NUCLEAR STRUCTURE IN THE HEAVIEST ELEMENTS

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Nuclear structure plays a crucial role in the heaviest elements. It is well known that the stabilization of the inherently Coulomb unstable structure of all nuclei beyond $Z \simeq 100$ is due only to shell effects [1]. In this context, the discovery in the sixties of new magic nucleon numbers well beyond the known ones at Z=82 and N=126 has been one of the most remarkable predictions of nuclear structure models. Since then considerable work, both experimental and theoretical, has been devoted to the identification and the characterization of the islands of increased nuclear stability that should be associated with these numbers. Especially, spectacular progress has been made in the experimental synthesis of very heavy elements, resulting in the identification since 1993 of a number of isotopes of elements beyond Z=106 at GSI and at Dubna [2, 3]. They have culminated with the discovery of element $^{277}112$ at GSI [4] and of one isotope of element 114 at Dubna in 1999.

Early theoretical calculations usually predicted that the spherical magic numbers beyond Z=82 and N=126 were Z=114 and N=184 [5]. Subsequent approaches using different parametrizations of single particle potentials or, more recently, calculating self-consistent mean-fields generated by various effective interactions have often found spherical closures which are at variance with these nucleon numbers (see below). This uncertainty in such a basic property as single particle level sequences clearly shows that the nuclear structure of transactinide and superheavy nuclei represents a critical test of nuclear models. Conversely, convergent theoretical descriptions of nuclear properties of very heavy systems can be helpful in planning future experiments. For instance, deformed shell closures are found around Z=108-110 and N=162 in many theoretical approaches [6, 7]. They explain very well the observed lifetimes and decay modes of the heaviest elements synthesized in recent years [8], and give confidence that many more nuclides in this mass region have long enough lifetimes to be observed.

Most of the theoretical models employed for deriving transactinide and superheavy element properties are based on the so-called macroscopic-microscopic (M-m) approach employing the Strutinsky shell correction technique. In present-day applications of this method [6, 7, 9], the macroscopic part of the nuclear binding energy is determined from the "Yukawa-plus-exponential model" [10]. The microscopic shell contribution is obtained from the single-particle levels of an average potential. The latter is taken in the form of a Woods-Saxon potential [6, 11] or expressed as the convolution of a Yukawa form factor with a generating density [7]. Single-particle potentials derived from the two-center shell model are also used [9]. In the work of Ref.[12], the macroscopic energy is taken from the droplet model [13], the single-particle space is generated from the modified oscillator model and the microscopic correction includes the fluctuation of collective variables and of pairing observables.

Nowadays more and more calculations in the transactinide region are made in the framework of the mean-field theory that is, on the extensions of the Hartree-Fock (HF) method that allow one to include pairing correlations (HF+BCS, HF-Bogolyubov (HFB)) and relativistic effects. In this class of approaches, the average field is derived self-consistently from a two-body effective nucleon-nucleon interaction or from a relativistic effective Lagrangian for meson exchange. In contrast to what is done in M-m methods, quantal effects are included from the start in a unique and consistent framework. In addition, no *a priori* assumptions have to be made concerning the shape or the functional form of the nuclear average field. This is important when high order multipole deformation tend to develop as in the ground states (gs) of Z=108 nuclei [6], or along fission barriers. Let us add that, in the case of finite range interactions such as the Gogny force [14], non-locality effects in the average field and all multipoles of the pairing field are taken into account.

Because of their numerical complexity, fully microscopic calculations have not yet been applied as extensively as M-m ones in the transactinide region. In particular they are usually restricted to even-even nuclei. The relativistic mean-field approaches will not be reviewed here since they are the topic of Pr. Maruhn's lecture. In non-relativistic calculations, essentially two kinds of effective nuclear interaction have been used in recent years: the Skyrme force and the Gogny force. In the case of the former one, many variants have been used in HF+BCS and HFB calculations with sometimes divergent results [15, 16]. The parametrization of the Gogny force [14] has not varied since 1983. Numerous calculations have shown that a very satisfactory account of nuclear properties is obtained all over the nuclear chart with this force.

As mentioned above, the main properties of transactinide nuclei depend, through the magnitude of shell effects, on their single-particle (sp) structure, and more precisely, on the location of large energy gaps. M-m methods constantly predict well developed spherical shells at Z=114 and Z=164 for protons, and at N=184 and N=228 for neutrons, while smaller gaps are often found at Z=92 and N=164 [15, 6]. Remarkably enough Z=126 does not appear to be magic with these methods, except in the two-center shell model approach of Ref.[9] where Z=120 and N=172 are also found, depending on model parameters. Concerning microscopic theories, level schemes strongly depend on the effective interaction used. The older Skyrme parametrizations, as SI-III, give spherical shell closures at Z=114 and N=164 and 228 [17], while more recent ones (SkM*, SkP, the SLy and SkI families) all predict that N=184 is a neutron magic number [16]. Some of them (SkP, SkM*) find that the proton shell closure next to Z=82 is Z=126 rather than Z=114. Let us mention that several of the most recent Skyrme forces have not yet been tested in extensive calculations of conventional nuclei. Calculations with the Gogny force give N=184 and also N=164 and 228 as neutron spherical closures [18]. As for protons, Z=114 is never found magic while Z=92 and 126 yield large gaps. In contrast to this variety of results, practically all approaches, either M-m or microscopic predict a deformed shell closure at N=162, the proton counterpart being Z=108 [6, 16] or Z=110 [7]. Sometimes a weaker deformed closure is also found at N=152 [6, 18]. Let us mention that in the FDSM approach [19], nuclei with Z=110 and 111 are found spherical.

Theoretical results on binding energies (BE) are important in transactinides since they can be compared directly with experiment and are an essential ingredient of α- and particle-decay calculations. M-m approaches being set up in order to accurately reproduce known nuclear masses, they give very accurate BE values. For instance, in the FRDM [7] and ETFSI [20] extensive compilations, deviations from experimental data are less than $\pm$.8 MeV. In the transactinide region, the approach of Refs. [6] describes known masses within $\pm$.25 MeV, although the isotopic dependence of them is not entirely satisfactory. In the case of microscopic theories, where BE calculations are complicated by the necessity of including gs correlations beyond the mean-field, deviations are significantly larger, typically of the order of several MeV [16]. Let us point out however that α- and particle-decay lifetimes depend only on differences between BE of neighbouring nuclei, quantities which are reproduced with reasonable accuracy by microscopic calculations. It must be noted that the different semi-empirical descriptions of nuclear masses do not always agree in regions where no experimental data exists, and that microscopic approaches might be more reliable when large scale extrapolations are envisaged.

Another important property of transactinide nuclei concerns fission barriers. Many barrier calculations have been made in axial symmetry using M-m [6, 7, 9, 12] and microscopic [15, 16] techniques. These approaches predict large fission barriers in nuclei displaying significant shell effects for both neutrons and protons, either spherical or deformed. The systematics described in [18] shows that the shape of fission barriers is governed mainly by neutron number. The higher barriers *i.e.*, the larger fission lifetimes are found for N around 184 and 162. The influence of non-axial deformation and of reflection asymmetry, which play an important role in actinide barriers, are usually found negligible in transactinide nuclei by M-m approaches, except in a few cases [6]. This question has also been adressed in microscopic calculations with slightly different and sometimes divergent conclusions. In Ref.[16], γ-deformation is found to lower the first hump of fission barriers for $Z < 114$ and $Z > 126$. In Ref.[15] the fission barrier of $^{288}112$ is stable against γ-deformation, while the one of $^{310}126$ is triaxial. It must be pointed out however that in the N=184 region, axial fission barriers are so high that, even with reduction of a few MeV, fission lifetimes remain larger than α-decay ones.

In mass regions where fission barriers are large, α emission is the dominant transactinide decay mode (β- and p-emission is expected to be slower than α-decay for neutron-poor nuclei in the Z=108-128 region [15]). Theoretical estimates of the α-decay lifetimes T_α are usually obtained from the Viola-Seaborg formula [21] with the Warsaw parameters [6]. Other simple models [22] are also used. M-m models in which nuclear masses are well reproduced give agreements with measured data within factors of less than 2-3 for transactinides decaying by α emission [7, 6]. Due to larger uncertainties in Q_α, deviations from data can be larger in microscopic approaches. Nonetheless,in many cases a fairly good agreement is obtained [15, 18], from which predictions for heavier transactinides can be reasonably envisaged. Let us note however that T_α predictions are expected to strongly depend on the location of shell closures [16].

Trends for the stability and decay modes of transactinide nuclei can be deduced from calculations where a large number of nuclei have been studied [6, 7, 18, 15]. Half-lives with respect to α-decay and fission appear governed essentially by neutron number. They both increase as functions of N up to $N \simeq 184$ with a bump around N=162, then decrease up to $N \simeq 190$ and seem to increase again to reach a maximum in the N=204-210 region. Beyond N=210, nuclei appear extremely unstable with respect to fission or other type of nuclear disassembly. Fission is always the dominant decay mode below $N \simeq 150$ and beyond $N \simeq 190$. In between these two numbers, nuclei decay by fission for $Z < 106$. A transition to α-decay occurs in Z=108-110 nuclei having N around 162, and in Z=112-120 nuclei when neutron numbers approach the N=184 region. The largest nucleus lifetimes are found in the N=184 and the N=162 regions with values T_α of a few minutes and a few seconds, respectively. These conclusions appear in good agreement with the lifetimes measured in the $Z \leq 114$ elements synthesized up to now.

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