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Pushing the limits of the Periodic Table and Nuclear Landscape

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The Periodic Table is still growing. In 2016, four new elements were added: nihonium, moscovium, tennessine and oganesson. These elements define the current upper limits of mass and atomic numbers. As such, they carry the potential to transform the way we currently understand nuclear and atomic physics, and chemistry.

All superheavy nuclei are part of a vast, totally unknown region of the nuclear landscape that scientists are trying to uncover. Questions motivating the search for these systems include: What are the heaviest nuclei and atoms that can exist? Are superheavy systems different from lighter nuclear species? Is there an island of very long-lived nuclei? Questions such as these provide formidable challenges for both experiment and theory, especially in the context of heavy-ion fusion and nuclear fission. This talk will review theoretical perspectives in this field of research.

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Onset of complexity outside the barrier in heavy-ion reactions: moving towards a more complete picture of fusion

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The coherent superposition of ground and excited states of the colliding nuclei is known to be critical to describe nuclear scattering and fusion outcomes [1]. As a result, the most widely applied class of quantum-mechanical barrier-passing models for fusion is the coupled channels formalism. As a barrier-passing model, absorption (irreversible energy dissipation) is implemented through an incoming-wave boundary condition or imaginary potential located inside the barrier, ensuring separation between channel coupling effects and absorption. Couplings to few-nucleon transfer channels are found to be important in selected cases, otherwise nuclei fuse essentially unchanged.

A wealth of experimental results suggest that this picture is too simple. Measured capture cross-sections for heavy-ion collisions at energies well above and well below the barrier are systematically smaller than model calculations [2,3]. Proposals to resolve these discrepancies include modifications to the the effective nuclear potential, including nuclear incompressibility and the Pauli exclusion principle [4,5]. Experiments suggest that there may be also be a dynamical origin resulting from exchange of nucleons and the loss of kinetic energy *outside* the barrier separation, prior to capture. Significant kinetic energy loss should lead to reduced cross-sections [2].

We therefore must understand the early stages of collisions, before significant matter overlap begins. Here, we seek to address the following question: is the state of the system at the barrier separation consistent with conventional models of fusion, that assume the nuclei are essentially unchanged prior to capture?

Measurements of reflected flux in reactions of ^{40}Ca + ^{208}Pb (having multinucleon transfer above the barrier [6]) were performed at a series of energies spanning from 80% of the fusion barrier to 99% of the fusion barrier using the PRISMA spectrometer. The isotopically-identified reflected flux reveals that the onset of energy damping occurs *outside* the fusion barrier. By the time the barrier radius is reached, the reflected flux highly fragmented into many nuclide pairs with high excitation energies, lowering their energy with respect to the fusion barrier. This provides a pathway that explains the observed above-barrier fusion hindrance and is critically neglected in barrier passing models.

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Near-barrier fusion reactions as a probe for exotic nuclei

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Fusion reactions at energies near and below the Coulomb barrier are incredibly sensitive to a number of factors affecting the dynamics, making them excellent probes for the properties of rare isotopes. Intricacies in nucleonic transfer, equilibration, and collective excitation all impact the measured fusion cross sections for a given reaction, and these dynamical effects are also affected by the structure properties of the incoming collision partners. To place these disparate effects on an equal footing, time-dependent simulations of fusion reactions have proven to be a useful tool for modeling near-barrier heavy-ion collisions. Recently, there have been studies which have indicated this link between dynamical quantities and the structure of nuclei in both systematic studies [1] and rigorous uncertainty quantification [2] of nuclear energy density functionals. These investigations have indicated a strong correlation between hard-to-reach structure properties like the neutron skin and fusion barriers extracted from the fusion cross sections. This talk will present results from recent work that explores this correlation in detail as well as motivating future experimental studies of heavy-ion fusion, particularly at facilities that can provide high rates of exotic nuclei far from stability.

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Pauli energy contribution to nucleus-nucleus interaction

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The Pauli exclusion principle plays a crucial role as a building block of many-body quantal systems comprised of fermions. It also induces a "Pauli repulsion" in the interaction between di-nuclear systems. It has been shown that [1] the Pauli repulsion widens the nucleus-nucleus potential barrier, thus hindering sub-barrier fusion. We investigate the proton and neutron contributions to the Pauli repulsion, both in the bare potential neglecting shape polarization and transfer between the reactants, as well as in the dynamical potential obtained by accounting for such dynamical rearrangements. As the basis of our study we utilize the Pauli kinetic energy (PKE) obtained by studying the nuclear localization function (NLF) [2]. Recently this approach has been generalized to incorporate all of the dynamical and time-odd terms present in the nuclear energy density functional [3]. This approach is employed in the density constrained frozen Hartree-Fock (DCFHF) and in the density constrained time-dependent Hartree-Fock (DC- TDHF) microscopic methods. The PKE spatial distribution shows that a repulsion occurs in the neck between the nuclei when they first touch. Inside the barrier, neutrons can contribute significantly more to the Pauli repulsion in neutron-rich systems. Dynamical effects tend to lower the Pauli repulsion near the barrier. Proton and neutron dynamical contributions to the PKE significantly differ inside the barrier for asymmetric collisions, which is interpreted as an effect of multinucleon transfer. The PKE is shown to make a significant contribution to nuclear interaction potentials. Protons and neutrons can play very different roles in both the bare potential and in the dynamical rearrangement. Further microscopic studies are required to better understand the role of transfer and to investigate the effect of pairing and deformation [4].

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Unexpected observations of heavy-ion fusion excitation functions above the Coulomb barrier

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Two unexpected behaviors have been observed in heavy-ion fusion excitation functions at energies above the Coulomb barrier. The first behaviour stems from the structure of the fusion excitation curve. Contrary to descriptions from coupled-channels or other model calculations, heavy-ion fusion excitation functions are not smooth near and above the Coulomb barrier. There appears to be weak but noticeable oscillations or structures within the excitation functions that can be observed clearly, shown in Figure 1, in the representation $d(\sigma E)/dE$ and in comparison with theoretical calculations $\sigma(E) - \sigma_{th}(E)$ [1]. The second unexpected behavior is observed in overlapping excitation spectra. Fusion excitation functions $\sigma(E)$ that have different entrance channels but fuse to the same compound nucleus appear to overlap in the energy domain above the barrier. The overlap emerges after scaling the center of mass energy of each excitation function by a constant scaling factor, SF [2]. Figure 2 shows an example of this behavior for the compound nucleus ^{216}Ra. The scaling factors are determined from the corresponding Coulomb barriers of each entrance channel. Moreover, the corresponding $d(\sigma E)/dE$ spectra also overlap well in this energy range, including their fine structures. It appears the two behaviors are correlated and the reasoning behind these behaviors are yet unknown, but may be due to the compound-channel effect [2].

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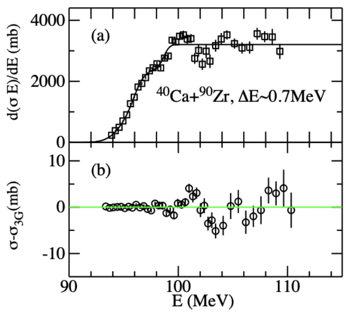

FIG. 1: Two representations $d(\sigma E)/dE$ and $\sigma - \sigma_{th}$ of fusion system ^{40}Ca + ^{90}Zr.

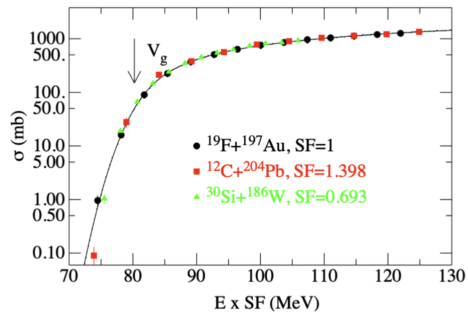

FIG. 2: A comparison of three fusion excitation functions which all lead to the same compound nucleus ^{216}Ra. The energies of each excitation function are multiplied by the indicated scaling factor, SF.

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Macroscopic-microscopic fission yields

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We utilize the macroscopic-microscopic approach to fission to calculate nascent fragment distributions. Assuming strongly damped shape motion, we run many iterations of a Metropolis-random walk across nuclear potential-energy surfaces to obtain sufficient scission statistics. Our nuclear potential surfaces consist of a macroscopic energy from the Finite-Range Liquid-Drop Model (FRLDM) and microscopic terms that arise from the single-particle spectra. We show our results at near-barrier incident energies for a wide range of fissioning systems. We exhibit the performance of our calculations by benchmarking to experimental data and present global trends that manifest as a function of neutron and proton number [1]. We end with a discussion of lessons learned and impact on nucleosynthetic outcomes [2].

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Dependence of total kinetic energy of fission fragments as functions of excitation energy and neutron excess for U and Pu isotopes

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Total kinetic energy (TKE) of fission fragments accounts for about 80 % of energy released by nuclear fission. Therefore, understanding of the behavior of TKE is crucial in designing nuclear energy systems as well as understanding local heat source in r-process nucleosynthesis where fission recycling plays an important role. We have investigated fragment mass and TKE correlation as functions of excitation energy and neutron excess for a series of nuclei of U and Pu in terms of a 4D Langevin dynamical model developed at Tokyo Tech. We found that decrease of TKE as a function of the excitation energy of fissioning nucleus could be understood by considering the change of shape of the heavy fragments from spherical to prolate deformation, which causes distance between the center-of-mass of the 2 nascent fragments longer, then the Coulomb repulsion of 2 fragments to decrease [1]. Then, we have done a systematic calculation of mass-TKE correlation ranging from proton drip to neutron drip line of U and Pu. We found that the TKE trend deviates from the $1/A^{1/3}$ rule as indicated by Viola and Unik systematics. The reason of such a deviation was again accounted for by change of the fragment deformation.

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Status of new element search at RIKEN

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After the successful discovery of Nihonium (Nh: Z=113), the RIKEN Nishina Center for Accelerator-Based Science (RNC) has started a new program aimed at producing additional new elements, the 119th and 120th, by hot fusion reactions. To achieve this goal, the RNC carried out the upgrade of a superconducting linac accelerator (SRILAC) and a superconducting ECR ion source to increase beam intensity and maximum acceleration energy and also constructed the new gas-filled recoil ion separator (GARIS-III) suitable for the hot fusion reaction[1]. Commissioning of these finished in 2019 for ^{51}V beam accelerated up to 6.5 MeV/u. After the commissioning, the new collaboration is established and named "nSHE collaboration", which is composed of RIKEN Japan, ANU Australia, IMP China, IPHC France, JAEA Japan, JINPA USA, KEK Japan, Kyushu Univ. Japan, Niigata Univ. Japan, ORNL USA, Osaka Univ. Japan, Saitama Univ. Japan, Tohoku Univ. Japan, UTK USA and Yamagata Univ. Japan.

The experiment to synthesize element 119 is currently underway using a $^{51}\mathrm{V}+^{248}\mathrm{Cm}\rightarrow \mathrm{Z}=119$ reaction with a highly intense beam. The highly enriched $^{248}\mathrm{Cm_2O_3}$ material was provided to RNC under the Material Transfer Agreement between RNC and Oak Ridge National Laboratory.

In this talk, we will present the status of the experiment for 119th element search. In particular, we plan to describe the experimental setup, how the irradiation energy is determined, and explain how the experiment is progressing.

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Superheavy elements in Dubna

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The journey to the borders of the world of atoms and nuclei began about 80 years ago and continues to this day. During this time, 24 artificial elements have been synthesized and they found their places in the Periodic Table of Chemical Elements.

The increased stability of superheavy elements is due to the existence of the "Island of Stability" - a hypothetical region on the nuclear chart, predicted in the mid of 1960s in the region of proton number 114 and neutron number 184. Confirmation of the existence of the Island of Stability of superheavy elements was one of the most important results of the experiments on synthesis of superheavy nuclei with the ^{48}Ca beam.

Today, earlier discovered superheavy elements have become available for a detailed study of their properties thanks to the creation of new accelerator complexes, such as the Superheavy Element (SHE) Factory in Dubna [1-3]. The synthesis of new even heavier elements and the related search for the limits of the existence of chemical elements remains an urgent task for the world's leading laboratories.

In the talk, an overview of results of the first experiments [4-6] performed at the SHE Factory as well as that of the facility itself will be given. Nearest prospects for developing the SHE Factory and extending its experimental program will be discussed too.

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Superheavy nuclei and other exotics – opportunities at SPIRAL2 and S^3

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The structure of very heavy and superheavy nuclei (SHN) as well as is still one of the most intriguing topics in modern nuclear physics [1]. Worldwide competitive, high beam intensities provided by the accelerator facility SPIRAL2 at GANIL [2] which started operation recently, will cover in future all ions up to uranium thanks to the new injector project NEWGAIN. Combined with the separator-spectrometer installation S^3 [3], it will provide the instrumental prerequisites for an ambitious science program [4]. Apart from SHN/SHE research, the envisaged physics case at S^3 covers, among other, the structure of N=Z nuclei, low energy physics (fundamental properties of the atomic nucleus etc.), interdisciplinary research, atomic physics and reaction studies (fission, deep inelastic reactions etc.) [4]. With an emphasis on the physics of the heaviest nuclear species [1], presenting some highlights of recent achievements, in my presentation I will discuss the challenges and opportunities the science program faces at S^3 which is expected to come online shortly.

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Collective subspace requantization for sub-barrier fusion reactions

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Non-empirical theoretical approaches to structure and reaction of unknown nuclei are becoming more and more important in these days. Radioactive isotope facilities of the new generation enable us to access unexplored territories of unstable nuclei with large neutron excess. In order to find new features and useful concepts for these exotic nuclei, we are developing computational approaches, which are capable of calculating structure and reaction properties and of performing systematic calculations for nuclei across the entire nuclear chart.

For studies of heavy-ion reactions, the time-dependent density functional theory (TDDFT) [1] has been a leading theory to provide great insights into nuclear collective dynamics. It is "non-empirical" in the sense that the dynamics is defined by a given energy density functional. On the other hand, its semi-classical nature is a drawback. For instance, it is known to be difficult to obtain sub-barrier fusion reaction in the TDDFT simulation.

The requantization of the dynamics is a possible method to overcome this classical nature. However, a conventional theory for the re-quantization requires us to identify a family of periodic orbits in the TDDFT phase space [2]. This is extremely difficult task and has never been realized in realistic applications in nuclear physics. Instead, we are trying to develop a new approach [3, 6], based on the adiabatic self-consistent collective coordinate (ASCC) method [1, 4]. In this approach, we first determine a subspace in the entire Hilbert space to describe a collective motion of interest. Then, within the obtained subspace, we perform the requantization. In fact, the method was applied to nuclear structure problems, including shape coexistence phenomena and pairing vibrations [1, 5]. Recently, we have succeeded to determine the reaction path and associated inertial mass parameters for relatively light nuclei. The asymptotic values of the inertial masses clearly indicate superiority of our method over conventional approaches, such as the constrained mean-field with cranking inertial masses [6]. We show our results on the low-energy reaction and calculation of astrophysical S factors for sub-barrier fusion reactions.

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Fusion dynamics for superheavy elements production and with weakly bound nuclei

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We present the microscopic studies of producing superheavy elements by combining time-dependent Hartree-Fock theory, coupled-channels approach, and dynamical diffusion models. The fusion probability and compound nucleus formation cross sections for cold-fusion reactions ^{48}Ca+^{208}Pb, ^{50}Ti+^{208}Pb, and ^{54}Cr+^{208}Pb are investigated and found to be consistent with experimental data [1]. Our studies demonstrate that the restrictions from the microscopic dynamic theory improve the predictive power of the coupled-channels and diffusion calculations.

We also investigate the capture, fusion, and evaporation-residue cross sections for the hot-fusion reaction $^{48}\mathrm{Ca} + {}^{238}\mathrm{U}$, in which the orientation effects of ^{238}U are self-consistently included in the capture and fusion processes. The fusion probabilities are found to be strongly dependent on the orientations and the present calculations without any free parameters show that the tip-orientation collision is favorable for both the capture process and the formation of compound nucleus. After considering the survival of the compound nucleus, our calculations well reproduce the experimental evaporation-residue cross sections for $^{48}\mathrm{Ca} + {}^{238}\mathrm{U}$.

We present a microscopic study on the fusion reactions $^{14,15}\mathrm{C} + {}^{232}\mathrm{Th}$ by emphasizing the effect of deformed halo structure on reaction dynamics within the framework of time-dependent density functional theory. Our microscopic calculations not only reproduce the enhancement of fusion cross sections at sub-barrier energies without any adjustable parameters, but also reveal the underlying mechanism of this enhancement, which is driven by the deformed halo structure of ^{15}C. More interestingly, by performing particle number projection based on the wave functions from time-dependent Hartree-Fock simulation we find that the one-neutron transfer probabilities are more sensitive to the orientations of ^{15}C than ^{232}Th, indicating the notable effects of halo structure on the reaction dynamics.

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Dreaming of Superheavy Nuclei: From Terrestrial Experiments to Celestial Origins

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What is the heaviest element that can, if it is very short lived, exist in nature? This simple, yet profound question has urged us to synthesize unknown superheavy nuclei (SHN) at terrestrial accelerator facilities all over the world. The synthesis of SHN is notoriously difficult due to its really tiny cross sections on the order of picobarn to femtobarn. While the cold fusion reactions, which take advantage of the stabilization effect of doubly-magic ^{208}Pb or its neighbor ^{209}Bi, reducing excitation energy of a compound system, have been successful to synthesize SHN up to the element 113, nihonium, it suffers from an exponential decrease of the cross section with increasing the proton number Z. On the other hand, the hot fusion reactions employ a neutron-rich calcium isotope, ^{48}Ca, as a projectile with an actinide target, leading to higher excitation energy as compared to the cold one, while subsequent neutron evaporation successfully cools it down. The latter sustain picobarn-level cross sections even for $Z > 113$ and up to the element 118, oganneson, have been synthesized so far. Although those artificially synthesized SHN are short-lived, their chemical as well as nuclear properties are of great interests, offering a unique opportunity to challenge our theoretical understanding.

One of the possibilities to synthesize SHN is the use of multinucleon transfer (MNT) reactions at energies around the Coulomb barrier. Recently, we have developed the stochastic mean-field (SMF) theory, which is a microscopic framework that incorporates quantal fluctuations and correlations on top of the mean-field (TDHF) dynamics, and applied for the ^{58,64}Ni+^{208}Pb [1] and ^{136}Xe+^{208}Pb [2] reactions, showing remarkable improvements of quantitative description of fragment mass, charge, as well as total kinetic energy (TKE) distributions. In this talk, I will present progress along this line, aiming at producing yet-unknown, neutron-rich heavy nuclei via MNT reactions.

What about other possibilities? If it is really difficult to synthesize SHN by terrestrial experiments, why don't we look for those of celestial origins, *i.e.*, SHN that are/were somewhere in the universe? That is the second topic I would like to discuss in this talk. Recently, we have investigated effects of a superstrong magnetic field (as large as 10^{18} G) on compositions of the outer crust of neutron stars and found that extremely neutron-rich SHN, including yet unknown elements ($Z > 118$), emerge as an equilibrium composition of the outer crust of a strongly-magnetized neutron star [3]. The main cause of the emergence of SHN is the Landau-Rabi quantization of electron motion perpendicular to the magnetic field, which enhances the electron (and, thus, proton) fraction, allowing for the outer crust to extend at a higher pressure (density) region. In this talk, I will discuss implications of the finding, building a new bridge between the studies of SHN and neutron stars.

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Theoretical estimation and reaction mechanism of synthesizing neutron rich nuclei in superheavy mass region

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Research on neutron-rich nuclei in the heavy and superheavy mass region is gaining importance in the fields as the synthesis of new elements [1,2,3], the r-process and multi-nucleon transfer reactions. Furthermore, the use of neutron-rich nuclei is indispensable for reaching the Island of Stability [4] that are predicted to exist in the superheavy element region, and the evaluation of the generation probability of neutron-rich nuclei is necessary.

To success the synthesis of superheavy elements, we must clarify the fusion-fission mechanism, which is included a role of the nuclear structure of colliding nuclei and the deformation of them in the fusion process. We calculate the probability of forming a compound nucleus using Langevin equation as the dynamical model [5]. We discuss the possibility to synthesize new elements $Z \geq 119$. Moreover, to approach to the Island of Stability, we propose the new way using the shell effect during the dynamical process.

To estimate the evaporation residue cross section, we must calculate the survival probability of the excited compound nuclei, in the decay process. At present, the statistical model is used as standard to evaluate the survival probability [6]. When dealing with very small probabilities, and because of the computation time, the use of the statistical mode is suitable.

However, in the neutron-rich nuclei in the superheavy mass region, we find that the inconvenience appears in the calculation of the statistical model code. In the code, we use the mass table by P. Möller [7], and there are cases where the ground state shell-corrected energies in these regions are close to zero or even positive. In the statistical model, the finite height of the fission barrier and the ability to define the saddle point are the basis of the theory construction. In this situation, it may not be applicable to nuclei without a fission barrier. In this research, we discuss based on these analyses, and discuss the introduction of a dynamical model and the modification of the mass table as solutions to the problem.

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The ^{12}C+^{12}C Fusion Reaction at Stellar Energies

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The carbon fusion reaction is a crucial reaction in stellar evolution. Due to its complicated reaction mechanism, there is a large uncertainty in the reaction rate which limits our understanding to various stellar objects, such as massive stars, type Ia supernovae, and superbursts. In this talk, I will review the challenges and the recent progress in the study of the ^{12}C+^{12}C fusion reaction at stellar energies. The outlook for the future experimental studies will also be presented.

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Sub-Coulomb nuclear studies using Indirect Methods: recent results with the Trojan Horse Method

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I discuss the basic concepts of indirect methods in nuclear astrophysics and the opportunity they offer to determine the cross sections and thus the rates of various stellar combustion reactions when it is difficult to perform the corresponding direct measurements. I will focus on recent results using the Trojan Horse method to study carbon burning in ^{12}C+^{12}C fusion-dominated conditions whose dominant evaporation channels at the relevant energies are α and proton, leading to ^{20}Ne and ^{23}Na, respectively. The deduced cross-sections exhibit several resonances that are responsible for very large increases of the reaction rate at relevant temperatures. Then, I will move on to a different application that contributes to understanding the charge symmetry breaking of nuclear forces by measuring the Coulomb-free proton-proton scattering length from the quasi-free $p + d \to p + p + n$ reaction.

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^{12}C+^{12}C fusion reaction rate at low temperatures from a microscopic nuclear model

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^{12}C + ^{12}C fusion is the primary reaction in the carbon-burning process, critical for various astrophysical phenomena such as X-ray superbursts[1]. However, it is highly uncertain at low temperatures, which is essential for X-ray superbursts. Experimentally, it is difficult to determine the low-energy fusion cross section by the direct reaction due to the thick Coulomb barrier[2,3]. An indirect reaction reports many low-energy resonances to enhance the fusion cross sections[4], but the absolute values are under debate[5]. Theoretically, phenomenological models have been unavailable to evaluate the reaction. The fusion reaction is a multi-nucleon rearrangement reaction in which α and p decays are the dominant exit channels, and coupling potentials between the entrance and exit channels have not been developed. Moreover, the resonant states significantly contribute to the ^{12}C + ^{12}C fusion reaction. Theoretical works for resonances treating their coupling have been challenging except for our previous work[6].

We have treated the coupling of the ^{12}C+^{12}C entrance channel and the α+^{20}Ne and p+^{23}Na exit channels using the antisymmetrized molecular dynamics, a microscopic model, and obtained the resonance state near the ^{12}C + ^{12}C threshold in ^{24}Mg. The fusion reaction rate is then evaluated. Several Gogny and Skyrme density functionals are used as nucleon-nucleon interactions.

By coupling the entrance and exit channels, fragments of 0^+ and 2^+ resonances containing ^{12}C+ ^{12}C components distribute around the ^{12}C + ^{12}C threshold, enhancing the ^{12}C + ^{12}C fusion cross sections. Those resonances contribute to the ^{12}C + ^{12}C fusion reaction rate at low temperatures. The reaction rate is sensitive to the resonance energies, and the Gogny functionals obtain lower resonances and larger reaction rates at low temperatures than the Skryme functionals. These discrepancies are a kind of uncertainty of microscopic models, which have to be evaluated by experiments.

The isoscalar transition matrix elements from the ground state to the 0^+ and 2^+ resonances near the ^{12}C + ^{12}C threshold are about a Weisskopf unit. It is large enough to be excited by inelastic scattering, indicating that inelastic scattering is a promising alternative to direct reactions for observing resonance states near the ^{12}C + ^{12}C threshold.

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News on the carbon burning at stellar energies from deep sub-barrier fusion measurements

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Fusion reactions play an essential role in understanding the energy production, the nucleosynthesis of chemical elements and the evolution of massive stars. The direct measurement of key fusion reactions at stellar energies is thus of very high interest for a reliable interpretation of the excitation functions, but very challenging since the associated cross sections are extremely small, of the sub-nanobarn range. Among the processes which are milestones for nuclear astrophysics, the carbon burning is a crucial ingredient to understand the late stages of massive stars [1]. It is essentially driven by the $^{12}C+^{12}C$ fusion reaction which is known to show resonances at energies ranging from a few MeV/nucleon down to the sub-Coulomb range [2]. The possible persistence of these resonances to deep sub-Coulomb barrier relative energies causes large uncertainties of extrapolations of $^{12}C+^{12}C$ fusion cross section down to the Gamow region.

This contribution will discuss recent results obtained in the $^{12}C+^{12}C$ system at deep sub-barrier energies using the STELLA setup combined with the UK-FATIMA detectors for the direct measurement of fusion cross-sections of astrophysical interest [3]. The gamma-particle coincidence technique combined with the merit of nanosecond-timing measurements have been used to minimize background contributions for cross-section determination at the highest precision reached so far [4]. New results of a campaign of the STELLA collaboration will also be presented.

The impact of these newly measured $^{12}C+^{12}C$ reaction rates on the stellar evolution and nucleosynthesis will also be discussed on the basis of newly developed hydrodynamics calculations taking into account possible resonant features as well as fusion hindrance effects [5].

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Reaction dynamics of proton drip-line nuclei at energies around the Coulomb barrier

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Reaction dynamics induced by proton drip-line nuclei at energies around the Coulomb barrier is one of the most popular topics in nuclear physics. In order to further investigate the reaction mechanisms of proton drip-line nuclei, we performed the complete-kinematics measurements of ^{8}B+^{120}Sn [1] and ^{17}F+^{58}Ni [2] at CRIB, University of Tokyo. Two detector arrays, i.e., the silicon telescope array of STARE and the ionization chamber array of MITA, were designed respectively for the measurements of ^{8}B and ^{17}F. Reaction products were completely identified with the help of these two arrays. For the ^{8}B+^{120}Sn system, the coincident measurement of the breakup fragments was achieved for the first time. The correlations between the breakup fragments reveal that the prompt breakup occurring on the outgoing trajectory dominates the breakup dynamics of ^{8}B. For ^{17}F+^{58}Ni, the complete reaction channel information, such as quasi-elastic scattering, breakup and total fusion, was derived for the first time. An enhancement of the fusion cross section of ^{17}F+^{58}Ni was observed at the energy below the Coulomb barrier. Theoretical calculations indicate that this phenomenon is mainly due to the coupling to the continuum states. Moreover, different direct reaction dynamics were found in ^{8}B and ^{17}F systems, suggesting the influence of proton-halo structure on the reaction dynamics.

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Coincidence measurements of fusion reactions involving carbon and oxygen with the high-precision STELlar LAboratory (STELLA)

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Fusion reactions involving carbon and oxygen are crucial for the understanding of the life cycle of massive stars and ultimately of the synthesis of chemical elements necessary for life. Besides the bottleneck reaction ^{12}C+^{12}C – mainly driving the carbon burning in massive stars – measurements of neighbor light systems as ^{12}C+^{16}O and ^{16}O+^{16}O are scarce although they are also relevant for the precise modeling of late carbon burning, oxygen burning in massive stars as well as explosive carbon burning of Type Ia supernovae [1]. Furthermore, a comprehensive picture of these alpha-conjugated systems might reveal the underlying microscopic origin of several puzzling observations in sub-barrier fusion which are still not fully understood such as the potential existence of cluster states [2] or of a fusion hindrance mechanism [3]. In particular, recent hints for low energy resonances in the ^{12}C+^{16}O [4] system call for more precise measurements and the study of the ^{16}O+^{16}O has the potential to shed light on whether or not the fusion hindrance also affects light systems.

Following the successful first phases of ^{12}C+^{12}C [5] measurements with STELLA, precise determination of the astrophysical S-factor for the ^{12}C+^{16}O and ^{16}O+^{16}O fusion is developed at the Andromède facility (France), exploiting the coincidence technique with ns-timing precision. The key experimental developments to achieve an enhanced energy resolution needed to unambiguously resolve the increased complexity of the final states of these systems will be detailed and the sensitivity expected after the upgrade will be discussed.

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Measurement of the ^{27}Al$(p,\alpha)^{24}$Mg fusion reaction at astrophysical energies via the Trojan Horse Method.

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The abundance of ^{26}Al carries a special role in astrophysics, since it probes active nucleosynthesis in the Milky Way and constrains the Galactic core-collapse supernovae rate. It is estimated through the detection of the 1809 keV γ-line and from the superabundance of ^{26}Mg in comparison with the most abundant Mg isotope (A=24) in meteorites. For this reason, high precision is necessary also in the investigation of the stable ^{27}Al and ^{24}Mg [1,2]. Moreover, these nuclei enter the so-called MgAl cycle playing an important role in the production of Al and Mg [3]. Recently, high-resolution stellar surveys have shown that the Mg-Al anti-correlation in red-giant stars in globular clusters may hide the existence of multiple stellar populations, and that the relative abundances of Mg isotopes may not be correlated with Al.

The common thread running through these astrophysical scenarios is the ^{27}Al(p,α)^{24}Mg fusion reaction, which is the main ^{27}Al destruction channel and directly correlates its abundance with the ^{24}Mg one. Since available spectroscopic data and tabulated reaction rates show large uncertainties owing to the vanishingly small cross section at astrophysical energies, we have applied the Trojan Horse Method (THM) to the three-body quasi-free reaction $d(^{27}\mathrm{Al},\alpha^{24}\mathrm{Mg})n$. This has allowed us to perform high precision spectroscopy on the compound nucleus ^{28}Si, from which we extracted important information on the ^{27}Al$(p,\alpha)^{24}$Mg fusion cross section in the energy region of interest for astrophysics, not accessible to direct measurements. All details can be found in refs.[4,5]. In particular, the indirect measurement made it possible to assess the contribution of the 84 keV resonance and to lower upper limits on the strength of nearby resonances.

In particular, in this work we have evaluated the effect of the THM recommended rate on intermediate-mass asymptotic giant branch stars experiencing hot bottom burning. Here, a sizeable increase in surface aluminum abundance is observed at the lowest masses due to the modification on the fusion cross section, while ^{24}Mg is essentially unaffected by the change we determined.

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On the optical model potentials of exotic nuclear systems

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The nuclear interaction potential is a basic element in the study of nuclear physics. The phenomenological optical model potential (OMP) not only includes the static bare potential but also reflects an overall feature of reaction dynamics. Usually, the OMP is extracted by fitting the angular distribution of elastic scattering. For tightly-bound nuclear systems, the phenomenon of threshold anomaly (TA) has been known for more than 30 years. A dispersion relation (a natural consequence of the causality principle) between the real and imaginary part of OMP is well established [1]. While for weakly-bound nuclear systems, a behaviour of abnormal threshold anomaly (ATA) was observed [2], but the relation between the real and imaginary parts of OMP is yet unclear so far. A novel method, i.e. the transfer reaction method, was proposed to extract the OMP of exotic nuclear system in the exit reaction channel [3]. The OMPs of ^{6}He+^{209}Bi were extracted by this method. The reaction energy reached to deep sub-barrier region, and therefore the threshold energy was determined for the first time [4]. The result offers strong evidence that the dispersion relation does not hold, which may be a common phenomenon for exotic nuclear systems. Recently, the elastic scattering data of ^{6}Li+^{209}Bi and ^{6}He+^{208}Pb were re-analyzed by the frequentist-bootstrap method with strong TA constraints imposed. A conclusion opposite to the currently-accepted ATA behaviour has been reached [5]. Considering this contradiction, we re-analyzed the elastic data of ^{6}Li+^{209}Bi and the transfer data of ^{6}He+^{209}Bi by the Bayesian method [6]. With the proper prior distributions, the ATA phenomenon is confirmed, and the applicability of the dispersion relation remains in doubt. It should be pointed out that the elastic scattering data is not informative enough to judge which prior condition (TA or ATA) is correct. Additional analyses on other reactions, such as transfer and/or fusion where the nuclear interaction plays a major role, can provide valuable information. Finally, we would like to emphasize that the Bayesian method has to be used with extreme caution, since the different prior knowledge could lead to completely different conclusions. Based on this work, we recommend the non-constraint frequentist approach or the the Bayesian method with a flat prior distribution as a priority. In order to further investigate the OMP of weakly-bound nuclear system, transfer reactions of ^{207}Pb(^{7}Li,^{6}Li)^{208}Pb and elastic scattering of ^{6}Li+^{208}Pb have been measured with high precision for energies around and well-below the Coulomb barrier. Reliable OMPs have been extracted via simultaneously analysing the transfer and elastic scattering data by the Bayesian method. New results will be present at the conference.

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Sequential fission and the influence of ^{208}Pb closed shells on the dynamics of superheavy element synthesis reactions

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Measured binary quasifission mass spectra in reactions with actinide nuclides show a large peak in yield near the doubly-magic ^{208}Pb. This has generally been attributed to the enhanced binding energy of ^{208}Pb causing a valley in the potential energy surface, attracting quasifission trajectories. To investigate this interpretation, binary quasifission mass spectra and cross-sections have been measured at near-barrier energies for reactions of ^{50}Ti with actinide nuclides from ^{238}U to ^{249}Cf. Cross-sections have also been deduced for sequential fission (a projectile-like nucleus and two fragments from fission of the complementary target-like nucleus). Binary cross-sections fall from $\sim$70% of calculated capture cross-sections for ^{238}U to only $\sim$40% for ^{249}Cf, with a compensating increase in sequential fission cross-sections. The data are consistent with the ^{208}Pb peak originating largely from sequential fission of heavier fragments produced in more mass-asymmetric primary quasifission events. These are increasingly suppressed as the heavy quasifission fragment mass increases above ^{208}Pb. The important role of sequential fission calls for re-interpretation of quasifission observables and dynamics in superheavy element synthesis reactions.

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The superheavy nuclei: non-fusion, fusion and fission

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The quest for the synthesis and study of superheavy nuclei (elements) situated on a hypothetical island of stability has been one of the main driving forces for several generations of physicists and chemists.

In recent decades, we came closer to this island thanks to fusion reactions with the doubly-magic ^{48}Ca as a projectile and actinides as targets [1]. Decay modes of these known SHN approved the concept of island of stability against the fission.

Some of current hot topics are syntheses of SHN beyond Og ($Z = 118$), neutron-rich SHN, and fission property of known SHN. To achieve the first two goals, we need to explore dynamics of fusion and multi-nucleon transfer reactions in more detail.

I will discuss these topics and will present the related recent experimental findings at the gas-filled recoil separator TASCA, GSI (e.g., [2,3]), the Heavy Ion Accelerator Facility of the ANU, Australia (e.g., [4]) and the recoil mass separator MARA of JYFL, Finland.

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Direct mass measurement of superheavy nuclides produced by fusion-evaporation reactions

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The atomic mass is an important quantity that faithfully reveals the interactions between nucleons of each nuclide. According to the classical liquid drop model, superheavy elements cannot exist due to the vanishing fission barrier. Therefore, their existence is governed by the shell effect, and mass is an exclusive quantity that can explore for the shell effect of each nucleus. We are performing the high-precision mass measurement of fusion evaporation residues by using the SHE-Mass facility [1] which consists of the gas-filled recoil ion separator (GARIS-II) [2] and the multi-reflection time-of-flight mass spectrograph (MRTOF-MS).

As a major improvement of the SHE-Mass facility, we have developed a novel "α-TOF" detector in order to simultaneously measure mass along with correlated decay properties [3]. The α-TOF technique initially allowed us to directly measure mass of the superheavy nuclide ^{257}Db from its 11 ions [4,5]. Recently, with the MRTOF and target improvements, we have also successfully measured the mass of ^{258}Db, and furthermore the precision of the mass of ^{257}Db was improved. In this presentation, we report the details of the experiment and result of the mass measurement of ^{257,258}Db isotopes.

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Structure of heavy nuclei investigated by laser spectroscopy and mass spectrometry at GSI/SHIP

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The nuclear structure of the heaviest elements with $Z \geq 100$ is determined by shell effects that stabilize them against spontaneous fission. In the region of deformed nuclei around $Z = 100$ and $N = 152$ as well as $Z = 108$ and $N = 162$ the occurrence of weak shell gaps has been established. However, there extension and how these gaps affect the structure is not fully known as the access to relevant nuclei is limited by production capabilities. In addition to restrictions from available beam-target combinations the generally low yields make experimental investigations every challenging.

In recent years the shell structure of nuclides in the region around $Z = 100$ and $N = 152$ was studied in great detail with the use of advanced methods of laser spectroscopy and mass spectrometry complementing nuclear spectroscopy studies. The development of tailored and highly sensitive techniques was a crucial prerequisite for such studies. This enabled pioneering experiments with SHIPTRAP and RADRIS leading to several accurate mass values and the first laser spectroscopy of nobelium isotopes [1-3].

In my contributions I will briefly introduce the methods and review the latest measurements performed at SHIP at GSI.

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Fusion-quasifission dynamics in a random-walk model

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The production of a superheavy element in a fusion reaction schematically proceeds through three stages: (i) the two colliding nuclei come into contact, (ii) the contact configuration evolve into a compact shape, (iii) the fused nucleus cools down by neutron evaporation. We investigate the dynamics of the fusion-quasifission process in stage (ii) using the Metropolis random walk method which has previously been applied to describe the shape evolution in fission [1].

The method is based on the same assumption of overdamped shape evolution as in the fusion-by-diffusion model [2,3], but the probability for the composite system to diffuse over the saddle is here obtained by performing random walks in a five-dimensional potential-energy landscape. This allows for detailed studies of the corresponding shape evolution into a compact shape. Quasifission is also described by sampling events where the system divides again, after diffusion in mass asymmetry, and total-kinetic-energy distributions are obtained.

The reactions considered correspond to different projectiles on a ^{208}Pb target typical in cold-fusion reactions. Figure 1 [4] shows the number of quasifission events in ^{50}Ti+^{208}Pb with respect to fragment mass number and total kinetic energy for angular momentum I=0 and for excitation energies $E^*_{\rm CN}$=12 MeV (a) and $E^*_{\rm CN}$=30 MeV (b). For the lower energy (a) the majority of events correspond to fragment mass numbers near that of the projectile and target with a rather large spread in kinetic energy, whereas a more symmetric parabolic behavior is obtained for the higher energy (b). The corresponding formation probabilities of 8% and 25% for these two cases compare reasonably well with the data in Ref. [5], where the values 2% and 19% were reported for energies $E^*_{\rm CN}$=14.2 MeV and $E^*_{\rm CN}$=32.7 MeV, respectively.

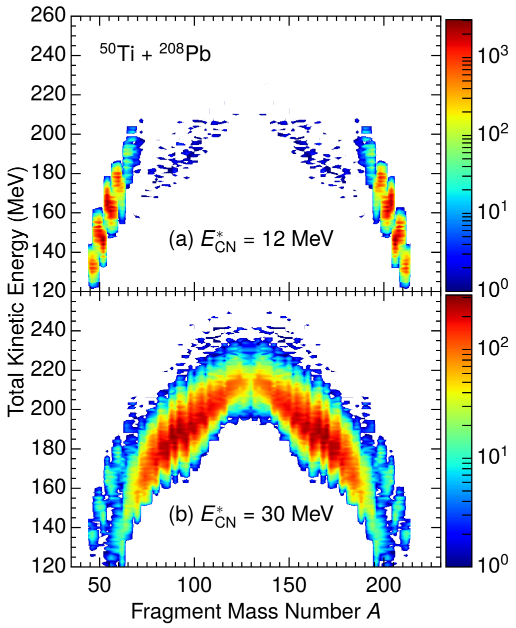

FIG. 1: Calculated number of events for walks resulting in quasifission vs. $(A, \rm TKE)$ (log scale) in the reaction ^{50}Ti+^{208}Pb with angular momentum I=0 and for two excitation energies $E^*_{\rm CN}$.

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Nucleon-nucleon correlations probed in sub-barrier transfer reactions and the nuclear Josephson effect

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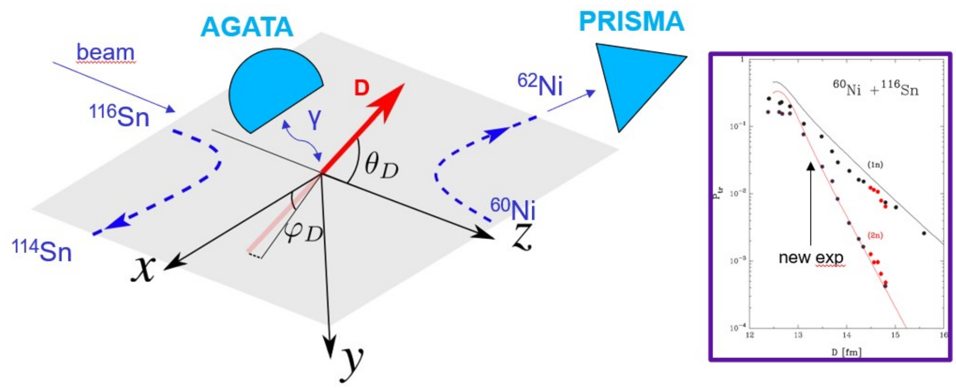
In recent years a series of near- and sub-barrier transfer experiments have been carried out at LNL, with reaction products detected in inverse kinematic and at forward angles with the large solid angle magnetic spectrometer PRISMA. Nucleon-nucleon correlation properties have been studied by measuring transfer cross sections far below the Coulomb barrier, making excitation functions down to very low energies and corresponding to very large distances of closest approach where the nuclear absorption is small [1,2,3]. For the (well Q-value matched) one and two neutron transfer channels in the system ^{60}Ni+^{116}Sn the microscopic calculations very well reproduce the experimental data in the whole energy range, both in magnitude and slope [2]. The fact that most of the cross section of the two neutron transfer channel is in the ground to ground state transition has been further confirmed by a second experiment [4].

The coupling of the AGATA gamma array to PRISMA offers a unique opportunity to study a nuclear (alternating current (AC)) Josephson-like effect [5], with Cooper-pair tunnelling between superfluid nuclei, whose manifestation has been recently proposed [6] using the data of Refs. [2,4] as a stepping stone. Predictions have been made of a specific gamma strength function associated with the dipole oscillations generated by the, mainly successive, two neutron transfer process. In a very recent experiment carried out at LNL with PRISMA+AGATA we directly tested for the first time the possible manifestation of this important effect of Cooper pair behaviour, observed to date only in condensed matter physics. After a general overview on the subject, the talk will focus on new results, addressing the new achievements and the critical issues.



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Spectroscopy of neutron-rich nuclei produced by multinucleon transfer reactions at KISS

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The nuclear properties such as lifetimes and masses of the neutron-rich nuclei are important parameters to investigate the astrophysical rapid neutron capture process (r-process). However, the difficulty in the production of those relevant neutron-rich nuclei, especially a the waiting points on the neutron closed shell $N = 126$ and beyond, makes their experimental studies unfeasible. Therefore, the theoretical nuclear models play crucial roles in the simulation of the r-process nucleosynthesis.

Experimental studies of the properties and structures of neutron-rich nuclei from near the β-stability line toward the r-process path provide significant inputs to those theoretical models to improve their predictability for the nuclear properties relevant to the formation of the r-abundance peak around $A = 195$ and actinide elements such as uranium and thorium. We are developing KEK Isotope Separation System (KISS) at RIKEN RIBF facility to produce and separate those nuclei for their spectroscopic studies [1]. The nuclei of interest are produced by multi-nucleon transfer (MNT) reactions, which are recently gaining renewed interest to provide pathways to access neutron-rich nuclei which are difficult to produce by other methods such as complete fusion and fragmentation [2]. It is an argon-gas-cell-based laser-ion-source coupled with an isotope separator on-line system, which allow to provide the mass and atomic number selectivity. A detector system consisting of a multi-segmented proportional gas counter [3] combined with high-purity germanium detectors is used for the β-γ spectroscopy and laser spectroscopy. A Multi-Reflection Time-Of-Flight Mass Spectrograph (MRTOF-MS) was recently installed, enabling high-precision mass measurements and unique identification of isobaric species [4]. We have performed nuclear and laser spectroscopy, and lifetime and mass measurements of neutron-rich nuclei of refractory elements around $N = 126$ region, using ^{198}Pt, $^{\mathrm{nat}}$Pt and $^{\mathrm{nat}}$W targets bombarded by a ^{136}Xe beam. We are also extending the spectroscopic research to the neutron-rich actinide region using ^{238}U beam [5].

In this presentation, we report experimental methods and results of KISS, including the future project towards further neutron-rich region [6].

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Population of heavy-neutron rich nuclei in multinucleon transfer reactions

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In recent years transfer processes between heavy ions at energies close to the Coulomb barrier have been recognized as a competitive tool for the production of exotic species, especially the heavy neutron-rich nuclei [1,2]. The recent progress in these studies is closely connected with the successful implementation of large solid angle magnetic spectrometers, which allow to identify the transfer products in mass, and charge with unprecedented efficiency [1,3]. Significant steps forward have been achieved by the coincident detection of both binary partners [4,5], or by the detection of the electromagnetic transitions [6,7,8], crucial for the identification of heavy fragments.

The results for ^{206}Pb+^{118}Sn [3], ^{197}Au+^{130}Te [4], and ^{94}Rb+^{208}Pb [6] will be presented, with the focus on the production of neutron-rich heavy nuclei via multinucleon transfers. In order to understand the production process for the heavy partner, we performed an experiment with a simultaneous detection of light and heavy transfer products in the ^{197}Au+^{130}Te [4] system, by using a dedicated set-up [5] specifically built and coupled to the PRISMA spectrometer. This allowed, via a high-resolution mass-mass correlation, to study the final mass distribution of the heavy partner and the effect of secondary processes.

In ^{94}Rb+^{208}Pb [6], we directly identified lead isotopes and determined their absolute cross sections by employing the high-efficiency MINIBALL γ-ray array coupled to a particle detector, and combined with the ISOLDE radioactive ^{94}Rb beam.

In ^{206}Pb+^{118}Sn [3], we investigated how the mass and charge yields and the final cross sections depend on the energy losses in their evolution from the quasi-elastic to deep-inelastic regimes. This is very important for very heavy systems, where the high Coulomb field and processes with large energy losses may strongly influenced the final yield distributions.

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Dissipation by transfer and its influence on fusion

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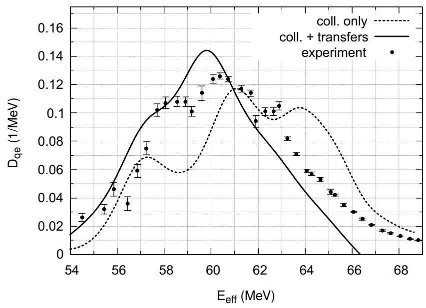
Coupled Channels (CC) model successfully explained the strong enhancement of sub-barrier fusion cross sections as well as the observed structures in the barrier distributions for many systems [1]. However, there are several mechanisms whose role in the fusion is still not clear, among these is the influence of dissipation, i.e. of the partial conversion of the projectile-target kinetic energy into their heating. There are two main mechanisms of dissipation: excitation of non-collective levels by nuclear and electromagnetic interactions and mutual projectile-target transfer of light particles. The first phenomenon has been treated by combining the CC method with the Random Matrix Theory with promising results [2, 3]. Concerning the transfers, the complicated nature of this many-body phenomenon makes the exact description of it impossible, particularly for heavier systems.

Recently, we have modified the codes CCQEL and CCFULL [4] upgrading the method of coupling of transfer channels during fusion and backscattering processes. In particular, the number of transfer reaction included have been increased and the dependence of the strength of transfer coupling on the transferred particle, Q-value and projectile kinetic energy was introduced.



The upgraded model was employed for the investigation of the influence of transfer on the smoothing of the measured quasielastic barrier distribution (D_{qe}) of the ^{24}Mg+^{92}Zr and ^{20}Ne+^{208}Pb systems and found interesting discrepancies with respect to the common approximations. According to the improved model, the fusion enhancement due to transfer is rather moderate and, in contradiction to the standard model, concerns mainly the near-barrier region. The study indicates the transfer responsible for generating strongly excited targets as the main cause of the smearing of the barrier distribution, as well as the no dominant role of the two neutrons transfer on fusion for certain systems. The two neutrons transfer, even having a positive Q_{gg} value, is not necessarily dominating. Indeed, the smoothing observed in the barrier distribution D_{qe} is dominated rather by one neutron transfer, despite the foreseen negative Q-value for the one transfer reaction and the positive Q-value for two neutrons transfer. The figure shows the influence of the four main transfer channels (1 and 2 neutrons pick-up, 1 proton and 1 alpha stripping) on the D_{qe} estimation of the ^{24}Mg+^{92}Zr system. The transfers significantly change the barrier distribution shape, smoothing out the structure resulting from the collective excitations and highlighting the importance of the couplings between different transfer channels.

Details of the method and obtained results will be shown in this contribution.

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Adsorption-based nuclear spectroscopy of superheavy nuclei with ANSWERS at TASCA

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The stability of superheavy nuclei ($Z \geq 104$) primarily depends on the arrangement of their nucleons. The radioactive decay modes of these nuclei, thus, are key to exploring their underlying nuclear structure. Currently, superheavy nuclei are producible only in heavy-ion induced fusion reactions with small cross sections, which limit the use of various common experimental techniques for nuclear decay spectroscopy. Presently, the main technique for performing nuclear decay spectroscopy experiments with superheavy nuclei is the implantation/correlation technique [1]. However, despite being the state-of-the-art, this technique has certain disadvantages, which limit comprehensive measurements of radioactive decays, e.g. detailed study of alpha-decay fine structure and fission-fragment mass distributions.

A complementary experimental technique for nuclear spectroscopy, named Adsorption-based Nuclear Spectroscopy Without Evaporation Residue Signal (ANSWERS), was introduced at the SHE Chemistry department at GSI Darmstadt, Germany, in 2020 [2]. ANSWERS had been commissioned with ^{211}Bi, No and Lr isotopes. The latter two were produced at the gas-filled recoil separator TASCA as 1-3 neutron-evaporation residues of the ^{48}Ca-induced reactions with Pb and Bi targets at energies around the fusion barrier. ANSWERS allowed an unambiguous identification of very low energy internal-conversion electrons from low-lying excited states, which usually sum up with alpha-particle energies in implantation-based setups. In addition, the fission-fragment mass distribution of ^{252}No was measured with significantly improved statistics compared to the literature data [3]. Therefore, ANSWERS shows a great potential for the future study of alpha-decay fine structure and fission-fragment mass distributions of the heaviest nuclei.

In this talk, the ANSWERS technique and first results from the above mentioned commissioning experiments will be presented.

We are grateful for GSI's the Experimental Electronics department and Target Lab for their continuous support of the experimental program at TASCA. We acknowledge the ion-source and UNILAC staff for providing the stable and high intensity ^{48}Ca beam. The results are based on the experiment U308, which was performed at the beam line X8/TASCA at the GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt (Germany) in the frame of FAIR Phase-0.

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Study of deformed structure in ^{254}Es and ^{249}Cf by Coulomb excitation

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Exploring the new elements toward the high end of the nuclear chart is one of the most interesting topics in nuclear physics. Currently a search for new element in so-called super-heavy region is on-going. Key ingredient to stabilize nucleus in this region is a nuclear shell structure and Z=114, 120, N=184 [1-4] are predicted to be new magic numbers. However, the access to such nucleus and study the shell structure are limited by the very low cross sections. To investigate the shell structure, we are focusing on the deformed nucleus of the A$\sim$250 heavy mass region including ^{254}Es, ^{249}Cf isotopes. By studying the excited states, spin and parity, and deformation, we will be able to access the single-particle orbital which is supposed to generate new shell structure at Z=114, 120, N=184 and try to investigate nuclear shell structure in the super-heavy mass region.

In A$\sim$250 nuclei, experimentally observed rotational bands indicate the existence of deformed structure in this region, however the studies of deformation, such as determination of quadrupole moment, are not performed well. To understand single-particle structure, it is important to determine the size of ground state deformation systematically.

In order to study nuclear deformation in A$\sim$250 region, we have performed Coulomb excitation experiments to determine the deformation of low-lying states of ^{254}Es and ^{249}Cf. The experiment was performed at the JAEA-Tokai Tandem accelerator using ^{58}Ni beam with an energy of 250 MeV. The very rare ^{254}Es was produced at the High-Flux Isotope Reactor at ORNL, USA, and it was separated at the ORNL's Radiochemical Engineering Development Center. The ^{254}Es target was produced at JAEA using less than a microgram of material. Particle-gamma coincidence measurements were conducted using segmented CD-silicon detectors placed backward and forward from the target and the Ge and $LaBr_3$ detectors placed around the target. From the gamma-ray spectrum analysis, rotational band structures in both ^{254}Es and ^{249}Cf were observed.

In the presentation, recent experimental results will be discussed.

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Reaction parameter studies of the ^{51}V beam onto deformed target: ^{51}V+^{159}Tb reaction

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With the syntheses of elements up to Oganesson ($Z = 118$), all the fusion evaporation reactions using the ^{48}Ca beams on deformed actinide targets have already been performed. Due to the lack of target material past the Californium, the use of ^{50}Ti, ^{51}V and ^{54}Cr is now becoming mandatory for accessing elements beyond the oganesson ($Z = 118$). In the SHE mass region, these beams have only been used in reactions on spherical Pb and Bi targets for the production of the neutron deficient Sg, Db, and Rf isotopes. In addition, the different cross-sections predictions for SHE elements past oganesson can only be extrapolated from the reaction performed using ^{48}Ca beams, leading to a wide range of prediction based on the model used.

Thus, in addition to reaction parameters measurements [1,2], precise systematic measurements of excitation functions of lighter systems based on deformed targets around lanthanide nuclei give an appropriate training dataset to improve the predictive power of existing models. These lighter systems are good substitutes for the deformed actinide targets used in the current search for new elements. They have similar deformation parameters, but at much higher production rate (μb range). In addition, the simultaneous measurement of the barrier distribution and excitation function, allows for the correlation between the barrier distribution and the maximum cross-section of production. This correlation is indeed an important part of the discussion in the selection of the optimal beam energy for the synthesis of SHE elements and presents significant differences between spherical and deformed targets as shown in [1,2].

The search of the new element $Z = 119$ is currently ongoing at RIKEN using the reaction ^{248}Cm(^{51}V,xn)$^{299-x}$119 on the GARIS-III experimental setup [3]. As stated in [2], the selection of the beam energy for the search of new elements is crucial to the success of the experiment, and is currently based on similar studies done with the ^{51}V+^{248}Cm system [1]. The goal of this work is thus to extend the systematic study of reaction parameters with deformed targets using the ^{51}V beam to see if this behavior can be reproduced with lighter surrogate systems. This work studied the effect of the beam energy and nuclear deformation in the reaction ^{159}Tb(^{51}V,xn)$^{210-x}$Ra by producing both the barrier distribution and the detail excitation functions. The goal is to extend the systematic study of the quasielastic (QE) barrier distribution with ^{51}V and compare it to the results obtained in [2,3] as well as theoretical prediction using the Couple Channel Calculation (CCFULL [4]). In addition, the production of the full and detailed excitation function for the xn, pxn and αxn, also allow us to study the correlation between the barrier distribution and the maximum cross-section of production. The experimental setup, analysis and preliminary results of both studies will be presented in this presentation.

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Shell effects in fission and quasifission

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Fission of atomic nuclei is often affected by quantum effects leading to asymmetric mass splits. These shell effects can be investigated at the mean-field level with single particles level densities, indicating that several proton and neutron shell effects are usually at play prior to scission [1]. In addition to shell effects in the compound nucleus, quantum shells stabilising fission fragments with octupole shapes have been invoked as a factor determining the distribution of nucleons between the fragments at scission, explaining the fact that the centroid of the heavy fragment charge distribution is found around $Z \simeq 54$ in actinide fission [2]. Shell effects have also been identified in the quasifission process [3]. Quasifission occurs in fully damped heavy-ion collisions following a significant mass transfer between the fragments, without formation of a compound nucleus. Microscopic calculations recently showed that similar shell effects were to be expected in both fission and quasi-fission [4,5]. Here, we use static and time-dependent mean-field approaches to investigate and compare the shell effects affecting fragment formation in both fission and quasifission. In particular, we discuss the possibility to use quasifission to obtain some information on fission modes in superheavy nuclei, which would benefit from the fact that quasifission cross-sections are much larger than for fusion-fission.

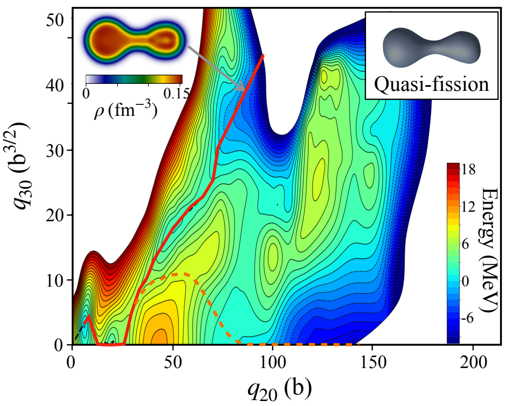

FIG. 1: Potential energy surface of ^{226}Th from mean-field calculations. The red solid (dashed orange) line shows a fission path leading to asymmetric (symmetric) fragments. Time-dependent mean-field calculations (grey isodensity) show that quasifission produces similar fragments as in asymmetric fission.

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Connection between nuclear structure, dissipation, and time in fission data

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Nuclear fission is still one of the most complex physical processes we can observe in nature due to the interplay of macroscopic and microscopic nuclear properties that decide the result. An example of this coupling is the presence of nuclear dissipation as an important ingredient that contributes to drive the dynamics and has a clear impact on the time of the process. However, different theoretical interpretations, and scarce experimental data make it poorly understood.

At low excitation energy, the relative production of fragments with even atomic numbers shows a clear difference with that of odd atomic numbers, which can be quantified with the so-called even-odd effect. This seemingly mundane property can be used to obtain information about the energy dissipated during the process, the role of structure in its dynamics, and it even appears as a potential contributor to the long-standing problem of the time scale in fission.

In this presentation, we shall discuss the study of the even-odd effect for transfer-induced fission data, which reveals a connection between particular fragment shells, the energy dissipated and the time from saddle to scission [1]. In addition, we shall present preliminary results on the measurement of the even-odd effect also in quasi-fission data, and discuss the similarities and differences of the effect between fission and quasi-fission.

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Mass-TKE distributions for symmetric fission in neutron-rich Fm and transfermium nuclei

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Spontaneous fission (SF) of neutron-rich Fm and transfermium nuclei exhibits three different types of fission competing or coexisting [1]. The one is the asymmetric fission which is typical in most of actinide nuclei with the mass number lower than 257. The second one is the high-TKE (total kinetic energy) symmetric fission which is observed in neutron-rich Fm and Md isotopes; this is interpreted as the fission with compact configuration at scission forming two spherical nuclei like Sn isotopes. The third one is the low-TKE symmetric fission which is observed as the main component in the SF of neutron-rich No, Lr, and Rf isotopes, and is also observed in the neutron-rich Fm and Md isotopes where both high- and low-TKE symmetric fissions coexist. Recent theoretical calculations can successfully reporoduce the competition between asymmetric and high-TKE symmetric fissions in neutron-rich Fm isotopes [2-6]. However, most of the calculations cannot reproduce the low-TKE symmetric component. To understand the mechanism of the competition among three types of fission and the origin of the low-TKE symmetric fission, new precise experimental data on the mass and TKE two-dimensional distributions are highly desired.

In this work, we have measured fission-fragment mass and TKE distributions for the spontaneous fission of ^{258}Fm, ^{259}Md, and ^{259}Lr. These nuclei were produced in the multinucleon transfer reactions with ^{18}O beam and ^{254}Es target and in the fusion-evaporation reaction of ^{248}Cm(^{15}N,4n)^{259}Lr at the JAEA tandem accelerator facilty. Reaction products were mass-separated with the gas-jet coupled on-line isotope separator (ISOL), and mass-separated ions were implanted into thin carbon foil to measure the kinetic energy of both fission fragments with 4 pairs of Si detectors, Based on the deduced mass-TKE 2D distribution data, we will provide new insights into the properties of the low-TKE symmetric fission as well as into the coexistence of the three types of fission in these nuclei.

*This work was carried out with many collaborators at JAEA, Ibaraki Univ., Tokushima Univ., RCNP, Osaka Uiv., Tokyo Institute of Technology, Niigata Univ., Univ. of York, Kanazawa Univ., Kyushu Univ., Nagoya Univ., RIKEN, QST, and ORNL.

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Mapping the influence of shell effects on fission and quasifission modes

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Shell effects are believed to produce asymmetric fission modes in heavy and superheavy nuclei [1–4]. It is believed that the same shell effects can play a role in quasifission, by stabilising the mass of the fragments [5–7]. The quasifission process differs from that of fission in both energy and through its dependence on entrance channel properties. Fission modes can be predicted from the emergence of valleys in the potential energy surfaces (PES) associated with nuclear shape deformations [8]. Their mass widths and centroids can be extracted from the position and size of the valleys and compared with experiments [9]. Quasifission may probe the same valleys and therefore experience the same shell effects, but as it is a dynamic, out-of-equilibrium process, it is not guaranteed to produce a given outcome. The potential energy surfaces of heavy and superheavy nuclei are calculated using a static Hartree-Fock approach with BCS pairing correlations [10]. Quasifission trajectories for central collisions at various energies and a range of target-projectile combinations are simulated with time-dependent Hartree-Fock theory [11]. The two are compared in order to understand how well the static PES predicts the behaviour of the quasifission system. The exit channel strongly depends on initial mass asymmetry and orientation, but it only exhibits small dependences in the reaction energy. This confirms that the majority of quasifission reactions experience near total kinetic energy dissipation before reseparation. Shell effects, both spherical and deformed, appear to drive quasifission modes, as defined by both the mass and kinetic energies of the fragments. The structure of the PES near the compound system ground state is of particular interest, as it appears to define the threshold between quasifission and fusion reactions. The topography of the ridge between the shell-effect dominated asymmetric valley and the symmetric valley influences the exit channel of the quasifission trajectories. The correspondence suggests that experimental measurements of quasifission, especially at low energies, have utility in indirectly measuring fission modes, and may also reveal key information concerning fusion. The relation between the topography of the underlying PES and the excitation energy of the compound nucleus remains an open question which should be addressed.

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Fission Fragment Angular Momenta: Generation and Observation

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The fission fragment angular momenta can generally be expressed in terms of the six normal modes of rotation for a binary system and different models populate those modes to different degrees reflecting the mechanisms involved.

For the Nucleon Exchange mechanism, the characteristic time scales for the various modes are discussed, leading to the expectation that the wriggling mode is fully populated, while twisting is unlikely to play a major role; bending probably has some presence which increases with mass asymmetry.

Subsequently it is discussed how information about the fragment spin directions can be determined by observation of E2 emissions in even-even nuclei. It is shown how the yield ratio $Y(0)/Y(90)$ in a modern Wilhelmy-type experiment can reveal the degree of twisting, a measurement that could be readily carried out now. Furthermore, with a view towards the future when the required technology has been developed, it is illustrated how the relative role of positive modes (wriggling) and negative modes (bending and twisting) can be determined by measuring the opening angle between two $E2$ photons whose helicities are also identified.

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Experimental fission study by multi-nucleon transfer reaction at JAEA

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The multinucleon transfer (MNT) reaction is not only expected as one of viable reactions to produce super-heavy nuclei with more neutrons [1], but also is a powerful tool to populate a variety of nuclides with a wide range of exciting energies. We have developed a measurement system for the MNT-induced fission and performed experiments using actinide targets and ^{18}O beams at the Tokai tandem accelerator facility of Japan Atomic Energy Agency [2,3,4,5,6]. The system, consisting of a silicon ΔE-E telescope and multi-wire proportional counters for detection of ejectiles and fission fragments, enable to measure fission observables such as fission-fragment mass distributions, fission-fragment angular distributions and so on.

In this presentation, we will show details of the measurements and the data analysis, and discuss on the systematics of the fission-fragment mass distributions and the angular momentum transferred in the MNT reaction obtained from the fission-fragment angular distributions.

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Excitation energy dependency of the low-energy fission dynamics: Probing through prompt gamma-ray spectroscopy

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Low-energy fission is one of the most captivating region of research since it provides an ideal ground to study the influence of both classical (macroscopic) and quantum (microscopic) world simultaneously on a physical system. The potential energy surface (PES) of a fissioning compound nucleus at low excitation energy indicates the existence of multiple valleys and ridges arising due to the superposition of classical liquid drop model (LDM) and quantum shell structure effects. Different fission barriers provide different paths (or modes) to the nucleus for fission, resulting in various distributions with multiple peaks coexisting simultaneously in a fissioning system [1]. According to the Random Neck Rupture Model (RNRM) [2], the lighter actinides are primarily composed of three distinct fission modes, namely - two asymmetric modes: standard I (S1) and standard II (S2), and one symmetric superlong (SL) mode. These modes have been found to be highly dependent on the fissioning system and the interplay of the underlying shell structure of the corresponding fission fragments. However, the present knowledge lacks a conclusive understanding of the dependency of different fission modes as a function of excitation energy. Till date, the major difficulty in such measurements arise from the technical limitation in measuring highly precise fission fragment mass distribution (FFMD). However, the difficulties can be resolved by employing the novel approach of fission fragment spectroscopy (FFS) [3].

In the present study, the role of excitation energy (E_{ex}) on the aforementioned various low-energy fission modes in the compound nucleus, ^{236}U* have been investigated by employing FFS measurement technique [4]. The concerned fissioning system has been produced at two different values of E_{ex} following the fission reactions: ^{235}U(n$_{th}$,f) and ^{232}Th(α,f). The experimental results have been interpreted on the basis of survival of proton- and neutron-shell closures and multichance fission phenomena [5]. Recently, the role of E_{ex} on the the relative probabilities of S1 and S2 fission modes have been studied for the low-energy fission reaction, ^{232}Th(p,f) [6]. In contrary to our present understanding of the fission dynamics, signature of a distinct feature in the behaviour of different fission modes with increase in E_{ex} has been found from the present investigation. The detailed results and interpretations will be presented during the conference.

The help and cooperation received from the Indian National Gamma Array (INGA) and EX-ILL collaborations are duly acknowledged. Help and support from the Cyclotron operation staffs at VECC, Kolkata, as well as the reactor operation staffs at ILL, Grenoble are thankfully acknowledged. Financial assistance received from BRNS, Govt. of India (Project Sanction No.: 37(3)/14/17/2016-BRNS), SERB, Govt. of India (File No.: CRG/2021/004680), and IUAC, New Delhi, India (Project Code No.: UFR71344) is gratefully acknowledged.

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Nuclear fission of neutron-rich nuclei based on a dynamical model toward r-process calculation

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Nucleosynthesis by the rapid-neutron-capture process, the so-called r-process, represents for cosmic origin of the heaviest elements (e.g., gold and uranium) beyond the iron-group peak. Although several astrophysical scenarios that bring about the r-process have been proposed, the mechanism itself is not completely understood. One of the main reasons is large uncertainties arising from the nuclear-physics properties of very neutron-rich nuclei, e.g., neutron capture rates and decay half-lives. Nuclear fission plays a key role in the termination of the r-process path toward heavier elements if the r-process flow is strong enough to reach actinides or transactinides. The effects of fission are also significant to shape the r-process abundances due to the fission recycling in which fission products become seed nuclei ($A < 200$) for the next r-processing during a single nucleosynthesis process. Besides those effects, fission also has a key role as the heating source of kilonovae at late times ($\sim$ 10 days to months), of electromagnetic transients of neutron star mergers [1,2]. A sign of fission heating may have been observed in the light curve of the kilonova associated with the gravitational wave, GW170817. The precise understanding of fission becomes much crucial in the era of gravitational astronomy. However, experimental data on nuclear fission are not available in the neutron-rich region. From this respect, we calculated in this study the fission fragment mass distributions (FFMDs) of very neutron-rich nuclei.

We employed Langevin equations to investigate fission based on the dynamical model, widely adopted in the study of low-energy fission [3]. We calculated the charge distribution based on the unchanged charge distribution (UCD) assumption. The charge distribution (charge density) remains unchanged during the whole fission process, i.e., the charge density of the compound nucleus is maintained. By combining Langevin calculations with a statistical model implemented in the CCONE [4], we calculated independent yields and prompt neutron emissions. Excitation energy partitions for two fragments are determined by the anisothermal model [5].

In this study, we focused on the transition of fission mode from asymmetric to symmetric in neutron-rich isotopes, which has been suggested in recent experiments for fermium isotopes. In the calculated FFMDs in neutron-rich uranium, the dramatic change of fission mode was observed with increasing mass number. Such a systematic behavior can be significant to shape the final abundances of the r-process calculations. The calculated prompt neutron emission multiplicity reproduced the sawtooth structure of experiment data. Our results, including further improvements, are expected to contribute to understanding the r-process.

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Low-energy fusion hindrance in medium-light systems

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The existence of hindrance in the fusion of light systems is critical for a variety of stellar environments and the accurate knowledge of sub-barrier fusion cross sections is essential for valid simulations of the nucleosynthesis processes. Moreover, heavy-ion fusion reactions give fundamental information on the quantum tunnelling of many-body systems where several intrinsic degrees of freedom are concurring [1].

The energy threshold of hindrance is often characterised by a maximum of the astrophysical S factor with decreasing energy. This phenomenon is regarded as an interesting link between heavy-ion fusion and astrophysics.

The existence of the hindrance effect and the underlying physical motivations are under debate, especially for the light systems relevant to astrophysics. It has been pointed [2] out that the Pauli exclusion principle influences the ion-ion potential. As a consequence, low-energy fusion hindrance is produced because the Coulomb barrier turns out to be thicker and higher.

Our group recently has performed systematic investigations on the fusion of several medium-light systems with the purpose of establishing a reliable basis for the extrapolation to the lighter cases of astrophysical interest. I will present the results obtained for ^{12}C + ^{24,26}Mg [3] and ^{12}C + ^{30}Si [4], where the fusion excitation functions have been measured down to a few μb (see Figure). Hindrance is observed in all cases, however, with differing features, so extrapolating to lighter systems is not straightforward. Additionally, almost identical oscillations are observed in the logarithmic slopes of the ^{12}C + ^{24,26}Mg excitation functions in the sub-barrier energy range, which complicates identifying the hindrance threshold in those two cases (see the right panel of the Figure). The comparison with the results of coupled-channels calculations for all systems will be shown.

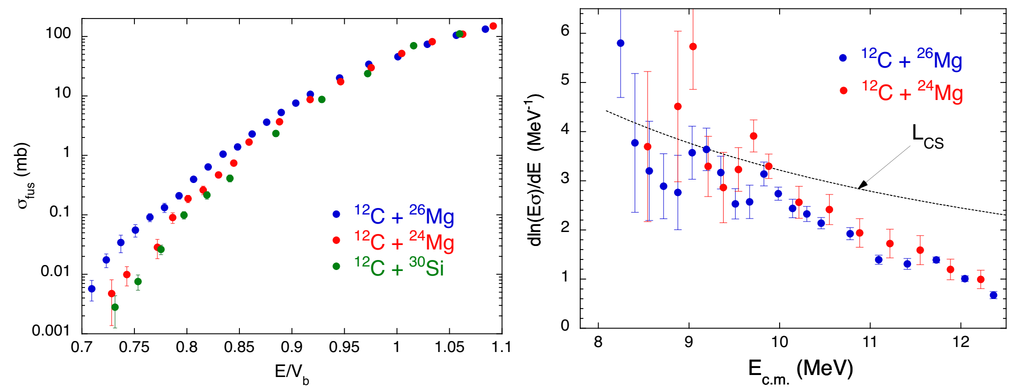

FIG. 1: *(left) Fusion excitation functions measured for ^{12}C + ^{24,26}Mg, ^{30}Si. (right) Logarithmic slopes for the first two systems.*

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Investigation of deep sub-barrier fusion in asymmetric systems

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Study of fusion reactions is important for synthesis of heavy elements as well as for understanding the process of nucleosynthesis in the stellar environment. Enhancement of fusion cross sections below the interaction barrier has been quite successfully explained by coupled-channels methods. However, extending the measurements to deep sub-barrier energies revealed a steeper descent of the fusion cross sections which could not be explained by standard coupled-channels calculations. The phenomenon, termed as *fusion hindrance*, was first reported for an intermediate-mass symmetric system [1]. Since then, a large number of heavy-ion and light-ion induced fusion reactions have been studied to understand the dynamics of fusion deep below the barrier [2].

However, fusion hindrance has been studied only for a handful of asymmetric systems. The reasons stem from the difficulty in measurement of very low fusion cross sections using recoil separators [3]. We report new measurements of fusion excitation functions for the systems ^{16}O+^{116}Cd and ^{16}O+^{142}Ce. The choice of the target-projectile systems is decided by the need to measure fusion data for asymmetric systems and compare the same with the data for existing symmetric systems having nearly similar value of the ζ parameter, characterizing the size of the colliding system. Here, $\zeta = Z_{\rm p} Z_{\rm t} \sqrt{\mu}$, where $Z_{\rm p}$ and $Z_{\rm t}$ are the atomic numbers of the projectile and the target, respectively, and μ is the reduced mass. The systems have been chosen such that all transfer channels have negative Q-value. This is to reduce the influence of these channels on fusion. The experiment has been performed using the Heavy Ion Reaction Analyzer (HIRA) [4]. We have extracted the logarithmic derivatives of the energy-weighted cross sections and the astrophysical S-factors. Experimental results have been reproduced well by coupled-channels calculations.

Additionally, to investigate the effect of entrance channel mass asymmetry on fusion hindrance, we have compared our results for ^{16}O+^{116}Cd ($\zeta = 1440$) with that of symmetric systems ^{36}S+^{48}Ca ($\zeta = 1451$) [5] and ^{32}S+^{48}Ca ($\zeta = 1402$) [6]. Similarly, the results for ^{16}O+^{142}Ce ($\zeta = 1760$) have been compared with that of ^{28}Si+^{64}Ni ($\zeta = 1730$) [7] and ^{40}Ca+^{40}Ca ($\zeta = 1789$) [8].

Appearance of background events at the focal plane of the spectrometer restricted our measurements down to 12.5% below the barrier, for both ^{16}O+^{116}Cd and ^{16}O+^{142}Ce. We have extrapolated our results beyond the threshold energy for fusion hindrance, obtained from the systematics [9,10]. From our measurements we conclude that the present asymmetric systems as well as the corresponding symmetric systems show hindrance phenomena and this feature is independent of the entrance channel mass asymmetry.

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Beta-delayed fission of laser-ionized isomers in ^{188}Bi and recent β-delayed fission experiments at ISOLDE (CERN)

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A unique dedicated program to study β-delayed fission (βDF) was initiated by our collaboration more than a decade ago at the ISOLDE (CERN) [1,2,3]. In the process of βDF, a β decay of precursor populates excited states close to the top of the fission barrier in the daughter nucleus, which then fissions. The Q_β value, typically $\lesssim$10 MeV, limits the achievable excitation energy and thus βDF represents the so-called low-energy fission, which is sensitive to the nuclear structure. It allows us to investigate fission properties of exotic isotopes, for which other low-energy fission studies would not be feasible with the current experimental techniques [2,4]. Moreover, βDF is important for the nucleosynthesis r-process, where alongside other types of fission, it is responsible for r-process termination and fission recycling (see for example [5]).

This contribution will report on our recent βDF investigations of the low-spin and high-spin isomers in ^{188}Bi at ISOLDE [6]. The key goal was to study βDF properties of the two states separately, thus to probe the scarcely-known spin dependence of fission. To obtain isomerically-pure beams, we employed selective power of Resonance Ionization Laser Ion Source (RILIS). Results from this measurement will be presented, including partial half-lives of βDF for each isomer and multimodal mass distribution of fragments for the fission of ^{188}Pb (β-decay daughter of ^{188}Bi). Findings will be compared with theoretical calculations of fission fragment mass distribution.

Our most recent measurements will be briefly presented as well. We searched for βDF in ^{178}Au, presumed to be located in the new region of asymmetric fission discovered in the vicinity of ^{180}Hg [1,2]. Moreover, we investigated neutron-rich ($A = 230 - 234$) actinium isotopes in an attempt to move βDF studies closer to the region of r-process path. Preliminary results from these experiments will be discussed in connection to βDF partial half-lives systematics.

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Probing the new island of asymmetric fission in the ^{180}Hg region by means of fusion-fission reactions

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Nuclei in the neutron-deficient region around ^{180}Hg$_{100}$ are different from the actinides traditionally used for fission studies, from the viewpoint of their fission barriers, separation energies and proton-to-neutron ratios. Fission properties of these neutron-deficient sub-led nuclei were expected to be similar to those of their heavier isotopes around the stability line, known to fission symmetrically. The picture changed drastically in 2010, when the asymmetric fission-fragment mass distribution of the ^{180}Hg nucleus was discovered in a β-delayed fission of ^{180}Tl in a dedicated experiment at ISOLDE (CERN) [1]. This much unexpected observation promptly attracted extensive attention from both theory and experiment. That led to several important conclusions, first of all regarding the importance of the microscopic (shell) effects and their dependence on the excitation energy. Moreover, existence of a new and extended region of asymmetric fission was predicted for neutron-deficient Re-Pb nuclei [2].

In order to investigate fission properties of nuclei in, and the extension of, this predicted region, a dedicated experimental campaign of prompt fusion-fission studies was initiated at the JAEA (Japan) [3]. In the framework of this program, we recently investigated, at different beam energies, fission properties of $N = 100$ nuclei ^{176}Os, ^{177}Ir, ^{178}Pt and ^{179}Au obtained from complete fusion-fission reactions of ^{35}Al and ^{36}Ar beams with ^{141}Pr, ^{142}Nd and ^{144}Sm targets [4,5], as well as fission of ^{178}Hg produced in the inverse-kinematics reaction ^{124}Xe + ^{54}Fe at GANIL [6].

The correlated fission-fragment mass and kinetic energy data have shown that the obtained mass distributions are composed of both asymmetric and symmetric fission modes. Modes parameters extracted from experimental data by different analysis approaches indicate $A_{\mathrm{L}} \approx 80$ and $A_{\mathrm{H}} \approx A_{\mathrm{CN}} - 80$ as fragments hosting the asymmetric mode in the studied nuclei. The dominant role of protons in the light fragment, average fragment N/Z ratio and prompt-neutron multiplicity could be derived, for the first time in the region, from the GANIL experiment [6], that allowed to identify the $A_{\mathrm{L}} \approx 80$ nucleus as ^{80}Se, this assignment supported by the $Z = 34$ and $N = 46$ deformed shells predicted by theory [7]. Both symmetric and asymmetric modes are found to exhibit close average total kinetic energies, which signifies virtually identical scission-point elongations, in contrast to actinides. In addition, analysis of the mass distribution width made for Os–Hg nuclei along the $N = 100$ line, at comparable temperature and angular momentum values, reveals an inverse parabolic-like behavior for width with atomic number, which paves the way for borders assessment for the new island of asymmetric fission.

The talk will also give a short overview of the experimental efforts made in fusion-fission reactions so far in the ^{180}Hg region and will highlight the current achievements and problematics.

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Systematic Measurements of Mass-Asymmetric Fission in the Pre-actinides: ^{144}Gd to ^{212}Th

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The discovery in 2010 by Andreyev et al. [1] of mass-asymmetric fission induced by the β-delayed fission of ^{180}Tl — fission of ^{180}Hg — demonstrated for the first time the existence of mass-asymmetric fission outside the actinides. The analysis of this data showed a novel mass-asymmetric fission mode not seen in the actinides, with peaks near $Z = 35, 45$. Being a single measurement neither peak could be considered dominant in the reaction, and many recent studies of the fission of nearby nuclei have demonstrated correlations with both of these features [2–4].

In this talk I will present the results of a systematic study of heavy-ion induced fission extending far below the actinides, down to $Z = 64$. The measurements were performed at the Heavy Ion Accelerator Facility at the Australian National University where beams of ^{32,34}S were used to form neutron-deficient isotopes at a similar N/Z ratio (1.28 − 1.34) from ^{144}Gd to ^{212}Th (Z = 64 to Z = 90). Notably, we are able to demonstrate conclusively the existence of a mass-asymmetric fission mode in all systems studied. Greatly extending the region of the nuclear chart where mass-asymmetric fission has been observed.

Utilising recently published techniques for *simultaneous* fitting of both the measured mass and kinetic energy of the fission fragments [2] we present evidence of a smooth transition of the main mass-asymmetric fission mode from the deformed shell effects near $Z = 34, 36$ for the isotopes below Pt and to $Z = 44, 46$ above. Furthermore, the data suggest the consistent presence of a second mass-asymmetric mode which appears correlated with $Z = 28, 30$. Fig. 1 shows the extracted Z centroids of the fission modes as a function of the atomic number of the compound nucleus.

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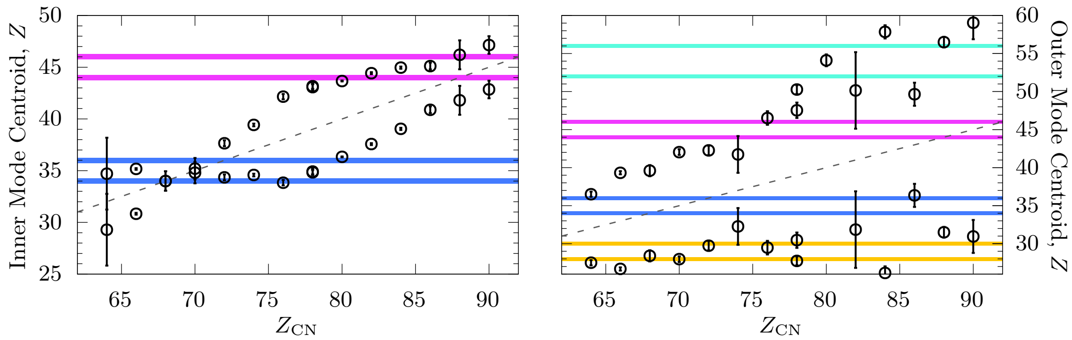

FIG. 1: The fitted centroids of the inner and outer mass-asymmetric fission modes are converted to proton number via the unchanged-charge distribution assumption. The highlighted regions correspond to known shell structure effects. The dashed line indicates the position of the symmetric mode for each system.

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Fission dynamics with five-dimensional Langevin equation using generalized Cassini ovals

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The generalized Cassini ovals provide an effective shape parameterization for describing the configurations of fissioning nuclei [1]. In this parameterization, five deformation parameters α, α_1, α_3, α_4 and α_6 are crucial for representing main nuclear fission coordinate, mass asymmetry, shape asymmetry, quadrupole deformation of fragments and octupole deformation of fragments, respectively. Recently, the fragment mass distribution of super-heavy nuclear fission was estimated using a static model that treats the potential in the $\{\alpha_1, \alpha_3, \alpha_4, \alpha_6\}$ coordinate space fixed at $\alpha = 0.98$ corresponding to the scission line [2]. In contrast, to study the fission process using dynamical approaches, all five deformation parameters $\{\alpha, \alpha_1, \alpha_3, \alpha_4, \alpha_6\}$ must be incorporated. In this study, we solve the five-dimensional (5D) Langevin equation for actinide nuclei.

As an example of the 5D calculation results, the fragment mass distributions for the spontaneous fission of Fm are shown in Fig. 1. The 3D $\{\alpha, \alpha_1, \alpha_4\}$ and 4D (3D + α_6) results are also presented to understand the roles of α_3 and α_6. In the case of ^{258}Fm, the distributions with a high peak at symmetric fission are obtained in 4D and 5D calculations. This is attributed to the fact that the fragment shape of super-short symmetric fission can be described with the addition of α_6, as demonstrated by the average shapes at scission in Fig. 1. Furthermore, by considering shape asymmetry α_3 in the 5D calculation, the peak of the 3D and 4D distributions around $A_H = 153$ disappears, resulting in a single peak distribution dominated by the symmetric fission. On the other hand, in the case of ^{256}Fm, the 5D result shows the distribution with two separate peaks indicating that asymmetric fission is dominant, which was not obtained in the 4D calculation. The 5D average shape presents a combination of a sphere and a prolate spheroid. This is considered to be due to the inclusion of α_3, strongly reflecting the shell effect of the double magic nucleus ^{132}Sn. From these discussions, it is concluded that the 5D $\{\alpha, \alpha_1, \alpha_3, \alpha_4, \alpha_6\}$ parameter set is essential for systematic Langevin calculations using the generalized Cassini ovals. In this presentation, we report on the fission fragment mass and total kinetic energy distributions for various actinide nuclei.

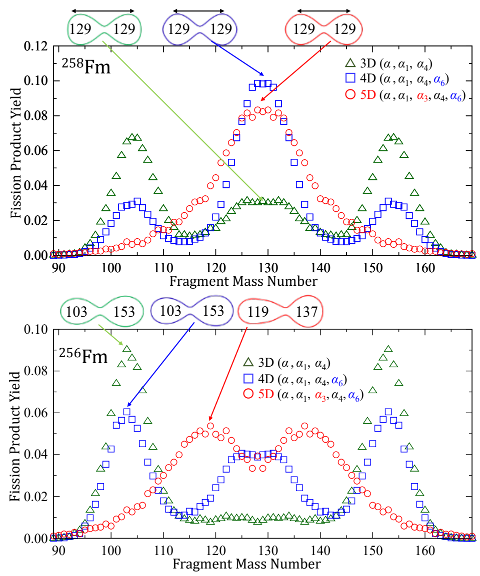

Figure 1: Fragment mass distributions for the spontaneous fission of ^{258}Fm (top) and ^{256}Fm (bottom). Triangles give 3D, squares give 4D, and circles give 5D results. The average scission shapes corresponding to the peak positions of the distributions are also shown.

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Microscopic description of spontaneous fission in nuclear energy density functionals

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Nuclear fission plays an important role in various phenomena such as synthesis of superheavy elements and r-process nucleosynthesis [1]. Spontaneous or low-energy fission involving many-body quantum tunneling is an important subject for developing a microscopic theory of large-amplitude collective motions. The nuclear energy density functional (EDF) theory can be one of the microscopic theories for providing a microscopic description of fission dynamics [2]. Recent EDF-based works on spontaneous fission employ the semiclassical WKB approximation for many-body quantum tunneling [3]. In WKB, with a suitable choice of collective variables, the collective potential energy has been calculated from a constrained EDF method, while the collective inertia has been calculated with the so-called cranking approximation. The cranking approximation needs a small computational cost because it neglects dynamical residual effects including time-odd terms of EDF. As a result, the collective inertia by the cranking approximation significantly deviates from the correct one. Since a huge computational cost is necessary to evaluate dynamical residual effects, only a few works have included those effects in the collective inertia derived within local quasiparticle random-phase approximation (QRPA) in the collective Hamiltonian method [4,5].

To overcome such difficulties, we have developed a framework to evaluate collective inertia in the local QRPA with Skyrme EDF. To avoid huge computations for solving the QRPA equation, we employ the finite amplitude method (FAM) [6] that enables us to evaluate response functions of an external one-body field with relatively small computations. Recently, we constructed the FAM with Skyrme EDF in three-dimensional coordinate [7], and applied the FAM to calculate the collective inertia along a spontaneous fission path in actinide nuclei [8].

In this contribution, we will show the results of the collective inertia along the fission path in actinide nuclei and the importance of the dynamical residual effects on the collective inertia. Then, we will discuss the impact on how correct evaluation of the collective inertia affects observables on spontaneous fission. We will further discuss an isotope dependence of the collective inertia and fission half-life in Fm isotopes.

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Microscopic description of induced fission in a configuration-interaction approach

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Since the discovery of nuclear fission nearly 80 years ago, many phenomenological models have been proposed and have successfully explained the observed behaviors. The statistical models based on the Hauser-Feshbach theory and the dynamical models based on a transport theory are good examples. In contrast, a microscopic understanding of induced fission has still been far from complete. This is due, in part, to the difficulty of a theoretical treatment of the large amplitude collective motion and the associated numerical complexity.

In this study, we will employ a configuration-interaction approach to model induced fission reactions at barrier-top energies. The model space is constructed based on particle-hole excitations of reference configurations labeled by deformation parameter Q, which can be seen as an extension of the Generator Coordinate Method (GCM) ansatz [1]. Then employing the non-equilibrium Green function method [2], we will calculate the branching ratio between the fission and the capture process.

At first, we shall apply our approach to a schematic uniform spacing model [3]. In induced fission, a mother nucleus is highly excited, and many particle-hole excited states should be included in the configuration mixing. Due to the huge number of included configurations, it is useful to examine fission dynamics based on this simple model. The Hamiltonian includes as the residual interaction the diabatic interaction that connects similar orbitals at different deformations, the pairing interaction between identical nucleons, and a schematic off-diagonal neutron-proton interaction. We will analyze the role of these interactions in the barrier transmission mechanism by focusing on how they affect the branching ratio. Furthermore, we will discuss the insensitivity of the branching ratio to the final-state scission dynamics, which is assumed in the well-known Bohr-Wheeler theory [4].

Subsequently, we will extend the model to a more realistic case and generate reference states by solving Skyrme-Hartree-Fock equation. In this case, we will restrict the particle-hole excitation to the seniority zero configurations for simplicity. As in the uniform model, we will discuss the role of residual interactions. Additionally, by introducing flux among configurations, we will analyze how it spreads among many configurations and clarify the microscopic process in induced fission.

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Interplay of breakup and fusion in near-barrier collisions of weakly-bound nuclides

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Light, weakly-bound nuclides such as ^{6,7}Li and ^{9}Be exhibit a diverse range of near-barrier reaction phenomena. Their weak binding leads to strong breakup via excitation of the continuum, but also via production of weakly-bound or unbound neighbouring nuclides via nucleon transfer [1,2]. Complete fusion is found to be suppressed by up to 35% with respect to barrier-passing model calculations [3,4], but such systems also exhibit strong *incomplete* fusion, which is correlated with cluster breakup thresholds for stable nuclides [4]. The situation for unstable nuclides is less clear. Complete fusion cross sections for ^{8}Li+^{208}Pb appear to be suppressed by 30% [5], despite the fact that the lowest cluster breakup threshold is significantly higher than in ^{6,7}Li. Conversely for unstable beryllium nuclides, the degree of fusion suppression was found to decrease with neutron richness, with the correlation between suppression and charged cluster breakup thresholds breaking down [6]. Disentangling these reaction phenomena and their complex interplay is one of the most interesting challenges in near-barrier reaction dynamics.

In this talk I will summarise recent our progress in understanding the interplay between breakup and fusion, through measurements of near-barrier ^{7,8}Li+^{209}Bi collisions made at the Australian National University Heavy Ion Accelerator Facility. For ^{8}Li [7], a diverse range of breakup modes were identified. In addition, a large yield of α-particles unaccompanied by another light charge particle was found, indicative of strong incomplete fusion. A subsequent comprehensive measurement of ^{7}Li+^{209}Bi [8] found the cross section for these unaccompanied α-particles to be consistent with previous measurements of incomplete fusion, but with an angular distribution peaked forward of those α-particles from breakup. This result is inconsistent with expectations of classical dynamical models [9], which assert a two-step mechanism for incomplete fusion of breakup followed by capture.

Together, these results strongly suggest that the dominant mechanism leading to incomplete fusion and the suppression of complete fusion is direct capture of the cluster constituents by the target. The consequences of these results for near-barrier reactions of exotic nuclides will also be discussed.

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Analysis of fusion reactions including weakly-bound nuclei

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In this study, we investigate fusion cross sections of weakly-bound nuclei around the Coulomb barrier. Specifically, we review our previous findings on the total fusion cross sections of the ^{6}He+^{209}Bi and ^{11}Li+^{208}Pb systems for showing the tendency of fusion reactions including weakly-bound nuclei. Then, we examine the impact of target nucleus deformation on the fusion reaction of the ^{15}C+^{232}Th system, where ^{15}C and ^{232}Th are a well-known one-neutron halo nucleus and deformed nucleus, respectively. Our approach involves constructing the potential between the ^{15}C and ^{232}Th nuclei using the double folding procedure, assuming that the projectile nucleus comprises the core nucleus, ^{14}C, and a valence neutron. We also consider the coupling to the one-neutron transfer process to the ^{14}C+^{233}Th configuration and show that such a calculation simultaneously reproduces the fusion cross sections for the ^{14}C+^{232}Th and ^{15}C+^{232}Th systems. Furthermore, we analyze the total fusion reaction of neutron-rich nuclei, specifically the ^{9}Li+^{70}Zn system. For this system, we construct a folding potential using the charge density distribution of the projectile and target nuclei. Our findings demonstrate that neutron transfer plays a crucial role in the fusion reactions of neutron-rich nuclei, such as ^{9}Li and ^{15}C nuclei, at energies around the Coulomb barrier.

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Exponential suppression of fusion at above-barrier energies

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The formation of superheavy elements (SHEs) by nuclear fusion is a fundamental challenge to our understanding of both experimental and theoretical nuclear physics. The fusion of heavy ions requires the dramatic rearrangement of nucleons from two separate nuclei into one nucleus, a process that can be conceptually divided into two steps: capture, and compound nucleus formation. Capture requires the system to have enough energy to overcome the electrostatic repulsion between the two nuclei, and stick together due to the attractive nuclear force. Once captured, the energy of the system is fully dissipated and shared between all the constituent nucleons. Even once captured, however, the two nuclei may reseparate before fusing to form a compact compound nucleus. This second step requires the system to achieve full equilibration in mass, shape and energy.

The thorough analysis of a number of above-barrier reactions has shown that measured capture cross sections (the sum of the evaporation residue, fusion-fission and quasifssion cross sections) are suppressed relative to single-barrier penetration calculations [1]. That work found that the suppression of capture has a near-linear dependence on entrance-channel charge product, Z_pZ_t, with suppression increasing as Z_pZ_t increases.

In order to examine the suppression of *fusion*, analysis must be made of only the fusion reaction outcomes - evaporation residues and fusion-fission. Fusion-fission, in many cases, leads to reactions outcomes indistinguishable from quasifission, and so separating the two becomes exceptionally difficult. Evaporation residue (ER) measurements are therefore the most reliable, direct experimental measurement of fusion, as ERs can only arise from the formation of the compound nucleus. Furthermore, ER formation (not just capture, or fusion) is required for SHE discovery, and so understanding the behaviour of ER outcomes is of particular importance as new SHE are pursued. One such study of ER cross section measurements forming the same compound nucleus, ^{220}Th, was performed by Hinde et al. [2]. This study examined ^{16}O, ^{40}Ar, ^{48}Ca, ^{82}Se and ^{124}Sn-induced reactions (covering $656 < Z_pZ_t < 1296$) and revealed that fusion was severely suppressed at large Z_pZ_t relative to the ^{16}O-induced reaction.

This presentation will outline the analysis of two new systems forming the same compound nucleus, ^{220}Th, and provide conclusive evidence that the ER cross section is exponentially suppressed as a function of Z_pZ_t. This exponential suppression is in contrast to the near-linear suppression of capture, indicating that the probability of forming an equilibrated, compact compound nucleus is additionally suppressed. The suppression has been quantified using only measured ER cross sections, and is thus model-free.

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Hints of quasi-molecular states in ^{13}B studied via ^{9}Li-^{4}He elastic scattering

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This presentation will report on an investigation on the possible existence of molecular resonances predicted to exist in the case of n-rich B-isotopes [1]. In particular, on the possibility that at high excitation energies, the ^{13}B nucleus could exhibit molecular type resonances with ^{4}He and ^{9}Li clusters coupled in rotational states. If such structures do exist in the compound nucleus they would be quite energy broadened. Therefore, the entrance channel of helium plus lithium reaction may be influenced by these rotational states, which nevertheless would be quite short lived. One of the most direct ways to investigate experimentally this theoretical result is study of the ^{4}He+^{9}Li elastic channel excitation function. The excitation function was measured over a broad energy range using an extended gas target at TRIUMF. Broad resonances were observed in the excitation region for ^{13}B 15 MeV $\leq E_x \leq$20 MeV. To understand the nature of such broad structures various theoretical approach were sought concerning possible reaction mechanisms for this neutron rich reaction. The most promising approach to interpret the data is within an orbiting reaction scenario.

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Measurements of fusion cross sections using an active-target Time Projection Chamber (TPC)

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The study of fusion reactions involving neutron-rich nuclei is crucial for modeling the superburst in neutron stars and understanding nuclear fusion mechanisms in reactions [1-2]. However, direct measurements of these reactions at astrophysical energies are challenging due to low cross sections and low intensities of radioactive ion beams. In order to overcome these difficulties, we conducted a study of the ^{12}C+^{12}C and ^{19}O+^{12}C fusion reactions at energies near the Coulomb barrier, using the Multipurpose time projection chamber for nuclear AsTrophysical and Exotic beam experiments (MATE TPC) [3-4]. Thanks to the TPC's exceptional tracking capability, we were able to measure fusion cross sections down to just a few millibarns using beams with intensities of a few hundred particles per second. During the study, we directly measured some complicated channels, such as the ^{12}C(^{12}C,3α)^{12}C (see Fig. 1), for the first time in the energy range of $E_{c.m.}$=9−21 MeV. Additionally, we identified various decay channels of the ^{19}O+^{12}C reaction. In this presentation, we will discuss the technical developments used in our study and present preliminary results.

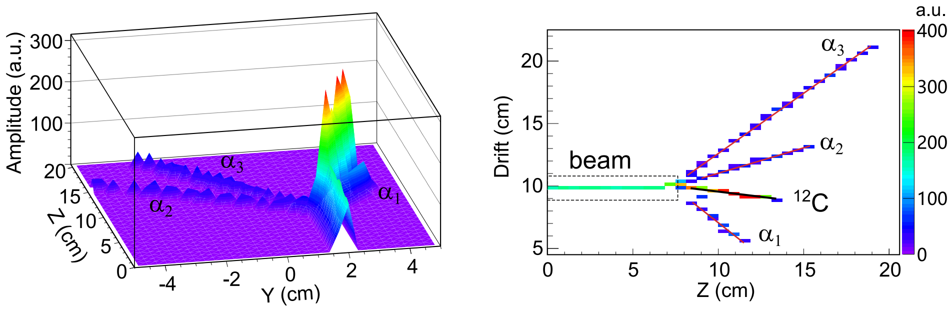

Fig. 1 (color online) A typical fusion event for ^{12}C+^{12}C reaction with three α emission. (left) Projection of the energy loss in the anode pad plane in MATE TPC. (right) Track projection in the drift plane. The straight lines are the linear fittings of the tracks identified by the Hough transform algorithm.

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Proton and neutron density distributions, asymmetry, Coulomb and symmetry-energy effects from low- to medium energy collisions of light to heavy systems

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Development of various proton and neutron densities in the course in heavy-ion collisions is one of the main points of interest for exploration of dense strongly interacting matter, especially in the supranormal region. We report results of simulation of proton and neutron density distributions in central collisions of the asymmetric ^{208}Pb + ^{212}Pb system within the beam energy range of $E_{\rm beam} \leq 800\,\mathrm{MeV/nucl}$. The results are contrasted with the outcome of our simulations of collisions of a heavy target-projectile system lighter symmetric ^{40}Ca +^{40}Ca, ^{48}Ca +^{48}Ca, ^{100}Sn +^{100}Sn and ^{120}Sn + ^{120}Sn and asymmetric ^{40}Ca +^{48}Ca and ^{100}Sn +^{120}Sn systems [1] and ^{54}Ca +^{48}Ca and ^{132}Sn +^{124}Sn [2]. The simulations are performed with the Boltzmann-Uhlenbeck-Uehling (pBUU) transport model incorporating symmetry energy from the three Skyrme forces, SV-bas, SkT3 and SV-sym34. The choice was made to explore sensitivity of the density characteristics to the symmetry energy and its slope at the saturation density of the symmetric cold nuclear matter. The Time-Dependent-Hartree-Fock (TDHF) model was applied to the heavy-ion collisions at $E_{\rm beam} \leq 40\,\mathrm{MeV/nucl}$. Time evolution of proton and neutron densities $\rho_{\rm p}$ and $\rho_{\rm n}$ was used to determine the maximum proton and neutron densities $\rho_{\rm p}^{\rm max}$ and $\rho_{\rm n}^{\rm max}$, reached during the collision. Two main finding of our work will be discussed: (i) The highest total densities predicted at $E_{\rm beam} = 800\,\mathrm{MeV/nucl}$ are of the order of $\sim 2.5\,\rho_0$ ($\rho_0 = 0.16\,\mathrm{fm}^{-3}$) for the Pb system, similar to the Sn and Ca systems; (ii) the proton-neutron asymmetry, $\delta = (\rho_{\rm n}^{\rm max} - \rho_{\rm p}^{\rm max})/(\rho_{\rm n}^{\rm max} + \rho_{\rm p}^{\rm max})$ at maximum density, is not exceeding in the majority of cases the asymmetry in the initial state of the collision at all beam energies investigated in this and the previous work. Importantly, again in line with the Ca and Sn systems, a significant part of this asymmetry has its microscopic origin in Coulomb forces.

To further make the current semiclassical tranport models more realistic, microscopy such as shell effects, and the affect of initial proton and neutron initial states will have to be consistently incorporated. Seeking ways to eliminate limitations of the present models should lead closer to relating simulations of dense matter in heavy ion collisions and in astrophysical compact objects.

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