Nuclear Theory Group

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Research Activities

I. LOW ENERGY HEAVY-ION COLLISIONS AND MACROSCOPIC QUANTUM TUNNELING

1. Calculation of the fusion cross section using double-folding potential
(N. Takigawa and T. Takehi)

We calculated the fusion cross section of the $^{16}O+^{144}Sm$ reaction using the double-folding potential assuming the M3Y force for the nucleon-nucleon interaction. We found that a renormalization of the potential depth by a factor of 0.91, which is consistent with the factor encountered in the analysis of elastic scattering, is required in order to reproduce the experimental fusion excitation function at energies above the Coulomb barrier. We have also shown that the fusion barrier height is very sensitive to the surface properties of the density distribution of the colliding nuclei.

2. Quantum diffusion in low energy heavy-ion collisions
(N. Takigawa, K. Washiyama, S. Ayik and S. Kimura)

We studied a quantum effect in the diffusion process by developing a theory, which takes the finite curvature of the potential field into account. The transport coefficients of our theory satisfy the well known fluctuation-dissipation theorem in the limit of Markovian approximation in the cases of diffusion in a flat potential and in a potential well. For the diffusion along a potential barrier, the diffusion coefficient can be related to the friction coefficient by an analytic continuation of the fluctuation-dissipation theorem for the case of diffusion along a potential well in the asymptotic time, but contains strong non-Markovian effects at short times. By applying our theory to the case of realistic values of the temperature, barrier curvature and the friction coefficient in heavy-ion collisions, we have shown that the quantum effects will play significant roles in describing the synthesis of superheavy elements, i.e. the evolution from the fusion barrier to the conditional saddle, in terms of a diffusion process. We especially pointed out the importance of the memory effect, which increases at lower temperatures. It makes the net quantum effects enhance the probability to cross the conditional saddle.

II. REEXAMINATION OF THE SCREENING EFFECTS ON NUCLEAR REACTIONS AT EXTREMELY LOW ENERGIES

1. Roles of electron capture by the projectile and of the Coulomb explosion of molecular projectiles
(N. Takigawa and Y. Kato)

We studied the effects of electron capture by the projectile and the Coulomb explosion of a molecular projectile on the electron screening in low energy nuclear reactions in laboratory. Using the idea of equilibrium charge, we have shown that the electron capture of projectile leads to a screening energy which significantly exceeds the adiabatic limit in the simple consideration for the D(d,p)T reaction and provides a possibility to explain the large screening energy claimed in the analysis of experimental data. We have then shown that the Coulomb explosion can result in a large apparent screening energy as large as that encountered in the analysis of ^{3}He(d,p)^{4}He reactions induced by the molecular D_2^+ and D_3^+ projectiles at very low energies.

III. STUDY OF NUCLEAR STRUCTURE WITH RELATIVISTIC MEAN FIELD THEORY

1. Study of C and Si isotopes
(N. Takigawa, T. Nakatsukasa and Nyein Wink Lwin)

We performed relativistic mean field calculations to study the structure of several light nuclei. We first studied the connection between the $\vec{\ell} \cdot \vec{s}$ interaction and deformation concerning ^{12}C. As remarked in previous papers, we confirmed that the parameter set NLSH with a strong spin-orbit interaction predicts a more spherical shape compared with the NL2 parameter set, which has relatively weak spin-orbit interaction. This can be explained in terms of the change of the degeneracy of energy levels with the spin-orbit interaction for a mid-shell nucleus. The situation for ^{24}Mg and ^{20}Ne is more complicated, because in those cases the strong spin-orbit interaction does not remove the degeneracy of levels at spherical shape. We have then studied the variation of the shape along Si isotopes, paying a special attention to the connection between deformation and magic number, and found that the magic number $N = 28$ which originates from the spin-orbit interaction does not lead to a spherical shape, whereas the magic numbers $N = 8$ and 20 originating from the central potential make nucleus spherical.

IV. INTERMEDIATE ENERGY HEAVY ION REACTIONS AND RELATED TOPICS

1. Nuclear liquid-gas phase transition studied with antisymmetrized molecular dynamics
(T. Furuta and A. Ono)

Nuclear liquid-gas phase transition was studied by using the antisymmetrized molecular dynamics (AMD). The time evolution of a many-nucleon system confined in a container is solved for a long time to get a microcanonical ensemble with given energy and volume. The AMD code was improved so that the time evolusion is solved very precisely for the long time calculations. The method to extract the temperature and pressure for the microcanonical ensemble was carefully considered. The obtained caloric curves for constant pressures show backbending (i.e. nagative heat capacity) which is expected for the phase transition in finite systems. We also studied the mass distribution of the exsisting nuclei in equilibrium, the behavior of which is found to be strongly correlated with the caloric curve.

2. Symmetry energy for fragmentation in dynamical nuclear collisions
(A. Ono, P. Danielewicz, W.A. Friedman, W.G. Lynch, and M.B. Tsang)

We extracted values for the free symmetry energy as a function of the fragment size (the proton number Z) from antisymmetrized molecular dynamics (AMD) calculations of calcium collisions. The isoscaling relation that is satisfied in the AMD results was employed in order to get the fragment yields for a wide region in the nuclear chart, which enables the extraction of the symmetry energy. Simple statistical physics can describe well the distribution of hot nuclei at breakup, provided the surface symmetry term in the free energy is much smaller at high excitation than in ground state nuclei. This result may reflect the low density and finite temperature when these systems disassemble.

V. MICROSCOPIC THEORIES OF NUCLEAR COLLECTIVE MOTION

1. Time-dependent-Hartree-Fock calculations for nuclear response in the continuum
(T. Nakatsukasa and K. Yabana)

The Skyrme energy functional is convenient for calculations in real space because of its local nature. We have been studying nuclear response functions using the time-dependent version of the Skyrme energy functional. First, the ground state is constructed with the imaginary-time method, then, an external field is applied, and the time development of the wave function is calculated in the three-dimensional lattice space. In order to take into account the continuum effects, we use the absorbing-boundary-condition method and an adaptive-coordinate space. Effects of time-odd densities upon giant dipole resonances (GDR) have been examined and turned out to be significant in some cases.

2. Variation after parity projection calculation with Skyrme interaction for light nuclei
(H. Ohta, K. Yabana, and T. Nakatsukasa)

We studied ground and and excited states of light nuclei by means of a variation after parity projection. This procedure provides a description of the ground state incorporating some correlation effects, and self-consistent solutions for the excited states of negative parity. Single particle orbitals are represented on a uniform grid in the three-dimensional Cartesian coordinates. The angular momentum projection is performed after variation to calculate rotational spectra. We carried out the calculation for ^{20}Ne and ^{12}C. In the ^{20}Ne nucleus, both cluster-like and shell-model-like states are described simultaneously in the present framework. For ^{12}C nucleus, the appearance of three-alpha clustering correlation in the ground state is investigated in relation to the strength of the two-body spin-orbit interaction.

3. Self-consistent collective path between oblate and prolate local minima in ^{68}Se
(M. Kobayasi, T. Nakatsukasa, M. Matsuo, and K. Matsuyanagi)

The application of large amplitude collective motion theories to "realistic" nuclear physics has been a long-standing problem. A few years ago, we developed a new practical theory called "adiabatic self-consistent collective coordinate (ASCC) method". We have applied it to the pairing-plus-quadrupole (P+Q) model for ^{68}Se, and succeeded to obtain a collective path between oblate and prolate local HFB minima. The path turns out to be well characterized by the parameter γ, which implies the importance of triaxial deformation. This is the first time that the self-consistent collective path is obtained in a medium heavy superconducting nucleus.

VI. QUANTUM REACTION THEORIES OF A FEW-BODY MODEL

1. Breakup reactions of a neutron halo nucleus ^{11}Be
(M. Ueda, K. Yabana, and T. Nakatsukasa)

Absorbing-boundary-condition approach to nuclear breakup reactions is applied to a breakup reaction of ^{11}Be+^{12}C. An absorbing potential outside the physical area simulates the outgoing boundary condition for scattered waves. No virtual states such as discretized continuum channels need to be introduced in the method. Angular distribution of the breakup cross section for ^{11}Be is qualitatively reproduced in our calculation.

Publications

[1] *Heavy Ion Fusion Reactions and Tunneling Nuclear Microscope*
N. Takigawa, T. Masamoto, T. Takehi and Tamanna Rumin,
Journal of the Korean Physical Society **43** (2003) S91-S99

[2] *Heavy ion fusion reactions at energies near and below the Coulomb barrier*
N. Takigawa, Tamanna Rumin, T. Masamoto, T. Takehi, K. Washiyama, S. Ayik and S. Kimura,
Proceedings of the 10th International Conference on Nuclear Reaction Mechanisms, Varenna 9-13 June, 2003, ed. E. Gadioli (Universita Degli Studi Di Milano) p. 393-402

[3] *Screening effects in nuclear reactions in laboratories at extremely low energies*
N. Takigawa and S. Kimura,
Journal of Plasma and Fusion Research 79(2003) p.891-896

[4] *Isospin fractionation and isoscaling in dynamical simulations of nuclear collisions*
A. Ono, P. Danielewicz, W. A. Friedman, W. G. Lynch and M. B. Tsang,
Phys. Rev. C **68** (2003), 051601(R) (5 pages).

[5] *Reaction dynamics and multifragmentation in Fermi energy heavy ion reactions*
R. Wada, T. Keutgen, K. Hagel, Y.G. Ma, J. Wang, M. Murray, L. Qin, P. Smith, J.B. Natowitz, R. Alfarro, J. Cibor, M. Cinausero, Y. El Masri, D. Fabris, E. Fioretto, A. Keksis S. Kowalski, M. Lunardon, A. Makeev, N. Marie, E. Martin, Z. Majka A. Martinez-Davalos, A. Menchaca-Rocha, G. Nebbia, G. Prete, V. Rizzi, A. Ruangma, D.V. Shetty, G. Souliotis, P. Staszel, M. Veselsky G. Viesti, E.M. Winchester, S.J. Yennello, W. Zipper, A. Ono,
Phys. Rev. C **69** (2004), 044610 (27 pages).

[6] *Time-Dependent Wave-Packet Approach for Fusion Reactions of Halo Nuclei*
K. Yabana, M. Ueda, and T. Nakatsukasa
Nucl. Phys. **A722** (2003) 261c–266c.

[7] *Oscillator Strength Distribution in C_3H_6 Isomers Studied with the Time-Dependent Density Functional Method in the Continuum*
T. Nakatsukasa and K. Yabana,
Chem. Phys. Lett. **374** (2003) 613–619.

[8] *Application of the Adiabatic Selfconsistent-Collective-Coordinate Method to a Solvable Model of Prolate-Oblate Shape Coexistence*
M. Kobayashi, T. Nakatsukasa, M. Matsuo, and K. Matsuyanagi,
Prog. Theor. Phys. **110** (2003) 65–91.

[9] *Giant Resonances in the Deformed Continuum*
T. Nakatsukasa, K. Yabana
Eur. Phys. J. A **20** (2004) 163–164.

[10] *Absorbing-Boundary-Condition Method for Drip-Line Nuclei*
T. Nakatsukasa, M. Ueda, and K. Yabana

Proceedings of the international symposium on Forntiers of Collective Motions (CM2002), (World Scientific, Singapore, 2003), pp. 267–270.

[11] *Continuum Response and Reaction in Neutron-Rich Be Nuclei*
T. Nakatsukasa, M. Ueda, and K. Yabana
Proceedings of the international conference on The Labyrinth in Nuclear Structure, AIP Conference Proceedings **701** (AIP Press, 2004) pp.179–183.

Master Thesis (March 2004)

M1) *Re-examination of screening effects in low energy nuclear reactions in laboratories*
Yasuo Kato

M2) *Study of Nuclear Structure Using Relativistic Mean Field Theory*
Nyein Wink Lwin

M3) *Quantum tunneling and quantum diffusion in heavy ion fusion reactions*
Kouhei Washiyama