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Reaction Mechanisms of Exotic Nuclear Systems at Low Energies

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A transfer reaction method has been applied to extract the optical potentials of neutron-halo ^{6}He+^{12}C, ^{64}Zn and ^{209}Bi systems via the one-proton stripping reactions induced by ^{7}Li. The complete picture of threshold anomaly behavior has been obtained for the ^{6}He+^{209}Bi system. It is shown that the dispersion relation connecting the real and imaginary parts does not work for the exotic nuclear systems. Possible reasons are discussed, but further study is strongly desired to discover the underlying physics. Besides, reactions induced by proton-rich exotic nucleus ^{17}F on ^{58}Ni, ^{89}Y and ^{208}Pb targets have been measured at energies around the Coulomb barrier. Thanks to the use of a powerful detector array, the reaction products over a large Z range can be identified clearly. Angular distributions of elastic scattering have been obtained at present. Continuum-discretized coupled-channels calculations indicate that the breakup coupling effects are not significant. Further analyses are still in progress.

KEYWORDS: exotic nuclear system, reaction mechanism, optical model potential, dispersion relation, breakup effect

1. Introduction

With the development of radioactive ion beams (RIBs) facilities and detection systems, reaction mechanisms of exotic nuclear systems at low energies become a hot topic of current interest in nuclear physics [1, 2]. The nuclear interaction is a fundamental ingredient in the study of mechanisms of nuclear reactions. The optical model potential (OMP) is universally adopted to phenomenologically describe the interaction of nuclear collisions. In this paper, we will introduce some new results obtained by the nuclear reaction group at CIAE (China Institute of Atomic Energy), on the properties of OMPs of neutron-halo ^{6}He systems as well as the reaction mechanisms of proton-rich ^{17}F systems at energies around the Coulomb barrier.

2. OMPs of neutron-halo ^{6}He systems

The OMP can be expressed as $U(r) = V(r) + iW(r)$, where the real part describes the refractive scattering process while the imaginary part represents the absorption of incident flux, i.e., all the nonelastic reaction processes. With decades of research, the basic properties of the OMPs of tightly bound systems have been recognized, e.g., the threshold anomaly (TA) was found at energies close to the Coulomb barrier [3, 4]. The dispersion relation, which is based on the causality principle, can be used to describe the connection between the real and imaginary parts [5]. It is well known that the OMPs are closely related to the internal structures of the colliding nuclei, thus particular properties

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of the potential arising from the exotic nuclear structure can be expected [6, 7].

Usually, OMPs are extracted by fitting angular distributions of elastic scattering. At energies close to and below the barrier, however, the angular distributions become insensitive to the nuclear interaction potential. It becomes much more worse for the reactions induced by unstable nuclei, because of limitations of the intensity and/or the phase-space qualities of RIBs. In view of this fact, we proposed a novel method, i.e., the transfer reaction method [8], to study the OMPs of exotic systems by the utilization of a stable beam. The detail of the transfer reaction method can be found in Refs. [9, 10], where the sensitivity test and the comparison with the traditional elastic scattering method were also introduced.

The transfer reaction method has been applied to study the OMPs of neutron-halo ^{6}He systems, by measuring the one-proton transfer reactions induced by ^{7}Li. With the high quality ^{7}Li beam accelerated by the HI-13 tandem accelerator at CIAE, three systems have been measured at energies around the Coulomb barrier, i.e., ^{11}B(^{7}Li, ^{6}He)^{12}C, ^{63}Cu(^{7}Li, ^{6}He)^{64}Zn [11] and ^{208}Pb(^{7}Li, ^{6}He)^{209}Bi [10, 12, 13], to study the OMPs of the light system ^{6}He+^{12}C, the medium-mass system ^{6}He+^{64}Zn and the heavy system ^{6}He+^{209}Bi. The energy dependence of the real and imaginary potentials at the sensitivity radius of 13.5 fm for the ^{6}He+^{209}Bi system is shown in Fig. 1.

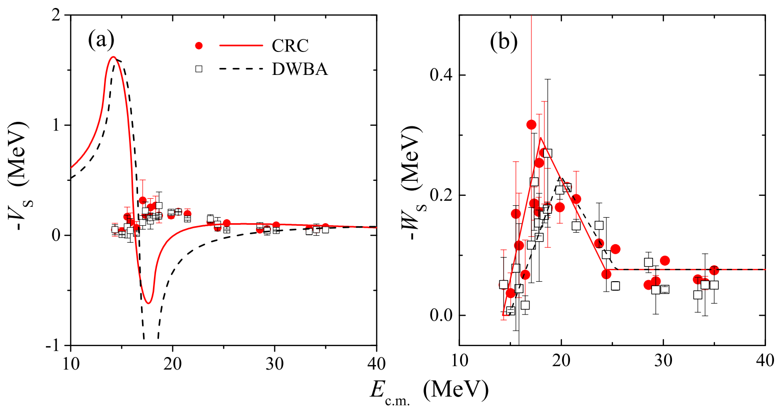

Fig. 1. Energy dependence of the depths of real (a) and imaginary (b) potentials at the sensitivity radius of 13.5 fm for the ^{6}He + ^{209}Bi system. The full circles and empty squares denote the CRC and DWBA results, respectively. Solid and dashed curves in (b) represent the linear-segment fitting for the imaginary potential derived by the CRC and DWBA approaches, respectively. The predictions of the dispersion relation according to the variations of the imaginary potentials are presented in (a) by the corresponding lines.

As shown in Fig. 1(b), the depth of the imaginary potential increases first as the reaction energy decreases in the sub-barrier region, demonstrating that some reaction channels are still open even though there exists strong Coulomb repulsive effect. As the energy reduced further, a decreasing trend is observed clearly, which vanishes at 13.73 ± 1.63 MeV (corresponding to $0.68V_B$) according to the extrapolation, where the threshold energy emerges. It is the first time that a complete OMP behavior of a halo nuclear system is observed clearly. Furthermore, according to the linear-segment fitting results of the imaginary potential as shown in Fig. 1(b), the dispersion relation calculation results with the linear schematic model [5] for the real part are shown in Fig. 1(a). It can be seen clearly the prediction of the dispersion relation cannot reproduce the experimental results, indicating that the dispersion relation does not hold for the halo system ^{6}He + ^{209}Bi, which may be universal for the weakly-bound exotic nuclear system. The possible reasons for the failure of dispersion relation are listed as follows [10, 13]: (a) the dispersion relation is based on the causality principle as expressed in the Kramers-Kronig relation, which is derived from Cauchys residue theorem. One prerequisite of the theorem is that there should be a finite list of isolated singularities, corresponding to the discrete states of the interacting nuclear system [5]. However, the continuum states may be more important for the weakly bound system because of the breakup reactions. Therefore, it is not mathematically rigorous to apply the dispersion relation directly to the exotic nuclear system; (b) the OMPs extracted from experimental data is a phenomenological potential, which is a equivalent local potential. Therefore, the so-called "spurious" energy dependence is introduced, which does not follow the dispersion relation; (c) the derived OMPs are only sensitive to the region located in the external part of the potential. However, the dispersion relation is derived only for a potential that can yield the wave function over all spatial regions. Thus the phenomenological potential, which can only generate the wave function in the external region, does not necessarily need to abide by the causality property [14]. Further study is strongly required to discover the underlying physics.

3. Reaction mechanisms of ^{17}F systems

We have performed a series of experiments to study the reactions induced by the proton-drip line nucleus ^{17}F at energies around the Coulomb barrier, such as ^{17}F+^{89}Y [15], ^{208}Pb [16] at the Radioactive Ion Beam Line at the Heavy Ion Research Facility in Lanzhou (HIRFL-RIBLL1) [17] and ^{17}F+^{58}Ni [18] at the low energy radioactive isotope beam separator CRIB (Center for Nuclear Study Radioactive Ion Beam separator) at University of Tokyo [19]. The valence proton of ^{17}F is bounded only by 0.6 MeV. The root mean square (rms) radius of the ground state is 3.7 fm [20], which is significantly larger than that of the ^{16}O core. The first excited state of ^{17}F, E_x = 0.495 MeV and $J^\pi = 1/2^+$, is the only bound state below the breakup threshold, and reported to have an extended rms radius, 5.3 fm [20], exhibiting a proton-halo structure [21].

The elastic scattering of ^{17}F+^{89}Y were measured at $E_{\rm lab}(^{17}{\rm F})$ = 50 and 59 MeV [15]. Continuum-discretized coupled-channels (CDCC) calculations were performed to understand the coupling effects resulting from the breakup channel. According to the results, the CDCC calculations can reproduce the elastic scattering data reasonably well. Compared with the results of no continuum couplings, the effects of couplings to continuum states (both the bound-continuum states and the continuum-continuum states couplings) is not significant, producing a small hindrance of the Coulomb rainbow peak and a very small enhancement in the case of 59 MeV at backward angles.

For the measurements of ^{17}F+^{58}Ni and ^{208}Pb, an innovatively designed Multilayer Ionization-chamber (IC) Telescope Array (MITA) [18] was employed to detect the reaction products over a large range of Z range. Thanks to the powerful array, both the light reaction products like p and α, and the heavy ions, i.e., ^{16}O and ^{17}F, can be clearly distinguished. Therefore, the angular distributions of elastic scattering, elastic and non-elastic breakup, as well as the fusion cross sections can be derived for the first time for a light target system of ^{17}F [18]. The elastic scattering results are shown in Fig. 2, where the CDCC calculation results are also presented. The data analysis of these two systems are still in progress.

4. Summary

We introduce a transfer reaction method to study the OMPs of exotic systems in the exiting channel. By measuring the one-proton transfer reactions ^{11}B(^{7}Li, ^{6}He)^{12}C, ^{63}Cu(^{7}Li, ^{6}He)^{64}Zn and ^{208}Pb(^{7}Li, ^{6}He)^{209}Bi, the OMPs of the neutron-halo systems ^{6}He+^{12}C, ^{6}He+^{64}Zn and ^{6}He)+^{209}Bi were extracted. For the system ^{6}He)+^{209}Bi, the deep sub-barrier energy region can be achieved, where abnormal behaviors of the optical potential were found: the imaginary potential increases first with energy decreasing below the barrier and then falls quickly down to 0. It is the first time the threshold of the imaginary potential has been determined in an exotic nuclear system. Moreover, experimental results show the dispersion relation is not applicable for this system, which may be a common phe-

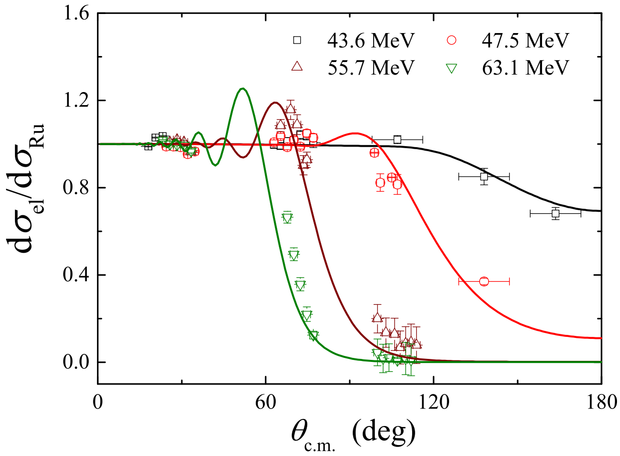

Fig. 2. Angular distributions of elastic scattering of ^{17}F on ^{58}Ni at $E_{lab}(^{17}F)$ = 43.6, 47.5, 55.7 and 63.1 MeV. The solid curves represent the CDCC calculations.

nomenon for exotic nuclear systems. We discuss possible explanations for such a peculiar behavior, but further study is still desired for the underlying physics.

We also performed experiments to study the reactions induced by the proton-rich nucleus ^{17}F. Three systems, i.e., ^{17}F+^{58}Ni, ^{89}Y and ^{208}pb, were measured at energies around the Coulomb barrier. Due to the limit ability of the particle identification of the detector system used in the ^{17}F+^{89}Y measurement, only the quasi-elastic scattering data were obtained. The CDCC analysis indicates that the breakup coupling effect is not significant for this system. A more powerful detector array was designed, to distinguish the reaction products of ^{17}F+^{58}Ni and ^{208}pb. Data analyses are still undergoing.

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References

[1] L. F. Canto, P. R. S. Gomes, R. Donangelo *et al.*, Phys. Rep. **596**, 1 (2015).
[2] J. J. Kolata, V. Guimarães, and E. F. Aguilera, Eur. Phys. J. A **52**, 123 (2016).
[3] B. R. Fulton, D. W. Banes, J. S. Lilley *et al.*, Phys. Lett. B **162**, 55 (1985).
[4] M. A. Nagarajan, C. C. Mahaux, G. R. Satchler, Phys. Rev. Lett. **54**, 1136 (1985).
[5] C. Mahaux, H. Ngô, G. R. Satchler, Nucl. Phys. A **449**, 354 (1986).
[6] A. M. Sánchez-Benítez, D. Escrig, M. A. G. Álvarez *et al.*, Nucl. Phys. A **803**, 30 (2008).
[7] M. S. Hussein, P. R. S. Gomes, J. Lubian and L. C. Chamon, Phys. Rev. C **73**, 044610 (2006).
[8] C. J. Lin, F. Yang, P. Zhou *et al.*, AIP Conf. Proc. **853**, 81 (2006).
[9] Z. D. Wu, L. Yang, C. J. Lin *et al.*, Chin. Phys. Lett. **31**, 092401 (2014).
[10] L. Yang, C. J. Lin, H. M. Jia *et al.*, Phys. Rev. C **96**, 044615 (2017).
[11] L. Yang, C. J. Lin, H. M. Jia *et al.*, Phys. Rev. C **95**, 034616 (2017).
[12] L. Yang, C. J. Lin, H. M. Jia *et al.*, Phys. Rev. C **89**, 044615 (2014).
[13] L. Yang, C. J. Lin, H. M. Jia *et al.*, Phys. Rev. Lett. **119**, 042503 (2017).
[14] R. Lipperheide and A. K. Schmidt, Nucl. Phys. A **112**, 65 (1968).
[15] G. L. Zhang, G. X. Zhang, C. J. Lin *et al.*, Phys. Rev. C **97**, 044618 (2018).
[16] Nan-Ru Ma, Cheng-Jian Lin, Jian-Song Wang *et al.*, Chin. Phys. C **40**, 116004 (2016).
[17] Z. Sun *et al.*, Nucl. Instrum. Methods Phys. Res. A **503**, 496 (2003).
[18] N. R. Ma, L. Yang, C. J. Lin *et al.*, Eur. Phys. J. A **55**, 87 (2019).
[19] S. Kubono *et al.*, Eur. Phys. J. A **13**, 217 (2002).
[20] R. Morlock, R. Kunz, A. Mayer *et al.*, Phys. Rev. Lett. **79**, 3837 (1997).
[21] R. Lewis and A. C. Hayes, Phys. Rev. Lett. **59**, 1211 (1999).