The Research Overview and Historical Review of Nuclear Forces and Nuclear Structure

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Abstract: review of historical and research about nuclear forces and nuclear structure

Opening remark

With regard to the nuclear elementary constituents and overall structure, and nuclear forces, after the discovery of an atomic nucleus has internal structure in 1932, in the eighty years, by great deal of researches, physicists have obtained a large number of measurement results and experimental data; have established fruitful and a series of models for the nuclear elementary constituents and overall structure; and have created and developed the phenomenological theoretical systems for the nuclear force. [1][2][3][4]

The main content

The details of the historical and progresses on the research of these issues, according to the relevant literatures, wraparound, induction and compilation as the following:

Since the discovery of radioactivity by H. Becquerel in 1896 (H. Becquerel, 1896); the discovery of the atom has internal structure by J. Thomson in 1897 (J. Thomson, 1897); the discovery of the nucleus by E. Rutherford in 1911 (E. Rutherford, 1911); the discovery of the hydrogen nucleus (the proton) by E. Rutherford in 1917 (E. Rutherford, 1917), especially, after the discovery of the neutron by J. Chadwick in 1932(J. Chadwick, 1932), physicists have finally understood that an atomic nucleus is composed of protons and neutrons. and in the same year, D. Ivanenko proposed the protons-neutrons model of the atomic nucleus (D. Ivanenko,1932) and the first nuclear shell model (D. Ivanenko, in collaboration with E. Gapon, 1932).[1][2][5]

Closely followed, W. Heisenberg, E. Majorana and E. Wigner, took steps to establish the foremost model of nuclear physics which with respect to the nuclear force and nuclear structure in quantum view: an atomic nucleus is quantum bound states of nucleons which two type particles, the positively charged proton and the uncharged neutron, nucleons are binding together and forming the nucleus by the nuclear force (also called nuclear forces, the nucleon-nucleon interaction), which is a short-range force whose magnitude is independent of the type of nucleons, even is enough strong and attractive to overcome the long-range Coulomb repulsion between protons (W. Heisenberg, E. Majorana, E. Wigner, 1930s).[1][4][6][7]

Ever since that time, the further research and progress achieved with regard to these issues, which the nuclear elementary constituents, the nuclear overall structure and the nuclear force, there be exist and includes:

1. With respect to the nuclear elementary constituents

Until the 1960s, the nuclear elementary constituents, nucleons, the proton and neutron were considered the most elementary particles, that without further internal structure and smaller components. [1][8]

However, with the more progress of experimental particle physics, a large number of mesons and hyperons have been discovered in the 1940–1950s, these particles are mostly strong role particles which called hadrons, but there was no an effective classification to them, hence, in 1949, E. Fermi and Chen-Ning Yang proposed the first hadrons structure model of particle physics, the model assumed that a meson as bound states of a nucleon and an anti-nucleon (E. Fermi and Chen-Ning Yang, 1949); and in 1956, Shoichi Sakata proposed another model of hadrons, also was an early precursor to the quark model, the model assumed that there be only protons, neutrons and lambda baryons are the most elementary particles and are the most elementary constituents of all hadrons (Shoichi Sakata, 1956). These models, has made satisfactory results about mesons, but lost effectiveness with baryons and the related data. [9][10][11][12]

Later, M. Gell-Mann, G. Zweig, in 1964, independently, proposed the quark model and superseded the Sakata model, the model assumed quarks are the most elementary particles and elementary constituents of matter; and there exists six types of quarks: up, down, strange, charm, top and bottom. Hadrons are bound states of quarks and anti-quarks, a meson is composed of one quark and one anti-quark, both a proton and a neutron are composed of three quarks, a proton is composed of two up-quarks and one down-quark, a neutron is composed of one up-quark and two down-quarks (M. Gell-Mann, G. Zweig, independently, 1964).[1][8][12]

After, in 1969, R. Feynman proposed the parton model, it was later recognized that partons describe the same objects now more commonly referred to as quarks and gluons. Therefore, a more detailed presentation of the properties and physical theories pertaining indirectly to partons can be found under quarks (R. Feynman, 1969). [13]

So far, the parton-quark model is still the classification scheme and structure model which with guiding position of lighter hadrons, simultaneously, the quark model and the theoretical system which it belongs to, the Standard Model of particle physics, also is one of three major effort areas in today of theoretical particle physics. [1][4][6][12] [13] [14]

2. With respect to the nuclear overall structure

in nuclear physics, to understand and describe the nuclear overall structure and behavior, thronging the systematic analyzed of experimental data and measurement results, physicists have proposed many microscopic and phenomenological theories and models, which on different phenomena, from different perspectives and with different emphases, these nuclear models have given a multiple perspectives and multifaceted explanations and descriptions regarding the nuclear overall structure and behavior to us.[1][4][6][14][15]

Protons-neutrons model: This model assumes that every atomic nucleus (A≥2) is composed of protons and neutrons. The model not only is the most elementary nuclear structure model, but also is the most fundamental frame for any nuclear structure theories and nuclear structure models (D. Ivanenko, 1932).[5]

Quantum bound states model: This model assumes that every atomic nucleus (A≥2) is a quantum bound states of nucleons; the nucleons are binding together and forming the nucleus by nuclear forces (W. Heisenberg, E. Majorana, E. Wigner, 1930s).[6]

Liquid-drop model: This model assumes that all nucleuses have similar of the mass densities, with binding energies approximately proportional to their masses, just as in a classical charged liquid-drop. The model leads to the SEMF, which gives a good description of the average masses and binding energies. It is largely classical, with some quantum mechanical terms (the asymmetry and pairing terms) inserted in an ad hoc way. Input from experiment is needed to determine the coefficients of the SEMF (N. Bohr, C.F. von Weizsäcker, 1935). [4][15]

Fermi gas model: This model assumes that nucleons move independently in a net nuclear potential. The model uses quantum statistics of a Fermi gas to predict the depth of the potential and the asymmetry term of the SEMF (E. Fermi, 1930s). [4]

Shell model: This is a fully quantum mechanical model that solves the Schrödinger equation with a specific nuclear potential. It makes the same assumptions as the Fermi gas model about the potential, but with the addition of a strong spin-orbit term. It is able to successfully predict nuclear magic number, spins and parties of ground state nuclear and the pairing term of the SEMF. It is less successful in predicting magnetic moments (proposed by D. Ivanenko and E. Gapon, 1932; developed by E. Wigner, M. Mayer, J. H. D. Jensen, independently,1949). [4][16]

Collective model: This is also a fully quantum mechanical model, but in this case the potential is allowed to undergo deformations from the strictly spherical from used in the shell model. The result is that the model can predict magnetic dipole and electric quadrupole magnetic moments with some success. Additional modes of excitation, both vibrational and rotational, are possible and generally confirmed by experiment (A. Bohr, B. Mottelson and L. Rainwater, 1950s). [4][17]

Interacting boson model: This model assumes that nucleons are represented as pairs, each of them acting as a boson particle. There are several branches of this model, in one of them one can group all types of nucleons in pairs, and in others one considers protons and neutrons in pairs separately (Akito Arima and F. Lachello, 1970s). [15]

Other more complicated theories and focus on a single phenomenon models for the nuclear structure have also been proposed, such as the Brueckner's many-body theory, the Pandharipande's variational many-body theory, the Davydov-Filippov model and superconductivity model.

In these models above, the more successful and being widely used are the liquid-drop model, the shell model and collective model. [2][4][6][15]

Besides, in recent years, physicists have obtained some new discoveries, and have put forward views and approaches for establishing more fundamental and general nuclear structure models with the excellent features of the different models existing. [18][19]

3. With respect to the nuclear force

In nuclear and particle physics, the main exploration methods for the nuclear force are phenomenological approach and quantum field theory.

The nuclear force was proposed by W. Heisenberg in 1932, and defined as a kind of interaction between two or more nucleons, that responsible for binding protons and neutrons together then formed an atomic nucleus. It is a short-range interaction whose magnitude is independent of the type of nucleons, even is enough strong and attractive to overcome the long-range Coulomb repulsion between protons (W. Heisenberg, E. Majorana, E. Wigner, 1930s). [1][4][6][7]

About the formation mechanism of the force, in 1934, D. Ivanenko and I. Tamm laid the basis of the first non-phenomenological theory of paired electron-neutron nuclear forces, and made the significant assumption that interaction can be undergone by exchange of particles with a rest mass wasn't equal to zero (D. Ivanenko and I. Tamm, 1934). [5]

Based on the model and theory of D. Ivanenko and I. Tamm, in 1935, Hideki Yukawa proposed his meson theory, he assumed that a kind of light particles which called π-meson was the "force-maker", the nuclear force between nucleons result from the exchange of π-mesons and other hadrons just as electromagnetic interactions result from the exchange of photons. Same time, he assumed a new field corresponds to the nuclear force and gave rise a new sub-field of modern physics, namely, elementary particle physics (Hideki Yukawa, 1935). [1][5][20]

On the π-meson, Yukawa assumed that π-mesons can have both positive and negative charge and that the magnitude of the charge is the same as that of an electron, he estimated the range from known experimental data and found that a π-meson should be about 200 times heavier than an electron, and according to a theory which had been proposed by E. Fermi, he assumed that a π-meson can be transformed into an electron and a light particle without charge called "neutrino" (Hideki Yukawa, 1935).[20]

Along with the establishment of quantum chromodynamics (QCD), the nuclear force was further defined as part of the strong interaction. In the modern theoretical physics, the strong interaction is the mechanism responsible for the strong nuclear force (also called the strong force, nuclear strong force or color force), which is one of the four foundational interactions of nature, the other three being electromagnetism, the weak interaction and gravitation. [7][21]

Quantum chromodynamics (QCD) that based on the parton-quark model is an important part of the Standard Model of particle physics, and is a theory for the strong interaction (quark-gluon interactions), which in the type of quantum field theory. [21][22]

In quantum chromodynamics (QCD), the gluon which a kind of massless particle is the "carrier and maker" of the strong interaction, the strong interaction is the interactions between quarks, antiquarks and gluons, that is mediated by the exchange of gluons and binding quarks and anti-quarks together then forming into hadrons, such as the nucleons and π-mesons.[21][22]

Moreover, in quantum chromodynamics (QCD), the nuclear force is defined as the residual interaction of the strong interaction and that is responsible for binding nucleons together then forming into an atomic nucleus, which is similar to the Van der Waals forces between neutral atoms. [21][22]

For now, quantum chromodynamics (QCD) is still the theory in the guiding position on the strong interaction and also contains nuclear forces. [1][4][6][7][8][9][21][22]

Regarding the properties and features of the nuclear force, the phenomenon observed, experimental data and measurement results by related experiments, there be exist and includes: It is a short-range force: a few fm; it is attractive and enough strong to overcome the long-range Coulomb repulsion between protons; it is a "saturated", each nucleon only occurs interaction with nucleons which it neighboring; it is "charge independent" of the type of nucleons. It is a "hard core" repulsive force at the least distances between their centers of nucleons less than 0.5fm; it becomes a net attractive force at the distance between nucleons larger than 0.5fm, becoming maximal at the center–center distance of about 1.0fm; it drops to negligibly small values; it would disappear at their separation distance exceeds about 2.0 to 2.5fm. [1][4][6][7]

Totally speaking, at the present stage, the knowledge and conclusion is that protons and neutrons (nucleons) are the elementary constituents of an atomic nucleus, a nucleon is composed and formed of three quarks that bound together by the strong interaction, the nuclear force that responsible for binding nucleons together and forming into an atomic nucleus is the residual interaction of the strong interaction; have established a series of models and theories, from many perspectives and aspects, and given the explanations and descriptions of the nuclear overall structure and behaviors; have created and developed the phenomenological theories of the nuclear force. [1][4][6]

Epilogue

Looking ahead, as knowledge and discovery evolves, it is natural and possible, to try and modifying or establishing the theories including models to become more general and fundamental, until we have a single and complete theory including model with an explicit express form and firm theoretical underpinning, which fully and completely enough for describing and explaining the behaviors, properties, generation principle and action mechanism of nuclear structure and the nuclear force. [1][4][6]

References

[1] *J.-L. Basdevant, J. Rich, M. Spiro, Fundamentals in Nuclear Physics, Springer, 2005*

[2] Nuclear physics http://en.wikipedia.org/wiki/Nuclear_physics

[3] *Atomic nucleus http://en.wikipedia.org/wiki/Atomic_nucleus#Nuclear_models*

[4] *Brian R. Martin, Nuclear and Particle Physics: An Introduction, 2nd edition, John Wiley & Sons, 2009*

[5] *Dmitri Ivanenko http://en.wikipedia.org/wiki/Dmitri_Ivanenko*

[6] *J. S. Lilley, Nuclear Physics, John Wiley & Sons, 2001*

[7] *Nuclear forces http://en.wikipedia.org/wiki/Nuclear_force*

[8] *Nucleon http://en.wikipedia.org/wiki/Nucleon*

[9] *Enrico Fermi http://en.wikipedia.org/wiki/Enrico_Fermi*

[10] *E. Fermi and C, N, Yang. Are mesons elementary particles? Phys. Rev. 76, 1739 (1949)*

[11] *Shoichi Sakata http://en.wikipedia.org/wiki/Shoichi_Sakata*

[12] *Quark model http://en.wikipedia.org/wiki/Quark_model*

[13] *Parton http://en.wikipedia.org/wiki/Parton_(particle_physics)*

[14] *Particle physics http://en.wikipedia.org/wiki/Particle_physics*

[15] *Nuclear structure http://en.wikipedia.org/wiki/Nuclear_structure*

[16] *Nuclear shell model http://en.wikipedia.org/wiki/Nuclear_shell_model*

[17] *Aage Bohr http://en.wikipedia.org/wiki/Aage_Bohr*

[18] *J.-P. Ebran, E. Khan, T. Nikšić & D. Vretenar, How atomic nuclei cluster, Nature.487. 341–344 (19 July 2012) doi: 10.1038/nature11246*

[19] *L. P. Gaffney, et al. Studies of pear-shaped nuclei using accelerated radioactive beams, Nature.497, 199–204 (09 May 2013) doi: 10.1038/nature12073*

[20] *Hideki Yukawa' theory (The award ceremony speech in the Noble Prize 1949) http://www.nobelprize.org/nobel_prizes/physics/laureates/1949/press.html*

[21] *Strong interactions http://en.wikipedia.org/wiki/Strong_interaction*

[22] *Quantum chromodynamics http://en.wikipedia.org/wiki/Quantum_chromodynamics*