

Recent progress in theoretical nuclear physics related to large-scale scientific facilities

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Several large-scale scientific facilities (LSSF) are running and several others are under construction in China. Recent progress made by Chinese scientists in theoretical study of nuclear physics related to these facilities is reviewed. The emphasis is put on those topics covered in the issue entitled “Special Topics on Some Theoretical Nuclear Physics Aspects Related to Large-scale Scientific Facilities” (in *Sci China Ser G-Phys Mech Astron*, Vol. 52, No. 10, 2009).

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The progress in nuclear physics is usually driven by the development of new accelerators, new detectors, and other advanced facilities. Worldwide there are many big facilities which are running or being constructed [1–6].

In recent years, several large-scale scientific facilities (LSSF) for nuclear science have been upgraded and constructed in China. The updated Beijing Spectrometer III (BES-III) at Beijing Electron Position Collider II (BEPCII) is a unique and powerful facility for the study of charmonium physics, D-physics, spectroscopy of light hadrons, and tau-physics in the energy range up to 4 GeV [7]. The Cooling Storage Ring of Heavy Ion Research Facility in Lanzhou (HIRFL-CSR) [8–10] was completed in 2007, which aims at the exploration of physics with radioactive ion beams, including the structure of unstable nuclei, isospin dependence of nuclear matter, heavy-ion fusion reactions, superheavy nuclei synthesis, hadronic physics, physics of high-energy density matter, physics of highly charged ions, and applications. Recently direct mass measurements of short-lived $A = 2Z - 1$ nuclides ^{63}Ge , ^{65}As , ^{67}Se , and ^{71}Kr were carried out at HIRFL-CSR and these results have a great impact on nucleosynthesis in the rp process [11–14]. Shanghai Synchrotron Radiation

Facility (SSRF) [15], which was finished and commissioned in April 2009, and Daya Bay nuclear power complex in China [16] also provides many opportunities for nuclear science.

Based on these and many other facilities in the world, the Chinese scientists have made many important contributions to the understanding of atomic nuclei and hadrons from the theoretical side. In order to introduce the major achievements by Chinese scientists in the field of theoretical nuclear physics, the editorial board of *Science in China Series G: Physics, Mechanics and Astronomy* has invited a number of the major players in the research of nuclear theory in China to contribute to a special issue entitled “Special Topics on Some Theoretical Nuclear Physics Aspects Related to Large-scale Scientific Facilities” (in *Sci China Ser G-Phys Mech Astron*, Vol. 52, No. 10, 2009).

In this paper, we present the scientific remarks on the work presented in this special issue and further progress made based on them.

1 Remarks and discussion

1.1 Hadron spectroscopy and decay properties

The spectroscopy study has played and is still playing impor-

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tant roles in revealing the quantum structure of atoms, atomic nuclei, and hadrons. With more and more data available, the hadron spectra show many new features. These features challenge very much conventional constituent quark models (CQM) which describe a baryon as a three-quark system and a meson as a two-quark one. On the one hand, many new states are observed and most of them cannot be naturally accommodated in the conventional CQM's. On the other hand, many predictions from the conventional CQM's are still missing in experiment. In order to solve these challenges, it has been proposed that there are considerable five-quark components in a baryon [17]. In recent years, this picture has been used to explain many spectroscopy and decay properties.

Among the low-lying nucleon excitations, the S_{11} state $N^*(1535)$ is an interesting one due to its large $N\eta$ decay rate, even though its mass is very close to the threshold of the decay. Recently it has been shown that the coupling of $N^*(1535)N\phi$ may be significant, which is consistent with the previous indications of the notable $N^*(1535)K\Lambda$ coupling deduced from the BES data. An et al. studied the decay properties of the $N^*(1535)$ resonance [18]. They investigated the strong decays of the $N^*(1535)$ resonance in an extended chiral quark model by including the low-lying $qqqq\bar{q}$ components in addition to the qqq component. It is shown that the description for the strong decays of $N^*(1535)$ is improved.

A recent extension of the picture leads to a prediction of narrow N^* and Λ^* resonances with hidden charm above 4 GeV [19]. This is an interesting suggestion toward the understanding of five-quark components in baryons and is awaiting experimental confirmation.

1.2 The equation of state and thermodynamics of nuclear matter

The isospin dependence of in-medium nuclear effective interactions and the equation of state (EOS) of isospin asymmetric nuclear matter, particularly its isospin-dependent term or the density dependence of the nuclear symmetry energy are very important for understanding not only the structure of radioactive nuclei, the reaction dynamics induced by rare isotopes, and the liquid-gas phase transition in asymmetric nuclear matter, but also many critical issues in astrophysics. Particularly, the investigation of EOS for cold and dense strongly interacting matter and its consequence for the possible phases of quantum chromodynamics (QCD) plays a crucial role in the study of neutron stars in astrophysics.

A phenomenological momentum-independent model is constructed to describe the EOS for isospin asymmetric nuclear matter, especially the density dependence of the nuclear symmetry energy $E_{\text{sym}}(\rho)$ [20]. This model can reasonably describe the general properties of the EOS for symmetric nuclear matter and the symmetry energy predicted by both the sophisticated isospin and momentum dependent MDI model and the Skyrme-Hartree-Fock approach. It also helps to determine the nuclear matter symmetry energy and the symme-

try energy coefficient in the mass formula [21].

Based on the updated UrQMD transport model [22], the effect of the symmetry potential energy on the two-nucleon Hanbury-Brown-Twiss (HBT) correlation is investigated with the help of the coalescence program for constructing clusters, and the CRAB analyzing program of the two-particle HBT correlation [23]. An obvious nonlinear dependence of the neutron-proton (or neutron-neutron) HBT correlation function ($C_{np,nn}$) at small relative momenta on the stiffness factor γ of the symmetry potential energy is found. It is also found that both the symmetry potential energy at low densities and the conditions of constructing clusters at the late stage of the whole process influence the two-nucleon HBT correlation with the same power.

Based on the method proposed in [24], the EOS of QCD at zero temperature and finite quark chemical potential is calculated under the hard-dense-loop (HDL) approximation [25]. A comparison between the EOS under HDL approximation and the cold, perturbative EOS of QCD proposed in [26, 27] is made. It is found that when μ is less than 4.7 GeV, the pressure density calculated using HDL approximation is much larger than that calculated using perturbation theory. This enhancement of the obtained pressure density with respect to that of perturbation theory can be regarded as a possible explanation for the strong coupled QGP. It is also expected that the obtained EOS can be applied in the study of neutron stars.

The thermodynamics of strange quark matter with density dependent bag constant is studied self-consistently in the framework of the general ensemble theory and the MIT bag model [28]. In this work, an additional term is found in the expression of pressure. With the additional term, the zero pressure locates exactly at the lowest energy state, indicating that the treatment is a self-consistently thermodynamic one. The self-consistent EOS of strange quark matter in both the normal and color-flavor-locked phase is derived. They are both softer than the inconsistent ones. Strange stars in both the normal and color-flavor locked phase have smaller masses and radii. It is also interesting to find that the energy density at a star surface is much higher than that in the inconsistent treatment for both phases. Consequently, the surface properties and the corresponding observational properties of strange stars in this treatment are different from those in the inconsistent treatment.

1.3 Structure and reactions of exotic nuclei

Thanks to the development of radioactive ion beam (RIB) facilities, new exciting discoveries have been made by exploring hitherto inaccessible regions in the nuclear chart. Theoretically much efforts has focused on the structure and dynamics of exotic nuclei.

The proton radioactivity half-lives of spherical proton emitters are investigated within a generalized liquid drop model (GLDM) [29, 30], including the proximity effects between nuclei in a neck and the mass and charge asymme-

try [31]. The penetrability is calculated in the WKB approximation and the assault frequency is estimated by the quantum mechanical method considering the structure of the parent nucleus. The spectroscopic factor is taken into account in half-life calculations, which is obtained by employing the relativistic mean field (RMF) theory [32–36]. The half-lives within the GLDM are compared with the data and other theoretical values. The results show that the GLDM works quite well for spherical proton emitters when the assault frequency is estimated by the quantum mechanical method and the spectroscopic factor is considered.

The direct proton capture and resonance proton capture properties of stellar reactions $^{22}\text{Mg}(p,\gamma)^{23}\text{Al}$ and $^{26}\text{Si}(p,\gamma)^{27}\text{P}$ are studied by employing a mean-field potential obtained from the Skyrme-Hartree-Fock (SHF) model [37]. Calculations with the SHF potential reproduce well the loosely-bound structure of the ground states as well as the widths of the resonant states in these nuclei. With the obtained potential the reaction rates of direct proton capture and resonance proton capture to nuclei ^{23}Al and ^{27}P are estimated. The effect of the ^{27}P loosely-bound structure on the S factor of the direct proton capture is also discussed.

The microscopic mechanism of four experimentally observed bands in ^{172}Tm is investigated [38] using the particle-number conserving (PNC) method in the framework of the cranked shell model (CSM) with monopole and quadrupole pairing interactions [39, 40]. The experimental results, including the moments of inertia and angular momentum alignments of four bands in ^{172}Tm are reproduced well by the particle-number conserving calculations. The ω variation of the occupation probability of each cranked orbital and the contribution to moment of inertia from each cranked orbital are analyzed. Other unobserved low-lying bands of 2-quasiparticles in ^{172}Tm are predicted. The CSM-PNC method is also used to study the recently observed high-spin rotational bands in odd- A nuclei $^{247,249}\text{Cm}$ and ^{249}Cf [41].

The relativistic consistent angular-momentum projected shell model (ReCAPS) [42, 43] is used in the study of the structure and electromagnetic transitions of the low-lying states in the $N = Z$ nucleus ^{52}Fe [44]. The model calculations show a reasonably good agreement with the data. The backbending at $I^\pi = 12^+$ is reproduced and the energy level structure suggests that neutron-proton interactions play important roles.

The configuration-fixed deformation constrained relativistic mean field approach with time-odd component [45, 46] has been applied to investigate the ground state properties of ^{33}Mg [47] with effective interaction PK1 [48]. The ground state of ^{33}Mg has been found to be prolate deformed, $\beta_2 = 0.23$, with the odd neutron in $1/2[330]$ orbital and the energy -251.85 MeV which is close to the data -252.06 MeV. The magnetic moment $-0.9134 \mu_N$ is obtained with the effective electromagnetic current which well reproduces the data $-0.7456 \mu_N$ self-consistently without introducing any parameters. The energy splittings of time reversal conjugate states,

the neutron current, the energy contribution from the nuclear magnetic potential, and the effect of core polarization are discussed in detail.

The ground state properties of La isotopes are investigated [49] with the reflection asymmetric relativistic mean field (RAS-RMF) model [50]. The calculation results of binding energies and the quadrupole moments are in good agreements with the experiment. The “kink” on the isotope shifts is observed at $A = 139$ where the neutron number is the magic number $N = 82$. It is also found that the octupole deformations may exist in the La isotopes with mass number $A \sim 145\text{--}155$.

1.4 Synthesis of superheavy elements (SHE) via heavy ion fusion reactions

The synthesis of SHE has been a hot topic in nuclear physics for decades. Many isotopes of SHE with $Z = 103$ to 118 have been produced by heavy-ion fusion reactions in experiments [51–54] and the elements with Z up to 112 have been named. In the heavy ion research facility at Lanzhou (HIRFL) China, two new super-heavy nuclides, ^{259}Db and ^{265}Bh , were also produced [55, 56] and an experiment was carried out recently which aims at repeating the synthesis of ^{271}Ds [57]. The production cross section and the corresponding life time of SHE decrease rapidly as the charge number Z increases. To understand the mechanism of the heavy-ion fusion reaction and to guide future experiments, many theoretical efforts have been made.

In a series of studies, Wang et al. [58–62] proposed an empirical barrier distribution for a unified description of the fusion cross sections of light and medium-heavy fusion systems, the capture cross sections of the reactions leading to superheavy nuclei, and the large-angle quasi-elastic scattering cross sections based on the Skyrme energy-density functional approach. By examining the barrier distributions in detail, it is found that the fusion cross sections depend more strongly on the shape of the left side of the barrier distribution while the quasi-elastic scattering cross sections depend more strongly on the right side [63]. Furthermore, by combining these studies and the HIVAP calculations for the survival probability, the formation probability of the compound nucleus is deduced from the measured evaporation residue cross sections for cold and hot fusion reactions.

In order to understand the fusion hindrance in nuclear reactions of heavy systems, a two-step model was proposed [64–66]. The fusion hindrance is studied on mass-symmetric systems using the liquid drop model with the two-center parameterization [67]. Following the idea that the fusion hindrance exists only if the liquid drop barrier (saddle point) is located at the inner side of the contact point after overcoming the outer Coulomb barrier, the reactions in which two barriers are overlapped with each other are determined. It is shown that there are many systems where the fusion hindrance does not exist for the atomic number of pro-

jectile or target nuclei $Z \leq 43$, while for $Z > 43$, all of the mass-symmetric reactions are fusion-hindered. Further study shows that the fusion hindrance also exists in the neck evolution [68] and the neck and the radial degrees of freedom might both be hampered by an inner potential barrier on their path between the contact configuration to the compound nucleus [69].

The production of superheavy nuclei with $Z = 108 - 116$ via hot fusion reactions of the neutron-rich projectiles with ^{238}U target is systematically studied [70]. The results show that the production cross sections of superheavy nuclei do not decrease monotonously as the atomic number Z increasing. The cross sections of the superheavy nuclei at $Z = 112$ and 115 are enhanced as compared with the whole Z -trend in synthesis of the superheavy nuclei, which clearly illustrates that the reactions with large negative Q -value and shell correction are more favorable to synthesize superheavy nuclei [71].

The shell effect is included in the improved isospin dependent quantum molecular dynamics (QMD) model in which the shell correction energy of the system is calculated using the deformed two-center shell model [72, 73]. This improved QMD model is used to calculate the capture cross sections of fusion reactions of heavy systems [74]. A switch function is introduced to connect the shell correction energy of the projectile and the target with that of the compound nucleus during the dynamical fusion process. It is found that the calculated capture cross sections reproduce the data quantitatively at the energy near the Coulomb barrier. The capture cross sections for reaction $^{80}_{35}\text{Br} + ^{208}_{82}\text{Pb} \rightarrow ^{288}_{117}\text{X}$ are also calculated and discussed.

1.5 Shape driven effects of Λ hyperon

Following the original work on the study of the shape-driven effects of Λ [75], Zhou et al. studied the deformations of light Λ hypernuclei with an extended nonrelativistic deformed Skyrme-Hartree-Fock approach with realistic modern nucleonic Skyrme forces, pairing correlations, and a microscopical Lambda-nucleon interaction derived from Brueckner-Hartree-Fock calculations [76]. Compared to the large effect of an additional Λ particle on nuclear deformation in the light soft nuclei within relativistic mean field method [77], this effect is much smaller in the nonrelativistic mean-field approximation. These results have inspired further studies of the shape driven effects of Λ hyperon in atomic nuclei [78–80].

1.6 Randomness of matrix elements of the nuclear shell model Hamiltonian

The randomness of matrix elements of the nuclear shell model Hamiltonian is an interesting topic [81–83]. Shen et al. studied the general behavior of matrix elements of the nuclear shell model Hamiltonian [84]. It is found that nonzero off-diagonal elements exhibit a regular pattern, if one sorts the diagonal matrix elements from smaller to larger values.

The correlation between eigenvalues and diagonal matrix elements for the shell model Hamiltonian is more remarkable than that for random matrices with the same distribution unless the dimension is small.

1.7 A new collective Hamiltonian from the SCC method

A new collective Hamiltonian up to the fourth order for a multi-O(4) model is derived for the first time [85] based on the self-consistent collective-coordinate (SCC) method [86, 87], which is formulated in the framework of the time-dependent Hartree-Bogoliubov (TDHB) theory. This collective Hamiltonian is valid for the spherical case where the HB equilibrium point of the multi-O(4) model is spherical as well as for the deformed case where the HB equilibrium points are deformed. Its validity is tested numerically in both the spherical and deformed cases. Numerical simulations indicate that the low-lying states of the collective Hamiltonian and the transition amplitudes among them mimic fairly well those obtained by exactly diagonalizing the Hamiltonian of the multi-O(4) model.

1.8 Nuclear shape phase transition

In recent years, quantum phase transition in atomic nuclei is an interesting topic [88–91]. Zhang et al. [92] studied systematically the evolution behaviors of some energy ratios, $E2$ transition rate ratios and isomer shift in the nuclear shape phase transitions. It is found that the quantities sensitive to the phase transition and independent of free parameter(s) are approximately particle number N scale invariant around the critical point of the first order phase transition, similar to that in the second order phase transition.

2 Summary and perspectives

Theoretical nuclear physics based on large-scale scientific facilities (LSSF) is one of the fastest developing subjects. Recent progress made by Chinese scientists in theoretical study of nuclear physics related to these facilities is reviewed. The emphasis is put on those topics covered in the issue entitled “Special Topics on Some Theoretical Nuclear Physics Aspects Related to Large-scale Scientific Facilities” (in *Sci China Ser G-Phys Mech Astron*, Vol. 52, No. 10, 2009).

Now several new facilities are under construction or being proposed in China, e.g. the China Spallation Neutron Source (CSNS) [93], the accelerator-driven system [94], the Beijing Rare Ion Beam Facility (BRIF) [95] and the China Advanced Rare Ion Beam Facility (CARIF) [95]. We believe that more important progress will be made in near future.

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