8th International Conference on Heavy-Ion Collisions at Near-Barrier Energies

Shizuoka, Japan

November 19-24, 2023

Book of Abstracts
(Poster Presentations)

Exploring effect of entrance channel parameter on incomplete fusion in the $^{16}O+^{89}Y$ system

Avinash Agarwal,[1,*] Anuj Kumar Jashwal,[1] Harsh Vardhan,[1]
M.Faizan Khan,[2] I. A. Rizvi,[2] and A. K. Chaubey[3]
[1] *Department of Physics, Bareilly College,*
M J P R University, Bareilly 243005, INDIA
[2] *Department of Physics, Aligarh Muslim University, Aligarh (U.P.)-202 002, India*
[3] *Department of Physics, Addis Ababa University, P.O.Box 1176, Addis Ababa, Ethiopia*

Heavy-ion reactions on low mass targets are challenging, even at low energies [1-4]. More experimental studies across a wide range of energies are needed to fully comprehend the phenomena at play in these nuclear reactions. In the context of this, present study show the measurements of residual cross sections resulting from ^{16}O induced reactions on ^{89}Y, covering the energy range of 4-7 MeV/nucleon. The off-line γ-ray spectroscopy associated with high purity HPGe detector method was employed. The data analysis was performed using the statistical model code PACE4. A noticeable fraction of incomplete fusion was observed in the production of reaction residues involving α particle(s) in the exit channels, even at energies close to the Coulomb barrier. This enhancement in the cross section clearly demonstrates that the incomplete fusion of projectile with target. The incomplete fusion probability has been calculated to better understand the reaction dynamics. The present findings and a reanalysis of the data for various projectile-target combinations strongly suggest that projectile structure plays a significant role in the onset of incomplete fusion. Additionally, a strong dependence on the Coulomb effect ($Z_P Z_T$) has been observed for the present system along with different projectile-target combinations available in the literature. A detailed description of this work will be presented during the conference.

[1] A. Agarwal et al., Phys. Rev. C **105**, 034609 (2022).
[2] A. Ojha, S. Gupta, U. Gupta, P. P. Singh, A. Yadav, D. P. Singh, Mohd Shuaib, B. P. Singh, and R. Prasad, Phys. Rev. C **104**, 034615 (2021).
[3] K. Kumar, T. Ahmad, S. Ali, I. A. Rizvi, A. Agarwal, R. Kumar, K. S. Golda, and A. K. Chaubey, Phys. Rev. C **87**, 044608 (2013).
[4] M. Kumar, A. Agarwal, S. Prajapati, K. Kumar, S. Dutt, I. A. Rizvi, R. Kumar, and A. K. Chaubey, Phys. Rev. C **100**, 034616 (2019).

*avibcb@gmail.com

Breakup and Incomplete Fusion Mechanisms of ^{7}Be + ^{208}Pb Reactions

M. J. Basson,[1,*] K. J. Cook,[2,1] I. M. Harca,[1] and K. Brown[1]

[1] *Facility for Rare Isotope Beams, Michigan State University, Michigan 48824, USA*
[2] *Department of Nuclear Physics and Accelerator Applications, Research School of Physics, The Australian National University, Canberra, ACT 2601, Australia*

Weakly-bound nuclei (e.g. ^{6,7}Li, ^{9}Be) are observed to have up to 35% suppression of complete fusion compared to single-barrier penetration models when reacting with heavy targets at above-barrier energies [1] [2]. This complete fusion suppression is associated with substantial yields of incomplete fusion, where only part of the projectile is captured. This phenomenon is known to be more complicated than simple projectile breakup [3][4][5]. The yields and characteristic breakup timescales cannot explain the degree of fusion suppression [6][7][8].

Instead, an additional mechanism of direct cluster transfer has been suggested, consistent with analysis of the alpha-particle leftover after incomplete fusion [3]. These reaction dynamics depend strongly on the cluster structure and degree of weak-binding These reaction dynamics are likely to become further complicated away from stability, as valence nucleons become more and more weakly bound. Therefore, to investigate breakup dynamics away from stability, we measured the breakup, complete fusion, and incomplete fusion of ^{7}Be, the mirror-nucleus of ^{7}Li, on ^{208}Pb at above-barrier energies. By comparing the breakup of ^{7}Be and ^{7}Li, we aim to disentangle the competing effects of low-lying structure with binding. The ongoing analysis of the 7Be breakup data will be discussed, including the use of random-forest machine learning classifiers to achieve particle identification.

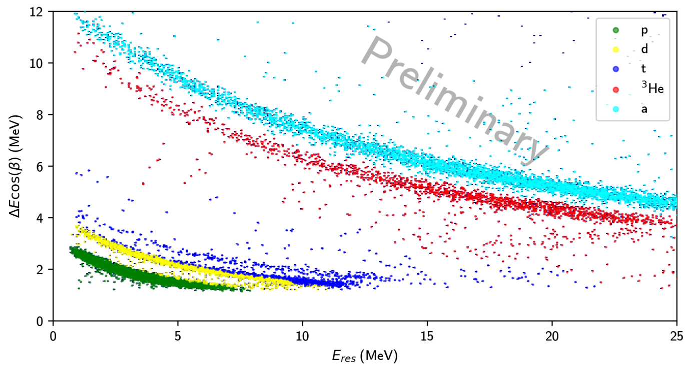

FIG. 1: Preliminary particle identification by a random forest classifier (see color legend) is overlaid on FABLE ΔE-E telescope data. The classifier is trained only on simulated data and helps achieve identification where species overlap, such as in the case where $Z = 1$.

[1] M. Dasgupta et al., Phys. Rev. C **70** (2004).
[2] C. Signorini et al., Eur. Phys. A **5**, 7 (1999).
[3] K. J. Cook et al., Phys. Rev. C **122**, 102501 (2019).
[4] D. H. Luong et al., Phys. Lett. B **695**, 105 (2011).
[5] A. Shrivastava et al., Phys. Lett. B **633**, 463 (2006).
[6] K. J. Cook et al., Phys. Rev. C **93** (2016).
[7] E. C. Simpson et al., Phys. Rev. C **93**, 24605 (2016).
[8] S. Kalkal et al., Phys. Rev. C **93**, 044605 (2016)

* basson@frib.msu.edu

Atomic models for description of high-Z impurities dynamics in tokamak plasmas - summary of 'HARMONIA' project

J. Bielecki,[1,*] D. Dworak,[1] A. Jardin,[1] K. Krol,[1] D. Mazon,[2] Y. Peysson,[2] M. Scholz,[1] and J. Walkowiak[1]

[1] *Institute of Nuclear Physics Polish Academy of Sciences, PL-31342 Krakow, Poland*
[2] *CEA, IRFM, F-13108, Saint-Paul-lez-Durance, France*

Since the year 2019, the project entitled 'Study of the mutual dependence between Lower Hybrid current drive and heavy impurity transport in tokamak plasmas' has been jointly executed by Polish (IFJ PAN) and French (CEA-IRFM) research teams. Among many important results obtained in the framework of the project [1] [2], a particularly crucial issue studied is the influence of not fully ionized high-Z impurities (e.g. tungsten ions) on suprathermal electrons dynamics. The primary source of such impurities in tokamak plasmas is the interaction with plasma-facing components made, in the modern machines, mostly of tungsten.

The influence of such impurities on the suprathermal electrons population can be studied using a Fokker-Planck solver. However, in this case, it is necessary to modify the electron-ion collision operator, in order to incorporate the effect of partially ionized high-Z elements, arising from uncontrolled influxes of impurities [3]. This, in turn, requires atomic models that are accurate enough but still allow preforming fast and efficient calculations for all elements present in the plasma regardless their local level of ionization.

For this purpose, a few simple atomic models have been proposed and implemented into a Fokker-Plank solver (LUKE code [4] developed in CEA). Those semi-empirical atomic models for elastic and inelastic collisions between fast electrons and ions have been calibrated and optimized using results of Density Functional Theory (DFT) calculations, Dirac-Fock-Slater method (as implemented in Flexible Atomic Code (FAC) code [5]), relativistic multiconfiguration Dirac-Hartree-Fock method (as implemented in GRASP2k code [6]) or available reference data [7].

This contribution summarizes the achievement of the whole project with a special emphasis on the modeling efforts to incorporate the physics of partially ionized high-Z elements in kinetic calculations.

Acknowledgment:

This work has been partially funded by the National Science Centre, Poland (NCN) grant HARMONIA 10 no. 2018/30/M/ST2/00799. We gratefully acknowledge Poland's high-performance computing infrastructure PLGrid (HPC Centers: ACK Cyfronet AGH) for providing computer facilities and support within computational grant no. PLG/2022/015994. This work was funded in part by the Swiss National Science Foundation. This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 - EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them. This work has been published in the framework of the international project co-financed by the Polish Ministry of Education and Science, as program "PMW", contracts 5235/HEU - EURATOM/2022/2 and 5253/HEU-EURATOM/2022/2.

[1] Y. Peysson et al., J. Fusion Energ. **39**, 270-291 (2020).
[2] D. Mazon et al., JINST **17**, C01073 (2022).
[3] L. Hesslow et al., Phys. Rev. Lett. **118**, 255001 (2017).
[4] Y. Peysson et al., Plasma Phys. Control. Fusion **58**, 044008 (2016).
[5] M. F Gu, Canadian Journal of Physics. **86**, 675-689 (2011).
[6] P. Jonsson, et al., Comput. Phys. Commun. **177** 597 (2007).
[7] S. P. Sauer et al., J. Chem. Phys. **148**, 174307 (2018).

* jakub.bielecki@ifj.edu.pl

Reaction dynamics of synthesis mechanism of superheavy nuclei in fusion-evaporation reactions

Peng-Hui Chen,[1,*] Geng Chang,[1] Hao Wu,[1] Xiang-Hua Zeng,[1] and Zhao-Qing. Feng[2,†]

[1] *School of Physical Science and Technology, Yangzhou University, Yangzhou, China*
[2] *School of Physics and Optoelectronics, South China University of Technology, Guangzhou, China*

In the framework of the dinuclear system model, the synthesis mechanism of the superheavy nuclides with the atomic number $Z = 112, 114, 115$ in the reactions of projectiles ^{40,48}Ca bombarding on targets ^{238}U, ^{242}Pu, and ^{243}Am at wide incident energy have been investigated systematically. Based on the available experimental excitation functions, the dependence of calculated synthesis cross-sections on collision orientations has been studied thoroughly. The TKEs of these collisions with the fixed collision orientation show its orientation dependence which can be used to predict the tendency of kinetic energy diffusion. The TKEs are dependent on incident energies which have been discussed. The method of the Coulomb barrier distribution function has been applied in our calculations which could treat all of the collision orientations from the tip-tip to side-side approximately. The calculations of excitation functions of ^{48}Ca + ^{238}U, ^{48}Ca + ^{242}Pu, and ^{48}Ca + ^{243}Am have a nice agreement with the available experimental data. The isospin effect of projectiles on production cross sections of moscovium isotopes and the influence of the entrance channel effect on the synthesis cross sections of superheavy nuclei have been discussed. The synthesis cross-section of new moscovium isotopes $^{278-286}$Mc have been predicted as large as hundreds pb, in the fusion-evaporation reactions of ^{35,37}Cl + ^{248}Cf, ^{38,40}Ar + ^{247}Bk, ^{39,41}K + ^{247}Cm, ^{40,42,44,46}Ca + ^{238}Am, ^{45}Sc + ^{242}Pu, and ^{46,48,50}Ti + ^{243}Np, ^{51}V + ^{238}U at some typical excitation energies. Based on this DNS model, the new SHE of $^{289-293}$119 has been predicted as the synthesis cross sections around one picobarn in the ^{44,46,48,50}Ti-induced reactions. Production cross-section of the element of ^{295}120 has been evaluated as large as 1 picobarn in the reactions ^{46}Ti (^{251}Cf, 2n) ^{295}120 at E^* = 26 MeV. The optimal projectile-target combinations and beam energies for producing new SHE with atomic number Z=119-120 are proposed for the forthcoming experiments.

[1] P.H. Chen, H. Wu, Z.X. Yang, X.H. Zeng, Zh.Q. Feng, Nucl. Sci. Tech. **34**, 016301 (2023).
[2] Z.H. Wang, P.H. Chen, X.H. Zeng, Zh.Q. Feng, Nucl. Phy. Rev. **39**, 421-433 (2022).

* chenpenghui@yzu.edu.cn
† fengzhq@scut.edu.cn

Examination of promising reactions with ^{241}Am and ^{244}Cm targets for the synthesis of new superheavy elements within the dinuclear system model with a dynamical potential energy surface

Xiang-Quan Deng[1,2] and Shan-Gui Zhou[1,2,3,4,5,6]

[1] *CAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China*
[2] *School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 100049, China*
[3] *School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, China*
[4] *Synergetic Innovation Center for Quantum Effects and Application, Hunan Normal University, Changsha, 410081, China*
[5] *Peng Huanwu Collaborative Center for Research and Education, Beihang University, Beijing 100191, China*
[6] *Corresponding author: sgzhou@itp.ac.cn*

Two actinide isotopes, ^{241}Am and ^{244}Cm, produced and chemically purified by the HFIR/REDC complex at ORNL are candidates for target materials of heavy-ion fusion reaction experiments for the synthesis of new superheavy elements (SHEs) with $Z > 118$ [1,2]. In the framework of the dinuclear system model with a dynamical potential energy surface (DNS-DyPES model) [3,4], we systematically study the ^{48}Ca-induced reactions that have been applied to synthesize SHEs with $Z = 112$–118, as well as the hot-fusion reactions with ^{241}Am and ^{244}Cm as targets which are promising for synthesizing new SHEs with $Z = 119$–122. Detailed results including the maximal evaporation residue cross section and the optimal incident energy for each reaction are presented and discussed. We show the excitation functions of the reactions ^{48}Ca + ^{241}Am and ^{48}Ca + ^{244}Cm in Fig. 1.

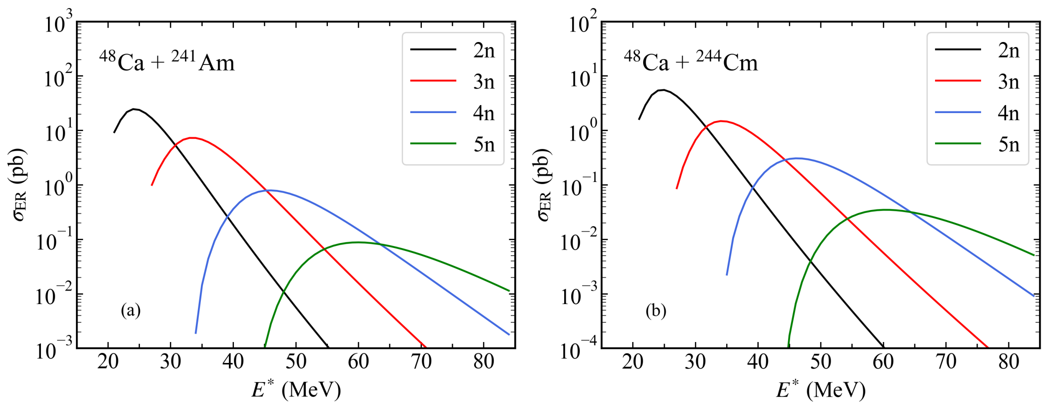

FIG. 1. Excitation functions of the reactions (a) ^{48}Ca + ^{241}Am and (b) ^{48}Ca + ^{244}Cm, calculated with the DNS-DyPES model.

[1] J. B. Roberto et al., Nucl. Phys. A **944**, 99 (2015).
[2] S. M. Robinson et al., Radiochim. Acta **108**, 737 (2020).
[3] N. Wang et al., Phys. Rev. C **85**, 041601(R) (2012).
[4] X. Q. Deng and S. G. Zhou, Phys. Rev. C **107**, 014616 (2023).

Spreading width converted from optical potential for α cluster incident scattering

T. Fumimoto,[1] M. Ishihara,[1] T. Maeda,[1] R. Nakamoto,[1] and M. Ito[1,*]

[1] *Department of Pure and Applied Physics, Kansai University, Suita, Osaka, Japan*

Optical model is quite successful in describing the differential cross section of the elastic scatterings in nuclear systems [1]. In a scattering process, a whole effect of coupling to non-elastic channels, such as inelastic, transfer and compound channels, is usually simulated by a negative imaginary potential, which is called an absorptive potential. In a neutron scattering at extremely low energy, for example, the absorptive effect is equivalent to an energy-averaged spreading width involving the compound nucleus (CN) formation [1].

Furthermore, the optical potentials, which are precisely determined to reproduce the elastic scattering, are used to calculate the energy spectra of the total scattering systems [2]. The typical examples of such the "unified studies of the nuclear scattering and structure" can be seen in the α scattering by the heavy targets: α + ^{16}O in ^{20}Ne, α + ^{40}Ca in ^{44}Ti, and so on [2]. However, in the structure calculation, the absorptive potentials, which are included in the scattering calculation, are completely neglected, and there is no discussion about the role of the absorptive potential in the analysis of the nuclear structure.

We consider the neglect of the imaginary potential in the structure calculation as shortcoming in the unified study of the scattering and the structure on the basis of the optical potential. According to the optical model originally used in the neutron scattering, the effect of the imaginary potential is considered to correspond to the "spreading width", in which the incident channel decays into the more complicated states. Therefore, we try to convert the imaginary potential into the spreading width for the α cluster incident channel.

The relation providing a bridge from the optical model calculation to the spreading width, $\Gamma(E)$, at the energy E [3] is given by

$$\Gamma(E) \ = \ \frac{1-|S(E)|^2}{2\pi\rho(E)} \quad . \tag{1}$$

Here $S(E)$ is a scattering matrix (S-matrix) calculated from the optical potential, while $\rho(E)$ is a level density of the compound system [4]. In the present study, we have extended the formula (1) and evaluated the spreading width in several scattering systems other than the neutron scatterings.

First, we have checked the CN width for the neutron scattering by employing the neutron optical potential [1]. For example, in the ^{40}Ca + neutron scattering, we have obtained the CN width (Γ ~100 eV) consistent to the experimental observation at E ~a few tens keV. Then, the similar calculation is applied to α + ^{40}Ca, which is a typical example of the α cluster systems, and the spreading width generated by the reaction of α + ^{40}Ca is calculated. We discuss the effect of the spreading width on the strength function for the α breakup reaction, ^{44}Ti $\rightarrow$ α + ^{40}Ca recently evaluated [5]. The results of the breakup strength will be compared with the single particle strength calculated by the mean-field model.

[1] H. Feshbach, C. E. Porter, W. Weisskopf, Phys. Rev. **96**, 448, (1954).
[2] F. Michel, S. Ohkubo and G. Reidemeister, Prog. Theor. Phys. Suppl. **132**, 7 (1998).
[3] Y. J. M. Blatt and V. F. Weisskopf, "Theoretical Nuclear Physics" (Wiley, New pork, 1966), p. 389.
[4] W. Dilg et al., Nucl. Phys. A217, 269 (1973).
[5] M. Nakao et al., Jour. Nucl. Sci. Tech. 57,1121 (2020).

*itomk@kansai-u.ac.jp

Study on the Supression of Elastic Scattering of Exotic Nuclei Using an Extended Optical Model.

Kyoungsu Heo,[1,*] Myung-Ki Cheoun,[1] Ki-Seok Choi,[2] K. S. Kim,[2] and W. Y. So[3]

[1]*Department of Physics and Origin of Matter and Evolution of Galaxy (OMEG) Institute, Soongsil University, Seoul 06978, Korea*
[2]*School of Liberal Arts and Science, Korea Aerospace University, Koyang 10540, Korea*
[3]*Department of Radiological Science, Kangwon National University at Dogye, Samcheok 25945, Korea*

In general, the optical model describes a one-channel based on the elastic scattering between the projectile and target nuclei. Consequently, all other non-elastic channels are treated as the absorption channel. However, starting with the extended framework that successfully separates direct and fusion reaction channels[1], we incorporate a more diverse range of approaches to separate the absorption channel using the extended optical model[2,3].

This extended optical model fundamentally relies on the dynamical polarization potential (DPP), which effectively separates various channels. In particular, for weakly-bound nuclei such as ^{11}Be and ^{11}Li[2,4], the effects of inelastic scattering and elastic breakup reaction due to E1 transitions are crucial. We effectively describe the cross-section for each channel using the Coulomb dipole excitation (CDE) potential[5], a CDE that employs the E1 strength distribution dB(E1)/dE. Additionally, we applied this extended optical model to the proton-rich nucleus collision of ^{17}F + ^{208}Pb, though the effects of Coulomb-induced elastic breakup reactions were found to be small[3]. Therefore, it was found that the E1 Coulomb interaction, which occurring at long distance between the projectile and the target, plays a significant role in reducing the elastic scattering from the forward angle. It was also studied that this effect is particularly evident in neutron-rich projectiles.

However, unlike the characteristics found in proton-rich nuclei studied so far, it was discovered that a suppression in the elastic scattering near the Coulomb barrier energy also occurs in collisions with projectiles that have a Borromean structure. Notably, ^{10}C (α + α + p + p) + ^{208}Pb [6] and ^{17}Ne (^{15}O + p + p) + ^{208}Pb [7] are examples where elastic scattering has been recently experimented with. This time, we studied the results of collision experiments with these two nuclei, which have such a Borromean structure, using an extended optical model[8].

[1] T. Udagawa, B. T. Kim, and T. Tamura, Phys. Rev. C **32**, 124 (1985).
[2] Kyoungsu Heo, Myung-Ki Cheoun, Ki-Seok Choi, K. S. Kim, W. Y. So, Eur. Phys. J. A **56**, 42 (2020).
[3] Kyoungsu Heo, Myung-Ki Cheoun, Ki-Seok Choi, K. S. Kim, and W. Y. So, Phys. Rev. C **105**, 014601 (2022).
[4] T. H. Kim, W. Y. So, Ki-Seok Choi, K. S. Kim, Kyoungsu Heo and Myung-Ki Cheoun, J. Korean Phys. Soc. **73(5)**, 553-560 (2018).
[5] M. Andrés, J. Gómez-Camacho and M. Nagarajan, Nucl. Phys. A **580**, 817c (1995).
[6] R. Linares, et al., Phys. Rev. C **103** (2021) 044613.
[7] J. D. Ovejas, et al., Phys. Lett. B **843**, 138007 (2023).
[8] Kyoungsu Heo, Myung-Ki Cheoun, Ki-Seok Choi, K. S. Kim, W. Y. So, arXiv:2309.09445 [nucl-th].

*pleasewhy@naver.com

Local QRPA inertia for symmetric-asymmetric fission dynamics

Nobuo Hinohara,[1,2,3,*] Sylvester Agbemava,[3] Kyle Godbey,[3]
Witold Nazarewicz,[3,4] Ante Ravlić,[3] and Jhilam Sadhukhan[5,6,3]

[1] *Center for Computational Sciences, University of Tsukuba, Tsukuba 305-8577, Japan*
[2] *Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba 305-8571, Japan*
[3] *Facility for Rare Isotope Beams, Michigan State University, East Lansing, Michigan 48824, USA*
[4] *Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[5] *Physics Group, Variable Energy Cyclotron Centre, Kolkata 700064, India*
[6] *Homi Bhabha National Institute, Mumbai 400094, India*

The nuclear fission process plays an important role in the r-process nucleosynthesis. The r-process ends with spontaneous or neutron-induced fission of very neutron-rich heavy nuclei, and predicting their half-lives based on a microscopic theory is required. The collective inertia has a large impact on the fission half-lives.

The perturbative/non-perturbative cranking approximation [1] has been widely used for calculating the collective inertia in the large-scale calculation of the fission dynamics based on the nuclear density functional theory. The cranking inertia has been known to neglect the time-odd contribution of the mean field, and thus it underestimates the value of the inertia. The inertia based on the local quasiparticle random-phase approximation (QRPA) that can include the time-odd contribution is proposed [2] and applied to the fission dynamics [3]. The computation of that collective inertia requires QRPA solutions at each point on the potential energy surface as a function of the deformation parameters. The large-dimensional QRPA matrix diagonalization can be avoided by using the finite-amplitude method [4], but it still requires contour integration in the complex energy plane [5] to extract the information of the collective inertia. A recently developed formulation [6] based on the reduced-order emulator technique (reduced basis method) [7-9] allows to compute the low-energy QRPA solutions based on the finite-amplitude method but without contour integration. It reduces the computational cost when evaluating the collective inertia by an order of magnitude.

In this presentation, we discuss the local QRPA collective inertia of ^{240}Pu as a benchmark case. We compare the inertia as a function of the axial quadrupole moment computed by the contour integration and the reduced basis method to assess the numerical accuracy of the reduced basis method. Then we will present the collective inertia for the two-dimensional quadrupole and octupole dynamics.

[1] A. Baran, J. A. Sheikh, J. Dobaczewski, W. Nazarewicz, and A. Staszczak, Phys. Rev. C **84**, 054321 (2011).
[2] N. Hinohara, K. Sato, T. Nakatsukasa, M. Matsuo, and K. Matsuyanagi, Phys. Rev. C **82**, 064313 (2010).
[3] K. Washiyama, N. Hinohara, and T. Nakatsukasa, Phys. Rev. C **103**, 014306 (2021).
[4] T. Nakatsukasa, T. Inakura, and K. Yabana, Phys. Rev. C **76**, 024318 (2007).
[5] N. Hinohara, M. Kortelainen, and W. Nazarewicz, Phys. Rev. C **87**, 064309 (2013).
[6] N. Hinohara, X. Zhang, and J. Engel, in preparation.
[7] D. Frame, R. He, I. Ipsen, D. Lee, D. Lee, and E. Rrapaj, Phys. Rev. Lett. **121**, 032501 (2018).
[8] C. Drischler, J. A. Melendez, R. J. Furnstahl, A. J. Gracia, and X. Zhang, Front. Phys. **10**, 1092931 (2022).
[9] E. Bonilla, P. Giuliani, K, Godbey, and D. Lee, Phys. Rev. C **106**, 054322 (2022).

* hinohara@nucl.ph.tsukuba.ac.jp

Implication of compact configuration of hexadecapole deformed actinides in the synthesis of superheavy nuclei

Shivani Jain,[1,*] Harshit Sharma,[1] Raj Kumar,[1] and Manoj K. Sharma[1]

[1] *School of Physics and Materials Science, Thapar Institute of Engineering and Technology, Patiala - 147004, India*

The study of synthesizing superheavy elements belonging to the transactinide region has been of great interest in the field of low-energy heavy-ion induced nuclear reactions for experimentalists as well as theoreticians. The superheavy nuclei (SHN) can be synthesized via hot and cold nuclear fusion mechanisms, at different scale of excitation energies. Instead of complex structural properties of SHN, the cross-sections are measured up to the range of femtobarn (fb) scale [1]. Besides, the relevance of deformation and orientation degrees of freedom is explored in view of production and decay products of SHN [2, 3]. It has been analyzed that, the 'compact' configuration for a hot fusion reaction (^{48}Ca-induced reaction) corresponds to the highest interaction barrier and the lowest interaction radius, whereas 'elongated' configuration for the cold fusion corresponds to the lowest interaction barrier and largest interaction radius among all the possible orientations. Recently in [4], we have obtained optimum orientations θ_{opt} corresponding to the elongated and compact configurations of hexadecapole deformations of light to heavy mass targets and analyzed their relevance on fusion barrier and fusion cross-sections. So, for further investigations, it would be of great interest to investigate the effect of higher-order deformations (up to $\beta_4^{\pm}$) and corresponding θ_{opt}, in reference to that of quadrupole ($\beta_2^{\pm}$) and octupole ($\beta_3^{\pm}$) deformations, in the decay products of SHN (^{286}Cn*) formed via ^{48}Ca (and neighborhood nuclei)-induced reactions. Thus, in the present work, we have opted the compact configuration of $\beta_4^{\pm}$ - deformed actinides taken as targets of above mentioned reactions and to carry forward with this idea, the fragmentation theory of the Dynamical Cluster-decay Model (DCM) [2] is used for the generalized nuclear proximity potential, with deformation included up to the hexadecapole deformations and optimum orientations related to the compact configuration of $\beta_4^{\pm}$-deformation. Due to significant change on the fusion barrier characteristics (barrier height V_B, barrier position R_B and barrier curvature $\hbar\omega_B$), it is expected to have corresponding impact on fragmentation structure of heavy/superheavy nuclei. Such theoretical inputs may motivate the experimentalists to understand the relevance of higher-order deformation in the synthesis and subsequent decay of superheavy nuclei.

[1] Y. T. Oganessian *et al*, Nucl. Phys. A **944**, 62 (2015).
[2] R. K. Gupta *et al*, J. Phys. G: Nucl. Part. Phys. **31**, 631 (2005).
[3] S. Jain *et al*, Phys. Rev. C **101**, 051601(R) (2020).
[4] H. Sharma *et al*, Eur. Phys. J. A **59**, 71 (2023).

*jain.shivani04@gmail.com

Investigation of translead nuclides produced from ^{136}Xe+^{209}Bi/^{nat}Pb to study the multinucleon transfer reaction process

D. Kumar,[1,*] T. Dickel,[1,2] A. Zadvornaya,[2,3] O. Beliuskina,[3]
A. Kankainen,[3] and the experiment I252 collaboration

[1] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt 64291, Germany*
[2] *II. Physikalisches Institut, Justus-Liebig-Universität Gießen, Gießen 35392, Germany*
[3] *Department of Physics, University of Jyväskylä, Jyväskylä FI-40014, Finland*

The multinucleon transfer (MNT) reaction process is the most promising method to reach towards very neutron-rich heavy and super-heavy nuclei, including the nuclei around shell closure $N = 126$ essential to understand the nucleosynthesis r-process for heavier elements [1-3]. The MNT approach offers a significant production of isotopic yield distributions over a wide mass range around target-like and projectile-like fragments and a high probability of transferring large amounts of angular momentum, which may result in the substantial production of high-spin isomers [3]. In this endeavor, the experiments were performed at the Ion-Guide Isotope Separator On-Line (IGISOL) facility in the JYFL Accelerator Laboratory of the University of Jyväskylä, Finland [4-6]. The neutron-rich Bi, Po, and At isotopes having masses 211/212 were produced through the MNT-induced reaction process using the 945 MeV ^{136}Xe beam obtained from the K-130 cyclotron on ^{209}Bi and ^{nat}Pb targets. The energetic MNT fragments were thermalized within the new MNT gas cell. The MNT-ions were subsequently extracted from the gas cell using a sextupole ion guide, accelerated to 30 keV downstream to the beamline, and mass-separated using a dipole magnet [4]. Finally, the α-characteristic peaks of MNT-ions were measured using a Si-detector placed at the Switch Yard (SW) of the IGISOL facility.

The isomer-to-ground state ratio (IR) of ^{211}Po and relative yield of ^{211}Po/^{211}Bi produced from ^{136}Xe+^{209}Bi/^{nat}Pb was deduced and compared with theoretical model calculations. Interestingly, the IR of ^{211}Po produced in the ^{136}Xe+^{nat}Pb reaction was found to be two times higher compared to that observed by ^{136}Xe+^{209}Bi. Unlike the previous measurements, for the first time, a large angular acceptance window around the grazing angle was covered using newly designed MNT-gas cells. Therefore, different angular coverage windows hardly affect the IRs populated from both production routes. The advanced theoretical model calculations based on the Langevin-type approach have been adopted to estimate the spin distribution of ^{211}Po for both systems [3]. Deduced IRs of ^{211}Po was well reproduced in case of ^{136}Xe+^{nat}Pb, while qualitatively explain for ^{136}Xe+^{209}Bi. The contribution will mainly focus on the discussion of the spin effect of the targets on the population of IRs, the possible reason for the production of significantly different IRs of ^{211}Po, compare the Langevin-type model calculations and Grazing estimations with the deduced relative yields of ^{211}Po/^{211}Bi, and dependence of isomer production by different nuclear reaction processes [6-8].

[1] T. Niwase et. al., Phys. Rev. Lett., **130**, 132502 (2023) and reference therein.
[2] A. Karpov, V. Saiko, Phys. Rev. C 96 (2017) 024618 ; 99 (2019) 014613
[3] T. Dickel et. al., EPJ. Conf. Ser. **1668**, 012012 (2020).
[4] A. Kankainen et. al., Hyperfine Interactions **241**, 43(2020).
[5] A Spataru et. al., Acta Polonica B **817** 51 (2020).
[6] T. Dickel et. al., Phys. Lett. B **137** 744(2015).
[7] L.R. Gasques et. al., Phy. Rev. C **74**, 064615 (2006).
[8] D. Kumar et. al., Phys. Rev. C **96**, 014617 (2017)

* email.de.kumar@gsi.de

Study on the fusion reactions of ^{9}Be with ^{181}Ta, ^{89}Y, and ^{197}Au

G. S. Li,[1,*] Y. D. Fang,[1] N. T. Zhang,[1] X. H. Zhou,[1]
M. L. Liu,[1] J. Lubian,[2] A. Diaz-Torres,[3] and D. Patel[4]

[1] *Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, People's Republic of China*
[2] *Instituto de Física, Universidade Federal Fluminense, Avenida Litorânea s/n, Gragoatá, Niterói, Rio de Janeiro 24210-340, Brazil*
[3] *Department of Physics, University of Surrey, Guildford GU2 7XH, United Kingdom*
[4] *Department of Applied Physics, Sardar Vallabhbhai National Institute of Technology Surat - 395007, India*

The cross sections of complete fusion(CF) and incomplete fusion(ICF) of the ^{9}Be projectiles with ^{181}Ta, ^{89}Y, and ^{197}Au targets were measured at energies around the Coulomb barrier, using online activation followed by offline γ-ray spectroscopy method. In the ^{9}Be+^{181}Ta system, the isomer yield ratios of ^{184}Re in the ICF process were extracted unambiguously. The PLATYPUS code managed to fairly reproduce the order of magnitude of the yield ratios at above barrier energies [1]. With the new experimental data of ^{9}Be+^{89}Y system, it is revealed that the extended CF excitation function is consistent with the systematical behavior that the prompt-breakup probability at above barrier energies is roughly independent of the target in the reactions induced by the same weakly bound projectiles. In addition, for the ^{9}Be+^{197}Au system, A CF suppression of about 35% was found, at energies above the barrier, whereas the total fusion cross sections are in agreement with the calculations [2].

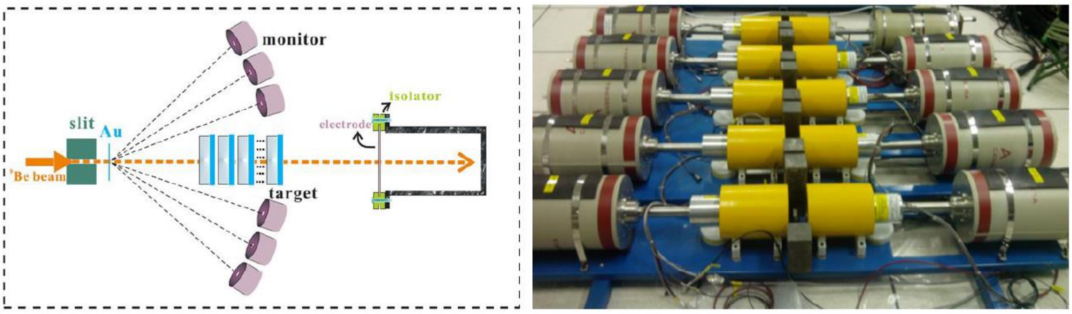

FIG. 1: Left: schematic drawing of the online experimental setup. Right: offline characteristic γ-ray measurement.

[1] G. S. Li, Y. D. Fang, *et al.*, Phys. Rev. C 99, 054617 (2019).
[2] G. S. Li, J. G. Wang, *et al.*, Phys. Rev. C 100, 054601 (2019).

*ligs@impcas.ac.cn

Development of a mosaic-type detector array based on Si photodiodes for charged particle detection

J. T. Li,[1,2,*] N. Imai,[1] R. Kojima,[1] R. Yokoyama,[1] S. Michimasa,[1] T. Chillery,[1] and M. Shiraishi[3]

[1] *Center for Nuclear Study, University of Tokyo, Wako-shi, Japan*

[2] *RIKEN Nshina Center, Wako-shi, Japan*

[3] *Rikkyo University, Tokyo, Japan*

Fusion-Evaporation reactions have been extensively employed for expanding the chart of nuclides and exploring the high excited states in heavy nuclear region. To identify the Evaporation Residues (ERs) produced in fusion reactions, the measurement of characteristic α-decay energies from unstable ERs has proven to be effective [1]. Si detectors are often applied [2] in the measurements owing to good energy resolutions. However, there are some long-standing limitations such as the deterioration of the detector performance due to radiation damage and the higher cost compared to other detectors like scintillators. To achieve a relatively low-cost charged-particle detection with the position sensitivity, we have developed a mosaic-type detector array based on Si photodiodes. Its high modularity enables the modification of the geometric configuration of the detector array according to specific experimental requirements.

The Si photodiode Hamamatsu S13955-01 [3] has a size of 7.52×7.52 mm^2 with the photosensitive area of 7.05×7.05 mm^2. The features of back-placed electrodes and the minimal dead space around the product make it possible to mount multiple photodiodes side by side. To read the signals of multiple photodiodes simultaneously, a Printed Circuit Board (PCB) was designed as shown schematically in Figure 1, where up to 10 pixels of the photodiode can be mounted through reflow soldering [3].

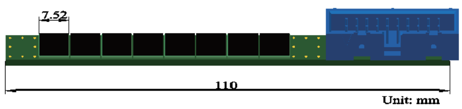

FIG. 1: The schematic plot of one PCB mounted with 8 photodiodes.

Several measurements were performed to evaluate the following characteristics of S13955-01 photodiodes:

- Energy resolution of a single photodiode
- Thickness of the dead layer
- Position uncertainty in a single photodiode
- Cross-talk effect
- Dynamic range

Multiple rows of PCB shown in Figure 1 were aligned to form a box-type detector array, called Mosaic. In July 2022, the array was commissioned in an experiment at HIMAC, during which α decays from ERs produced in ^{136}Xe + ^{nat}Zn were measured.

In this talk, details of the detector development and experimental results will be presented.

[1] L. Ma *et al.*, Phys. Rev. Lett. **125**: 032502 (2020).
[2] D. Ackermann and Ch Theisen, Phys. Scr. **92**(8): 083002 (2017).
[3] https ://www.hamamatsu.com/jp/en.html

*jt.li@cns.s.u-tokyo.ac.jp

Comprehensive treatment of shell and cluster models for α resonant scattering

T. Maeda,[1] T. Fumimoto,[1] R. Nakamoto,[1] and M. Ito[1,*]

[1] *Department of Pure and Applied Physics, Kansai University, Suita, Osaka, Japan*

Nuclear shell models, which are based on an independent particle picture inside of a self-consistent mean-field, have been successful in describing ground and low-lying states over a wide nuclear systems with few exceptions [1] For example, the spin parities of the ground states are consistent with the shell model predictions. Furthermore, the configuration interaction, which takes into account the particle-hole excitation of valence nucleons around a core nuclei, can reproduce observed energy spectra of low-lying states in high precision.

On the contrary, cluster model is based on a different picture from the nuclear shell model [2]. In the cluster model, the valence nucleons form subunits called clusters, and the relative motion among the clusters is solved. The cluster model has succeeded in explaining the structural changes from the shell model structure in the ground and low-lying states to the developed cluster structure appearing above the respective cluster threshold. One of the typical and simple example is α + ^{16}O in ^{20}Ne and so on [2].

In the present study, we try to construct the comprehensive model to take into account the advantages of the shell and cluster models on the basis of the naive viewpoint about the scattering phenomena [3]. The cluster configuration is an appropriate configuration before contacting the nuclear surface of the cluster and the target but the cluster must be melted after touching the the surface, and it breaks into individual nucleons inside the target nucleus, which corresponds to the shell model configuration. Thus, we solve the coupling of the cluster scattering states (external states) and the shell model states (internal states) according to the prescription in Ref. [3]. Here we consider the α + ^{16}O resonant scattering, and the total wave function Ψ of this scattering system is given by

$$\Psi \ = \ \chi^{(+)}(\boldsymbol{R}, \boldsymbol{\rho}_1, \boldsymbol{\rho}_2, \boldsymbol{\rho}_3) \ + \ \psi(\boldsymbol{r}_1, \boldsymbol{r}_2, \boldsymbol{r}_3, \boldsymbol{r}_4) \ , \tag{1}$$

where the first term denotes the (external) cluster scattering state with the α − ^{16}O relative coordinates $\boldsymbol{R}$ and the α internal coordinate $\boldsymbol{\rho}_1 \sim \boldsymbol{\rho}_3$, while the second term shows the (internal) shell model state is written by the independent four nucleon coordinate of $\boldsymbol{r}_1 \sim \boldsymbol{r}_4$.

The scattering boundary condition for the cluster configurations $\chi^{(+)}$ is imposed by employing the method of the continuum level density under the absorbing boundary condition [4]. As for the shell model configuration, we include the spreading width, which represents the decays of the four particle shell model configuration into the more complicated compound states, according to the theory of the doorway state [5].

The sharp resonant structures are generated by solving the coupling of the cluster scattering state and the shell model state in Eq. (1) although a broad structure appears in the results calculated only by the cluster scattering state. The resultant excitation function of the α elastic scattering nicely reproduces the experimental observation, which contains the sharp resonant structures.

[1] T. Otsuka, A. Gade, O. Sorlin, T. Suzuki and Y. Utsuno, Rev. Mod. Phys. **92**, 015002 (2020).
[2] H. Horiuchi, K. Ikeda, and K. Katō, Prog. Theor. Phys. **192**, 1. (2012).
[3] M. Ito and N. Itagaki, Phys. Rev. C**78**, 011602 (R) (2008).
[4] T. Maeda, Y. Taniguchi, T. Fumimoto and R. Nakamoto, Prog. Theor. Exp. Phys. **2023**, 023D03 (2023)
[5] B. Lauritzen, P. F. Bortignon, R. A. Broglia and V. G. Zelenvinsky, Phys. Rev. Lett. **74**, 5190 (1995).

*itomk@kansai-u.ac.jp

Analysis for the shell effect of fission fragments in the quasi-fission process in superheavy mass region

H. Maekawa,[1,*] S. Amano,[1] S. Takagi,[1] and Y. Aritomo[1]

[1] *Graduate School of Science and Engineering, Kindai University, Higashi-Osaka, Osaka, Japan*

In the quasi-fission process synthesizing superheavy nuclei, the effect of shell structure appears prominently, especial the effects for 82 protons and 126 neutrons. The dynamical model is highly reproducible in calculating the total kinetic energy (TKE) of fission fragments [1]. However, there is a problem in the reproducibility of TKE of quasi-fission in the current our calculations. The calculations show that the TKE of mass asymmetric fission fragments is lower than the experimental data. The reason for this is that the shell effect of fission fragments is not considered properly. In this study, we improve the model and attempt to reproduce mass-asymmetric quasi-fission fragments with shell effects. The purpose of this study is to clarify the mechanism of quasi-fission process by analyzing the time evolution of the nuclear shape.

[1] Y. Miyamoto, Y. Aritomo, S. Tanaka, K. Hirose, and K. Nishio, Phys. ReV. C **99**, 051601 (2019).

*email: 2233340419r@kindai.ac.jp

Medium-dependent relativistic NN potential in alpha radioactivity

Joshua T. Majekodunmi,[1,*] M. Bhuyan,[2] K. Anwar,[1] and R. Kumar[3]

[1] *Institute of Engineering Mathematics, Universiti Malaysia Perlis (UniMAP), 02600, Arau, Perlis, Malaysia*
[2] *Center for Theoretical and Computational Physics, Department of Physics, Faculty of Science, University of Malaya, Kuala Lumpur 50603, Malaysia*
[3] *School of Physics and Materials Science, Thapar Institute of Engineering and Technology, Patiala, Punjab 147004, India*

This work presents the incorporation of in-medium effects into the microscopic description of the effective nucleon-nucleon (NN) interaction potential named DDR3Y, through density-dependent nucleon-meson couplings within the Relativistic-Hartree-Bogoliubov (RHB) framework for DDME2 parameter set [1]. The constructed DDR3Y NN interaction potentials are integrated over the nuclear matter densities of the decay fragments using the double-folding approach. The estimated nuclear potentials are used as input into the preformed cluster-decay model (PCM) [2], in which the emitted cluster is assumed to undergo a quantum tunneling process across the potential barrier. The WKB approximation is employed to obtain the penetration probability, while the preformation probability (P_α) is estimated using our newly derived formula [3], which is based on parameters well known to influence α-particle and cluster radioactivity. For relative comparison, similar calculations are carried out using the density-dependent DDM3Y and the density-independent M3Y [4] and R3Y NN interaction potentials. The results clearly show that the estimated half-lives from the constructed DDR3Y NN potentials give a closer agreement with the experimentally measured data [5] compared with the bare R3Y and the phenomenologically fitted M3Y and DDM3Y potentials. The success of this study makes us anticipate the inclusion of in-medium effects in modeling astrophysical events.

[1] G. A. Lalazissis, T. Niksic, D. Vretenar, P. Ring, Phys. Rev. C **71**, 024312 (2005).
[2] J. T. Majekodunmi, M. Bhuyan, D. Jain, K. Anwar, N. Abdullah, R. Kumar, Phys. Rev. C **105**, 044617 (2022).
[3] J. T. Majekodunmi, Raj Kumar, M. Bhuyan. EPL **143**, 24001 (2023).
[4] G. Bertsch, J. Borysowicz, H. McManus, and W.G. Love, Nucl. Phys. A **284**, 399 (1977).
[5] M. Wang, W.J. Huang, F.G. Kondev, G. Audi, S. Naimi, Chin. Phys. C **45**, 030003 (2021).

* majekjoe1@gmail.com

Non-empirical description of nuclear collective motion with optimized basis for multi-reference density functional theory

M. Matsumoto,[1,*] Y. Tanimura,[1] and K. Hagino[2]
[1] *Tohoku University, Sendai, Japan*
[2] *Kyoto University, Kyoto, Japan*

The generator coordinate method (GCM) has been a well-known method to describe nuclear collective motions [1]. In GCM, one *a priori* specifies collective degrees of freedom (collective coordinates), such as nuclear deformations, and superposes many Slater determinants (SDs) within the selected collective subspace. However, there always exists arbitrariness in this approach in the choice of collective coordinates, for which one has to rely on empirical and phenomenological theory. With such choice, it is not trivial whether the collective motion of interest can be optimally described (See e.g., [2-3]). Therefore, a description of the collective motion without pre-set collective coordinates is desirable in order not to miss important degrees of freedom.

In this contribution, we present a new extension of GCM in which both the basis SDs and the weight functions are optimized according to the variational principle [4]. With such simultaneous optimization of the basis states, one does not have to specify beforehand the relevant collective degrees of freedom covered by the set of basis SDs. In this presentation, we will show results for *sd*-shell nuclei with the Skyrme energy functional. We will show that some collective coordinates often assumed in conventional GCM calculations, such as quadrupole moment, may not provide optimum basis to describe the ground state. This would be an important step towards consistent description of nuclear collective motions.

[1] P. Ring and P. Schuck, *The Nuclear Many-Body Problem* (Springer, 1980).
[2] N. Hizawa, K. Hagino and K. Yoshida, Phys. Rev. C **103**, 034313 (2021).
[3] N. Hizawa, K. Hagino and K. Yoshida, Phys. Rev. C **105**, 064302 (2022).
[4] N. Shimizu *et al.*, Prog. Theor. Exp. Phys. **2012**, 01A205 (2012).

*moemi@nucl.phys.tohoku.ac.jp

Sub-barrier fusion in ^{28,30}Si induced reactions with medium mass targets

Rinku Prajapat,[1] Malvika Sagwal,[1] Moumita Maiti,[1,*] Rishabh Kumar,[1] Pavneet Kaur,[1] Himanshu Sharma,[1] Yasir Arafat,[1] Gonika,[2] Chandra Kumar,[2] J. Gehlot,[2] S. Nath,[2] and N. Madhavan[2]

[1] *Department of Physics, Indian Institute of Technology Roorkee, Roorkee-247667, Uttarakhand, India*
[2] *Nuclear Physics Group, Inter-University Accelerator Centre, New Delhi-110067, India*

Heavy-ion collisions around the Coulomb barrier offer comprehensive information on the nuclear structure of the colliding nuclei. The dynamics involved in the sub-barrier fusion enhancement compared to the one-dimensional barrier penetration model have been recently addressed by nuclear structural features, such as static deformations, collective excitations, etc. [1,2]. Also, understanding how neutron transfer, which is unaffected by the Coulomb barrier, influences sub-barrier fusion processes is of topical importance. The scarcity of experimental data for asymmetric systems demands more exhaustive studies to comprehend the nature of positive Q-value neutron transfer (PQNT) and couplings to vibrational/rotational degrees of freedom of nuclei on sub-barrier fusion.

Two separate experiments have been performed to measure the fusion excitation functions for ^{28,30}Si+^{158,156}Gd systems leading to same compound nucleus ^{186}Pt* and ^{30}Si+^{140}Ce system using Heavy-Ion Reaction Analyzer (HIRA) and HYbrid Recoil mass Analyzer (HYRA), respectively, at the Inter-University Accelerator Center, New Delhi, India. The beam energies were considered from above to the deep sub-barrier regime. Two silicon detectors were placed on the horizontal plane at an equal distance from the target foil in the target chamber to normalize the evaporation residue (ER) cross section. A multiwire proportional counter of active area 15×5 cm^2 was installed at the focal plane of spectrometers to detect the heavy recoiling ERs. A clear separation between ERs and beam-like particles has been shown for the focal plane of HIRA [see Fig. 1(a,b)]. The simulation has been done for the transmission efficiency of the recoil separators using a semi-microscopic Monte Carlo code TERS [3]. The coupled channel (CC) computations framework (CCFULL [4] and ECC [5]) has been used to examine the role of couplings to inelastic excitations and PQNT channels on measured fusion cross sections and on the derived fusion barrier distributions. Furthermore, the fusion barrier parameters (height and position) have been extracted using the measured fusion data and compared with other theoretical frameworks.

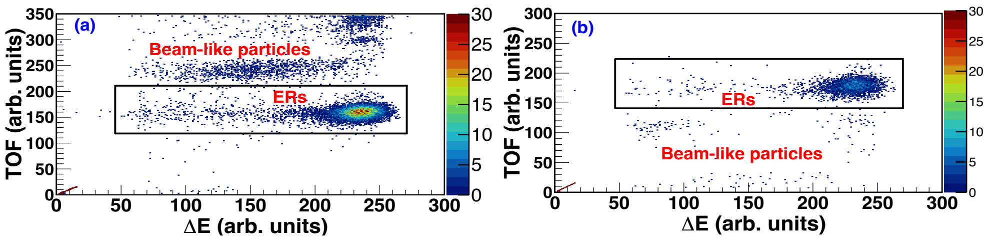

FIG. 1. Two-dimensional spectra of ER energy loss (ΔE) vs ER time of flight (TOF) for ^{28}Si+^{158}Gd reaction at (a) $E_{c.m.}/V_b$ = 0.98, and (b) $E_{c.m.}/V_b$ = 1.09. The black contours show the group of ERs, well separated from beam-like particles.

[1] C. L. Jiang *et al.*, Eur. Phys. J. A **57**, 235 (2021).
[2] R. Prajapat *et al.*, Phys. Rev. C **105**, 064612 (2022).
[3] S. Nath *et al.*, Comput. Phys. Commun. **179**, 492 (2008).
[4] K. Hagino *et al.*, Comput. Phys. Commun. **123**, 143 (1999).
[5] V. I. Zagrebaev, Phys. Rev. C **64**, 034606 (2001); **67**, 061601(R) (2003).

* Corresponding author E-mail: moumita.maiti@ph.iitr.ac.in

Fission trajectory analysis using ML techniques

Y. Mukobara,[1] S. Chiba,[1,2] T. Katabuchi,[1] and C. Ishizuka[1,*]
[1] *Tokyo Institute of Technology, Tokyo, Japan*
[2] *NAT Research Center, Tokai, Japan*

Nuclear fission is a well-known phenomenon to produce massive amounts of energy for nuclear power plants. However, its mechanism has been a hot research topic even though more than eighty years have passed since its discovery. A complete understanding of nuclear fission is complex because the fission pattern is very sensitive to proton and neutron numbers of fissioning systems. Sometimes, neighboring nuclei on a nuclear chart suddenly show different fission patterns. One good example of such a sudden change can be seen in Fm isotopes.

The dominant fission patterns in nuclear fission among Fm isotopes change from asymmetric to symmetric when the proton and neutron numbers of fission fragments get close to those of the double shell closure, ^{132}Sn. Measured fission fragment distributions of Fm isotopes below ^{256}Fm show two peaks (asymmetric fission). In ^{257}Fm, the dominant component is asymmetric, but a symmetric component was simultaneously observed. At ^{258}Fm, the dominant fission mode suddenly changes to symmetric. Then, the symmetric fission is favored towards ^{264}Fm. Our four-dimensional Langevin model can reproduce continuous change in the abovementioned fission modes [1]. Our Langevin results on Fm isotopes suggest a strong influence of ^{132}Sn because heavy fragments' shapes are spherical.

Although the four-dimensional Langevin model can explain the nuclear fission of Fm isotopes well, we cannot find any clear difference in minimized potential energy surfaces of ^{257}Fm and ^{258}Fm. For a more detailed understanding of such a sudden change in nuclear fission mode among Fm isotopes, we have analyzed the fission trajectories of our Langevin calculations using Recurrent Neural Network (RNN). In this presentation, we will report the common feature in fission trajectories extracted by the RNN.

[1] M.D. Usang, F.A. Ivanyuk, C. Ishizuka, S. Chiba, Scientific Reports **9**, 1525 (2019).

* ishizuka.c.aa@m.titech.ac.jp

Alpha-decay measurement of evaporation residues produced in multinucleon transfer reactions and separated by JAEA-Recoil mass separator

K. Nakajima,[1,2,*] F. Suzaki,[2] K. Nishio,[2] K. Hirose,[2] H. Makii,[2] R. Orlandi,[2] and J. Smallcombe[2]

[1] *Graduate School of Science and Engineering,*
Kindai University, Higashi-Osaka, Osaka 577-8502, Japan
[2] *Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan*

Multinucleon transfer (MNT) reaction is attracting interest as a method to produce neutron-rich heavy nuclei. Understanding of the reaction mechanism is, however, still limited due to its complexity. To understand the MNT process quantitatively, we started to measure cross sections of various evaporation residues (ERs) produced in the MNT reaction by changing various conditions such as incident-beam energy and emission angles of ERs. For the experiment, we use the Recoil Mass Separator (JAEA-RMS) [1] installed at the JAEA tandem facility, which can rotate around the target chamber. As a first step, we studied the reaction 30Si+209Bi, in which alpha-decaying ERs are produced. Among the technical developments, we are attempting to identify short lived nuclei produced in this reaction. For this a data acquisition system based on digital electronics was installed. In the presentation, identification of the produced nuclei in the pile-up signal-trace events will be discussed.

[1] H. Ikezoe et al., Nucl. Instrum. Meth. A **376**, 420 (1996).

*kohta.nakajima@kindai.ac.jp

Local alpha strength functions and alpha knockout reactions

T. Nakatsukasa[1,2,3,*] and N. Hinohara[1,2]
[1] *Center for Computational Sciences, University of Tsukuba, Tsukuba 305-8577, Japan*
[2] *Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba 305-8577, Japan*
[3] *RIKEN Nishina Center, Wako 351-0198, Japan*

Clustering is an intriguing phenomenon in nuclear structure. Correlations between nucleons result in the formation of subunits (cluster) inside the nucleus. The most typical cluster is the alpha particle, which is present not only in light nuclei, but also observed in heavy nuclei as the alpha decay phenomena. In light nuclei, the prominent clustering often takes place in excited states whose energy is close to the threshold of the corresponding cluster decomposition. This is known as the Ikeda diagram.

The mean-field (energy density functional) theory [1,2] is able to provide the optimal single-particle wave functions to minimize the total energy of a Slater determinant. One of the advantageous features of the theory is capability of describing light to heavy nuclei using a single energy density functional which is a functional of normal and pair densities. Another advantage can be treatment of the pairing correlations, which become indispensable especially for heavy nuclei with open-shell configurations. However, the obtained (generalized) single-particle states are, in most of the cases, spread over the entire nucleus. Therefore, it is difficult to find a signature of the alpha clustering in terms of the single-particle wave functions. In relatively light nuclei, prominent cluster structure could be observed by the nucleon density profile [3,4]. However, the identification of the cluster structure has some ambiguity and relies on one's intuition.

Recently, we have proposed a quantity "local alpha strength function" $S(\mathbf{r}, E)$, as a measure of localized four nucleons ($p\uparrow, p\downarrow, n\uparrow, n\downarrow$). When we remove an alpha particle at the position $\mathbf{r}$ from a nucleus, the final state in the residual nucleus can be expanded in the energy eigenstates. Thus, the local alpha strength function $S_\alpha(\mathbf{r}, E)$ corresponds to the strength to produce the state at energy E in the residual nucleus. Introducing approximations, such as the mean-field with no rearrangement and point-alpha approximation, the calculation becomes feasible.

Experimentally, the alpha correlations in nuclei can be investigated by quasi-free alpha knockout reactions. A recent experiment on the alpha knockout reactions in Sn isotopes by Tanaka and collaborators [5] reveals that the cross section monotonous decreases as the neutron number increases. They interpret this trend as a tight interplay between the alpha formation and the neutron skin [6] The distorted wave impulse approximation study shows that the reaction takes place in a peripheral region and probes the alpha particles in the nuclear surface [7]. We calculate the local alpha strength functions for Sn isotopes. and examine consistency between the calculated alpha strength function and the result of Ref. [5]. It turns out that the experimental findings may be explained by a mean-field model without explicit consideration of alpha correlation.

[1] M. Bender, P.-H. Heenen, and P.-G. Reinhard, *Rev. Mod. Phys.* **75**, 121 (2003).
[2] T. Nakatsukasa et al., *Rev. Mod. Phys.* **88**, 045004 (2016).
[3] H. Ohta,K. Yabana and T. Nakatsukasa, *Phys. Rev. C* **70**, 014301 (2004).
[4] Y. Fukuoka et al., *Phys. Rev. C* **88**, 014321 (2013).
[5] J. Tanaka et al., *Science* **371**, 260 (2021).
[6] S. Typel, *Phys. Rev. C* **89**, 064321 (2014).
[7] K. Yoshida, K. Minomo, and K. Ogata, *Phys. Rev. C* **94**, 044604 (2016).

*nakatsukasa@nucl.ph.tsukuba.ac.jp

Coupled reaction channel analysis for proton transfer in ^{116}Sn+^{60}Ni

Chandra Kumar[1,*] and S. Nath[1]

[1] *Inter-University Accelerator Centre, Aruna Asaf Ali Marg, New Delhi 110067, India*

Study of multi-nucleon transfer (MNT) is important for understanding the pairing correlation and Josephson effect [1-3] as well as the transition from quasi-elastic (QE) to deep-inelastic (DIC) regime [4]. A significant amount of experimental and theoretical work on MNT in intermediate and heavy mass systems has been reported in recent years. However, a relatively smaller body of work exists on proton transfer channels at near barrier energies compared to the same on neutron transfer channels in the literature.

Evidence of proton-proton correlations has recently been reported in the system ^{116}Sn+^{60}Ni [5]. Measured transfer probabilities ($P_{\rm tr}$) for one-proton ($1p$) and two-proton ($2p$) transfer were compared with semiclassical calculations. While experimental $P_{\rm tr}$ for $1p$-transfer was fairly well reproduced by theory, the same for $2p$-transfer had to be scaled down by a large factor to match with the theory. The authors attributed the mismatch to strong proton-proton correlations that were not taken into account in the calculations, which considered only successive transfer mechanism.

Here we report coupled reaction channel (CRC) calculations using the code FRESCO [6] for $1p$- and $2p$-transfer in ^{116}Sn+^{60}Ni system. The double folding São Paulo Potential (SPP) [7] was used for the real and the imaginary parts of the optical potential. The spectroscopic amplitudes were taken from the literature, if existed. For the other cases, we performed large-scale shell model calculations employing the code KSHELL [8]. No arbitrary normalization had to be introduced in our analysis. Comparison of our results with measured $P_{\rm tr}$ is shown in Fig. 1.

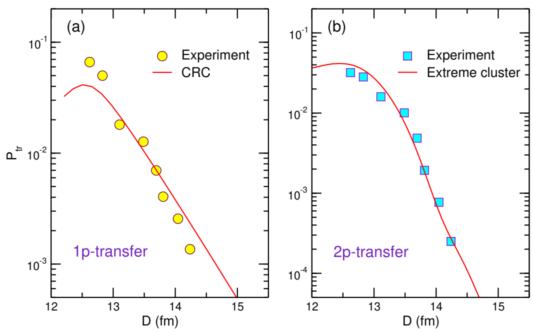

FIG. 1. Experimental and calculated $P_{\rm tr}$ as a function of the distance of closest approach (D) for (a) $1p$- and (b) $2p$-transfer in the system ^{116}Sn+^{60}Ni.

We observed that the ground and the first excited states of ^{59}Co in the exit channel significantly contributed to the cross sections for $1p$-transfer. We further performed simultaneous, *i.e.*, one-step transfer calculations for $2p$-transfer using the extreme cluster and the microscopic cluster approaches. It was found that successive, *i.e.*, two-step transfer and microscopic cluster transfer mechanisms underestimated the experimental data. Measured cross sections were successfully reproduced by the extreme cluster model.

Encouraged by the results of $1p$- and $2p$-transfer, we are inclined to carry out CRC analysis for one-neutron ($1n$) and two-neutron ($2n$) transfer [2,9] in this system.

[1] R. A. Broglia and A. Winther, Heavy-Ion Reactions, Addison-Wesley, Reading, MA, (1981).
[2] D. Montanari, L. Corradi, S. Szilner, G. Pollarolo *et. al.*, Phys. Rev. Lett. **113**, 052501 (2014).
[3] G. Potel, F. Barranco, E. Vigezzi, and R. A. Broglia, Phys. Rev. C **103**, L021601 (2021).
[4] J. Diklić, S. Szilner, L. Corradi, T. Mijatović *et. al.*, Phys. Rev. C **107**, 014619 (2023).
[5] L. Corradi S. Szilner, G. Pollarolo, T. Mijatović *et. al.*, Phys. Lett. B **834**, 137477 (2022).
[6] Ian J. Thompson, Comput. Phys. Rep. **7**, 167 (1988).
[7] L. C. Chamon, B. V. Carlson, and L. R. Gasques, Comput. Phys. Commun. **267**, 108061 (2021).
[8] N. Shimizu, T. Mizusaki, Y. Utsuno, and Y. Tsunoda, Comput. Phys. Commun. **244**, 372 (2019).
[9] D. Montanari, L. Corradi, S. Szilner, G. Pollarolo, Phys. Rev. C **93**, 054623 (2016).

* dwngn10chandra@gmail.com

Theoretical estimation of synthesizing superheavy nuclei using neutron rich targets

S. Nishikawa,[1,*] Y. Aritomo,[1] S. Amano,[1] S. Takagi,[1] and H.Maekawa[1]
[1] *Kindai University, Higashi-Osaka, Japan*

The next double magic nucleus after the double magic nucleus lead (208Pb) proton number Z=82 and neutron number N=126 is predicted to be flerovium 298Fl, Z=114 and N=184, and "Island of Stability" around this nucleus is predicted in the nuclear chart [1]. In the synthesis of new elements, it was assumed that the projectile and target nuclei used in the experiments would be stable nuclei. In particular, it was experimentally impossible to use unstable nuclei as target nuclei. Therefore, it was considered difficult to synthesize nuclei on Island of Stability because of the insufficient number of neutrons when it came to fusion between stable nuclei. To approaching Island of Stability, it is necessary to use unstable nuclei with an excess of neutrons. However, until now there has been no method to achieve this. Recently, a new method of colliding unstable nuclei has been planned [2]. It has also been reported that neutron-rich nuclei in the superheavy mass region have lower neutron binding energy than stable nuclei and lower temperature due to neutron emission more quickly, resulting in a high survival probability even at medium and high excitation energies [3].

The goal of this study is to create and analyze neutron emission and mass distribution of fission fragments in the superheavy mass region using the statistical and the dynamical model. In addition, we present the results of calculations using neutron-rich nuclei.

[1] W. D. Myers and W. J. Swiatecki, Nucl.Phys **81**,1 (1966); A. Sobiczewski, F. A. Gareev, and B. N. Kalinkin, Phys.. **22**, 500 (1966).
[2] RIKEN NEWS 2019 September No.459 **p6**.
[3] Y. Aritomo PHYSICAL REVIEW **75**, 024602 (2007)

*email: 2233340490m@kindai.ac.jp

Nuclear Mutation of Molecular CsH_2 Eigenvalues in Pd_{12}'s Coulomb Field

S. Oryu,[1,*] T. Watanabe,[1] and Y. Hiratsuka[1]

[1] *Department of Physics, Faculty of Science and Technology, Tokyo University of Science, Noda, Chiba 278-8510 Japan*

Three-body binding energy of CsH_2 is calculated by using traditional five potentials (three-nuclear Woods-Saxon potentials, three-ion Coulomb repulsive potentials, ion-Pd repulsive Coulomb potentials, electron-ion-Pd effective potentials, nuclear three-body short range force potentials) [1] and adding a nuclear three-body long range force (3BLF) potential [2] for six potentials in a "cuboctahedron Pd_{12} cluster". We obtained several binding energies between the CsH_2 molecular ground state and the first excited state where four of them are named as "ion oscillation (IOS)" states and other low lying (LL) states have very large root mean square (RMS) radius.

A critical value $C_{low/high}$ was defined by a (density)×(energy)×(duration-time). The thermal nuclear fusion was planed by C_{high}=$(3.3 \times 10^{14}/[\mathrm{cm}^3])\times(2.2 \times 10^4[\mathrm{eV}])\times(1.0[\mathrm{sec}])$=$7.26 \times 10^{18}[\mathrm{sec} \cdot \mathrm{eV/cm}^3]$=$1.16 \times 10^6[\mathrm{sec} \cdot \mathrm{Ps}]$ for a unit duration time in the well-known ITER project, although our low energy values give C_{low}= 4.68×10^{18} [sec·eV/cm^3]$\sim$$1.09 \times 10^{23}$[sec·eV/cm^3], or 7.50×10^5[sec·Pa] $\sim$$1.75 \times 10^{10}$[sec·Pa] for a unit duration time in IOS states (see **Table**). We calculated an E2 transition from the IOS states to the La ground state in CsH_2Pd_{12} molecule, where H denotes a proton (p), a deuteron (D), and a triton (T). The reaction probabilities are compared with and without "3BLF " potential for a nuclear reaction: $Pd_{12}Cs(2H,\gamma)LaPd_{12}$. We obtained that the E2 transition time from molecular CsH_2-IOS states ($J^\pi = 7/2^+$) to the $^{139}_{57}$La nucleus ground state ($7/2^+$) is about $\tau = 10^{-1} \sim 10^{-6}$[sec] for the five traditional potentials, while $\tau = 10^{-2} \sim 10^{-8}$[sec] for six potentials. However, the other molecular states are very stable, where the CsH_2 ground state has an order of $\tau \sim 10^{24}$[sec] transition time regardless of the 3BLF.

We also found that the IOS states cause an "isotropic high pressure" in the Pd-cage, which could give rise to a "quantum tunneling" effect from the molecular to the nuclear region, because the bulk modulus of Pd (180GPa) is much larger than "that". Several excitation (or ignition) methods from the molecular ground state to IOS states were proposed. It is interesting that the radiative capture of hydrogen by $CsPd_{12}$ is analogous to the neutron capture by the heavy nucleus.

$C_{low}(n)$	t[sec]	ρ [cm^{-3}]	T [eV]	$t\rho T$ [sec · eV/cm^3]	$t\rho T$ [sec· Pa]	transition time τ[sec]
$C_{low}(23)$	1.0	3.44×10^{22}	3.18	1.09×10^{23}	1.75×10^{10}	7.36×10^{-8}
$C_{low}(22)$	1.0	3.44×10^{22}	2.05×10^{-2}	7.05×10^{20}	1.13×10^8	1.02×10^{-6}
$C_{low}(21)$	1.0	3.44×10^{22}	2.40×10^{-4}	8.26×10^{18}	1.32×10^6	4.23×10^{-4}
C_{high}	1.0	3.3×10^{14}	2.2×10^4	7.26×10^{18}	1.16×10^6	——
$C_{low}(20)$	1.0	3.44×10^{22}	1.36×10^{-4}	4.68×10^{18}	7.50×10^5	1.92×10^{-2}
$C_{low}(19)$	1.0	3.44×10^{22}	7.73×10^{-5}	2.66×10^{18}	4.26×10^5	7.21×10^0

[1] T. Watanabe, Y. Hiratsuka, M. Takeda, S. Oryu, N. Watari, H. Kakigami, I. Toyoda, J. Phys. Commun. **6** 045003 (2022): Three-body CsD_2 calculation in Pd_{12} cage and E2 transition in ultra-low energy nuclear reaction.

[2] Shinsho Oryu, J. Phys. Commun. **6** 015009 (2022): Generation of long- and short-range potentials from atom-molecules to quark-gluon systems by the GPT potential.

*oryu@rs.noda.tus.ac.jp

Dynamical fluctuations, dissipation coefficients and energy dependencies in TD-BCS for nuclear fission

Junchen Pei[1,*] and Yu Qiang[1]
[1]*School of Physics, Peking University, Beijing, China*

The Time-dependent Hartree-Fock+BCS (TD-BCS) approach has been successfully applied to study the non-equilibrium and non-adiabatic nuclear fission dynamics. With the developments of supercomputing, the microscopic TD-BCS approach is promising for a comprehensive and quantitative description of multiple fission observables. To achieve this goal, in our approach, random transitions between single-particle levels are adopted to mimic dynamical fluctuations[1], which is essential to produce a spreading distribution of fission yields. We also employed HF-BCS solutions at finite temperatures for initial TD-BCS evolutions to study the energy dependencies in fission observables[1,2]. Furthermore, the dissipation coefficients in fission evolutions are obtained by mapping the TD-BCS fission trajectories into a classical equation of motion[2]. Thus, the energy dependencies and shape dependencies of fission dissipation coefficients are studied.

[1] Yu Qiang, J. C. Pei, and P. D. Stevenson, Phys. Rev. C 103, L031304 (2021)
[2] Yu Qiang and J. C. Pei, Phys. Rev. C 104, 054604 (2021)

*peij@pku.edu.cn

Nuclear incompressibility of Sn-isotopes and its impact on nuclear fusion dynamics

Shilpa Rana,[1,*] M. Bhuyan,[2] and Raj Kumar[1]

[1] *School of Physics and Materials Science, Thapar Institute of Engineering and Technology, Patiala, Punjab 147004, India*

[2] *Center for Theoretical and Computational Physics, Department of Physics, Faculty of Science, University of Malaya, Kuala Lumpur 50603, Malaysia*

The incompressibility of nuclear matter is an essential parameter of the nuclear equation of state (EoS). It is vital to explore the behavior of the nuclear system under small density variations. The isoscalar giant monopole resonance (ISGMR) data of the heaviest doubly magic ^{208}Pb is the widely adopted tool to constrain the value of the incompressibility of nuclear matter [1-2]. However, the experimental ISGMR data of even-even $^{112-124}$Sn isotopes are found to be incompatible with the value of nuclear matter incompressibility established using the ISGMR data of ^{208}Pb. Theoretical models which reproduce the experimental ISGMR data of ^{208}Pb nucleus are observed to overestimate that for Sn-isotopes [1-3]. The present analysis aims to probe the influence of this peculiar softness of Sn-isotopes on the nuclear fusion dynamics. For this purpose, we have considered nuclear fusion reactions containing ^{64}Ni as the projectile and even-even isotopes from the chain $^{112-124}$Sn, which are known for their anomalous soft or compressible nature along with the doubly magic ^{132}Sn and ^{208}Pb nuclei as targets. The cross-section for the considered reactions is obtained using the ℓ-summed Wong model furnished with nuclear interaction potential calculated within the well-known relativistic mean field (RMF) formalism [4]. The calculations are done for the three sets of RMF parameters, namely, NL3* [5], hybrid [2], and NL1 [6], which give different values for various characteristics of nuclear matter at saturation. When comparing the barrier characteristics obtained using sets of NL3* and hybrid parameters, which produce almost similar values for the characteristics of nuclear matter at saturation except for the symmetry energy and incompressibility, it is observed that the height of the fusion barrier increases with increasing values of the symmetric nuclear matter energy and incompressibility. Further, a decrease in the barrier height and a rise in the cross-section is observed for the nuclear potential calculated using the NL1 parameter set, which gives a soft EoS. On comparing the theoretical cross-section with the available experimental data, a reasonable match for ^{64}Ni+^{208}Pb reaction is observed. On the contrary, an underestimation of fusion cross-section with respect to the experimental data at the sub-barrier energies is noted for ^{64}Ni+$^{112-124,132}$Sn reactions. These observations infer that the incomprehensible softness of Sn-isotopes also persists in their fusion dynamics, and the nuclear potential obtained within the RMF formalism, which gives a satisfactory agreement for the reaction involving ^{208}Pb nucleus, is observed to underestimate the fusion probability for the reactions involving Sn-isotopes. The compressible nature of Sn-isotopes is inferred to enhance the fusion cross-section, and a barrier modification is done to account for the softness of Sn-isotopes.

[1] K. B. Howard *et al.* Phys. Lett. B **807**, 135608 (2020).
[2] J. Piekarewicz, and M. Centelles, Phys. Rev C **79**, 054311 (2009).
[3] T. Li *et al.* Phys. Rev. L **99**, 162503 (2007).
[4] S. Rana, M. Bhuyan and R. Kumar, Phys. Rev. C **105**, 054613 (2022).
[5] G. A. Lalazissis, S. Karatzikos, R. Fossion, D. Pena Arteaga, A. V. Afanasjev and P. Ring, Phys. Lett. B **671**, 36 (2009).
[6] P. G. Reinhard, M. Rufa, J. Maruhan, W. Greiner and J. Friedrich, Z. Phys. A-At. Nucl. **323**, 15 (1986).

*srana60_phd19@thapar.edu

Study of effect of transfer coupling on quasi-elastic barrier distribution of $^{16}O+^{144}Sm$

Kavita Rani,[1,*] A. Jhingan,[2] M. Kumar,[2] H. Arora,[1] D. Arora,[2] Amit,[1] V. Srivastava,[3] N. Saneesh,[2] K.S. Golda,[2] P. Sugathan,[2] and B. R. Behera[1]

[1]*Department of Physics, Panjab University, Chandigarh, India-160014*
[2]*Inter-University Accelerator Centre, Aruna Asaf Ali Marg, New Delhi, INDIA-110067*
[3]*ASET, Amity University Patna, Rupaspur, Patna, India-801503*

The enhancement of the sub-barrier fusion cross-sections as compared to one dimensional barrier penetration model has intrigued a number of experimental as well as theoretical studies. The insights about the role of numerous degrees of freedom of the colliding nuclei, such as vibrations, rotations, and transfer of nucleons between the colliding nuclei on fusion dynamics are experimentally interpreted by fusion or quasi-elastic barrier distribution (BD) measurements [1]. The effect of strong channels like collective excitations on fusion dynamics theoretically can be justified by coupled channel (CC) calculations [2]. The fusion BD and QE-BD contains the similar information except for $^{16}O+^{144}Sm$ reaction which is a case of discrepancy [1]. The structure of experimental fusion BD and QE-BD for this reaction differs, the latter is smoothened at higher energy where a peak is expected as per the fusion BD. Various CC calculations have been performed to understand the smearing of QE-BD but is still unjustified. Drawing conclusions by means of CC codes to the influence of transfer channels on the shape of the BD from fitting experimental data is still questionable. It was suggested that the smoothing can be the results of residual reaction channel such as nucleon transfer [1]. The effect of weak channels (transfer channels, non collective excitations) on QE-BD has been recently studied through various experiments [3-4].
To study the effect of weak transfer channels and with the motive of resolving the case of discrepancy between the two barrier distributions, the transfer cross sections have been measured for the $^{16}O+^{144}Sm$ reactions at various angles around the grazing angle corresponding to E_{lab}=72 MeV where the second peak is expected. For a comparative study, we performed the measurements for $^{16}O+^{154}Sm$ which shows the transfer channel coupling effect in its fusion BD [5]. For the measurement of the transfer reactions at this near barrier energy, an experiment has been performed at IUAC, New Delhi using the General Purpose Scattering Chamber (GPSC). On one of the arms of GPSC, a multiwire proportional counter (MWPC) (at 26.5 cm) was placed for the detection of the target-like transfer products whereas on the other arm, MWPC (at 35 cm) followed by an ionization Chamber (IC) was placed for the detection of the projectile-like transfer products. To have better mass resolution in the detection facility, another MWPC developed at IUAC was placed at 6 cm as a master start detector to improve the time of flight resolutions, and generate the absolute timing. Two monitors placed at $\pm 10^o$ with respect to the beam direction helps beam monitoring and used in normalization to extract the transfer reaction cross sections. The differential cross sections of 1p and 2p transfer channels are extracted at each taken angle by normalizing with respect to the monitor detectors and the detailed DWBA as well as CRC calculations for the same using FRESCO code [6] is underway. Details of the experimental techniques and results of the theoretical investigations will be delineated and discussed in the conference.

[1] H. Timmers et al., Nucl. Phys. A 584, 190 (1995).
[2] K. Hagino et al., Comp. Phys. Comm. 123, 143 (1999).
[3] E. Piasecki et al, Phys. Rev. C 80, 054613 (2009).
[4] E. Piasecki et al, Phys. ReV C 85, 054604 (2012).
[5] J. R. Leigh et. al., Phys. Rev. C 52, 3151 (1995).
[6] Ian J. Thompson, Comput. Phys. Commun. 7, 167 (1988).

* kavita.arora298@gmail.com
Present address: Variable Energy Cyclotron Centre, 1/AF, Bidhannagar, Kolkata, INDIA-700064

Measurement of the γ Decay Probability of the Hoyle State

K. Sakanashi,[1,*] T. Kawabata,[1] T. Furuno,[1] A. Tamii,[2] R. Niina,[2] S. Okamoto,[3] S. Adachi,[4] M. Itoh,[4] H. Akimune,[5] Y. Matsuda,[5] S. Kubono,[6] S. Aogaki,[7] P.-A. Söderström[7],[7] M. Teodora,[7] H. Pai,[7] M. Cuciuc,[7] D. Testov,[7] R. Borcea,[8] A. Turturica,[8] C. Mihai,[8] and C. Neacsu[8]

[1]Department of Physics, Osaka University, Toyonaka, Osaka 505-0043, Japan
[2]Research center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan
[3]Department of Physics, Kyoto University, Toyonaka, Kyoto 606-8502, Japan
[4]Cyclotron and Radioisotope Center, Tohoku University, Sendai, Miyagi 980-8578, Japan
[5]Department of Physics, Konan University, Kobe, Hyogo 658-8501, Japan
[6]Nishina Center for Accelerator-Based Science, Wako, Saitama 351-0198, Japan
[7]Extreme Light Infrastructure - Nuclear Physics, Magurele, Bucharest 077-125, Romaina
[8]Horia Hulubei National Institute of Physics and Nuclear Engineering, Magurele, Bucharest 077-125, Romaina

The triple alpha (3α) reaction is one of the most important processes in the nucleosynthesis. In this reaction shown in Fig.1, an α particle is captured by the 2α resonance of ^{8}Be, and form a 3α cluster state with weakly bound α particles. Most of the 3α resonance states decay to three α particles, but a tiny fraction of them decays to the ground state in ^{12}C via radiative processes of γ decay or e^+e^--pair emission. Therefore, the γ-decay probability is an important parameter that directly determines the amount of ^{12}C produced in the nucleosynthesis. Many γ decay probability measurements were performed by 1976 and radiative-decay probability $\Gamma_{\mathrm{rad}}/\Gamma = 4.16(10) \times 10^{-4}$ [1] from the Hoyle state has been widely accepted.

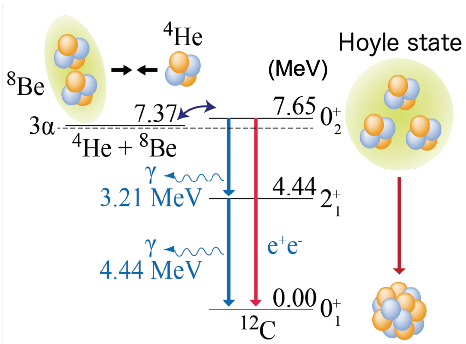

FIG. 1: triple alpha reaction

Recently, a striking result of the γ decay probability of the Hoyle state was reported from a measurement of two γ rays from the cascade decay of the Hoyle state. The new value of $\Gamma_{\mathrm{rad}}/\Gamma = 6.2(6) \times 10^{-4}$ [2] is 50% higher than the recommended value in Ref.[1]. Most of the old data were taken by measuring ^{12}C nuclei surviving after the Hoyle state decayed. The authors of Ref.[2] claimed that such measurement might not be appropriate and the discrepancy between the new and old results should be due to the different experimental methods. In order to solve this puzzle, it is necessary to measure surviving ^{12}C nuclei and γ rays at the same time.

In this study, the experiment was performed at the tandem accelerator facility of IFIN-HH in Romania. We populated Hoyle state in ^{12}C by the α+^{12}C scattering using a α particle beam at $E_{\mathrm{beam}} = 25$ MeV, and emitted charged particles are detected by a DSSD and γ rays by the ROSPHERE $LaBr_3$ detector array [3]. In this talk, we will report the experimental details and results of the γ decay probability measurements.

1] J. Kelley, J. Purcell, and C. Sheu, Nucl. Phys. A **968**, 71 (2017).
[2]T. Kibédi *et al.*, Phys. Rev. Lett. **125**, 182701 (2020).
[3]D. Bucurescu *et al.*, Nucl. Instrum. Methods Phys. Res. A, **837**, 1 (2016).

*sakanashi@ne.phys.sci.osaka-u.ac.jp

.

The number of virtual photon by the Coulomb excitation

Kyoungsu Heo,[1] Myung-Ki Cheoun,[1] Ki-Seok Choi,[2] K. S. Kim,[2] and W. Y. So[3,*]

[1] *Department of Physics and Origin of Matter and Evolution of Galaxy (OMEG) Institute, Soongsil University, Seoul 06978, Korea*

[2] *School of Liberal Arts and Science, Korea Aerospace University, Koyang 10540, Korea*

[3] *Department of Radiological Science, Kangwon National University at Dogye, Samcheok 25945, South Korea*

We study the number of virtual photon obtained from the general, relativistic, non-relativistic, and intermediate methods, which is a very important factor in obtaining the Coulomb dipole strength distribution. We investigate the number of virtual photon according to the incident energy $E_{\rm lab}$ for five methods. The general method is valid in all energy region and the relativistic method is effective in the region with high β values. The relativistic method is used instead of the general one for convenience because the difference between the two methods is around 2%. In addition, the validity of the non-relativistic approximation is confirmed by comparing with the general method in the low incident energy region and the intermediate method is not effective in the high excitation energy region.

Next, we investigate the dependency of the number of virtual photon for the charge number of projectile and target nuclei. With the same R-value, target nuclei, and incident energy, we find that the number of virtual photon does not depend on the charge number of projectile in the relativistic method. With the same R-value, projectile, and incident energy, also, it can be seen that the number of virtual photon depends on the square of charge number of target nuclei.

[*] wyso@kangwon.ac.kr

The application of the Langevin method for estimating fission from proton-induced ^{238}U

C. Song,[1,*] S. Takagi,[2] I. J. Shin,[3] Y. Kim,[4] Y. Aritomo,[2] and C. H. Lee[1]

[1] *Department of Physics, Pusan National University, Busan 46241, Republic of Korea*
[2] *Electronic Engineering, Kindai University, Higashi-Osaka 577-8502, Japan*
[3] *Rare Isotope Science Project, Institute for Basic Science, Daejeon 34000, Republic of Korea*
[4] *Center for Exotic Nuclear Studies, Institute for Basic Science, Daejeon 34126, Republic of Korea*

The RAON facility in Korea will be producing rare isotopes (RIs) through the Isotope Separation On-Line (ISOL) method, with a focus on producing fission fragments by bombarding protons onto a ^{238}U target. To calculate the fission yields and corresponding cross sections reliably, we employ the Langevin method, which has been successful in predicting nuclear reactions in the heavy mass region[1]. While the Langevin approach is known to have issues with the disappearance of the shell effect at high excitation energies, we overcome this by considering multichannel fission (MCF)[2,3]. Using this method, we obtain a precise estimation of the fission fragment mass distribution (FFMD) for the p+^{238}U reaction. To validate our results, we compare our calculations based on the Langevin equation with empirical formulas that expand the experimental dataset[4]. Our study demonstrates the feasibility of predicting the FFMD of proton-induced fission reactions in the unreported energy region using the Langevin method with MCF.

[1] Y. Aritomo and M. Ohta, Nuclear Physics A **744**, 3 (2004).
[2] K. Hirose, K. Nishio, S. Tanaka, R. Léguillon, H. Makii, I. Nishinaka, R. Orlandi, K. Tsukada, J. Smallcombe, M. J. Vermeulen, S. Chiba, Y. Aritomo, T. Ohtsuki, K. Nakano, S. Araki, Y. Watanabe, R. Tatsuzawa, N. Takaki, N. Tamura, S. Goto, I. Tsekhanovich, and A. N. Andreyev, Phys. Rev. Lett. **119**, 222501 (2017).
[3] S. Tanaka, Y. Aritomo, Y. Miyamoto, K. Hirose, and K. Nishio Phys. Rev. C **100**, 064605 (2019).
[4] F. A. Khan, D. Bhowmick, D. N. Basu, M. Farooq, and A. Chakrabarti, Phys. Rev. C **94**, 054605 (2016).

*schoon@pusan.ac.kr

Measurement of evaporation residues produced in the multinucleon transfer reaction using a Recoil Mass Separator

F. Suzaki,[1,*] K. Nishio,[1] H. Makii,[1] K. Hirose,[1] R. Orlandi,[1] and J. Smallcombe[1]
[1] *Japan Atomic Energy Agency, Tokai, Ibaraki, 319-1195, Japan*

Multinucleon transfer (MNT) reaction has attracted much attention as it produces neutron-rich nuclei. The production cross section of these neutron-rich nuclei is expressed as the product of the cross section of compound nuclei in MNT reactions and the probability that the compound nuclei survive by evaporate neutrons in competition with fission. However, these processes are not well understood. In order to elucidate the MNT reaction, we have started the measurement of evaporation-residues (ER) cross sections in various conditions. Experiments were carried out using the JAEA Recoil Mass Separator (JAEA-RMS[1]). As a first attempt, we studied the reaction ^{30}Si + ^{209}Bi. The production rate as a function of recoil angle, recoil energy (thus Q-value), and incident beam-energy dependence were studied. The alpha-decay of the implanted ERs at the focal plane Si detector was observed online. The result is the first to realize the decay measurement correlated with the ERs, produce in the MNT reaction at a finite angle.

[1] H. Ikezoe et.al., Nucl. Instrum. Meth. A376, 420 (1996).

*suzaki.fumi@jaea.go.jp

Analysis of the kinetic energy of fission fragments using dynamical model

S. Takagi,[1,2,*] Y. Aritomo,[1] K. Hirose,[2] and K. Nishio[2]

[1] *Graduate School of Science and Engineering, Kindai University, Higashi-Osaka, Osaka 577-8502, Japan*

[2] *Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan*

Nuclear fission is one of the most important phenomena in nuclear physics and nuclear engineering. Since the discovery of nuclear fission, various models have been developed to understand the phenomenon. Among them, the fission fragment mass distribution (FFMD) and the total kinetic energy (TKE) generated by the fissioning nuclei have been extensively discussed. However, the kinetic energy of each fission fragment has not been discussed theoretically very much. For example, low-energy neutron-induced fission of actinide nuclei has kinetic-energy distribution of each fragment to have constant energy over the fragment mass. This phenomenon is not clearly explained theoretically yet.

We calculate the kinetic energy of each fission fragment by using the dynamical model that can reproduce the fission fragment mass and total kinetic energy distributions [1,2]. Although the TKE is expressed only by the Coulomb potential of the fission fragments in many models, we also take into account the kinetic energy just before scission in this calculation (pre-scission kinetic energy). The results well reproduced the experimental data of neutron-induced fission of ^{239}Pu [3,4].

[1] Y. Aritomo, S. Chiba, and F. Ivanyuk Phys. Rev. C **90**, 054609 (2014)

[2] Y. Miyamoto, Y. Aritomo, S. Tanaka, K. Hirose, and K. Nishio, Phys. Rev. C **99**, 051601(R) (2019).

[3] K. Nishio, Y. Nakagome, I. Kanno, and I. Kimura, J. Nucl. Sci. Technol. **32**, 404 (1995).

[4] C. Wagemans, E. Allaert, A. Deruytter, R. Barthélémy, and P. Schillebeeckx, Phys. Rev. C **30**, 218 (1984).

*shinya_takagi@kindai.ac.jp

Current status of the high field cable test facility at Fermilab

G. velev,[1] D. Arbelaez,[2] C. Arcola,[1] R. Bruce,[1] V. Kashikhin,[1] S. Koshelev,[1] A. Makulski,[1] V. Marinozzi,[1] V. Nikolic,[1] D. Orris,[1] S. Prestemon,[2] G. Sabbi,[2] T. Tope,[1] and X. Yuan[1,*]
[1]*Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*
[2]*Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

Fermi National Accelerator Laboratory (FNAL) and Lawrence Berkeley National Laboratory (LBNL) are collaborating to construct a new High Field Vertical Magnet Test Facility (HFVMTF) designed for testing superconducting cables in high magnetic fields. This state-of-the-art facility will be situated at Fermilab and will provide capabilities comparable to EDIPO at PSI and FRESCA2 at CERN. The HFVMTF's background magnetic field, reaching 15 T, will be generated by a magnet supplied by LBNL. The HFVMTF is a collaborative effort supported by the US DOE Offices of Science, High Energy Physics, and Fusion Energy Sciences. It will serve as a vital testbed for superconducting HTS cables, subjecting them to high magnetic fields and a wide range of temperatures, benefiting both scientific communities. Additionally, this facility will play a key role in testing high-field superconducting magnet models and demonstrators, including hybrid magnets, developed by the US Magnet Development Program (MDP). These hybrid magnets, utilizing both LTS and HTS superconductors, are significant advancements toward achieving 18+ T dipoles for future hadron-hadron colliders. The presentation outlines the current status of the facility, covering aspects such as construction progress, cryostat designs, top and lambda plates, and systems for powering, quench protection, and monitoring.

*xyuan@fnal.gov

Microscopic study of fission dynamics: dissipation, fluctuation and entanglement

Y. Qiang[1]

[1] *State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China**

In TD-DFT the sharing of particles and excitation energies, total kinetic energies, energy dependence, equilibration effects, and scission configurations can be described self-consistently. In this work, with the developed TDHF+BCS with random transitions [1], the obtained fission yields, TKE with fluctuations can be divided into two channels, S1, S2, which explain well experimental results and give microscopic support to the Brosa model. With increasing fluctuations, S2 takes over the S1.

The dissipation and fluctuation are key ingredients in fission dynamics as well as in general nonequilibrium dynamical systems. By means of macroscopic reduction procedure [2], the friction coefficients is obtained, which have a strong dependence of deformations, and averagely match the coefficients adopted in statistical models. The dissipation indeed increase with increasing initial excitation energies.

Also, during TD-DFT evolution, entanglement of fragment wave functions is persistent even after separation and impacts the particles(energies) partition between fragments. By utilizing the particle number projection (in partial space) for each fragments, it is shown that quantum entanglement is indispensable in the appearance of sawtooth distributions of average excitation energies of fragments and thus neutron multiplicities.

[1] Y. Qiang, J.C. Pei, and P.D. Stevenson, Phys. Rev. C 103, L031304 (2021).
[2] Y. Qiang and J.C. Pei, Phys. Rev. C 104, 054604 (2021).

*yqiang@pku.edu.cn