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Studies on Superheavy Nuclei

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ABSTRACT

The present thesis deals with some properties of even-even superheavy nuclei (SHN), namely, their binding energies and α-decay half-lives. The binding energy of some even-even superheavy nuclei with the proton number Z = 98–120 is studied using a semi-microscopic but not self-consistent model. The macroscopic energy part is obtained from the Skyrme nucleon-nucleon (NN) interaction with kinetic energy density derived from the semi-classical extended Thomas-Fermi (ETF) approach. A simple but accurate method is derived for calculating the direct part of the Coulomb energy. The microscopic shell plus pairing energy corrections are calculated from the traditional Strutinsky method. Within this semi-microscopic approach, the total energy curves with the quadrupole deformation of the studied superheavy nuclei behave in a similar way as the well known ^{208}Pb or ^{238}U nuclei. The properties of some superheavy nuclei are predicted and these are useful for future experimental researches. We give for each nucleus the model predictions for the binding energy, the deformation parameters (with axial and reflection symmetry assumed), the half density radii and comparison with other theoretical models. The calculated binding energies are in good agreement with the available experimental data.

In chapter 4, we present a systematic calculation on α-decay half-lives of even-even heavy and superheavy nuclei in the framework of the preformed α-model. The microscopic α-daughter nuclear interaction potential is calculated by double folding the density distributions of both α and daughter nuclei with a realistic effective M3Y nucleon-nucleon interaction, and the microscopic Coulomb potential is calculated by folding the charge density distributions of the two interacting nuclei with proton-

proton Coulomb interaction. The half-lives are found to be sensitive to the density dependence of the nucleon-nucleon interaction and the implementation of the Bohr-Sommerfeld quantization condition inherent in the WKB approach. The obtained α-decay half-lives agree reasonably well with the available experimental data. Moreover, the study has been extended to the newly observed superheavy nuclei. The interplay of closed-shell effects in the α-decay calculations in giving the associated known magic or submagic closed-shell structures of both the parent nuclei and daughter products is also investigated. The α-decay calculations give the closed shell effects of known spherical magicities, Z = 82 and N = 126, and further predict enhanced stabilities at N = 152, 162 and 184 while Z = 100, 108 and 114 due to the stability of parents nuclei against α-decays. It is worth noting that the aim of this study is not only to reproduce the experimental data better, but also to extend our understanding of α- decay half lives around shell closures.

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ملخص الرسالة:-

الرسالة تتناول بعض خصائص الأنوية فائقة الثقل وخاصة طاقات الربط و فترات عمر النصف لتحلل الفا. طاقات الربط لبعض الأنوية فائقة الثقل والتى عددها الذرى يتراوح بين 98 الى 120 قد تم دراساتها بإستخدام نموذج شبه ميكروسكوبى ولكنه ليس ذاتى متسق. لقد تم استخدام تفاعل "سكيرم" النيكليونى-النيكليونى "Skyrme nucleon-nucleon" من خلال طريقة "توماس فيرمى" الممتدة "Extended Thomas-Fermi" وذلك لحساب الطاقة الماكروسكوبية بديلا عن استخدام النموذج الكلاسيكى لقطرة السائل بالإضافة الى استنتاج طريقة مبسطة ولكنها دقيقة لحساب الجزء المباشر من طاقة كولوم "Coulomb energy". وفيما يتعلق بالطاقة الميكروسكوبية فقد تم إستخدام الطريقة التقليدية لشتروتينسكى "Strutinsky". من خلال النموذج الشبه ميكروسكوبى فقد تم دراسة تأثير التشوه للجزءالرباعى القطب على الطاقة الكلية للأنوية فائقة الثقل بالإضافة الى ذلك فقد تم حساب كلا من طاقة الربط وقيم التشوه المختلفة ونصف القطر عند منتصف الكثافة لكل نواة وإجراء مقارنة مع الحسابات النظرية للنماذج المختلفة والقيم العملية المتاحة وذلك لاختبار النموذج الشبه ميكروسكوبى المستخدم فى الدراسة. ووجد ان طاقات الربط للأنوية فائقة الثقل المحسوبة بإستخدام النموذج الشبه ميكروسكوبى تتفق مع القيم العملية المتاحة.

الفصل الرابع يتناول القيام بحسابات منتظمة لفترات عمر النصف لتحلل الفا للأنوية الثقيلة وفائقة الثقل. التفاعل النووى المجهرى بين كلا من نواة "الفا" والنواة "الابنة" يتم عن طريق نموذج الطى الثنائى بإستخدم تفاعل "M3Y" والتفاعل الكولومى يتم كذلك بإستخدام نموذج الطى الثنائى للكثافات المشحونة فى كلا من نواة "الفا" والنواة "الابنة" بالإضافة الى ذلك فقد امتدت الدراسة فى حساب فترات عمر النصف لتحلل الفا الى الانوية فائقة الثقل حديثة التكوين عمليا ووجد أن فترات عمر النصف لتحلل الفا تتفق مع القيم العملية لهذه الأنوية. دور تحلل الفا فى الحصول على الانوية المستقرة اوما يسمى بالأنوية "السحرية" قد تمت دراسته من خلال علاقة فترة عمر النصف لتحلل الفا مع أعداد النيترونات او البروتونات وقد حصلنا على الاعداد السحرية المعروفة $N = 126$ & $Z = 82$ لنواة الرصاص بالإضافة الى توقع اعدادا سحرية للنيترونات عند $N = 152,162,184$ بينما الاعداد السحرية المتوقعة للبروتونات هى $Z = 100,108,114$.

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Chapter 1

The Macroscopic Energy Part for Superheavy Nuclei

1.1 Introduction

1.1.1 Superheavy nuclei

The synthesis of superheavy elements (SHEs) was and still is an outstanding research object. Exploration of the domain of superheavy nuclei has been pursued for a long time and limits on stability and feasibility of creating superheavy nuclei have been tested time and again. The properties of SHEs were studied both experimentally (e.g., [1-18]) as well as theoretically (e.g., [19-32]). Also chemical research on SHEs contributes very importantly to this development (e.g., [33-43]), as it needs the synthesis of SHEs, which is done by physical methods and supplies us with a knowledge of the process of this synthesis and also of the properties of SHEs, in particular on their decay. Although the history of this piece of nuclear physics is rather short (about 50 years), the results are quite rich and significant.

Based on the liquid drop model (LDM), in 1939 Lise Meitner understood that very heavy nuclei would never exist because there would be no potential barrier against spontaneous decay [44]. At that time, the maximum atomic number of elements was expected to be about 100. This number results from the balance of two fundamental nuclear parameters, the strength of the attractive nuclear force which binds neutrons and protons together and creates a surface tension and the repulsive electric force.

In a conference to celebrate Niels Bohr's 70th birthday, the famous theoretical physicist Wheeler proposed that many nuclei with very large mass number can have the long lifetimes which are suitable for experimental measurements. He estimated that the mass number of nuclei with a lifetime from seconds to years can be as large as A = 300 – 600 [45]. In 1958 Prof. Wheeler and his collaborator used the word 'superheavy nuclei' as the title of their article [46]. It is interesting to note that their studies were made without the inclusion of both nuclear shell effect and the shell correction because the idea of shell correction on the binding energy had not been proposed in 1950s.

Among the 2000 known nuclei, only 287 have survived in nature since nucleosynthesis [47]. The changes of the proton-to-neutron ratio in these nuclei generate β-decay. The neutron excess in a nucleus brings forth the decrease of the neutron binding energy; the limit of existence of neutron-rich nuclei is at the neutron drip-line (i.e. those nuclei with vanishing neutron separation energy $S_n = 0$). Similarly, a zero proton separation energy, $S_p=0$ (the proton drip-line), determines the limit of existence of proton-rich nuclei [47]. Another limitation is the maximum number of nucleons a nucleus can hold. Formally, the existence of the heaviest nuclei is determined by the probability for disintegration into parts of smaller mass. Such a process of nuclear transformation, the spontaneous fission of heavy nuclei, was observed for the first time for the isotope ^{238}U ($T_{1/2} = 10^{16}$ y) in 1940 by Flerov and Petrzhak [48]. At that time, Hahn and Strassmann had already discovered the induced fission of uranium. For the description of this phenomenon, Bohr and Wheeler offered the liquid drop model of the fissioning nucleus [49]. In the origin of this beautiful and essentially classical theory lies the assumption that nuclear matter is a macroscopically structureless (amorphous) body similar to a drop of charged liquid. The deformation of the drop induced by the Coulomb forces, which finally brings forth its fission into two parts of almost equal mass, is due to the overcoming of the potential barrier. For the ^{238}U nucleus, the fission barrier amounts to approximately $B_f \approx 6\,\text{MeV}$ [47]. The height of the fission barrier decreases rapidly with an increase in the atomic number Z; at a definite critical atomic number, the nucleus becomes absolutely unstable to spontaneous fission ($T_{SF} \sim 10^{-19}$ s). According to the estimations of Bohr and Wheeler, such a critical situation is reached for values of Z = 104-106. This image was completely changed in the 1960s, when it was possible to take properly into account not only the collective motion of nucleons (as is done in the LDM) but also their individual characteristics, which are described within a quantum single-particle microscopic model like the Nilsson model, the two-centre shell model, Woods–Saxon, etc. When shell and pairing correction energies, according to the macroscopic-microscopic approach, are added to the LDM deformation energy, a potential barrier shows up stabilizing superheavy nuclei. In this way many superheavy nuclei (SHN) are so well stabilized against spontaneous fission that their main decay mode is α-decay [44].

Small cross sections for synthesis of SHN (generally below nanobarns) and, simultaneously, short half-lives (generally below seconds) resulted in a specific property of physics of SHN. Presently, by superheavy nuclei, one usually understands the very heavy nuclei which exist, or are expected to exist, only due to shell effects [50]. As the description of shell structure and its effects on half-lives of nuclei depends on the approach used, this definition is not sharp. All realistic descriptions, however, indicate that these are roughly nuclei with atomic number $Z \geq 104$, i.e., nuclei of transactinide elements.

The continuing progress in synthesis and study of the properties of the heaviest nuclei and in the search for SHN demands further improvements in the theoretical studies and predictions for these nuclides. The theoretical investigation of the superheavy region has been very intense in recent years. Theoretical calculation is very important for the proposal of the new experiment with the aim of producing new SHEs. In searching for the *island of stability* and the next doubly magic nucleus many of approaches were employed by different authors, e.g., fully self-consistent calculations such as Skyrme-Hartree-Fock (SHF) [51] or the relativistic mean-field (RMF) model [52,53] and on the other hand Strutinsky-like calculations with more refined macroscopic-microscopic (MM) formulas such as the finite range droplet model (FRDM) [54], Yukawa plus-exponential (YpE) [55], or the recent Lublin-Strasbourg drop (LSD) [56,57]. Different approaches, however successful in determining of some properties of studied superheavy nuclei, are not fully consistent in their predictions, e.g., magic numbers beyond the well-known Z = 82 and N = 126 [58]. The major magic proton number Z = 114 indicated in MM calculations was also found in the RMF model with NL-SH parametrization [59]. However, Skyrme-Hartree-Fock calculations do not support this prediction, anticipating the shell closure instead at Z = 124, 126 [60] also several models agree that a shell gap should occur at the neutron number N = 184 but various RMF calculations predict no strong shell effects for this number [61]. The differences in the description of shell effects are followed by various predictions of deformation properties of superheavy nuclei. The recent RMF results [61] suggest shape coexistence and super-deformed minima for the heaviest nuclei, whereas the MM approaches disfavor any super-deformation [62]. The disagreements between MM and fully microscopic approaches as well as the differences in predictions of the same type of calculations should be clarified basing on the available experimental data.

Although it was believed for many years that superheavy nuclei will exist due to spherical shell closure, this is only an assumption before experimental confirmations of its validity. Theoretical predictions locate the center of stability at the hypothetical doubly-magic spherical nucleus with Z=114 and N=184. In consequence, many calculations of the properties (especially of half-lives) of nuclei around the nucleus $^{298}114$ have been done (e.g., [24-27]). The results of some of them were quite optimistic, stimulating works on synthesis of them in the laboratory and even on searching for them in nature (e.g., [63-66]).

In the 1980s, an expectation of the existence of also deformed very heavy nuclei (around the nucleus $^{270}108$), with half-lives long enough to be observed in experiment, has appeared. Some indications for this prediction have come from relatively long spontaneous-fission half-lives [67], local minima (on the nuclear chart) of energy (maxima of binding energy) of nuclei [68,69], and relatively long, both α-decay and spontaneous-fission half-lives [70-71], obtained in calculations.

Experimentally, significant progress in synthesis of new elements was made from 1950s to 2000s. With the successful synthesis of elements Z = 104-106 in 1960s and 1970s at Berkeley in USA and at Dubna in Russia, Prof. Oganessian proposed the idea of the cold-fusion reaction for further research of superheavy elements. In 1980s Münzenberg and his collaborators at GSI used the cold-fusion reaction to produce the elements Z = 107-109. In 1990s Hofmann *et al.*, at GSI further developed the