so short ($<10^{-6}$ sec) due to decay by spontaneous fission as to preclude their production and study. However, during the period from 1966-72, a number of theoretical calculations based upon modern theories of nuclear structure showed that in the region of proton number Z=114 and neutron number N=184, the spherical ground states of nuclei were stabilized against fission. This stabilization was due to the complete filling of proton and neutron shells and is analogous to the stabilization of the chemical elements, such as the noble gases, due to the filling of electronic shells in these atoms. Even more interesting, some of these "superheavy" nuclei were predicted to have halflives of the order of the age of the universe, thus stimulating efforts to find these "missing" elements in nature. The superheavy elements were predicted to form an island of relative stability extending both above and below Z=114 and N=184 and separated from the peninsula of known nuclei by a sea of instability.(Figure 2)

Following this initial period of optimism about the existence and accessibility of the superheavy nuclei, a worldwide effort was launched to "jump the gap" between the peninsula of known nuclei and the predicted island of stability by combining two nuclei in a nuclear reaction, thus synthesizing superheavy nuclei in the laboratory. In the two decades that have passed since the original optimistic predictions were made, many attempts to synthesize superheavy nuclei have failed, the theoretical predictions about the nature and shape of the superheavy "island" have changed, and some striking successes in the synthesis of isotopes of elements 107 and 108 (and possibly element 109) have occurred. Our purpose in writing this article is to review and clarify the situation and to indicate why this search for new elements continues. One fact should be emphasized from the outset; while the various theoretical predictions about the superheavy nuclei differ as to the expected halflives and regions of stability, all theoretical predictions are in agreement as to the existence of superheavy nuclei. Thus the search for superheavy nuclei remains as a unique, rigorous test of the predictive power of modern theories of the structure of nuclei.

II. Properties of the Superheavy Elements

The general properties of unknown nuclei, such as their masses, decay modes, etc., are calculated using the macroscopic-microscopic approach in which the potential energy of the nucleus as a function of shape is calculated as the sum of a macroscopic term and a microscopic term. The macroscopic term which is usually calculated using a refined version of the liquid drop model gives the average smooth variation of nuclear properties with particle number and shape. The microscopic term which (for the heaviest elements) is a 0.5% correction to the macroscopic term accounts for the non-uniform distribution of single particle levels in the nucleus. The microscopic term will lower the ground state mass of closed shell nuclei due to increased stability of these "magic" nuclear configurations. There are two major parts of the microscopic term, a shell correction part and a pairing correction part. They are both determined from a set of single particle levels that is used as an input to the calculation. The shell correction is calculated using the Strutinsky method (Strutinsky,1967) while the pairing correction is made using the BCS approximation (see, for example, Nix,1972).

The crucial factor in these calculations is the set of assumed single particle levels. Some years ago, Chasman used a set of realistic single particle levels that had been fit to the known levels of the actinide nuclei to calculate the microscopic correction term for the superheavy elements (SHE) (Chasman,1978). He found special stability associated with Z=114 and N=164,178,and 184. But he also found that because of the uncertainties in our knowledge of the single particle level schemes and the calculational methods used in estimating the microscopic term, the spontaneous fission halflives of the SHE were uncertain by a factor of $10^{\pm 7}$-$10^{\pm 10}$, in agreement with a previous estimate by Bemis and Nix (Bemis,1977). With this information as a background, it is not surprising that as our best theoretical prescriptions for the single particle levels have changed, so have our estimates of the character of the superheavy island.

In Figure 3, we show the results of three calculations of the properties of the superheavy nuclei, as performed in 1972, 1976, and 1985. While the differences between these predictions are understandable, they are maddening to the experimentalists who must seek to "hit" a moving target whose characteristics are changing. The early calculations emphasized that the superheavy island was centered at N=184, with either a broad slope to lesser values of N ('72 calculation) or a steep wall towards lower N crashing into the sea of instability ('76 calculations) with the '72 calculations predicting halflives of the order of the age of the universe which the later calculations failed to confirm. The significance of the '76 calculations was that they forced experimentalists to attempt to assemble composite nuclei with N~184, a very difficult task, in their attempts at a laboratory synthesis of SHE. The most recent calculations point to the most stable nuclei having lesser values of N (178-180) with halflives less than a year. Also recent calculations confirm the earlier work about the special stability associated with N~164, (the gap between the $j_{15/2}$ and $d_{5/2}$ neutron levels) for Z=108-111.

Since most of the data used to deduce the single particle levels that are used in the calculation come from fits to data from the rare earth and actinide regions, it would be reassuring to find some experimental evidence that the recent calculations have some measure of accuracy in the transactinide region. In Figure 4, we show a portion of such evidence in the form of a comparison of current theoretical calculations and experimental data for the alpha decay energies for the N=157 isotones. The agreement between the calculations and data is generally excellent.

Once one has formed a superheavy nucleus, one would like to find a unique signature for its existence amongst the many other products of possible synthesis reactions. The higher Z of the superheavy nuclei should lead to increased total kinetic energy of the fission fragments during spontaneous fission (~50 MeV higher than for Z=92) (Mosel and Schmitt,1972) and a very large number of neutrons emitted per fission event ($\bar{\nu}$ ~ 10-14 for Z=114 compared to 2.4 for ^{235}U). (This latter conclusion about $\bar{\nu}$ is sensitive to the fragment shapes and could be as low as $\bar{\nu}$ = 5-6.) (Hoffman,1978) To identify the atomic number of any superheavy nucleus, one would try to detect any emitted alpha particles (with $8<Q_{\alpha}<10$ MeV) especially those in time correlation with particles emitted in the decay of known daughter, grand daughter, etc., nuclei or use some other signature such as the energy of characteristic X-rays.

One further consequence of our current thinking about the properties of the SHE is that, contrary to the belief of some concerning the initial optimistic picture of the late 60's and early 70's, we do not now believe that it is fruitful to search for the existence of the superheavy elements in nature. We think the halflives of these elements are short compared to the age of the universe. Also it seems unlikely that the r-process of heavy element nucleosynthesis will lead to the production of superheavy nuclei.(Mathews, 1976)

III. Laboratory Synthesis of SHE

The laboratory synthesis of the heaviest elements is a formidable challenge to experimentalists. The heavy element formation cross sections are less than 10^{-8} of the total reaction cross section, corresponding to the production of <1-3 heavy element atoms per day of irradiation. The synthesis process can be broken down into two related steps; (a) the initial formation of a composite nucleus with the appropriate Z and A and (b) the deexcitation of that composite species by the emission of neutrons (in competition with the much more probable fission process which will destroy the nucleus). Understanding how this overall process might occur is difficult because the surviving products from a reaction frequently arise from the poorly characterized low excitation energy (E^*), low angular momentum (J) tails of the primary product distributions.

The nuclear reactions used for superheavy element synthesis are heavy ion reactions (which have been discussed previously in this journal (Hodgson, 1982)). A smaller projectile nucleus is made to collide with a larger target nucleus to form a composite species. Because all successful elemental syntheses have involved complete fusion reactions, we shall generally restrict our attention to this type of reaction in which the projectile nucleus completely amalgamates with the target nucleus forming a composite system. The probability of fusion of the projectile and target nuclei depends on their specific properties,their interaction potential, and any dissipative processes that occur during fusion. For low energies where the fusion and reaction cross sections are the same, a simple classical model for fusion gives for the fusion cross section, σ_{fus},

$$\sigma_{fus} = \pi R_B^{\ 2} \ (1- (V(R_B)/E_{cm}))$$

where E_{cm} is the center of mass energy of the projectile and the nuclear radius R_B and interaction potential $V(R_B)$ are given by

$$R_B = 1.4(A_1^{\ 1/3} + A_2^{\ 1/3}) \ (fm)$$

$$V(R_B) = Z_1 Z_2 e^2/R_B$$

Z_1, Z_2 are the atomic numbers of the projectile and target nuclei. These same equations can be translated into angular momentum space giving

$$\sigma_{fus} = \pi ƛ^2 \Sigma \ (2l+1) = \pi ƛ^2 (l_{max}+1)^2$$

where $ƛ$ is the reduced wavelength of the projectile and l_{max}, the highest partial wave to fuse, is the highest partial wave at energy E_{cm} that just passes over the reaction barrier, $V(R_B)$. This simple classical model can be modified to account for barrier penetration and the effects of nuclear dissipation during the collision (Birkelund,1979). The results of calculations based upon these modifications give a good general description of fusion cross sections for light and intermediate mass nuclei.

For the heavy target nuclei involved in attempts to synthesize SHE, additional phenomena occur that significantly affect the fusionability of nuclei. The first of these effects involves the enhancement of the fusion probability at low projectile energies, i.e., sub-barrier fusion. Two effects appear to lead to this enhancement; (a) the static deformation of one (or both) of the reacting nuclei which creates a strongly preferred (and highly favorable) orientation of the colliding nuclei (Stokstad,1980), and (b) dynamic deformations of the nuclei due to coupling of the vibrational modes of the reacting nuclei which also lead to enhanced fusion cross sections (Reisdorf,1981). In Figure 5, we show a case of sub-barrier fusion compared to "normal" fusion. The significance of sub-barrier fusion for the synthesis of heavy nuclei is that it allows experimenters to combine two nuclei with reasonable probability at low projectile energies, thus leading to composite systems with low excitation energies and relatively high survival probabilities.

Unfortunately, there is a competing dynamical effect in the reaction of heavy nuclei that lowers the fusion probability. The Coulomb repulsion between the reacting heavy nuclei hinders their fusion. If the values of the atomic numbers of the projectile and target nuclei, Z_p and Z_t respectively, become large enough ($Z_p + Z_t > 120$), then fusion is virtually impossible. For lesser values ($120 \geq (Z_p + Z_t) \geq 80$), fusion is significantly hindered. Asymmetric projectile-target combinations do lead to higher fusion probabilities than symmetric systems. Swiatecki has developed a schematic model that has been used widely to represent this dynamical limitation to fusion (Swiatecki,1982). The model is illustrated in Figure 6. Three configurations in the dynamical evolution of a nucleus-nucleus collision are identified. They are: (a) the configuration where the colliding nuclei touch,(b) the "conditional" saddle configuration where the colliding nuclei have interpenetrated somewhat to form a mononucleus and are about to lose their identity, and (c) the "unconditional" saddle configuration beyond which the product mononucleus will equilibrate and suffer "amnesia" about the collision partners from which it was formed. The energy required to make the nuclei touch is called the interaction barrier, V_B, while the extra radial energy above the barrier required to make the two nuclei fuse to make a mononucleus is called the "extra push" energy. The extra energy above the barrier required to form the true compound nucleus is referred to as the "extra-extra push" energy. Within the framework of the schematic model due to Swiatecki, there are relatively simple algebraic expressions that allow one to calculate the extra push and the extra-extra push energies and the complete fusion cross section. The concepts embodied in this model appear to describe a large amount of heavy element fusion data. A typical example of an "extra push effect" is shown in Figure 5c. In the synthesis of transactinide nuclei, these "extra push" effects are predicted to occur for $Z_{proj} \geq 18$(Ar).

Because of the intrinsically low probability of fusion reactions leading to new elements and the complex interplay of sub-barrier enhancement and dynamical limitations of fusion probability, it is difficult to make theoretical estimates of fusion probability that are reliable enough to guide experimental efforts. With this in mind, Armbruster has developed a semi-empirical representation of fusion probability which uses the Swiatecki model as a basis. This representation takes the form of the equation

$$p(V_B) = 0.5 \exp[-a\ (x_{mean} - b)]$$

where $p(V_B)$ is the probability of fusion at the s-wave (l=0) fusion barrier V_B ($\sigma_{fus}(V_B)/\pi\lambda^2$), x_{mean} is the mean fissility of the composite system (Armbruster,1985) and where the coefficients a and b are determined to be 71 and 0.72, respectively from fitting experimental data. Qualitatively, the more fissile the fusing system is, the harder it will be to form a stable mononucleus. The fissility of a nucleus is proportional to Z^2/A (the ratio of the repulsive Coulomb energy to the attractive surface energy, see p. 1). The mean fissility, x_{mean} is taken to be the geometric mean of the fissility of the colliding ions, x_{eff} and the composite system, x_{cn}. Formally

$$x_{mean} = (x_{eff} x_{cn})^{1/2}$$

$$x_{eff} = 4A_1A_2(Z_1+Z_2)^2/(A_1A_2)^{1/3}(A_1{}^{1/3}+A_2{}^{1/3})(A_1+A_2)^2(Z^2/A)_{crit}$$

$$x_{cn} = (Z_1+Z_2)^2/(A_1+A_2)(Z^2/A)_{crit}$$

$$(Z^2/A)_{crit} = 50.883(1-1.7826\{(N_1+N_2-Z_1-Z_2)/(A_1+A_2)\}^2)$$

This representation of the fusion probability which combines the effect of both enhancements and limitations to σ_{fus} is also shown in Figure 7. The maximum fusion probabilities are observed in light projectile-heavy target reactions with the decrease in fusion probability with increasing projectile and target atomic numbers becoming more severe as Z_{proj}

increases.

Thus our best current estimates (Figure 7) lead us to believe that superheavy composite systems having appropriate values of Z and A can be formed with adequate probability in nuclear reactions. The next problem is to evaluate whether such composite systems will survive. As noted earlier, the composite systems are excited and the question is whether they can get rid of that excitation energy by the relatively benign processes of particle evaporation as opposed to the more probable and destructive fission process. The lower the excitation energy of the composite species (i.e., the "cooler" it is), the more likely it will survive. The minimum excitation energy of various heavy composite systems formed in nuclear reactions is shown in Figure 8. One can see that for $Z_{target} \sim 82$ (Pb), the special stability of the target nuclei leads to a low value of Q and E^*. This realization , the "cold fusion" mechanism (Oganessian, 1975), has been used in the synthesis of elements 107 and 108. Also the use of a doubly magic projectile, such as ^{48}Ca, can lower E^* significantly. (Figure 8)

The person attempting to synthesize a new heavy element or superheavy element will select a product of maximum stability (Figure 3) and then juggle the competing considerations of minimum excitation energy (Figure 8) and reasonable probability of composite nucleus formation (Figure 7) to pick the projectile-target combination that seems most promising. If one is thorough in this treatment, he or she will also assess the probable outcome of the competition between fission and neutron emission in the de-excitation of the composite species. Given the excitation energies, neutron binding energies and fission barriers for the nuclei involved, detailed procedures that are accurate to an order of magnitude exist for making such estimations (Oganessian, 1985). A very crude approximation to these calculations for the heaviest nuclei is that for each 8-10 MeV of excitation energy (i.e., the average excitation energy removed by an evaporated neutron), the survival probability drops by a factor of ~100. Thus a species excited to 15-20 MeV will have a survival probability of 10^{-4}. This arithmetic reflects the fact that at each stage of the deexcitation of an excited nucleus, 100 nuclei "die" due to fission for every nucleus that emits a neutron.

Thus one can see a reason for keeping the excitation energy of the composite species as low as possible, i.e., to reduce the number of times this species will undergo the rigors of struggling for survival against fission. But there are even more compelling reasons for minimum excitation energy in that as the excitation energy rises, the chances of survival at each step in the deexcitation process decrease. This is because if the excitation energy is high enough, the nuclear "shell effects" that stabilized any potential superheavy nucleus against fission, "wash out", i.e., the fission barriers vanish. There is some disagreement as to when this occurs with some estimates being as low as $E^* = 15$ MeV for spherical superheavy nuclei (Armbruster, 1985) while most estimates of this energy are in the range of 30-50 MeV (Mustafa, 1978; Oganessian, 1985). Nonetheless it is clearly important to achieve the minimum excitation energy of the composite species. For analogous reasons, it is important to minimize the angular momentum of any intermediate nuclei and thus, in this article, we have restricted our attention to the production of 1-0 product nuclei.

To see how all the aforementioned factors act in element synthesis, we review the successful efforts to synthesize two elements, element 106 and element 108. Ghiorso, et al. at Berkeley used the nuclear reaction 95 MeV $^{18}O + ^{249}Cf \rightarrow ^{263}106 + 4n$ to synthesize the 0.9 ± 0.2 sec $^{263}106$ (Ghiorso, 1974). This reaction produced a composite species of $^{267}106$ at an excitation energy of 40 MeV. For this system, one calculates $x_{mean} \sim 0.605$ with a corresponding l=0 fusion cross section of ~5 x 10^{-28} cm^2. The survival probability of the composite species should be ~10^{-8} leading to an estimated production cross section of ~5 x 10^{-36} cm^2 (the measured cross section was 3 x 10^{-34} cm^2). The 0.9 sec $^{263}106$ was detected by following its α-decay to the known $^{259}104$ which in turn decays to the known ^{255}No. Oganessian et al. at Dubna used the "cold fusion" approach to synthesize this element with the reactions 280 MeV $^{54}Cr + ^{207,208}Pb \rightarrow 106 + xn$ (Oganessian,1974). The composite species $^{261,262}106$ were formed "colder" than in the Ghiorso et al. work with an excitation energy of ~22-23 MeV. The predicted l=0 fusion cross section would be ~3 x 10^{-30} cm^2 with a survival probability of 10^{-4} giving a predicted formation cross section of ~3 x 10^{-34} cm^2(measured cross section ~ 10^{-33} cm^2). A spontaneous fission activity with a halflife of 4-10 msec was detected and based upon nuclear reaction systematics, this activity was assigned to $^{259}106$. We now know this assignment was in error in that the observed activities were probably primarily due to the daughters of element 106, $^{256,255}104$ and not element 106 (Demin, 1984). The isotope $^{260}106$ (which may have been produced also in the Oganessian et al. work) is now known to have a halflife of ~4 ms with a partial halflife for decay by spontaneous fission of ~7 ms (Münzenberg,1985).

Following the pioneering work of Oganessian that showed that a minimum excitation energy of the composite species occurs when one of the two

reacting nuclei has Z~82 and the successful use of these ideas by the Darmstadt and Dubna groups to synthesize element 107 (Münzenberg, 1981, Oganessian, 1976), Münzenberg et al. (Münzenberg, 1984) synthesized 1.8 msec $^{265}108$ by the reaction 292 MeV $^{58}Fe + ^{208}Pb \rightarrow ^{265}108 + n$.
The excitation energy of the $^{266}108$ composite was about 20-23 MeV. One estimates that the l=0 fusion cross section was 5×10^{-31} cm^2 with a survival probability of 10^{-4} giving rise to a predicted production cross section of 5×10^{-35} cm^2 (measured cross section is 2×10^{-35} cm^2). Clearly if it were not for the enhanced survival probability associated with the low excitation energy, this elemental synthesis would have been impossible. (The survival probability can be estimated to be ~10^4 greater than in the synthesis of element 106 using the actinide target.) Typical reactions with actinide targets that could be used to synthesize element 108 would have predicted production cross sections that are at least one order of magnitude lower.

One important result from this recent heavy element research is the finding that contrary to the trends shown in Figure 1, the halflives of the known isotopes of elements 107 and 108 are roughly similar ($t_{½}$ ~ 1 msec) and furthermore, these nuclei have α-decay halflives that are shorter than their spontaneous fission halflives. This result has been interpreted as confirming recent theoretical calculations that the fission barrier heights of the most stable isotopes of elements 106-110 are approximately constant (B_f ~ 5-6 MeV). This constancy of the barrier height is thought to be due to microscopic shell corrections since the macroscopic liquid drop fission barriers decrease by a factor of 4 for this Z range.

Since the first predictions of the stability of the SHE, there have been over 25 reported attempts to synthesize SHE in the laboratory. All of these attempts have ended in failure for a variety of reasons which have been discussed previously (Seaborg, 1979; Kratz, 1983). The most intensively studied synthesis reaction is the $^{48}Ca + ^{248}Cm$ reaction. (The "landing spot" of this reaction on the superheavy island is shown in Figure 3c.) The composite nucleus $^{296}116$ was expected to have an excitation energy of ~30 MeV, giving rise to a survival probability of 10^{-6}. If the l=0 fusion cross section was 3×10^{-30} cm^2, then the predicted formation cross section should have been ~3×10^{-36} cm^2. The experimental upper limits for superheavy element formation for this reaction are 10^{-35} - 10^{-34} cm^2, at least an order of magnitude higher than the predicted cross section.

But the situation may even be worse. In nuclear reactions that produce the "shell-stabilized" light actinides like ^{216}Th (where stabilization is due to the N=126 shell), the survival probabilities of the spherical Th products were smaller by two orders of magnitude than predicted while the deformed products showed nearly "normal" survival probabilities. This observation, which has been called "a dark cloud on the superheavy element horizon"(Bjørnholm, 1982) has been interpreted as meaning either (a) there is some problem in the calculation of survival probabilities for spherical nuclei or (b) the nuclear shells that stabilize spherical nuclei, like the superheavy nuclei, are ineffective at excitation energies greater than 15 MeV (Armbruster, 1985), or (c) there is, contrary to the numerical estimates of the Swiatecki model, a significant "extra extra push" energy needed in these cases to go beyond the deformed mononucleus to the spherical compound nucleus (Sierk, 1986). This extra-extra push energy has been estimated to be of such a magnitude as to cause the compound nucleus excitation energy to be 50 MeV, which would cause a negligibly small survival probability. Thus, whatever the cause, we suspect one must pay an additional penalty beyond that considered in our normal estimates of survival probability when one forms a spherical shell-stabilized heavy nucleus.

Alternative superheavy synthesis reactions, such as ^{48}Ca + ^{244}Pu or ^{48}Ca + ^{243}Am offer some improvement in the nominal fusion probability over the ^{48}Ca + ^{248}Cm reaction and lead to products of similar properties (Fig. 3c) but should suffer from the same catastrophies during the deexcitation of any composite species formed. The superheavy element synthesis reaction, ^{48}Ca + ^{254}Es, which forms a more neutron-rich composite species, would have a decreased fusion probability relative to the ^{48}Ca + ^{248}Cm reaction (~4x), but might afford increased product survival due to the lower excitation energy ($E^* = 25$ MeV).

Up to now, we have restricted our attention to the production of SHE in complete fusion reactions. Another nuclear reaction mechanism has also been used, unsuccessfully, in attempts to synthesize superheavy nuclei. This mechanism, deep inelastic transfer, involves an inelastic scattering of a large projectile nucleus by a target nucleus where there is a large transfer of nucleons from the projectile to the target nucleus. Spurred on by studies of the ^{238}U + ^{238}U reaction in which 20 or more protons appeared to be transferred from the projectile to the target nucleus with moderate excitation energies, hopes were raised that from the tails of the E^* and J distributions of the heavy nuclei produced in these reactions, a sufficient number of surviving SHE could be made (Riedel, 1979; Schädel, 1982). To date, the upper limits for superheavy element formation in the

$^{238}U + ^{238}U$ and the more favorable $^{238}U + ^{248}Cm$ reactions are $10^{-35} - 10^{-34}$ cm^2 (Gäggeler,1980; Kratz, 1986). Further attempts at superheavy element synthesis using this approach appear unlikely to be successful due to the relatively high excitation energies and deformed character of the intermediate species.

IV. What's Next?

By now, the reader should have a feeling for why those who would synthesize SHE are discouraged. Our best efforts to synthesize these elements appear to have fallen short by one or more orders of magnitude. We believe that the superheavy elements exist, but the way to make them in sufficient quantities to be observed has eluded us. There are several natural roadblocks in our journey to the superheavy island; we seem to have exhausted the obvious or easy routes. If we are to continue using complete fusion reactions to synthesize superheavy nuclei, our element production rates (i.e., beam currents, target properties) must improve by one or more orders of magnitude.

Faced with this situation, most workers in this field have shifted their sights to the more modest (yet still difficult) goal of synthesizing element 110. These efforts have focussed on the production of Z=110, N-162-164, a species calculated to have special stability due to nuclear shell effects(Figure 3c). The overall halflife of this species is calculated to be approximately 40 msec (Möller, 1986), a lifetime which is very compatible with existing equipment for studying and identifying short-lived nuclei. Furthermore, this species is calculated to be deformed in its ground state, thus possibly avoiding some of the difficulties encountered in forming spherical superheavy nuclei in the $^{48}Ca + ^{248}Cm$ reaction. Armbruster has suggested the best cold fusion reaction to synthesize this element is $^{64}Ni + ^{208}Pb \rightarrow ^{271}110$ + n.(Armbruster, 1985) If the projectile energy is chosen to be near the interaction barrier, the excitation energy of the $^{272}110$ composite is 10-15 MeV, allowing the 1n reaction. But the dynamical hindrance to fusion is large and the overall formation cross section is predicted to be about 10^{-36} cm^2. (Figure 9). Another cold fusion reaction, ^{59}Co + $^{209}Bi \rightarrow ^{266}110$ + 2n (suggested by Ghiorso) has a slightly higher fusion probability but produces a more excited product with lower survival probability and, because of the lower value of N, a product with a considerably shorter $t_{1/2}$ (Fig. 3c).

It is also possible to use a reaction with an actinide target and a lighter projectile to synthesize element 110. For example, the reactions

$$^{23}Na + ^{254}Es \rightarrow ^{273}110 + 4n$$
$$^{26}Mg + ^{249}Cf \rightarrow ^{271}110 + 4n$$

should not suffer any significant dynamical hindrance to fusion. The survival probabilities of the intermediate species are low (10^{-8}) and the overall formation cross sections are of the order of 10^{-36} cm^2. Another set of possible reactions employing heavier projectiles and lighter actinide targets, such as

$$^{40}Ar + ^{235}U \rightarrow ^{271}110 + 4n$$

offer an alternate path to element 110. These reactions have the advantage of employing readily available projectile and target nuclei and have the same or somewhat improved survival probabilities as the previously discussed reactions.

One interesting question that has been discussed recently is whether we have already discovered SHE. Certainly nuclear shell effects are already playing a crucial and important role in the stability of elements

102-108 (viz, the observation of the constancy of B_f ~ 5-6 MeV for these nuclei while the macroscopic liquid drop model fission barrier heights decrease by a factor of 5 for this range of Z). If "superheavy element" is synonymous with "element whose stability is determined primarily by a nuclear shell effect", then the answer is "Yes--we have 'discovered' SHE"

However we believe that the term "superheavy element" connotes an element whose lifetime is strikingly longer than its neighbors in the Chart of the Nuclides (an island of stability in a sea of instability) and whose stability is determined primarily by a spherical nuclear shell effect.(Myers, 1966; Strutinsky, 1967) Thus we conclude that SHE have not been discovered. If the measured halflife of element 110 is as long as predicted, the first criterion would be satisfied and we might be justified in referring to this as part of an "islet of the superheavy island."

In summary, it appears that the superheavy island has so far resisted all attempts to land. Because the superheavy elements are such a unique and important test of our knowledge of nuclear structure and the dynamics of the reactions used to synthesize them, we do not want to give up. The problem of synthesizing them is more difficult than we imagined in the 1960's when this research began. But it has been possible to overcome extraordinary difficulties in the synthesis and study of elements 107 and 108. We understand many of the reasons for our past failures. If improvements of orders of magnitude in the production and detection of superheavy reaction products are achieved, our current theoretical understanding of the superheavy elements and their properties provides a realistic basis for optimism. We therefore think it will be possible eventually to synthesize and identify the superheavy elements.

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Figure Captions

Figure 1. The halflife of the longest-lived isotope of a given element vs. atomic number, as known in 1970.

Figure 2. An allegorical representation of the stability of nuclei, showing a peninsula of known nuclei and an island of superheavy nuclei (predicted to be relatively stable) in a sea of instability.

Figure 3. Contour plots of predicted spontaneous fission halflives for SHE as calculated (a) in 1972 (Fiset) (b) in 1976 (Randrup) (c) in 1986 (Möller). In making the plot shown in (c) the shell corrections of Möller, et al. were transformed into spontaneous fission halflives using a semiempirical relationship while the alpha decay halflives are those of Möller et al.. The triangle designates the composite species in the $^{48}Ca + ^{248}Cm$ reaction.

Figure 4. Comparison between experimental (Armbruster, 1985) and calculated (Möller,1986) values of Q_α, the alpha decay energy, for N=157 isotones. The experimental Q_α values are lower limits for most of the nuclides because the transitions are believed to populate excited states of the daughter nuclei rather than the ground state. The length of the arrows shows the expected uncertainty in the Q_α values.

Figure 5. Three examples of excitation functions for complete fusion reactions. In each case, the dashed line represents the behavior for "normal", i.e., unhindered or not enhanced fusion. (a) sub-barrier enhancement of fusion probability (b) "normal" fusion (c) dynamic limitation of fusion due to "extra push" effects. From Armbruster (1985).

Figure 6. A schematic view of the stages of a heavy ion reaction in the Swiatecki model. The nuclear shapes at various stages of the reaction are shown along with the projectile energies needed to get to the various stages and the reactions mechanisms associated with each stage.

Figure 7. Plot of the contours of $-\log_{10} \sigma_{fus}(l=0, E=V_B)$ in cm^2 for various values of Z_{proj} and Z_{target} according to the semiempirical formula of Armbruster (1985). The actual fusion cross sections (neglecting survival probabilities)may include other partial waves besides

l=0. For a given maximum l value contributing to fusion, l_{max}, these l=0 cross section values should be multiplied by $(l_{max} + 1)^2$.

Figure 8. Plot of the minimum excitation energy E^* (MeV) of the composite species formed from a given target-projectile combination. "Extra push" effects are not considered in the computation of E^* although contours of E_x (extra push energy) > 0 and E_{xx} (extra extra push energy) > 0 are shown. The nuclear masses used are those of Möller and Nix (1981) and Möller et al. (1986) with droplet masses where not otherwise available taken from Myers (1966). The reactions were assumed to occur at a projectile energy (cm system) of 0.96 V_B (Swiatecki, 1982).

Figure 9. Variation of element formation cross sections for reactions involving the emission of one neutron as a function of the parameter, x_{mean}. From Armbruster (1985).

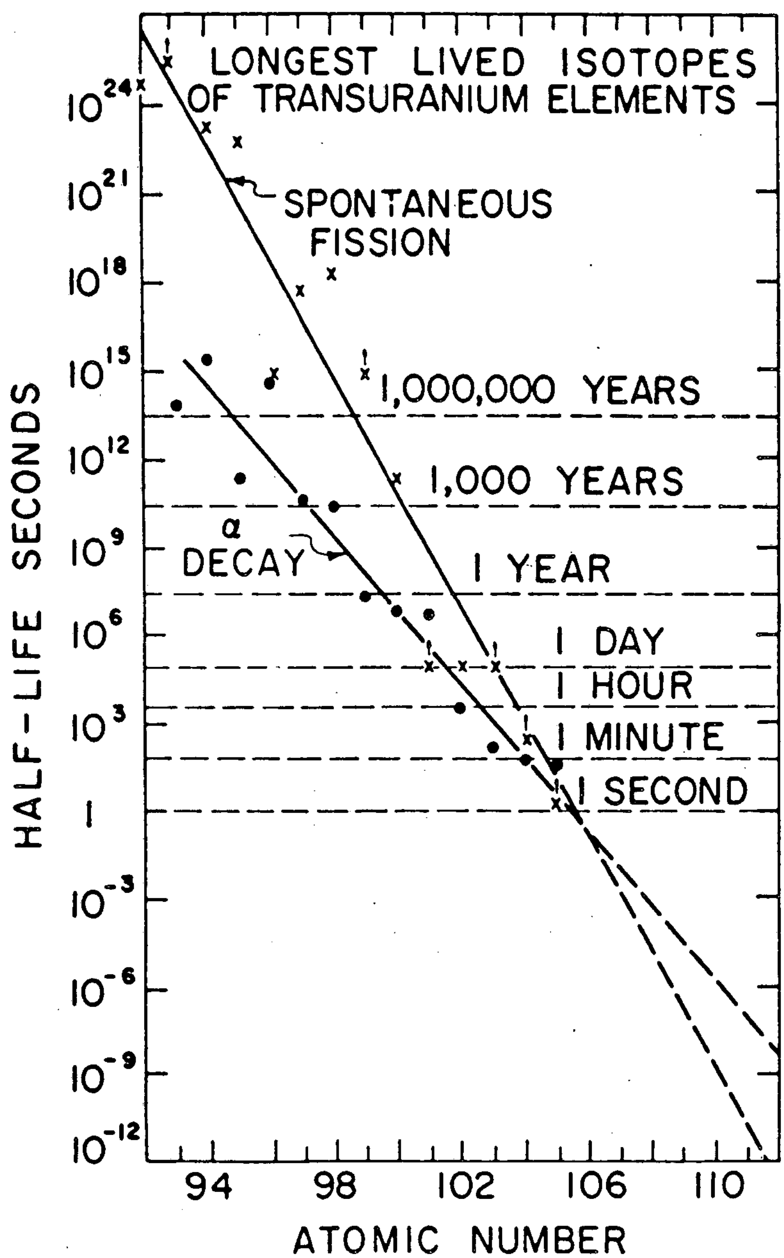

LONGEST LIVED ISOTOPES OF TRANSURANIUM ELEMENTS
SPONTANEOUS FISSION
α DECAY
1,000,000 YEARS
1,000 YEARS
1 YEAR
1 DAY
1 HOUR
1 MINUTE
1 SECOND
HALF-LIFE SECONDS
10^24
10^21
10^18
10^15
10^12
10^9
10^6
10^3
1
10^-3
10^-6
10^-9
10^-12
94
98
102
106
110
ATOMIC NUMBER

Fig. 1

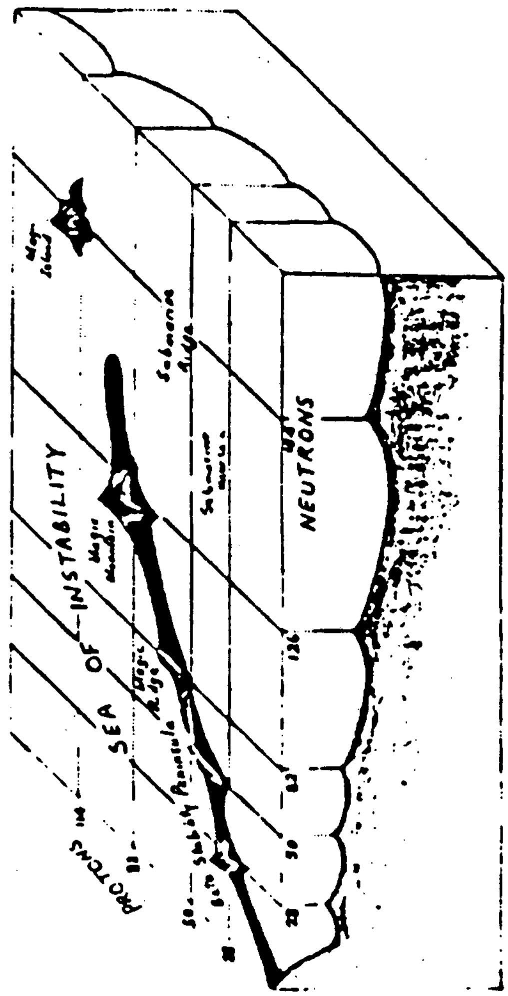
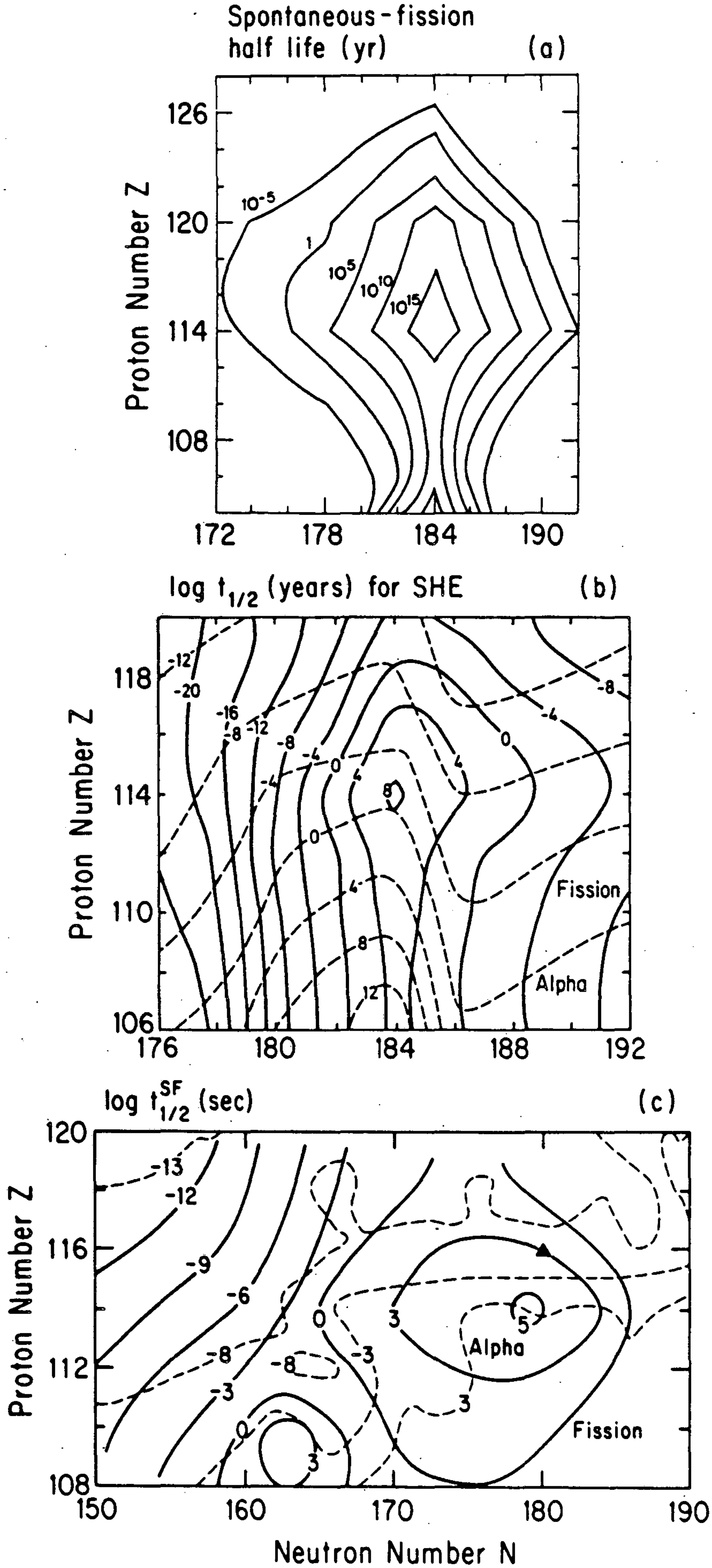

SEA OF INSTABILITY
NEUTRONS
PROTONS
126
82
50
28
Stability Peninsula
Magic Mountain
Submarine Ridge

Fig. 2



Spontaneous-fission
half life (yr)
(a)
Proton Number Z
126
120
114
108
172
178
184
190
10^-5
1
10^5
10^10
10^15
log t1/2 (years) for SHE
(b)
Proton Number Z
118
114
110
106
176
180
184
188
192
Fission
Alpha
log t^SF 1/2 (sec)
(c)
Proton Number Z
120
116
112
108
150
160
170
180
190
Alpha
Fission
Neutron Number N

Fig. 3

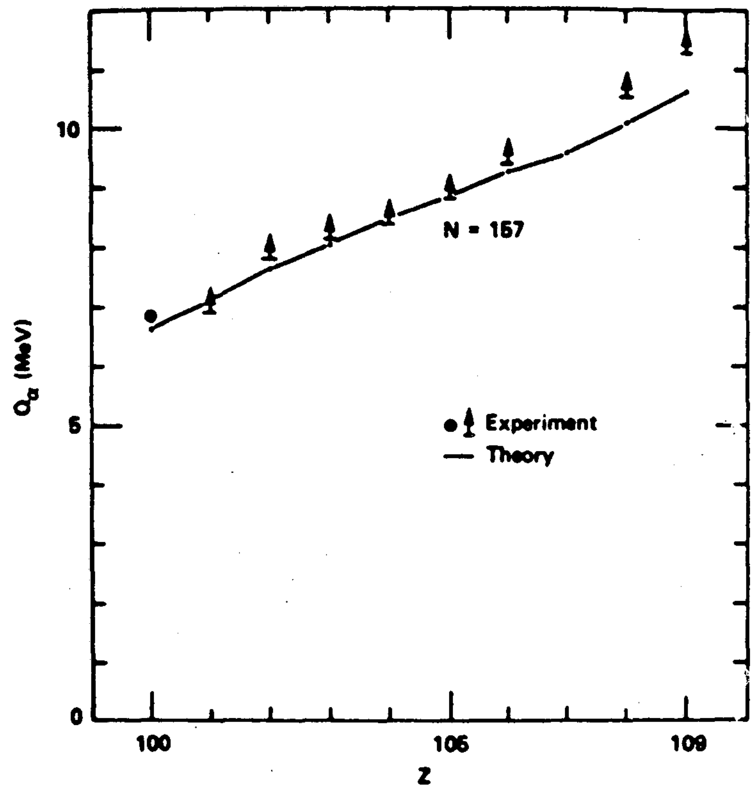


Fig. 4

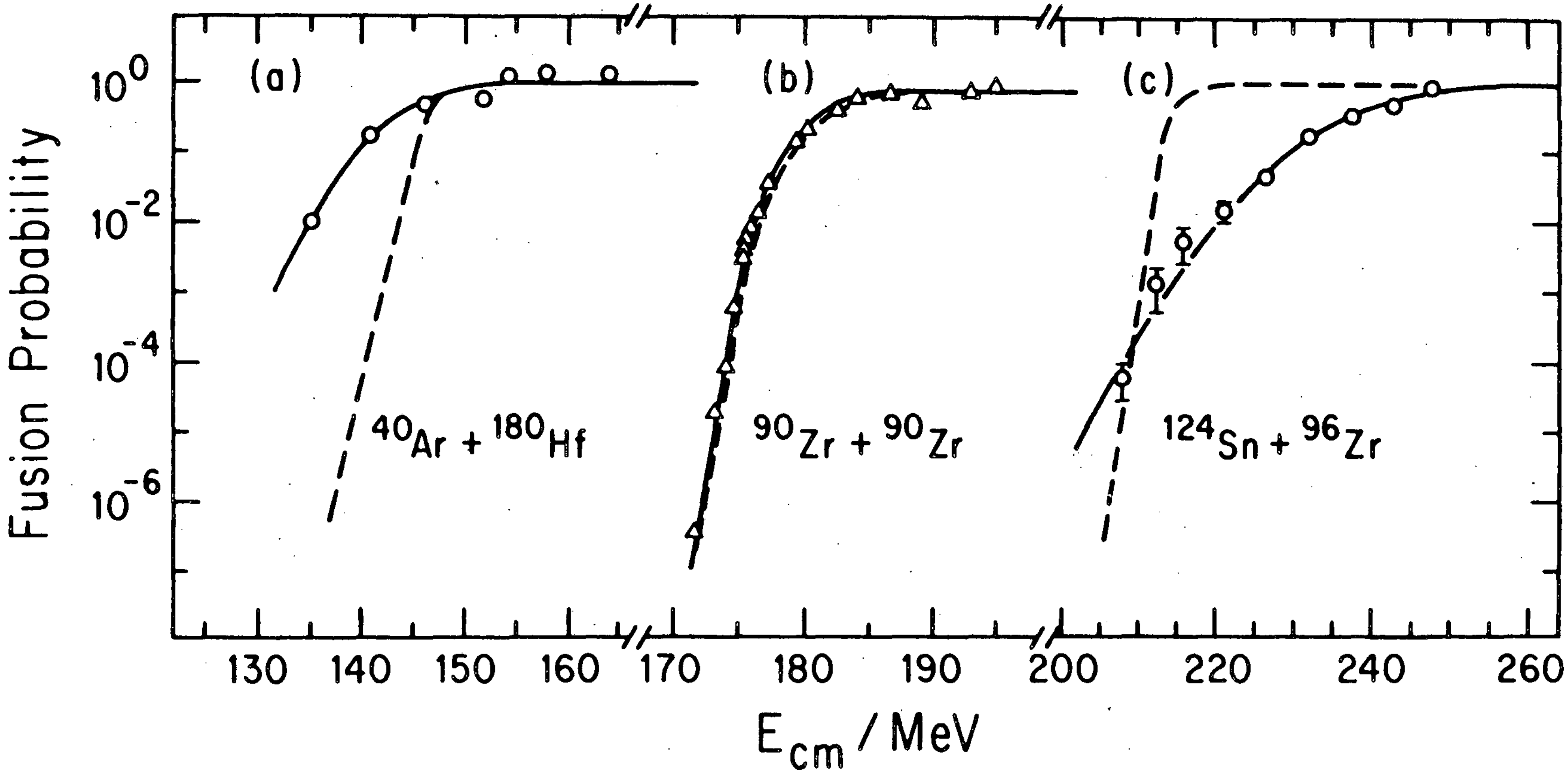

Fusion Probability
10^0
10^{-2}
10^{-4}
10^{-6}
(a)
(b)
(c)
$^{40}Ar + ^{180}Hf$
$^{90}Zr + ^{90}Zr$
$^{124}Sn + ^{96}Zr$
130
140
150
160
170
180
190
200
220
240
260
E_{cm} / MeV

Fig. 5

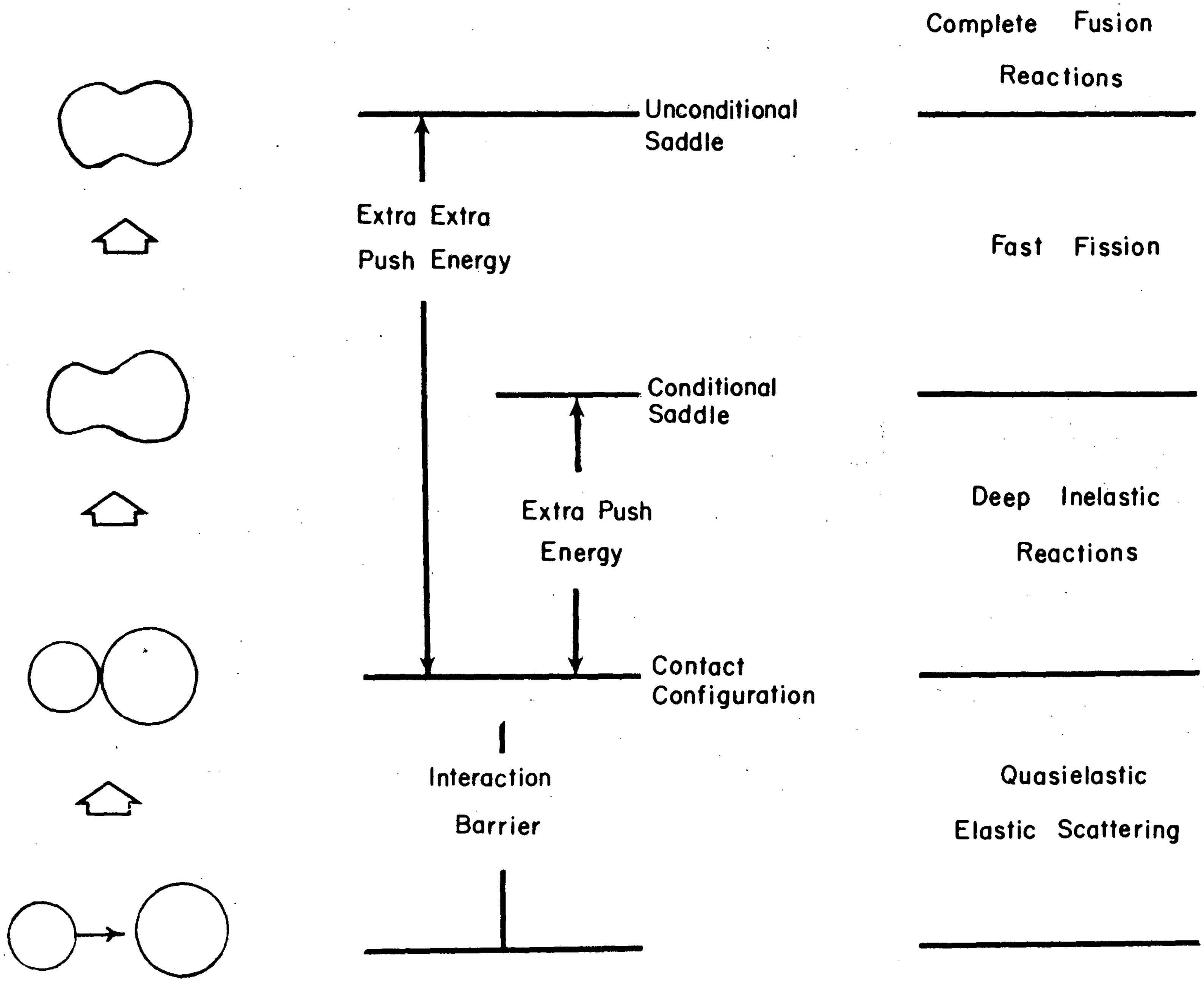

Complete Fusion
Reactions
Unconditional
Saddle
Extra Extra
Push Energy
Fast Fission
Conditional
Saddle
Extra Push
Energy
Deep Inelastic
Reactions
Contact
Configuration
Interaction
Barrier
Quasielastic
Elastic Scattering

Fig. 6

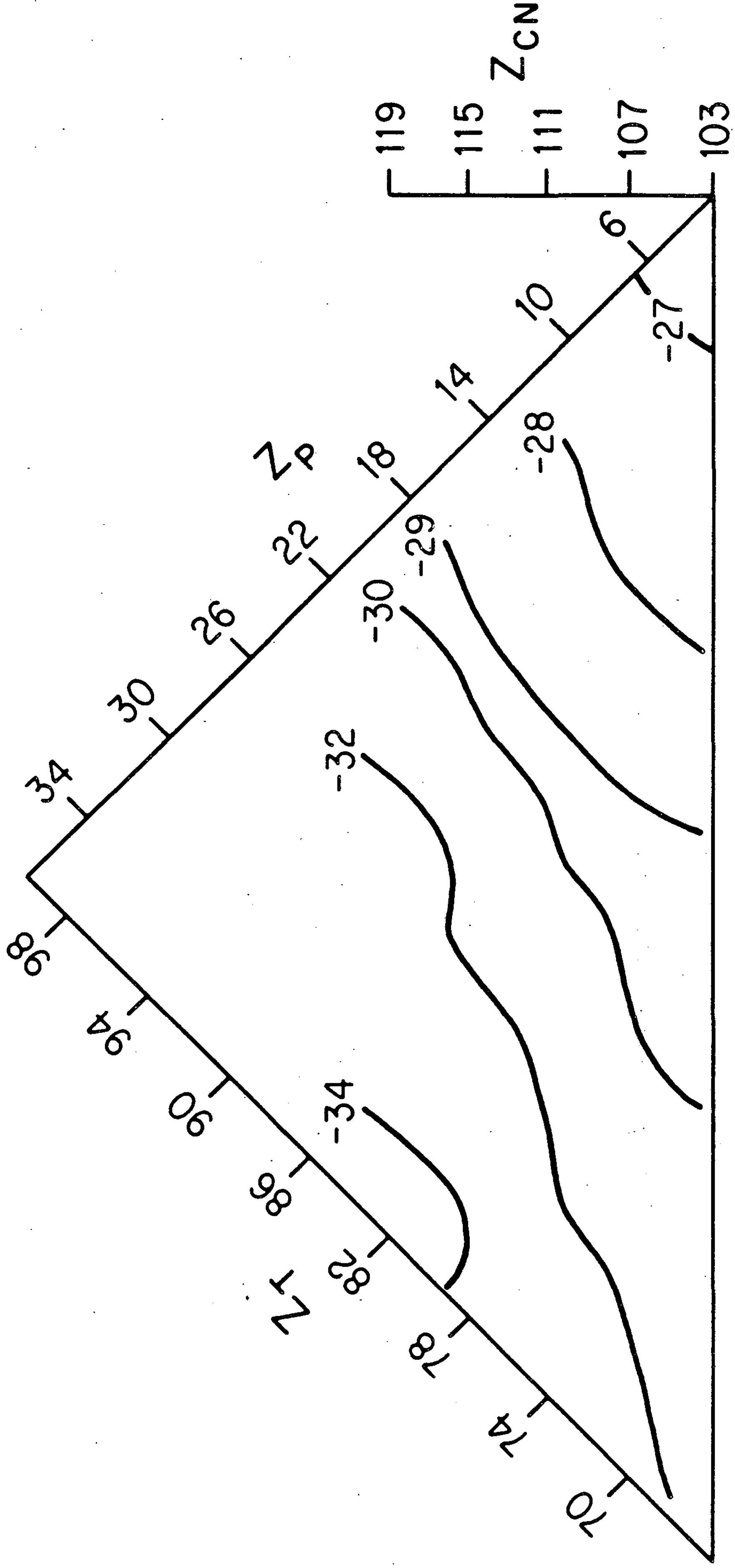
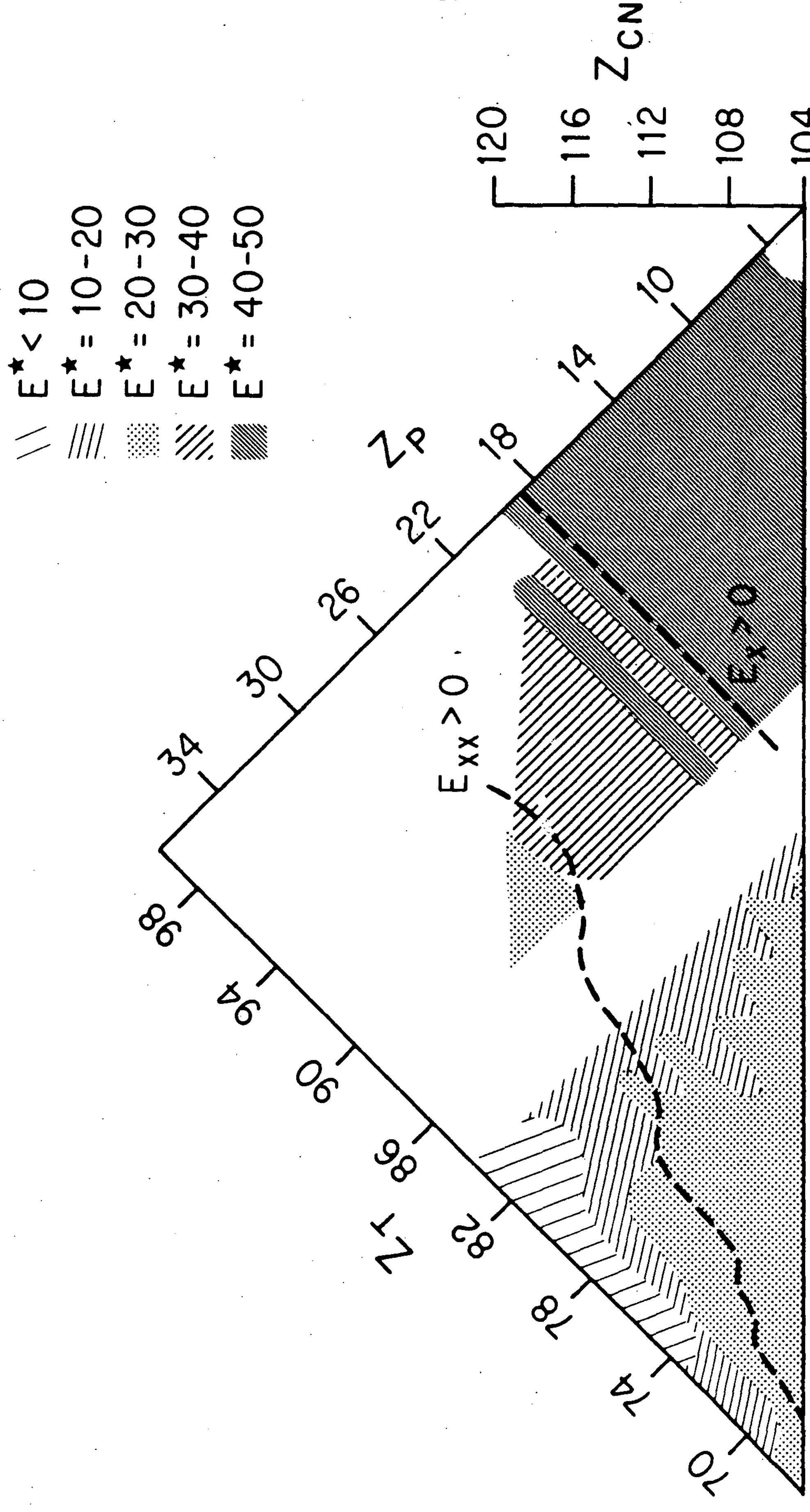
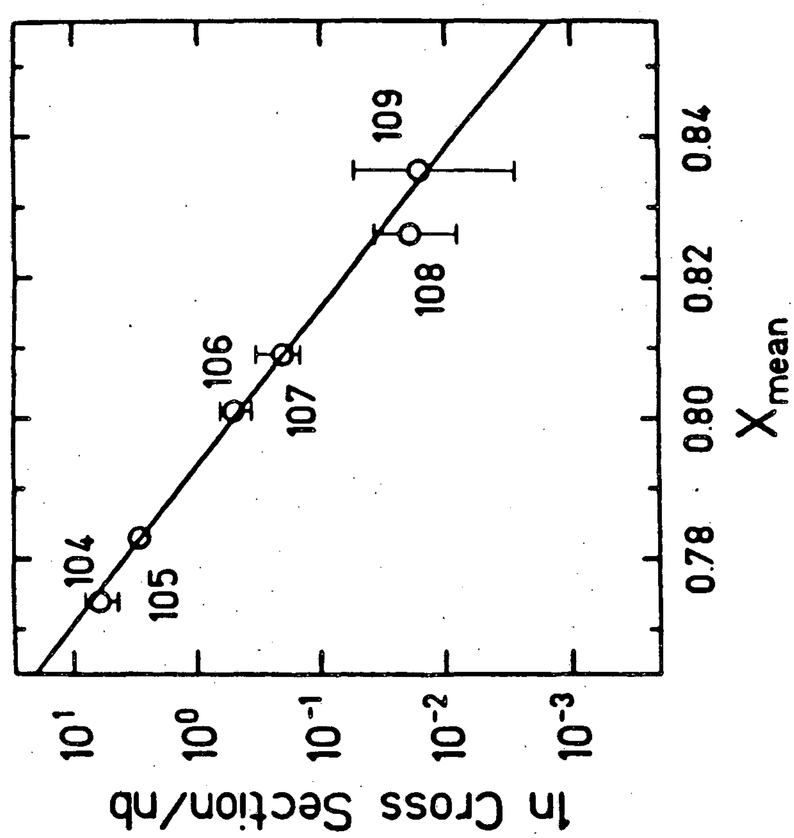

Z_CN
119
115
111
107
103
Z_P
6
10
14
18
22
26
30
34
Z_T
98
94
90
86
82
78
74
70
-27
-28
-29
-30
-32
-34

Fig. 7



E* < 10
E* = 10-20
E* = 20-30
E* = 30-40
E* = 40-50
Z_CN
120
116
112
108
104
Z_P
10
14
18
22
26
30
34
Z_T
70
74
78
82
86
90
94
98
E_xx > 0
E_x > 0

Fig. 8



In Cross Section/nb
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
X_{mean}
0.78
0.80
0.82
0.84
104
105
106
107
108
109

Fig. 9