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Theoretical Study on the Properties of New Nuclide $^{271}110$ and Its Alpha-Decay Chain *

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Abstract The structures of the nuclei on the alpha decay chain of $^{271}110$ are investigated using self-consistent relativistic mean-field (RMF) model. The calculated alpha-decay energies are in good agreement with experimental data. The theoretical lifetimes reasonably agree with the data. The properties of $^{275}112$ are predicted. A discussion on the deformed shell around $Z = 108$ is made.

Key words new nudide, binding energy, alpha decay energy, lifetime, relativistic mean-field model

Recent progress on superheavy elements attracts both theoreticians and experimenters in nuclear physics[1-8]. Among the newly discovered superheavy elements, there is no argument on the element $Z = 110$ because it was produced by GSI, Berkeley, and Dubna[1,2,4,5]. All these experiments lead to that four nuclides $^{267,269,271,273}110$ of $Z = 110$ are identified. Among these four nuclides with $Z = 110$, the alpha decay chains of $^{267}110$, $^{269}110$ and $^{273}110$ have been known since 1995[1,4,5] and also studied theoretically[10]. The experimental result on the alpha decay chain of $^{271}110$ has been formally published very recently[9,2] although the experiment was finished a few years ago. It is known from the experiment that the chain of $^{271}110$ is a complete series of alpha decays to the known nuclides ^{255}No and ^{251}Fm[9,2]. As far as we know, there is no theoretical calculation on this chain of alpha decays[9,2] up to now. In this paper we report a deformed relativistic mean-field (RMF) calculation on the chain of $^{271}110$. This is also a supplement to our investigation of superheavy nuclei[10]. In numerical calculations of the ground state properties the blocking effect of odd neutron is omitted[10] because our purpose is to discuss the alpha decay properties and binding energies. The contribution of the blocking effect on the total binding energy is very small and it does not alter the conclusion of this paper. The alpha decays occur from an odd-N nucleus to another odd-N nucleus and therefore the net effect of the blocking effect on the decay energies can be cancelled each other[10]. This approximation is widely used for calculations of alpha decay energies[10,11]. The experimental alpha decay energy is a smooth function of nucleon number for an isotope chain and this is a well-known fact in textbooks. Usually the blocking effect on alpha decays of heavy nuclei is mainly on the probability of the alpha particles or alpha clusters in the range of nuclear surface[12-14]. This

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is the most important thing from the blocking effect but its treatment is beyond the current mean-field model and the other similar model such as the Moeller-Nix model[15]. Although this effect is not included for the calculations of the ground state properties, it is approximately included for the calculation of the lifetime. For the theoretical lifetime of the alpha decay, the blocking effect of odd neutron is included by using the famous Viola-Seaborg formula which will be given in the following.

The theoretical results are listed in Tables 1 and 2 where the deformed RMF codes in harmonic bases[16,10] are used. The force parameters TMA[10] and NLZ2 are inputted and the number of bases is chosen to be $N_f = N_b = 20$. The inputs of pairing gaps are $\Delta_n = \Delta_p = 11.2/\sqrt{A}$ MeV. An axial deformation is assumed in calculations. For the details of calculations please see the relevant publications[16,10].

In Tables 1 and 2, the first column is for nuclei. B^{th} is the theoretical binding energy. The symbols β_n and β_p denote the quadrupole deformations of neutrons and protons, respectively. Further, the symbols Q_α^{th} and Q_α^{exp} are used for the calculated alpha-decay energies and experimental ones. The Q_α^{th} is obtained by the binding energy difference of the daughter nucleus, the parent nucleus, and $Q_\alpha^{th}(Z, N) = B^{th}(Z-2, N-2) + 28.3 - B^{th}(Z, N)$[10,17,15]. The experimental binding energies of ^{255}No and ^{251}Fm are known[17] and their values are 1891.54 and 1871.69 MeV, respectively[17]. T_α^{th} and T_α^{exp} are the lifetime of the theoretical result and that of experimental one where the lifetime T_α^{th} is calculated according to the Viola-Seaborg formula on alpha-decays[18,15]

$$\log(T_\alpha) = (aZ + b)(Q_\alpha)^{-1/2} + (cZ + d) + h_{\log}, \tag{1}$$

where T_α is given in the second and Q_α in MeV, and Z is the proton number of the parent nucleus. This is a well-known formula and it is often used to estimate the lifetime of alpha-decays by the decay energies[18,15]. The constants in this expression have been determined as $a = 1.66175$, $b = -8.5166$, $c = -0.20228$, $d = -33.9069$, $h_{\log} = 1.066$ for odd-N nuclei. These values are obtained by fitting the experimental data of middle and heavy nuclei[18,15].

It is seen from Table 1 that the theoretical binding energies are very close to the experimental data for ^{255}No and ^{251}Fm. The average difference between the theoretical binding energy and experimental one is approximately 2 MeV. This corresponds to a relative difference 0.1 %. The RMF model works well for the binding energy of the superheavy nuclei studied here. The theoretical alpha decay energies agree well with the experimental ones within 1 MeV. This ensures the good predicting ability of the RMF model for the alpha decay properties. The theoretical lifetime is close to the data. It is known from the binding energy formula that the alpha decay energies will vary smoothly with nucleon number if there is no shell effect or sub-shell effect. However there will be a sudden increase of alpha decay energies when there is a shell or a sub-shell[8,15,5]. There is a sudden increase of the experimental alpha decay energy when the proton number varies from $Z = 108$ to 110 (see Table 1). This corresponds to the possible closure $Z = 108$ of the deformed shell effect. The RMF model can reproduce it to some extent. Calculations show that there is a prolate deformation in the ground state of these nuclei. This agrees well with the calculation by Moeller et al[15]. For nuclei ^{259}Rf and ^{255}No, a similar increase of their alpha decay energies is observed and it could be associated with the deformed subshell $N = 152$[2,8]. It is seen from Table 1 that the theoretical lifetime is close to experimental value. The biggest difference on the lifetime is approximately 3×10^2 times for ^{255}No. We would like to stress that it is very difficult to give an accurate value for lifetime by theories. The nuclear lifetime in the nuclear chart is between infinite value and a very small value near zero. Usually the difference between theory and experiment could be as large as 10^5. This is because the lifetime is very sensitive to the nuclear structure effect and the alpha decay energy. A small difference between the theoretical alpha decay energy and experimental value will lead to a very large difference of the lifetime.

Table 2 is the RMF results with NLZ2 force. It is seen again that the theoretical results agree well with the experimental data of the binding energies and alpha decay energies. The precision of the force NLZ2 is as good as the force TMA. A quadrupole deformation in the ground state of these nuclei is also obtained for NLZ2. Its value is close to that of TMA force. This indicates that the RMF model is stable in this mass range. All previous discussions on Table 1 hold true for Table 2.

Table 1. The binding energies, deformations, alpha-decay energies, and the lifetimes of nuclei on the alpha decay chain $^{271}110$. Calculated with TMA force[17].

nuclei	B^{th}/MeV	β_n	β_p	Q_α^{th}	T_α^{th}	Q_α^{exp}	T_α^{exp}
$^{275}112$	1985.58	0.20	0.20	11.36	1.57ms		
$^{271}110$	1968.64	0.21	0.22	11.18	1.07ms	10.75	0.62ms
^{267}Hs	1951.52	0.23	0.23	9.54	4.58s	9.88	74ms
^{263}Sg	1932.76	0.26	0.27	9.27	5.94s	9.26	117ms
^{259}Rf	1913.73	0.26	0.27	8.60	141.1s	8.88	1.72s
^{255}No	1894.03	0.26	0.27	7.85	9626s	7.93	37s
^{251}Fm	1873.58	0.26	0.27	7.43	5.89×10^4s		

Table 2. The binding energies, deformations, alpha-decay energies, and the lifetimes of nuclei on the alpha decay chain $^{271}110$. Calculated with NLZ2 force[17].

nuclei	B^{th}/MeV	β_n	β_p	Q_α^{th}	T_α^{th}	Q_α^{exp}	T_α^{exp}
$^{275}112$	1983.09	0.24	0.24	11.42	1.14ms		
$^{271}110$	1966.21	0.26	0.26	10.62	24.3ms	10.75	0.62ms
^{267}Hs	1948.53	0.28	0.29	10.14	99.6ms	9.88	74ms
^{263}Sg	1930.37	0.29	0.30	9.15	13.6ms	9.26	117ms
^{259}Rf	1911.22	0.30	0.31	7.69	2.36×10^5s	8.88	1.72s
^{255}No	1890.61	0.30	0.31	7.65	5.37×10^4s	7.93	37.0s
^{251}Fm	1869.96	0.31	0.31	7.75	3661.6s		

When we compare Table 1 and Table 2 together, we notice the experimental binding energy is between the theoretical value with TMA and that with NLZ2. This is very useful for the prediction of binding energies of superheavy nuclei because both obtained values with TMA and NLZ2 are very close. In view of the fact that the nuclear binding energy is an important input to calculate the production cross-section of superheavy nuclei, the conclusion here is interesting for a good estimate of the unknown binding energy and for the production cross section of superheavy nuclei.

In summary the structure of the nuclei on the alpha decay chain of $^{271}110$ is investigated in the deformed RMF model. This is the first mean-field calculation on these new data from GSI[9,2]. The calculated binding energy agrees well with the available data. The calculations show that there are prolated deformations in these nuclei. This agrees with the experimental facts that there may be a prolate deformation around $Z = 108$. The RMF results are in good agreement with the experimental data on the alpha decay energies and the lifetimes of the superheavy nuclei. The properties of $^{275}112$ are predicted and may be useful for future experiments on it.

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新核素 ^{271}110 及其 α 衰变链的理论研究*

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摘要　用自洽的相对论平均场模型研究了核 ^{271}110 及其 α 衰变链核的结构. 理论的 α 衰变能与实验数据符合. 理论的核寿命也与实验数据比较接近. 预言了未知核素 ^{275}112 的性质,并讨论了质子数 $Z = 108$ 附近的形变壳效应.

关键词　新核素　束缚能　α 衰变能　寿命　相对论平均场模型

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