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NUCLEAR STRUCTURE/NUCLEI FAR FROM STABILITY

Report of Working Group II

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1 Introduction

Our current knowledge of nuclear structure is confined to nuclei produced with projectiles and targets that have equilibrated for a significant fraction of the lifetime of the universe. Such a long equilibration (a few billion years) must evade many of the most exotic nuclear configurations, which due to their special properties, decrease the stability of the nucleus. The present basis of nuclear structure is phenomenlogical, that is, it is not derivable from a simple set of master equations. Not only is the structure of the nucleus sensitive to bulk properties, such as its mass and charge, but it also is strongly dependent on the details of the independent-particle quantal states that the protons and neutrons occupy and how these states interact with each other and modify the bulk nuclear properties. Far from stability the various possible combinations of exotic single-particle states make the problem even more complicated. Therefore, it is not possible simply to extend the present knowledge theoretically to such exotic situations not accessible to experimental study. Thus the use of Radioactive Ion Beams (RIBs) should provide unique opportunities, not only to answer critical issues concerning some of the most fundamental current nuclear structure themes, but it also will allow the study of entirely new phenomena unavailable with current techniques and not derivable from our present knowledge of nuclear theory.

It is useful to highlight a few such possibilities in these introductory remarks in anticipation of the more detailed discussions given below: (i) The long-predicted island of superheavy stability may be established. Not only is this of interest as a long-standing, elusive, historic goal, but it also is perhaps the ultimate test of the predictive power of current nuclear models and, therefore, of our understanding of the interplay of independent-particle and macroscopic structure in nuclei. (ii) The nuclear equation of state will be refined and the enticing hints of the possible binding of pure neutron matter can be probed by mass measurements and the associated definition of the drip lines. (iii) New information in neutron-rich nuclei may finally provide sufficient detailed information to pin down the site, environment, and mechanism of r-process nucleosynthesis. (iv) Detailed measurements of the properties of predicted closed-shell nuclei, such as ^{78}Ni, ^{100}Sn, and ^{132}Sn, will offer a stringent test of the microscopic independent-particle quantum structure forming the foundation of the nuclear shell model itself. (v) New data and analyses of the spectrum of single-particle states will provide detailed new information on the fundamental single-particle structure of nuclei and on the residual interactions that modify that structure. (vi) New manifestations of collectivity, such as the long-sought stable triaxial nuclei, may be found and a better understanding of others (for example reflection asymmetric shapes, which only now are beginning to be probed) should be in the offing. (vii) The study of neutron halos, or skins, representing nearly-pure, low-density neutron matter is a most intriguing and exciting venture. (viii) Complete spectroscopy near stability will allow the first comprehensive connections between low- and high-spin physics to be forged making possible uniquely-sensitive tests of modern nuclear structure models. The exciting concept of quantal chaos in nuclei can be more readily studied in such nuclei and in others that can be formed with extremely-high beta-decay energies. (ix) In the realm of high spin, the increased fission barriers in newly accessible neutron-rich nuclei may allow the discovery of hyperdeformed nuclear shapes with a 3:1 ratio of major to minor nuclear axes. (x) Access to exotic hig-h-j, low-Ω configurations and the associated magnified Coriolis effects should open unique new vistas in which the single-particle effects are dominated by rotation.

In the following pages we briefly outline some of these and other topics. It should be recognized that it is impossible to do justice to such a broad field in these few pages. Since this work represents the collective viewpoints of a diverse Working Group, and since it is not clear which of the topics discussed will in fact turn out to be the most interesting in an operating facility a number of years hence, we have resisted the temptation to discuss only a couple of topics in detail and rather try to present as broad a coverage as possible. At the other extreme we try to avoid making this report a mere listing of an even larger number of topics by attempting to present sufficient material to indicate an interest in each case. That is, in each subarea we try to identify the main themes, undercurrents, and motivations, and to identify a few experimentally-accesible examples. Finally, since this is the collective report of a Working Group discussing scientific applications, and is neither a complete nor a review paper, we have dispensed with a complete set of references. The field covered by this report is so vast and active that, to have done otherwise, would have highlighted a miniscule segment of the literature at the expense of numerous equally deserving accomplishments. A few "typical" references, however, are included to assist the nonexpert. For additional information the reader is referred to one of several recent reviews and/or conferences on this subject [3,4,5,6].

Although the scientific justification for further studies of nuclei far from stability with RIBs should be amply demonstrated below, and elsewhere in this report, it is interesting to reflect for a moment on the history of such studies. A few examples that come to mind include that of ^{146}Gd and the discovery that, for certain neutron numbers, $Z = 64$ acts as a closed shell [7]. This was one of the earliest additions to the traditional complement of magic numbers. Similarly, recent studies of deformation near ^{31}Na and ^{80}Zr show that $N = 20$ and $Z = 40$ does not ensure a spherical nuclear shape [8,9]. The discovery, in the early 1970's, of an abrupt spherical-deformed phase or shape transition region at $N{=}60$ near $A{=}100$ [10] and within a few mass units of a significant neutron subshell closure at $N = 56,58$ [11] hinted at the need for a more detailed understanding of the onset of collectivity in nuclei and led, several years later, to the Federman-Pittel mechanism [12] in which the valence p–n interaction modifies the underlying single-particle structure of one type of particle as a function of the number of nucleons of the other type. The discovery of beta-delayed nucleon, or few-nucleon, radioactivity (β–p,β–2p,β–n,β–2n,...), often near the drip lines [4], revealed the spectroscopic richness of regions with high-decay energies and offered new insights into the structure and stability of nuclei at the extremes of isospin. Nearer stability, the discovery, in recent years, of examples of multiparticle radioactivity in which intact ^{14}C or even ^{24}Ne or ^{34}Si nuclei are emitted [13] pointed to the amazing complexities of the nuclear potential-energy surface and to the possibility of exotic-cluster formation near the nuclear surface. The discovery of symmetric fission in the heaviest known actinides [14] demonstrated the key role played by structure (extra binding) in the fission fragments. Finally, the discovery of superdeformation in rapidly-rotating neutron-deficient heavy nuclei [15] has opened up wholly new high-spin phenomena that continue to reveal remarkable discoveries, such as essentially identical rotational sequences in neighboring isotopes and isotones [16]. Together, these and other studies have led to new ideas on shell effects (e.g., Strutinsky shell corrections) and residual interactions, to the discovery of dynamical symmetries in nuclei, to the development of new generations of more sophisticated macroscopic-microscopic models, and to a more profound understanding of pairing and collectivity in nuclei.

2 Masses, Stability, Beta Decay, and the Heaviest Elements

Under this rubric gross nuclear properties are stressed. These properties reflect, in a sense, the most obvious and global characteristics of each nucleus and are, therefore, the net result of the single-particle motion, collective correlations, and interactions that are active. The motivation for studying such properties is, of course, to elucidate these facets but also, more specifically, to understand such important concepts as the nuclear equation of state, in particular its compressibility and charge distribution. Studies in this area are also of paramount importance to eradicating the nuclear uncertainties in the r-process of stellar nucleosynthesis. Finally, work here is also directed toward discovering and studying the heaviest elements and, possibly, a superheavy island of stability. Even work on nuclei far removed from this island is important, since it leads to improved modelling of nuclear masses and lifetimes and therefore to more sophisticated extrapolations to unknown nuclei.

2.1 Fission/Heaviest Elements

As noted, a prime interest is the creation and study of nuclei in the predicted superheavy island of stability [17]. This is a long sought goal of nuclear physics, which has often been thought to be unattainable. However, recent improvements in macroscopic-microscopic models offer greater confidence in predicting the existence and properties of superheavy nuclei [18]. Such models are quite sophisticated and are capable of handling complex potential energy surfaces with multiple minima and saddle points. Moreover, they take into account the structure not only of the fissioning system, but also that of the daughter products, since this is the barrier to that fission which determines the stability of a given nuclear species. It is only with RIBs that any realistic chance exists to reach the superheavy island, thereby discovering the heaviest nuclei, and testing the ultimate single-particle bases for all nuclear structure. Aside from the general issue of producing superheavy nuclei there are other associated goals. The fission of excited nuclei in the lead region is symmetric, that is, the fission product masses are nearly equal. The spontaneous fission of most of the actinide nuclei, on the other hand, is highly asymmetric. Therefore, the identificaton of the onset of asymmetric fission near A = 220–230 is critical to the understanding of the fission process and an understanding of the competition among fission modes as a function of Z, N, excitation energy and angular momentum of the fissioning system in terms of both macroscopic, droplet behavior and modulations due to the underlying shell structure. Studies might center on the light Ra isotopes. A second area concerns heavy actinides with $N > 160$. Figure 1 shows a calculation of the fission barriers near $A = 264$ [19]. There is a fascinating competition between asymmetric and symmetric fission with very high kinetic energy associated with the fission of nuclei such as $^{264}\mathrm{No}_{162}$, $^{264}\mathrm{Md}_{163}$, and $^{264}\mathrm{Es}_{165}$. In these nuclei the barrier to symmetric fission can be offset by the extra binding of the symmetric, doubly-magic, daughter nuclei $^{132}\mathrm{Sn}_{82}$. (Incidentally, since fission probabilities depend not only on the structure of the parent but also on that of the daughter, this is yet another motivation for the study of nuclei in the vicinity of $^{132}\mathrm{Sn}$.) About 12 MeV of energy is gained for each Sn fragment, thereby opening a symmetric fission path characterized by an anomalously-high kinetic energy of the fission fragments. Conversely it is noted that the inverse process, the fusion of two nuclei in the vicinity of the $^{132}\mathrm{Sn}$ closed shell, should have an enhanced cross section and might, indeed, be a method of synthesising some of the heaviest elements. Less complicated transfer reactions, using RIBs, to produce nuclei with A ≈ 264 include $^{254}Es_{155} + {}^{96}Rb_{59} \rightarrow {}^{264}Fm_{164}$, $^{264}Md_{163}$, $^{264}No_{162}$, and $^{264}Lr_{161}$.

2.2 Drip Lines

The study of both proton and neutron drip lines is important in indicating the limits of particle stability of nuclei in general, in further testing of macroscopic-microscopic models and (see below) in gaining access to nuclei with extremely high decay energies which offer the possibility of exotic decay modes. The neutron drip line is a particularly-important regime which is of critical interest to the study of neutron halos and skins. The discovery of nuclei with halo properties such as ^{11}Li [20,21] hints that pure or nearly-pure neutron matter may even be bound under certain circumstances. Recent nuclear matter calculations directed toward this issue [22], therefore, take on renewed interest. They are parameterized in terms of a constant that can be fixed empirically by the precise location of the neutron drip line. (Additional information on neutron halos is contained in subsecton 3.2.1 and in a separate chapter in this report.) Finally, the locus of the proton and neutron drip lines is of interest in limiting possible nucleosynthesis scenarios.

2.3 Masses

The mass is a fundamental nuclear property. Since masses give binding energies and, therefore, neutron and proton separation energies, they are essential to the understanding and the modelling of the r-process for nucleosynthesis (discussed below). They also give indirect information on the nuclear equation of state, provide crucial tests of macroscopic-microscopic models, and yield information on the structure of the nuclear ground state.

Masses are particularly useful in delineating the nuclear equation of state. The concept of nuclear compressibility plays a key role here, determining, for example, the energy of giant monopole resonances and the "skin" properties of nuclei. Since the compressibility essentially reflects the restoring force against oscillations of the outermost nucleons, its determination relies on the empirical knowledge of nuclear masses. RIB studies will enable many new and critical mass determinations.

An interesting concept which has arisen in connection with nuclear halos as well as in other contexts is that of Coulomb redistribution, or the suppression of the proton density in the nuclear interior due to a combination of Coulomb repulsion and an associated in-filling of neutrons. This effect has been empirically detected in electron-scattering experiments [24] and also appears in some Hartree-Fock calculations [25]. Liquid-drop models do not incorporate such proton-deficient cores, but droplet models, which agree better with the masses of the heaviest elements, do. Therefore, additional masses of heavy nuclei will aid the delineation of such models and refine the understanding of proton core suppression.

Certain double differences of nuclear masses can be used to extract empirical proton-neutron two-body residual matrix elements [26]. It has become increasingly evident recently that these matrix elements, representing a T=0 residual interaction, are of critical importance in understanding the evolution of nuclear shell structure as a function of particle number, isospin, and angular momentum and, therefore, of the onset and development of collectivity and phase transitions in nuclei. Such interactions will be considered in greater detail in the following section, but suffice it to say here that new mass determinations in certain critical regions would go far toward reducing the uncertainty in two-body residual interaction matrix elements.

Aside from specific theoretical reasons for measuring the masses of selected nuclei, there are several mass regions where no empirical data exists in which the various theories exhibit large deviations. Clearly, the measurement of even a few masses in these regions would help distinguish between the models and, inevitably, refine them. In particular, neutron rich nuclei with Z = 10–20, the Z = 28–36 nuclei with N > 50, and the Z = 44–50 nuclei with N ≈ Z are such examples.

A particularly enigmatic region occurs near ^{34}Na. Here, not only do significant deviations exist between theoretical and experimental masses, but the measured Na masses themselves have a different isotopic trend relative to the neighboring isotones. Some of these masses have sizable experimental uncertainties. Recently an "island of inversion" has been proposed for these nuclei [27] in which $0\hbar\omega$ and $2\hbar\omega$ excitations cross, leading to the sudden onset of deformation at N = 20, a neutron number previously considered as a classic magic number. Improved masses for the neutron-rich Na isotopes and new results for neighboring isotones would test these ideas and help to solidify our understanding of how and where nuclear deformation arises in terms of the detailed spectrum of single-particle states.

2.4 Beta Decay and Lifetimes

Beta decay is valuable for a variety of reasons: a measure of Gamov-Teller (G-T) matrix elements as a test of weak interaction theory, a source of nuclear lifetimes, or as a means of access to interesting nuclear structure questions. In the present section we focus on the first two points leaving the discussion of the last topic with regard to the study of nuclei far from stability for the following section.

One of the interesting beta-decay puzzles is the apparent empirical quenching of G–T strength. G–T matrix elements are often substantially smaller than predicted, even in nuclei near closed shells where both parent and daughter configurations are simple and, presumably, well known [28]. Before the question can be fully addressed, though, it is necessary to determine that the full empirical strength has been found. Strength can be missed either if it is fragmented (by the mixing of states in the daughter nucleus) into too fine a structure to be observed or (again due to mixing) if some of it is pushed to excitation energies above the effective threshold for significant beta feeding. Both sources of error are minimized for nuclei with high beta-decay energies. More levels in the daughter nucleus are available for population; therefore, a more complete and reliable level scheme can be constructed and the range of excitation energies in which to search for the beta-decay strength is also increased. The use of RIBs to populate beta-decaying nuclei extremely far from stability with their associated higher beta-decay energies thus offers an opportunity to more thoroughly address the long-standing G–T quenching problem. Likewise access to neutron-rich nuclei just below the Pb closed shell using RIBs will allow the first measurement of beta-decay matrix elements connecting states differing by two major shells.

Beta decay far from stability with high Q_β values also can lead to particle-unstable daughter nuclei. A number of cases of such beta-delayed particle (β–p, β–2p, ...) emission have been discussed [4]. They are interesting because they provide structure information for the daughter nucleus, information on the position, strength, and distribution of the G–T giant resonance, and a study of super-allowed beta-decay matrix elements. Moreover, β^+ decay populates isobaric analogue states and, especially in light nuclei, or medium nuclei with N $\approx$ Z, allows a determination of the isotopic-spin purity. An example of the advantage of RIBs for populating exotic nuclei where such questions can be addressed is given by a comparison of fusion-evaporation calculations for various reactions leading to ^{51}Co. The ^{40}Ca(^{16}O,xp,yn) reaction at 170 MeV has a cross section of 0.004 mb. In contrast, the corresponding ^{14}O reaction, ^{40}Ca(^{14}O,xp,yn), at the more convenient lower energy of only 70 MeV has a cross section, 0.17 mb, over 40 times larger. The lower required beam energy helps to compensate for the difficulty of providing ^{14}O beams.

The use of RIBs to make beta-unstable nuclei, either by reactions or as fission products of heavy actinides, allows the study of many new nuclei along the r-process path [29]. A critical issue in supernova r-process nucleosynthesis is the time scale ("cycle" time) needed for the production by neutron capture and beta decay, of the actinides from "seed region" nuclei near ^{56}Fe. This time scale is dominated by the half lives of the so-called waiting-point nuclei where the r-process abundance peaks cross a neutron magic number. At such points the r-process halts until these nuclei can beta decay. It is, therefore, crucial to determine the lifetimes and binding energies of nuclei in these waiting-point regions so as to determine, or set limits on, the required duration of the intense supernova explosion. Recently, some of these nuclei have been studied for the first time, but more information is needed on all three waiting point regions near ^{80}Zn, ^{130}Cd, and especially ^{195}Tm, where no experimental information exists. It may be possible to study such species either through reactions with RIBs or through the beta decay following the fission of heavy, very neutron rich actinides produced with RIBs.

In modern "network" r-process calculations [29], the waiting-point approximation (of ignoring all but the lifetimes of the waiting point nuclei) is bypassed by incorporating the properties ($T_{1/2}$, binding energies, etc.) of all nuclei along the r-process path into these complex calculations. Therefore, these data are needed so that a larger fraction of the information inserted into these calculations is empirical. This is especially important because, even though recent models are greatly improved over their predecessors, the discrepancies between measured and predicted lifetimes even near stability average at least a factor of 2–3 (in both directions) and can exceed an order of magnitude in selected cases. This constitutes a significant impediment to determining the site and environment (neutron flux, duration, and temperature) of the r-process.

2.5 Cluster Decay

A fascinating phenomenon, now known in several cases, is heavy-ion radioactivity, in which an unstable nucleus decays by emitting a massive chunk, such as ^{14}C, or even ^{25}Ne or ^{34}Si [13]. This process is clearly a major challenge to nuclear theory, since it requires an understanding of both the formation amplitudes of such fragments near the nuclear surface, as well as the probability of their emission through a complicated barrier. Though this decay mode was actually predicted before its observation, it is still far from well understood and new empirical examples, and their systematics, would be valuable. There is the intriguing possibility that this decay mode may be even more prominent farther from stability in nuclei accessible with RIBs.

2.6 Laser Spectroscopy

The access to nuclei with extremes of isospin also introduces exciting possibilities for using laser-spectroscopic methods. Many of the most fundamental properties of a nuclear state, e.g. the mean-square radius $< r^2 >$, the magnetic moment μ, the magnitude and **sign** of the quadrupole moment Q, and in some cases the spin, can be measured using techniques based on lasers [30].

Laser techniques generally involve exciting ions resonantly and mapping out the isotope shifts and hyperfine structure by scanning the laser wavelengths. The use of radioactive beams circumvents the usual problem of producing and transporting short-lived nuclei to the laser beam. The exotic nuclei could be obtained either as a direct beam or as the residue of a reaction based on RIBs. Laser methods well matched to both production methods are available: e.g., the collinear method [31] for direct beams and recoil into gas [32] for less intense production by reactions.

Nuclear phenomena that can be studied include unusual distributions of nuclear matter, shape changes, and high-spin effects including superdeformation. Several of these possibilities are discussed in more detail in the following paragraphs:

Local deviations of the neutron to proton density ratio. Nuclei with a large deficit or excess of neutrons may minimize their energy by local variations in the properties of nuclear matter, e.g. the neutron "skins" or "halo" and Coulomb redistribution discussed elsewhere in this article. Indeed at the extremes of isospin, accessible with RIBs, even more extreme variations in the N/Z density ratio, e.g. a local "precipitation" may occur. Such effects could be studied by comparing results of laser spectroscopy, which measures properties of the proton distribution, and hadronic probes, that determine the matter distribution. Deviations of $< r^2 >$ from an $A^{1/3}$ dependence alone, can yield an indication of a separation of the neutrons from the protons.

Specific properties of exotic states. Measurements of $< r^2 >$, μ, and in some cases Q can be made using laser techniques for special nuclear states, such as the superdeformed and other exotically-deformed states described elsewhere in this report.

Transitional nuclei. The most definitive signature of a nuclear shape transition is a sudden change in $< r^2 >$ and an associated change in the sign of Q. An example is that observed using laser techniques in the Pt, Au, Hg, and Tl isotopes [30,33]. The use of RIBs will allow an extension of measurements in this mass region to lighter nuclei and for similar measurement in the region of the more exotic shape transitions discussed elsewhere in this report.

Radii of closed-shell nuclei far from stability. Measurements of $< r^2 >$ would be a test of the proposed double-shell closure in, e.g. ^{100}Sn and ^{132}Sn. The charge radii for the tin chain studied thus far ^{108,125}Sn [34] show a smooth parabolic variation. Measurements and extrapolations indicate smaller values than calculated from microscopic theories for $^{118-132}$Sn.

3 Nuclear Shell Structure, Shapes, Collectivity, and Shape/Phase Transitions

Neglecting effects, such as quark degrees of freedom, coupling to baryon excitations (e.g., delta resonances), which appear to be superfluous for low-energy (say < 100 MeV/A) phenomena, the Fermion Shell Model is the most fundamental model of nuclear structure. This model is based on a mean field (mostly due to a central potential) leading to quantal single-particle states, and residual interactions that contribute in a many-body environment. Where calculations are practical, it is the paradigm. In general, it is the rationalization and microscopic justification for other models, models which are themselves generally simplifications or truncations of the Shell Model designed to avoid its calculational complexities and to focus on simple, often collective, excitation modes, symmetries and the like. In view of this theoretical hierarchy, tests of the fundamental properties of shell structure are vital to a profound understanding of nuclear physics and, ultimately, to providing the input for the development of a realistic nuclear theory which remains elusive. Nuclei in the new frontiers far from stability offer wholly new vistas leading toward this goal. In addition, access to new combinations of N and Z, the exploitation of high decay energies, and of opportunities for "complete spectroscopy" will reveal new manifestations of collective many-body behavior, symmetries, and afford a qualitative leap in our appreciation of the interplay of the single-particle and collective facets of nuclear structure.

3.1 Single-Particle Structure

The underlying microscopic basis for all nuclear structure is the Shell Model whose most important characteristic is a set of single-particle eigenstates and eigenvalues. This is fundamental to all other manifestations of single-particle and collective behavior. As alluded to earlier, however, the single-particle energies of nuclei do not constitute an immutable substructure. Rather, due to gross changes (e.g., radius) in the mean field and to the effects of residual interactions, the single-particle structure, and its attendant patterns of major and minor gaps, is an evolving, dynamic concept, which is dependent, separately and in concert, on the numbers of protons and neutrons and, in particular, on the numbers of valence particles of each type. Even the magic numbers are not sacrosanct in that some nuclei with $N = 20$ or $Z = 40$ (e.g., ^{31}Na and ^{80}Zr) are well deformed and nucleon numbers such as $Z = 64$ can provide strong inducements to spherical shapes. Thus one of the most important roles of RIBs in nuclear structure will be the study of such as yet unreachable doubly-magic nuclei as ^{78}Ni, ^{100}Sn, and ^{132}Sn and the mapping of single-particle structure in the neighboring odd-proton and odd-neutron nuclei. This can be done only by exploiting reverse kinematic stripping and pickup reactions using RIBs. Nickel–78, ^{100}Sn, and ^{132}Sn all are expected to be doubly closed-shell nuclei with properties similar to ^{208}Pb. If these expectations should turn out to be false, it would be a devastating assault on our most basic concepts of nuclear structure and, just as clearly, a challenge and mandate for a deeper understanding of the shell structure of nuclei, which results from the interplay of fundamental quantum degeneracies in central potentials and the critical residual interactions which modulate that shell structure.

The two most obvious and predominant components of these residual interactions are nucleon pairing and the valence p–n interaction. Though the former has been rather thoroughly studied, recent work suggests new features such as a possible dependence of pairing on neutron excess, (N–Z)/A. Whether such effects are due to a fundamental neutron-excess dependence of the pairing interaction or whether they arise from macroscopic effects or p–n interactions is an open, and basic, question. RIBs will make possible the production and study of new nuclei spanning extended isotopic or isotonic chains. One case where such chains have recently provided intriguing data is the set of neutron rich V–Fe isotopes where no isospin effects are observed [35].

The valence p–n interaction affects nuclear structure in several ways

[36]. It appears in two forms, as a T=1 interaction identical to the nuclear p–p and n–n forces, and, more importantly, as a T=0 force that leads to single-nucleon configuration mixing and hence, perforce, to collectivity and deformed nuclear shapes. The T=0 interaction appears, predominantly, in two guises, a monopole and a quadrupole component. The latter, which is dependent on the angular orientation of the respective proton and neutron orbits plays a key role in the evolution of collective behavior in deformed regions and contributes to the saturation of collectivity near midshell (where individual quadrupole p–n matrix elements vanish). The monopole component is, perhaps, even more crucial, and certainly less well known: depending on radial overlaps, it varies with the (nlj) single-particle quantum numbers of the interacting orbits and contributes effective shifts to their single-particle energies. These shifts can eradicate shell and subshell gaps, both for spherical and deformed shapes, and therefore, vitally affect the evolution of nuclear structure. An example is the A = 100 and 150 phase-transitional nuclei where the dynamics of the Z = 38 or 40 and Z = 64 gaps contributes to the sudden onset of deformation at N = 60 and to that at N = 90. This effect is particularly dramatic for the Sr isotopes where the onset of deformation is gradual below N = 50 but virtually instantaneous on the neutron-rich side at N = 60 [37]. Another example is the structure of the heavy N = Z nucleus ^{80}Zr which, despite having nucleon numbers of 40, is deformed rather than spherical in its ground state.

Unfortunately, the monopole p–n interaction matrix elements are not well known and it is not yet possible to account quantitatively for the known shifts of single-particle energies (e.g., the inversion of the neutron $2d_{5/2}$ and $1g_{7/2}$ orbits between Zr and Sn). Excellent empirical sets of two-body matrix elements are available for the 2s-1d shell in light nuclei but the reliability of such empirical sets falls off rapidly beyond the $1f_{7/2}$ shell. Partly, this is due to the lack of accessible nuclei where the appropriate combinations of proton and neutron single-particle states are available. As a specific example, the proton Z = 50–82 and neutron N = 82–126 shells have five and six orbits, respectively, and hence 30 two-body p–n T=0 matrix elements. However, since these shells tend to fill together near stability, empirical information is only available on the matrix elements between orbits occupying similar positions in each shell. Thus, for example, one can estimate the $\pi(2d_{5/2})$–$\nu(2f_{7/2})$ interaction, but not the $\pi(2d_{5/2})$–$\nu(3p_{1/2})$ or the $\pi(2d_{3/2})$–$\nu(2f_{7/2})$ interactions. Determination of the latter two interactions requires binding energies of the 0^+ ground states of even-even nuclei and single-particle energies in odd-mass nuclei that have, for example, two valence nucleons of one type and many of the other (e.g., the neutron-rich Te, $Z = 52$, isotopes or the proton-rich $N = 84$ isotones). Such studies can revolutionize our knowledge of residual interactions. Combined with the capabilities of modern computers, this offers the hope that realistic *ab initio* microscopic nuclear-structure calculations in heavy nuclei may become possible for the first time.

Empirical p–n interactions of the last proton and last neutron may be estimated from double differences of binding energies of neighboring nuclei [26]. Figure 2 shows such empirical interactions for the ground states of even-even nuclei. The microstructure (see inset) reflects primarily the complementary contributions of the monopole and quadrupole components. In deformed nuclei, the behavior of the latter is usually understandable (at least qualitatively) in terms of the angular orientations of the respective Nilsson orbits. This gives the hope of another approach to extracting the monopole part. This is easiest in regions (near midshell) where the quadrupole component is small. However, to do this requires new data (binding energies) on such nuclei as ^{240}Cf, ^{244}Fm, ^{250}No, and ^{254}104, beyond point "A" in Fig. 2. A similar region may exist in the rare-earth region near $N = 100$, but it is less obvious empirically (region "B" in Fig. 2). Precise binding energies for such nuclei as ^{156,158}Er, $^{160-164}$Yb, ^{164,166}Hf, and ^{168}W, which should be accessible using RIBs, would be enormously useful. Indeed, measurement of these eight masses would immediately give p–n interactions in fourteen additional nuclei. Dysprosia–168,170 would fill in critical *lacunae* as well.

Lastly, it is known that $T=0$ p–n interactions in light $N = Z$ nuclei are anomalously large (indeed, they appear as singularities in region "C" of Fig. 2), and also that they decrease in magnitude with increasing N or A. Shell-model calculations with realistic interactions reproduce this effect, as a consequence of the enhanced $T = 0$ matrix element in orbit combinations having high spatial symmetry that occur for $N = Z$. It will be especially interesting to extend such data (requiring sets of four adjacent masses) to still heavier $N = Z$ regions where one might expect the spatial symmetry to be reduced due to the effects of the Coulomb force in altering the proton single-particle energies. Studies between $Z = 40$ and 50 would be particularly intriguing since ^{80}Zr has recently, and surprisingly ($N,Z = 40$ are often considered magic numbers), been discovered to be deformed [9] and ^{100}Sn is expected to be a good doubly-magic nucleus such as ^{208}Pb. With RIBs one can expect to form the entire $N = Z$ sequence from ^{80}Zr to ^{100}Sn and perhaps beyond.

The overriding goal, which is now barely on the verge of achievement even in the phenomenological sense, is to achieve a truly unified macroscopic and microscopic understanding of nuclear structure, collectivity, phase transitions, and deformation.

3.2 Access to New N,Z Combinations

Much of the discussion in the preceeding subsection, of course, relies on access to new regions of N and Z in the sense that the $T = 1$ and 0 residual interactions are dependent on the proton and neutron orbits; hence new effects and new information, often crucial not just incremental, can be obtained by extending the ranges of N and Z. Here we focus on different aspects of this, in particular on the interplay of single-particle and collective effects that may give rise, in uncharted nuclei, to new types of collective motion or shapes or to new examples of known types that will aid in an improved understanding of their structure and microscopic origins.

3.2.1 Neutron Halos and Skins

One of the most interesting and exotic new nuclear phenomena involves the concept of neutron skins or halos in extremely neutron-rich nuclei, such as ^{11}Li or ^{14}Be. Greatly-enhanced nuclear radii are observed for these cases [20,21] see Figure 3, where the last pair of neutrons is only barely bound. The opportunities for future studies here are many, ranging from the structure of the halos themselves to the exploitation of the loose binding and beta-decay lifetime of these nuclei in reactions, where such phenomena as neutron flow, large isospin transfer, and the like can be studied. The halo regions may be conceived of as an extremely low-density form of (neutron) nuclear matter. As such they are intermediate between free nucleons and normal-nuclear matter and one might think that they could provide a third regime in which to study nuclear interactions and medium modifications (e.g., EMC type effects). Clearly such experiments on halo nuclei will be extremely difficult at best, but measurements of, for example, the neutron magnetic moment in odd-neutron halo nuclei by laser spectroscopy, could be fascinating. The entire subject of neutron halos and skins is treated in greater detail in a separate chapter of this report [22].

3.2.2 New Collective Modes

Collective shapes are favored microscopically when single-particle orbits with that specific shape are occupied. Collective modes appear when orbits are occupied that have large matrix elements of the particular mode creation operator with another nearby orbit. Therefore, access to new more exotic N,Z combinations affords the possibility to observe even more exotic shapes and collective excitations. Some of these, such as super and hyperdeformed shapes, which depend on large angular momentum for stability will be discussed in the next section.

Despite years of use of models of triaxial nuclei, there is essentially no firm evidence that nuclei exist with stable rigidly-asymmetric shapes [38]. Indeed, it is difficult to distinguish between stable triaxial shapes and fluctuations with respect to the triaxial (gamma) degree of freedom. Similarly, nuclei with oblate ground-state shapes are very few (e.g., some Pt and Au nuclei) and in those it also is likely that one is observing a gamma-soft configuration with a slightly oblate rms shape rather than a static oblate deformation.

Triaxial nuclei are likely to occur when the protons are filling prolate orbits and the neutrons oblate orbits or vice versa. In a Nilsson context these are, respectively, the downsloping and upsloping orbits that occur at the bottom or the top of a shell. In heavy nuclei examples of such "schizophrenic" nuclei are, therefore, to be sought in extremely neutron-poor or -rich species such as, isotopes of Hf – Pt nuclei with $N \approx 90$ which could be produced with neutron deficient RIBs.

Oblate shapes occur when both protons and neutrons have nearly full shells. The Fermi surface then lies near highly oblate-driving orbits that cancel the normal prolate-driving preference that has been accumulated by the filled orbits. The oblate-prolate competition can often lead to two minima in the potential energy surface, one of each shape, and the nuclear ground state is then determined by rather subtle details. Coexistence is possible, as evidenced, for example, by nuclei with $A \approx 130$ [39], as is gamma-softness (e.g., Pt, Au), if there is a path between the minima through the gamma plane. Interesting searches for oblate nuclei in the neutron deficient Se, Kr region, the light ($N < 82$) Ba nuclei, and the light Au nuclei will again be facilitated by the use of fusion-evaporation reactions with neutron-deficient RIBs.

Of course, nuclear shape coexistence, just alluded to, is now known to be a widespread phenomena. Indeed the classic example is ^{152}Dy in which slightly-deformed oblate, "normally-deformed" prolate and superdeformed prolate states coexist at the same angular momentum [15,40]. Other beautiful examples of shape coexistence have been mapped out in the Pb, Tl, Hg region, down to neutron midshell (e.g., $^{182}\mathrm{Hg}_{102}$ [41]) [see Figure 4]. The energy systematics of the intruding configuration shows a parabolic drop towards midshell against N. This is consistent with the most popular interpretation of such states which predicts an energy minimum near midshell where the enhanced proton-neutron interaction in the intruder (particle-hole) excitation is a maximum. The Cd nuclei, known on both sides of neutron midshell, indeed suggest that the intruder energies rise roughly symmetrically about midshell. However, the absolute intruder excitation energies depend on the strength of the residual interaction relative to the energy gap that must be overcome and, in Cd, these energies happen to lie very close to the vibrational two-phonon states. While this gives a possibility to study the mixing of normal and intruder configurations, it also obscures the behavior of the latter. Therefore, a better testing ground would be even more neutron deficient-nuclei in the Hg region than can currently be populated. RIBs are crucial to further study of this issue. Another fascinating region centers on the N = 60 isotones near ^{100}Zr where the lowest known excited 0^+ states of any deformed nucleus have been discovered. The physics of intruder states is intimately linked with mechanisms for the onset of deformation and provides a unique view of those mechanisms.

In the last few years many examples of reflection-asymmetric nuclei [42] have been identified, usually by their signatures of parity-doublet rotational bands (0^+, 1^-, 2^+, 3^-, ... sequences, usually slightly displaced from each other), relatively enhanced E1 transitions and, in odd-mass nuclei, anomalous decoupling parameters. (An example [43] is shown in Figure 5.) Nevertheless, it remains an open question to what extent such fundamental shapes, which break an important spatial symmetry, are static or dynamic. Octupole shapes are expected in regions where both valence neutrons and protons filling the orbits of a "$\Delta l = 3$" pair (e.g., $\pi(2d_{5/2}$–$1h_{11/2})$ and $\nu(2f_{7/2}$–$1i_{13/2})$ in the rare earths). These orbits are strongly connected by the Y_3 operator. Octupole collective nuclei are known in the light Rn-Th region and in the rare earths near ^{146}Ba. With RIBs, other examples, in lighter nuclei, such as ^{90}Se and ^{94}Kr or their odd-mass neighbors, could be sought. Also, in many neutron-deficient nuclei formed in heavy-ion fusion-evaporation reactions, the low-j (especially the 3^-) states are not observed and therefore the octupole collectivity remains poorly established. Access to these nuclei by "softer" reactions using RIBs is an intriguing possibility. The light (A $\approx$ 120) Xe, Te region would be especially interesting for such studies.

Higher moments in the nuclear shape, such as hexadecapole deformations, are also well established, especially in the stable W nuclei where diagonal Y_4 matrix elements among high-j, unique-parity, orbits are large. Hexadecapole vibrations are also a likely component of low-lying ($\approx$ 1 MeV)

K = 4 bands in Os. A positive ϵ_4 (barrel shape) is naturally expected when the configurations with the largest radii are filling mid-K Nilsson orbits. These orbits are oriented $\approx 45°$ relative to the nuclear equator and thus favor an infilling of nuclear matter in the "corners". Such shapes also should appear in lighter nuclei, for example, heavy Pd nuclei ($^{116-120}$Pd) which could be produced with very neutron rich RIBs or by fission of the heaviest actinides.

Finally, there are sporadic hints of even higher moments (e.g., β_5 and β_6 deformations [44]). Five-minus levels are often considered as rotational excitations built on lower-lying 3^- states. However, near the top of each shell in heavy nuclei, there is the possibility of a direct $\Delta l = 5$, two-quasiparticle, excitation, such as an $h_{11/2} \otimes s_{1/2}$, in the 50–82 shell. Indeed, the Te–Ba nuclei with $N \approx 70$ have anomalously low 5^- states (relative to the 3^- states). In some cases even $E_x(5^-) < E_x(3^-)$. It is interesting to speculate whether the analogous $\Delta l = 5$ excitations in heavier nuclei, namely $i_{13/2} \otimes p_{3/2}$ and $j_{15/2} \otimes d_{5/2}$ in the 82–126 and 126–184 shells have sufficient degeneracy to allow the development of collective 5^- correlations. However, the present knowledge of 5^- states in the rare earth and actinide nuclei is limited, e.g. to Dy isotopes with $A < 158$, Ra with $A \leq 158$, and Th with $A \leq 232$, where the $i_{13/2}$ or $j_{15/2}$ are barely occupied. If substantially more neutron-rich Dy, Er, Ra, or Th nuclei could be studied using RIBs, this new collective mode might be disclosed.

The possibility of observing new collective modes or symmetries implies as well the likelihood of discovering new shape/phase transitional regions, or of extending existing ones. This is an attractive opportunity since, historically, more has probably been learned about (collective) nuclear structure, its manifestations and dynamics, from such regions than in any others. Recent work in the very neutron-deficient rare earth nuclei, especially the light Ce and Nd isotopes with A = 120–130, has provided evidence [45] for a new, gradual, spherical to soft shape transition that has the earmarks of becoming stably-deformed for slightly-smaller neutron number. This region has only begun to be mapped out; the largest $E_x(4^+)/E_x(2^+)$ ratios in the region are still only ≈ 3.0, and the vibrational modes are as yet virtually unstudied). This region is interesting because its smooth evolution is in contrast with the sharp onset of deformation in the A = 100 and 150 mass regions. A thorough study, using proton-rich RIBs, will be helpful in understanding the mechanism for deformation and the interplay of the dynamics of the underlying single-particle structure and the collective correlations that develop.

Of course, one of the most exciting new regions centers on the heaviest known N = Z nuclei (discussed earlier in a different but related context). Zirconium-80 has recently been found [9] to be deformed despite having 40 protons and 40 neutrons (see Figure 6). Neighboring nuclei as well as the heavier N = Z species approaching ^{100}Sn will provide perhaps the most exciting opportunity yet to observe the evolution and coexistence of shapes and the persistence of magic numbers, since it is widely expected that the so far elusive ^{100}Sn will be doubly magic. Where, along the N = Z path, does the spherical configuration become the ground state? How stable are the 40 and 50 magic numbers? These are key questions at the heart of our understanding of shell and collective structure. Experimentally, these nuclei might be reachable with reactions on unstable, long-lived targets, such as $^{40}\text{Ca} + {}^{56}\text{Ni} \rightarrow {}^{96}\text{Cd}^*$ or $^{40}\text{Ca} + {}^{44}\text{Ti} \rightarrow {}^{84}\text{Mo}^*$, or with neutron-deficient RIBs.

3.2.3 Other Issues

The Fermion Dynamical Symmetry Model [46] suggests sudden "breaks" in nuclear systematics (e.g., in the actinides when the normal-parity neutron shell is 1/3 filled) due to special Pauli effects. In simple terms, the filling of certain classes of states ultimately blocks some collective modes, causing others (in this scheme) to suddenly become the ground state. Concomitant effects in transition rates should accompany this phenomenon. The use of RIBs to establish either the existence, or the nonexistence, of such effects, for example in the neutron-rich actinides, could be a litmus test for these models.

Finally, other models, currently nearing the stage of practical calculations, attempt, for the first time, to encompass multi-$\hbar\omega$ spaces and to incorporate the collectivity of giant resonances and low-lying structures into a single unified framework, without effective charges [47]. The study of higher-spin states of stable nuclei (e.g., ^{168}Er), which is accessible with RIBs (see below), would provide the critical tests of these models.

3.3 Complete Spectroscopy and Chaos

The access to high decay energies far from stability allows numerous opportunities for extending spectroscopic studies as a function of N, Z, and E_x. Several of these possibilities have already been mentioned, e.g. the study of beta-delayed particle instability, cluster emission, and G–T quenching. However, one aspect of high decay energies remains to be considered: namely the possibility for "complete" spectroscopic studies [48]. This term refers to the experimental establishment of sets of levels, in certain ranges of excitation energy and spin, that are known to be essentially complete, and the further delineation of as many of their properties, e.g. decay routes, moments, lifetimes, etc., as possible. Such complete data not only provide the most strigent tests of nuclear models, they also provide a very detailed information base for a specific quantum system that can be utilized for understanding even more general physical ideas and for technical applications. A currently-fashionable example is analyses to determine whether nuclear levels are "ordered" or "chaotic."

3.3.1 Complete Spectroscopic Measurements

The classic tool for ensuring that the set of states populated is complete, only usable along the stability line, is the (n,γ) reaction, especially in the Average Resonance Capture (ARC) mode. However, other reactions, which feed the nucleus at suffiently-high excitations energies (temperatures) and which deexcitate statistically, also offer a virtual guarantee of completeness in the appropriate cases. One can cite, for example, the $(n,n'\gamma)$ reaction for low-spin states, the $(\alpha, xn\gamma)$ or (light heavy-ion,$xn\gamma$) reactions for intermediate spin states and (heavier heavy-ion,$xn\gamma$) reactions for still higher spins, as well as, to a lesser degree, beta-decay with extremely large Q_β values.

There are two conceptually-distinct areas of work here. One is the study of low-spin states very far from stability (primarily by beta decay) providing the first tests of nuclear models of, for example, collective modes, in such new N,Z regions. Perhaps even more intriguing is the opportunity to use neutron-rich RIBs to study high-spin states of stable or near-stable nuclei, in order to complement already existing, complete, low-spin data, and thereby, forging the first comprehensive links between high- and low-spin nuclear structure. Perhaps the best heavy case for this is ^{168}Er which is known, for I = 0–6, in an essentially complete form up to about 2 MeV. Here, the use of reactions, such as ^{130}Te(^{42}S,4n)^{168}Er, and/or ^{154}Sm(^{18}C,4n)^{168}Er, would provide a comparable completeness for high-spin levels and offer perhaps the only nucleus where the full panoply of nuclear structure models could be simultaneously tested. In general, low-spin data is abundant in rare earth nuclei near stability. Figure 7 shows the loci of nuclei that could be produced at high spin using RIBs with 6 neutrons beyond stability. Today's models aim at being more and more comprehensive but require correspondinglythorough data for their testing. This is not a program to be carried out on every possible nucleus, but as history has shown, such studies in isolated, well chosen, cases can be extremely valuable. Another example, this time an odd-mass nucleus, might be ^{109}Pd in which a nearly full set of unique-parity favored and unfavored anti-aligned states based on the $\nu(h_{11/2})$ orbit is known and where disclosure of the complementary aligned states would permit the best test to date of particle-rotor models.

3.3.2 Average Nuclear Properties

Complete spectroscopic data will provide a means of establishing average nuclear properties and thereby distinguishing these average properties from the "truely-novel" exceptions. For example, neither the low-lying collective states (the subject of much of the past two decades of low-spin experimental studies) nor the highly-aligned near-yrast high-spin states (likewise the main subject of the past two-decades of high-spin studies - see the following section) are representative of the average nuclear states. Both are strongly-populated in statistical reactions, hence available for study, because their special properties (correlations and the Coriolis force respectively) cause them to occur at low excitation energies. More complete data, however, will establish average quantities (e.g. level densities, transition rates, decay widths, ...) as a function of the experimentally accesible quantities N, Z, I, π, and E_x. Such information would be of considerable importance for a variety of applications.

3.3.3 Is the Nuclear Spectrum of States Ordered or Chaotic?

Finally, complete spectroscopy will provide a greatly-expanded opportunity to investigate seriously the issue of quantum chaos in nuclei [49]. Sufficient data exists to indicate that the spacing of nuclear states at the neutron and proton thresholds is describable by random-matrix theory [50], i.e. nuclei under these conditions are "chaotic." Yet special states (such as isobaric analogue states, molecular resonances, superdeformed states, very high-K states, ...) at the same excitation energy seem to remain "pure." They apparently do not mix with the background of strongly-mixed, "chaotic" states. Attempts at extending such analyses to lower excitation energies to study the temperature and angular-momentum dependence of the transition from ordered to chaotic systems have not been conclusive [51] because of the lack of complete nuclear data.

The description of the nuclear quantum system in terms of the currently-fashionable concept of "order" and/or "chaos" is by no means complete. Fundamental questions, such as: how the nuclear quantum system evolves from ordered to chaotic behavior, the coexistence of ordered and chaotic states, transition rates in chaotic systems, the role of symmetries in preserving order, more efficient (i.e. simpler) descriptions of chaotic quantal systems, and the relation between a chaotic nucleus and other chaotic quantal systems, remain to be answered. Detailed studies of nuclei like ^{26}Al [52] have already set the stage; however, complete data for selected nuclei sampling the variety of phenomena described in the previous sections are needed to answer the questions posed by this new approach to nuclear physics.

4 High-Spin Studies with Radioactive Ion Beams

The use of radioactive ion beams, not only will allow high-spin studies similar to those in vogue today (see e.g. [53,54]) to be extended to a wider range of nuclei testing our current understanding of rapidly-rotating nuclei, it also will allow new physical concepts to be studied. Some of these ideas are summarized in this section.

4.1 Exotic Nuclear Shapes at High Spin

The exotic equilibrium shapes, such as superdeformed (2:1 ratio of major to minor axis), octupole (pear-shaped), and triaxial that nuclei can assume in the extreme condition of rapid rotation are an excellent illustration of the intimate connection between independent-particle and collective degrees of freedom. Since these shapes depend on the details of the spectrum of single-particle quantum states, the greater variety of such states that nuclei at the limits of isospin will provide is desirable. The condition of minimum energy and the strong, attractive, short-ranged nuclear interactions tend to select "conventional" equilibrium shapes. By enlarging the variety of single-particle states by forming nuclei at the extremes of both isospin and angular momentum more exotic shapes become feasible. For example:

Superdeformed states occur [15] when large gaps (providing negative single-particle energy contributions) develop in the spectra of single-proton and single-neutron states for a 2:1 ratio of the major to minor axis. Calculations [55] indicate that such gaps occur in prolate nuclei for $Z \approx$14–17, 34, 39–42, 65–69, and 82–94 and $N \approx$ 30–47, 63–67, 78–92, 104–112, and 138–158. Superdeformed shapes already have been observed for $(Z, N) =$

(65–69,78–92), (82–94,104–112), and (82–94,138–158) corresponding to the ^{152}Dy region, the ^{192}Hg region, and the fission isomers, respectively [54]. The use of radioactive beams should provide other mass regions where both proton and neutron single-particle spectra favor superdeformed shapes, for example, (Z, N) = (65–69,63–67), (39–42,63–67), and (39–42,30–47), and extend the possible superdeformed studies in other regions only partly accessible to stable targets and beams.

Shell corrections also should occur for oblate superdeformed shapes (2:1 ratio of major to minor axis, but with two major axes *versus* one major axis for prolate superdeformed systems). As yet no oblate superdeformed nuclei have been identified. The nucleus ^{148}Sm, which is not accessible at high spin with (heavy-ion, xn) reactions using stable beams and targets, is predicted to be one of the most favorable cases for superdeformed oblate collective shapes.

Hyperdeformed equilibrium shapes (3:1 ratio of major to minor axes) also have been predicted, but not yet observed. The most favorable predicted [56] cases for experimental studies, rapidly-rotating nuclei near ^{166}Er, can only be populated at maximum angular momentum with radioactive ion beams. The increased neutron excess of this isotope relative to those accessible with the fusion-evaporation reaction using stable heavy-ion beams also increases the angular momentum that the compound system can accomodate and survive fission. Such an angular momentum increase is crucial for observing hyperdeformed states. The nucleus requires a great deal of angular momentum to stablize such enlongated nuclear shapes. Indeed the added angular momentum associated with the radioactive beams may be the difference between observing and not observing hyperdeformation.

4.2 Exotic Configurations Dominated by the Coriolis Force

Many of the current topics of high-spin physics (e.g. band crossings ("backbends"), loss of collectivity at high spin, and signature dependent energies and transition rates) are associated with high-j, low-Ω configurations that have a large projection of the intrinsic angular momentum, j_x, on the rotational axis. These phenomena are the result of modifications of the spectrum of single-particle states by the Coriolis plus centrifugal interaction leading to a term in the independent-particle hamiltonian equal to $-\omega j_x$. Configurations always exist in the next higher shell with even larger values of j_x. For prolate deformations these "exotic" configurations lie low in the higher shell. (For superdeformed and hyperdeformed systems they intrude into the lower shell and are important components in producing the deformed shell gaps that lead to stability.) In a rapidly rotating system such orbits also can intrude into the lower shell for normal deformations. Anomalous moments of inertia [57] and band crossings [58] are associated with the few cases where such high-j_x intruders presently are observed in near transitional nuclei. Using neutron-rich radioactive beams, it should be possible to populate such configurations in stably-deformed nuclei testing whether the observed anomalies are associated with these orbits or the stability of the nuclear shape.

In the actinides such high-j_x intruders correspond to shell-model states from above the superheavy shell gaps, e.g. the $j_{15/2}$ proton state and the $k_{17/2}$ neutron state. The low-ω components of these configurations, which are predicted [59] to lie just above the Fermi level for the heaviest possible actinide targets (e.g. ^{248}Cm and ^{252}Cf), should become yrast at moderate spins, I =20–30. Because of Q-value considerations (see below) radioactive beams probably are necessary for the population of such states in Coulomb excitation plus transfer reactions.

4.3 Residual Proton–Neutron Interactions at High Spin

The major modifications of the single-particle quantal states at large angular momentum described in the preceeding paragraphs also will change the overlaps of the nucleonic orbitals thereby modifying the residual nucleon-nucleon interactions. Not only are the high-j, low-Ω orbitals most-strongly affected by the Coriolis and centrifugal forces, but they also are the most localized [60], and therefore, the most sensitive to residual interactions. Interesting attempts at extracting empirical estimates of such interactions are described in [60,61,62]. The possibility of studying even higher-j, low-Ω intruder orbitals using RIBs, as described in the preceeding subsection, should allow even more exotic nucleon-nucleon interactions to be studied as a function of rotation.

In the limit of very large angular momentum, where the single-particle structure of the nucleus is dominated by Coriolis and centrifugal forces, the occupation of configurations associated with nucleons moving in equatorial orbitals in the direction of the nuclear rotation is increased [60]. Such orbitals have large spatial overlap. This is a necessary, though not sufficient, condition for a new type of correlation that might be termed "Coriolis correlations." The increased localization associated with the various substates of the even higher-j "intruder" orbitals that should be available in selected nuclei that can be populated with RIBs (see the preceeding paragraph) will enhance this possible new type of collectivity.

Residual p–n interactions also can affect the alignment of angular momenta with the rotational axis, and hence band crossings [63]. As with all residual p–n interactions such phenomena are largest where the protons and neutrons are filling, not only the same shell, but also similar orbits of the same shell. Therefore, these effects, which to date have been largely negelected will be largest in those neutron-defficient, deformed nuclei with $N \approx Z$ that can be studied using neutron-deficient RIBs.

4.4 Transfer Reactions

Many of the possibilities of using heavy-ion transfer reactions, for example, to populate neutron-rich nuclei or the high-spin states based on intruder orbits originating from above the superheavy shell, as described in the preceeding subsections, are limited by the reaction mechanism. Heavy-ion induced transfer reaction cross sections are strongly Q–value dependent. Positive Q values enhance such cross sections. This is especially true for proton transfer reactions. Unfortunately the decrease in the binding energy curve for $A > 56$ leads to negative relative binding in the target for stripping reactions and hence requires projectiles with very weakly-bound protons or neutrons to compensate. For example, heavy-ion beams with a single proton or neutron outside a doubly-closed shell are desirable for single-proton and single-neutron transfer reactions. However, except for light heavy ions, such as ^{17}O (and ^{209}Bi in which the proton remains quite strongly-bound) these nuclides are not stable. ^{37}S and ^{49}Ca seem ideal for single-neutron transfer, and ^{38}S and ^{50}Ca are interesting beams for two-neutron stripping. Likewise, ^{41}Sc and ^{57}Cu beams are optimal for single-proton stripping as is ^{42}Ti for two-proton stripping. It is emphasized that transfer reactions and Coulomb excitation are the most efficient methods of populating the actinides at high spin, since the dominant decay of the highly-excited actinide residues of the heavy-ion fusion reaction is fission.

4.5 Coulomb Excitation of Exotic Radioactive Beams

It would be possible to determine the magnitude of the quadrupole moment of any RIB nuclei by Coulomb exciting the beam nuclei using, for example, a ^{208}Pb target. This technique would be important in exploring the new shell closures, transitional nuclei, and regions of deformation described elsewhere in this report. It also would allow the first comparison of transition rates obtained from Coulomb excitation and Doppler-shift lifetime measurement based on (heavy-ion,xn) reactions.

5 Summary

This report outlines some of the nuclear structure topics discussed at the Los Alamos Workshop on the Science of Intense Radioactive Ion Beams. In it we also have tried to convey some of the excitment of the participants for utilizing RIBs in their future research. The introduction of radioactive beams promises to be a major milestone for nuclear structure perhaps even more important than the last such advance in beams based on the advent of heavy-ion accelerators in the 1960's. RIBs not only will allow a vast number of new nuclei to be studied at the extremes of isospin, but the variety of combinations of exotic proton and neutron configurations should lead to entirely new phenomena. A number of these intriguing new studies and the profound consequences that they promise for understanding the structure of the atomic nucleus, nature's only many-body, strongly-inteacting quantum system, are discussed in the preceeding sections. However, as with any scientific frontier, the most interesting phenomena probably will be those that are not anticipated—they will be truly new.

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Figure Captions:

Figure 1. Potential energy contours as a function of r, the distance between the mass centers, and σ, the fragment elongation, for $^{252}\mathrm{Cf}_{154}$, middle portion, and $^{258}\mathrm{Fm}_{158}$, lower portion. The family of shapes considered are shown as a function of r and σ in the upper portion of the figure. The two fission paths are illustrated by the arrows superimposed in the lower-portion of the figure. For further details see [19].

Figure 2. The empirical residual interactions, δV_{pn}, extracted from double differences of the ground-state binding energies in neighboring even-even isotopes and isotones, see [26], are shown as a function of the number of neutrons. The inset gives an expanded view for N = 40–160. The portions of the curve labelled "A", "B", and "C" are discussed explicitly in the text.

Figure 3. Measured interaction radii, R_I, of neutron-rich isotopes of He, Li, Be, B, and C as a function of A. Note the striking deviation of r_I from 1.18 $A^{1/3}$ for ^{11}Lu, ^{11,12,14}Be, and perhaps ^{17}B. See ref. [21], the source of this figure, for reference to the original data.

Figure 4. Plot of the excitation energy of the intruding coexisting deformed states in the isotopes of Tl, Pb, and Bi. See ref. [41], the source of this figure, for reference to the original data.

Figure 5. Partial level scheme for the nucleus $^{223}\mathrm{Th}_{133}$ [43] showing two "parity-doublet" rotational sequences, connected by enhanced E1 transitions, characteristic of stable octupole deformations.

Figure 6. Low-lying level schemes [9] of self-conjugate nuclei $^{76}\mathrm{Sr}_{38}$ and $^{80}\mathrm{Zr}_{40}$, indicating the rotational behavior of these nuclei, $E_x(4^+)/E_x(2^+) \approx 2.85$ for both nuclei.

Figure 7. Comparison of stable nuclei (circles) and all the nuclei (squares) that can be populated as compound nuclei using heavy-ion fusion reactions

on stable targets and with beams of $Z \geq 13$ and six neutrons beyond the heaviest stable isotope. Note that even allowing for the emission of 4-5 neutrons in the (H.I., xn) reaction, it is possible to overlap low-spin studies near stability and high-spin studies populated using (H.I.,xn) in the same nuclei.

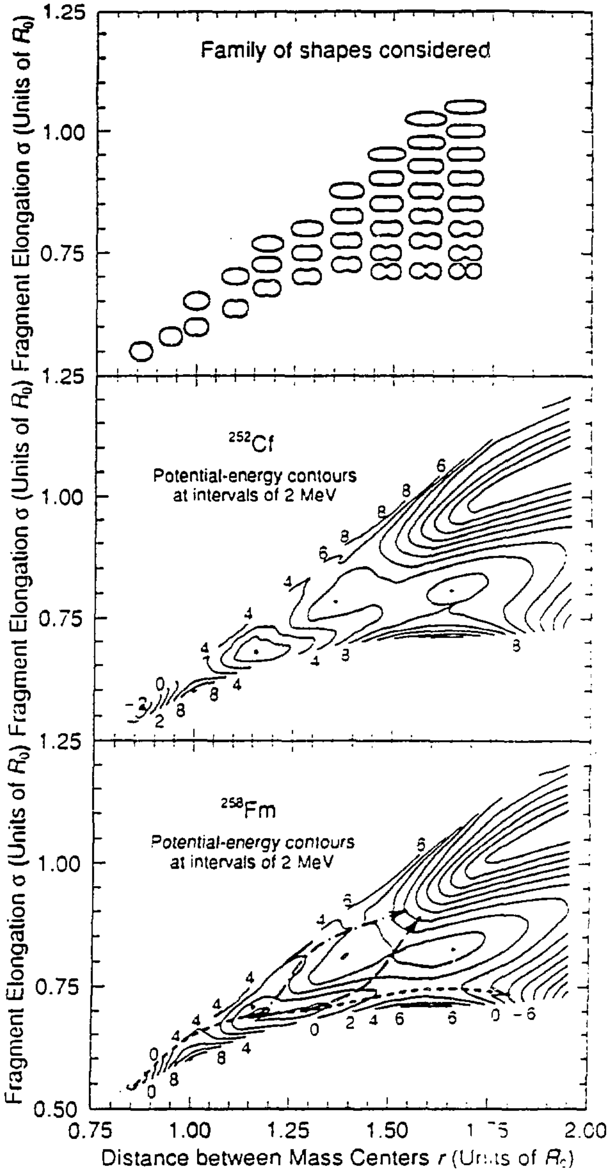

Family of shapes considered
^{252}Cf
Potential-energy contours at intervals of 2 MeV
^{258}Fm
Potential-energy contours at intervals of 2 MeV
6
8
4
0
2
-2
-6
1.25
1.00
0.75
0.50
Fragment Elongation σ (Units of R_0)
0.75
1.00
1.25
1.50
1.75
2.00
Distance between Mass Centers r (Units of R_0)

FIGURE 1

Multiplot V2.1 File 2DUA0:[VESSELSOE.VPH]CLOCLO R.10

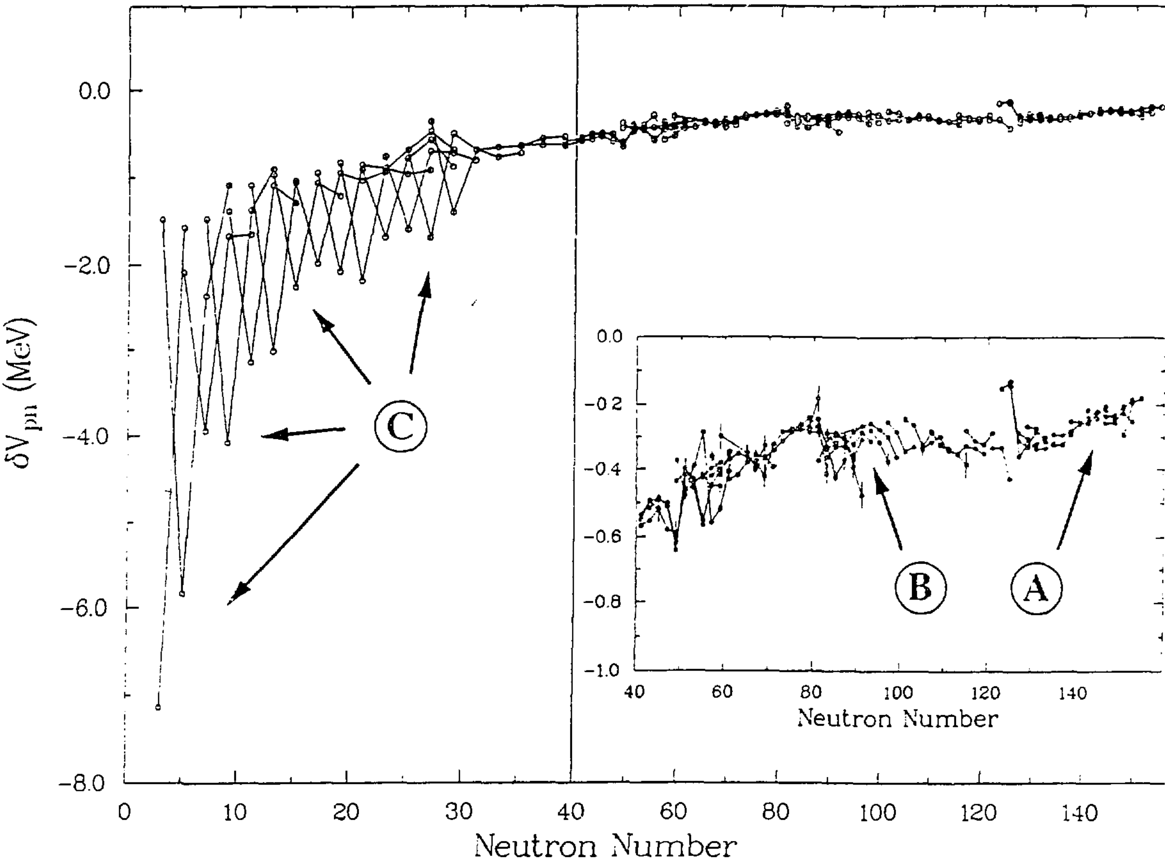


FIGURE 2

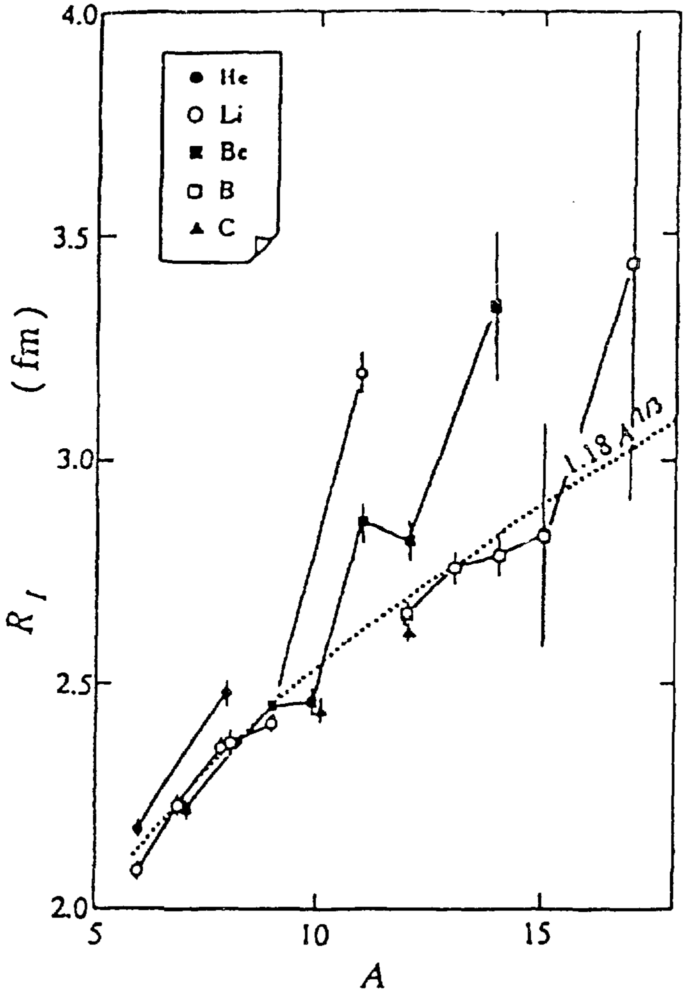
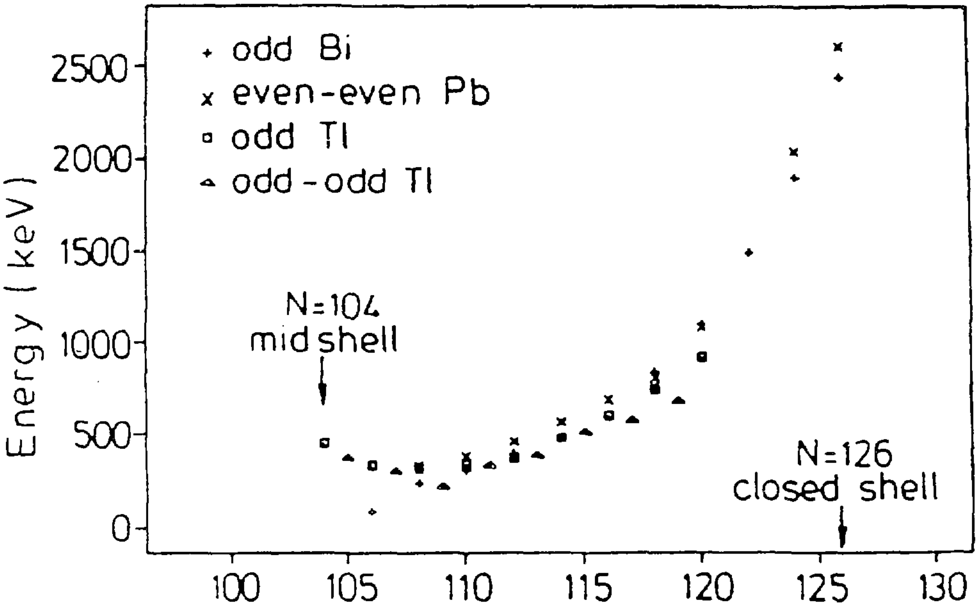


FIGURE 3



+ odd Bi
x even-even Pb
▫ odd Tl
▵ odd-odd Tl
Energy (keV)
2500
2000
1500
1000
500
0
N=104
mid shell
N=126
closed shell
100
105
110
115
120
125
130

FIGURE 4

ORNL-DWG 89M-15905

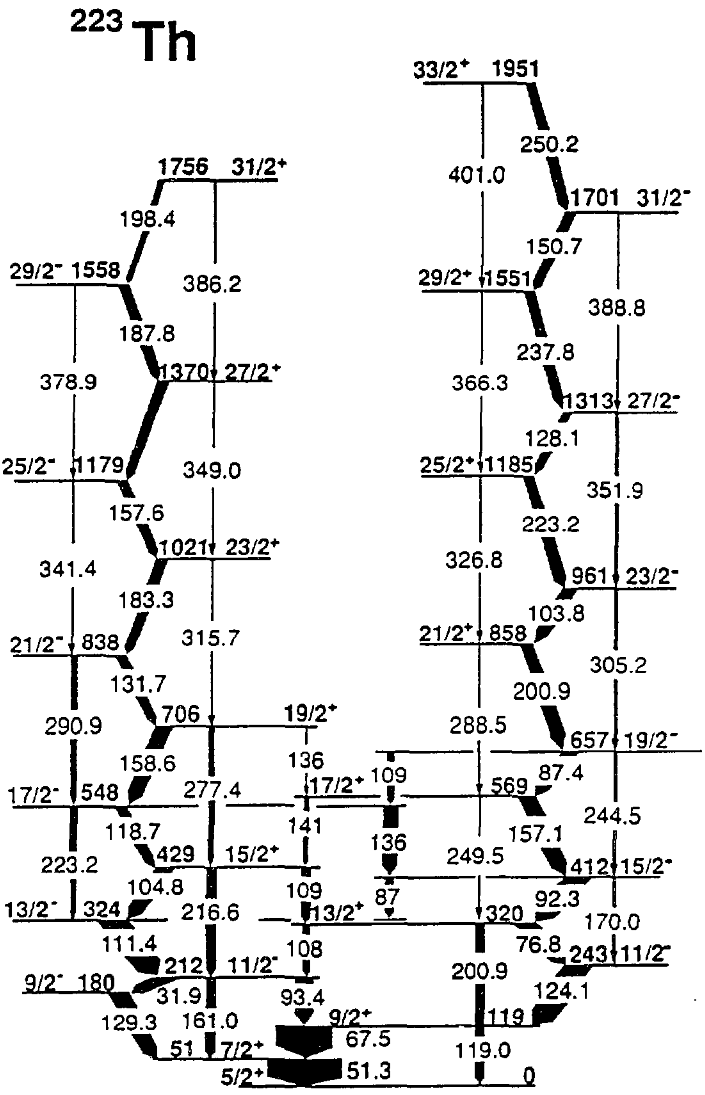


FIGURE 5

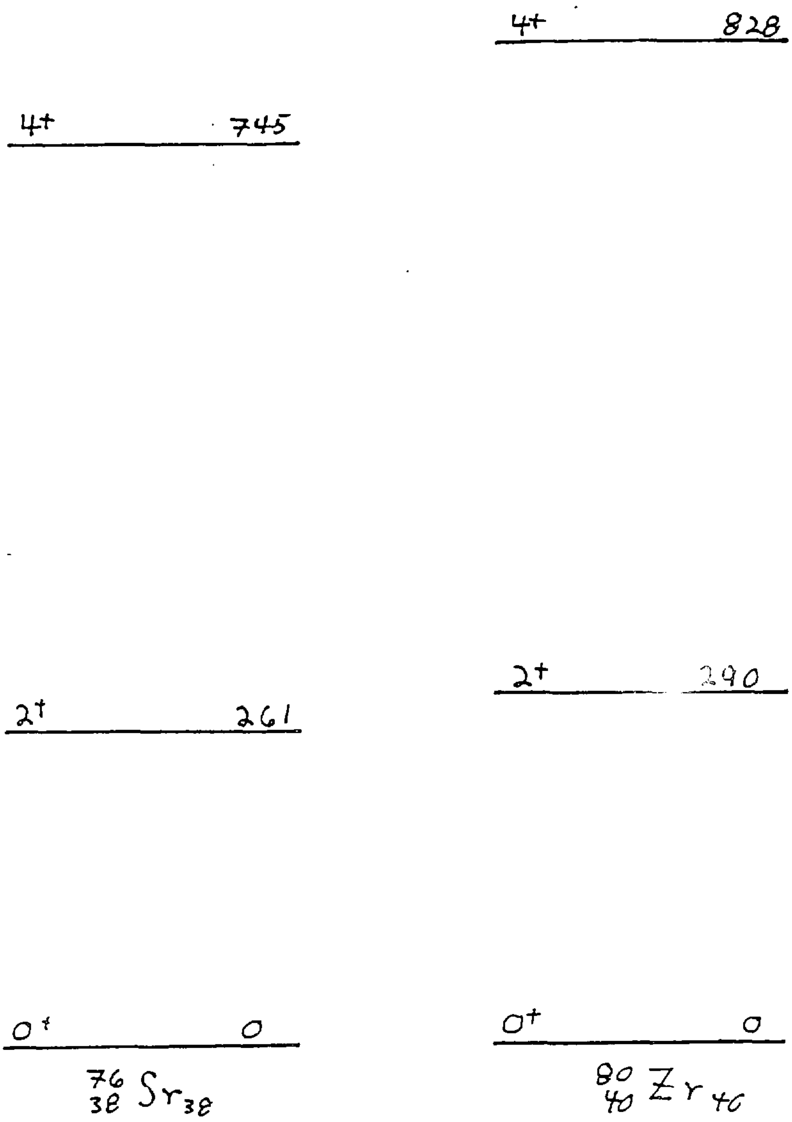


FIGURE 6

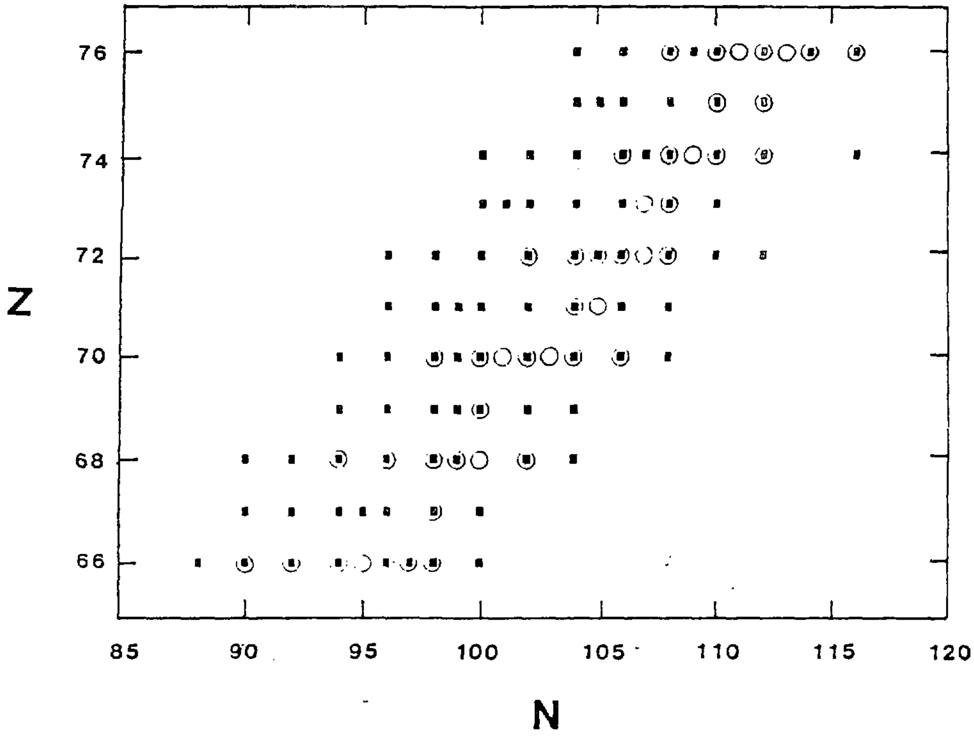


FIGURE 7