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A comprehensive analysis of in-complete fusion reactions in $^{16}$O+$^{159}$Tb System

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In recent years a great deal of interest has generated in the study of incomplete fusion (ICF) in heavy ion interactions [1], specially at low energies that too below 10 MeV/n. At these energies above the Coulomb barrier, the complete fusion (CF) of projectile and target nuclei is most likely to take place and is well explained by statistical model predictions. However, the measured cross-section for the reactions involving alpha particle(s) in the exit channel is found to show enhancement over the theoretical predictions done by code PACE4. This enhancement has been attributed due to the contribution from incomplete fusion. In order to ascertain this, three distinct and complementary experiments, i.e., measurement of excitation functions (EFs) [2] using stacked foil activation technique, measurement of recoil range distribution (RRD) employing recoil catcher technique and measurement of spin distribution (SD) of heavy residues populated via CF and/or ICF employing the particle-gamma coincidence technique using the Charged ParticleDetector Array (CPDA) and Gamma Detector Array (GDA) set up, have been done for the system $^{16}$O+$^{159}$Tb. These experiments have been carried out using Pelletron accelerator at the Inter University Accelerator Centre (IUAC), New Delhi, India. The excitation functions are measured in the energy range $\approx$70-95 MeV while the RRD measurements are done at 90MeV incident energy. The spin distributions are measured [3] at four distinct energies i.e., 83.5, 88.5, 93.5 and 97.6 MeV. Such comprehensive analysis for the same system is not available in literature. The analysis of excitation functions indicates significant ICF contribution for almost all the alpha emitting channels. The measurement of recoil range distribution which is most direct and irrefutable method to study ICF, based on the linear momentum transfer from the projectile to the target nucleus clearly indicate the contribution of ICF in the alpha emitting channels. The measured data has been analyzed within the framework of break-up fusion model. The measured spin distributions of the reaction residues populated via CF and ICF processes are found to have distinctly different de-excitation patterns, as expected. The analysis done indicates the observation of significant ICF contribution even at energies as low as $\approx$4-7 MeV/n. The three complimentary experiments confirm the observation of ICF and the relative contributions obtained are found to agree within 5%. Further details of the experiments and the results will be presented.

References:
Charge-clustering and weak binding in direct reactions of $^8\text{Li}$: consequences for complete fusion

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A key challenge in understanding the reactions of weakly bound nuclei is the observed suppression of above-barrier complete fusion (e.g. [1]). The mechanism causing the suppression is uncertain, especially for exotic neutron-rich radioactive nuclei, but is assumed to be related to low thresholds for breakup into charged clusters. However, the observed 30% suppression of complete fusion in reactions of the neutron-rich radioactive nucleus $^8\text{Li}$ [2] presents a puzzle: breakup into $^7\text{Li}+\text{n}$ has lowest breakup threshold, but cannot contribute to complete fusion suppression (defined as complete charge capture) as $^7\text{Li}$ retains all the projectile charge, while breakup into two or more charged particles have much higher thresholds. In studies of breakup in reactions of stable $^6\text{Li}$, $^7\text{Li}$ and $^9\text{Be}$, it has been shown that transfer to unbound states of neighbouring nuclei (“transfer triggered breakup”) forms a significant portion of the total breakup yield (e.g. [3]), but no such study has yet been performed for neutron-rich radioactive weakly bound nuclei.

Here we present the first comprehensive study of direct reactions of $^8\text{Li}$ in collisions with $^{209}\text{Bi}$, investigated at energies slightly above the Coulomb barrier using the SOLEROO radioactive beam capability at the Australian National University [4], some results of which are shown in Fig. 1. By measuring correlations between charged breakup fragments, we demonstrate (for the first time) the wide variety of breakup modes for $^8\text{Li}$, and show that breakup occurs too slowly ($>\text{few }10^{-21}\text{ s}$) to result in suppression via the commonly assumed mechanism of fast charged-cluster breakup.

This work conclusively demonstrates that this almost universally assumed mechanism for complete fusion suppression cannot be correct in reactions of $^8\text{Li}$. In doing so, we provide evidence that it is instead clustering in the ground-state that is the crucial factor in producing fusion suppression, and thus identify a new mechanism for fusion suppression. This motivates further studies of fusion suppression in neutron-rich nuclei.


FIG. 1: Reconstructed Q-values [panels (a),(b)] and differential cross-sections [panels (c)-(e)] demonstrating the variety of direct reactions in $^8\text{Li} + ^{209}\text{Bi}$. 
Effects of non-zero spin in sub-barrier fusion involving odd mass nuclei: the case of $^{36}S + ^{50}Ti, ^{51}V$

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Sub-barrier fusion of the two systems $^{36}S + ^{50}Ti, ^{51}V$ has been measured at the Laboratori Nazionali di Legnaro (INFN). The purpose of the experiment was to investigate the possible effect of the non-zero spin of the ground state of the $^{51}V$ nucleus on the sub-barrier excitation function, and in particular on the shape of the barrier distribution. No previous data were available for these two systems near and in particular on the shape of the barrier distribution.

The CCFULL code [2] has been modified so that one can include the $^{51}V$ excitations. Preliminary calculations have been performed where we have included the $2^+$ excitation in $^{36}S$ as well as the couplings to the $5/2^-, 3/2^-, 9/2^-$, and $3/2^+$ states in $^{51}V$. 8 transitions among those states in $^{51}V$ are known experimentally, and we have used this information [3]. Fig. 1 shows the experimental excitation functions and barrier distributions, together with CCFULL calculations. From the measured B(E2) values, the sign of $\beta$ cannot be determined. For the couplings from the ground state to the $5/2^-, 3/2^-, 11/2^-$, and $9/2^-$ states, we have fixed the sign assuming the weak coupling scheme (the core $2^+$ with one proton in the $1f_{7/2}$ shell). We could not fix the sign for the other transitions, but we found that the sign is not very important (the shape of the barrier distribution does not change much even when using the opposite sign).

The barrier distribution for $^{36}S + ^{50}Ti$ looks indeed very similar to the barrier distribution for $^{36}S + ^{51}V$. This would indicate that 1) the low-lying levels in $^{51}V$ can be interpreted in the weak-coupling scheme, that is, $^{51}V (I) = ^{50}Ti (2^+) \otimes (1f_{7/2})$ (see Ref. [4]) and 2) that the extra proton in the $1f_{7/2}$ shell does not have any significant influence on sub-barrier fusion behaviour. A small difference between the two barrier distributions might be observed around 51-52 MeV (see lower left panel of the figure) but it would not be easy to have good data for fusion barrier distribution in this region. As a perspective, a measurement of the quasi-elastic barrier distribution may be considered to access the difference in this energy range.

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Fig. 1: Excitation functions and fusion barrier distributions of $^{36}S + ^{50}Ti, ^{51}V$, compared with the CC calculations described in the text.
Suppression of fusion by energy dissipation in heavy ion collisions

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The formation of new superheavy elements through heavy ion fusion reactions is a topic of great interest in nuclear physics. Not only it is an extremely challenging experimental task but also important work to make a self-consistent model to describe the fusion process and give an insight into the formation of the next heavy element.

A discrepancy between experimental data and theoretical fusion cross sections has been found, particularly at energies above fusion barrier by using standard fusion models such as coupled-channels calculations [1]. A significant contribution of deep inelastic collisions (DICs) has been observed through a range of experiments exploring heavy ion reactions. Thus it was suggested that an increase in the contribution DICs might be responsible for the enhancement of fusion suppressions, since DICs lead to energy and angular momentum dissipation [2, 3].

The work being presented here aims to investigate on factors leading to fusion suppression and explore potential implications of the role energy dissipation plays in heavy ion reactions.

To probe energy dissipative processes, we have been conducted a series of experiments with a range of projectiles impinging on fissile targets at beam energies from well below to above fusion barrier. A systematic study of fusion-fission, quasifission, and transfer fission processes has been achieved through analysis of their kinematic properties and mass-angle distributions (MADs).

From this work, we found that an increasing proportion of quasifission yields has been identified from the presence of strong mass-angle correlations in observed MADs with increasing the charge product. In addition, a significant contribution of transfer-induced fission has been observed, indicating an occurrence of energy dissipative processes. This observation provides important evidence supporting the idea that DICs should be taken into account in models describing the fusion process in heavy ion reactions.

di-Omega from lattice QCD

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In recent years, there is a renewed interest in the dibaryons due to exclusive measurements in hadron reactions as well as the direct measurement in relativistic heavy-ion collisions. In this talk, we will present the result of the dibaryon searches from lattice QCD. Particularly we focus “Most strange dibaryon”, which is composed of two $\Omega$ baryons. We will show the result of $\Omega$-$\Omega$ interaction in the $^1S_0$ channel at almost physical point and show that it leads to a shallow bound state. We may talk about the Delta-Delta interaction in the $^7S_3$ channel in the case of the heavy pion mass. In the interaction, there appears a deep bound state that is observed as a resonance of two-nucleons in experiment by CELSIUS/WASA Collaboration.

References

p–p, p–Λ and Λ–Λ femtoscopy in pp and p–A collisions

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Femtoscopy is a method relating particle correlations to their emission source and interaction potential. Applying this technique to a small collision system, such as pp, has the advantage of probing the inner part of the interaction potential. In order to allow for an accurate determination of the correlation function for small sources, we have developed a new C++ analysis tool called "Correlation Analysis Tool using the Schrödinger equation" (CATS), which will be presented in this talk.

We also present ALICE results on baryon–baryon correlations obtained from the RUN 2 operation of the LHC in pp collisions at 13 TeV and p-Pb collisions at 5.02 TeV. The statistics of RUN 2 data provides a higher precision in the analysis of the p–p, p–Λ and Λ–Λ correlations. Thanks to ongoing collaborations with theory groups working on chiral and lattice calculations, we are in the position to compare the predicted correlation functions with the experimental data.

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Studying the p-Ξ− and p-K interactions with femtoscopy in pp and p-Pb collision systems at ultrarelativistic energies with ALICE

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Recent ALICE studies showed great promise in using femtoscopy to study baryon-baryon interactions. Small collision systems, like pp and p-Pb, proved to be particularly sensitive to the short-ranged strong potentials. In our previous analyzes we have developed new femtoscopic tools that allow translations of the potentials or wave functions predicted by theory into correlation functions between particle pairs, which is the experimentally accessible observable of femtoscopy.

In this presentation we will show the latest results of p-Ξ− analysis in p-Pb collisions at 5.02 TeV. The high-quality data allows us to probe the effect of the strong interaction, in particular we are able to test lattice calculations performed by the HAL QCD collaboration.

The second focus of the presentation is on the analysis of p-K correlations obtained in pp collisions. The ALICE data provides a statistically rich data sample, which allows to test the interaction with an unprecedented precision. The p-K+ channel is much easier to model by the theory, therefore we use this channel as a benchmark. On the other hand, the p-K− interaction involves absorption effects and can couple to n-K0. The opening of this coupled channel, difficult to disentangle in scattering experiments, can instead be studied in details in femtoscopic analyses.
Precise measurement on hypertriton and antihypertriton masses with the STAR
Heavy Flavor Tracker

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The Hyperon-Nucleon (YN) interactions play an important role in understanding the strong interaction. It is suggested that alternative YN couplings can be a possible solution to the recent observations of neutron star exceeding two solar masses, the so-called “hyperon puzzle”. A precise measurement on masses of hypertriton and antihypertriton can enrich our knowledge on YN interactions.

In this talk, we will present the first precise measurement of both hypertriton and antihypertriton masses in heavy-ion collisions at STAR with the Heavy Flavor Tracker (HFT). Hypertritons and antihypertritons are reconstructed through both two-body ($^3$He + π$^-$) and three-body (p + d + π$^-$) decay channels using the high-statistics data collected in 2014 and 2016 Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The measured masses will be used to extract the binding energies for hypertriton and antihypertriton. Physics implications on the understanding of YN interactions will be discussed.
Nuclear structure and dynamics from ab initio theory*

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In recent years, significant progress has been made in ab initio nuclear structure and dynamics calculations based on input from QCD employing Hamiltonians constructed within chiral effective field theory. One of the recently developed approaches is the No-Core Shell Model with Continuum (NCSMC) [1,2], capable of describing both bound and unbound states in light nuclei in a unified way. I will present latest NCSMC calculations of unbound nuclei such as $^7$He, $^9$He and $^{11}$N and highlight the role of chiral NN and 3N interactions. Further, I will present our ongoing calculations of the astrophysical relevant $^6$Li(p,γ)$^7$Be and $^{11}$C(p,γ)$^{12}$N radiative capture. Finally, I will discuss polarization effects in the $^3$H(d,n)$^4$He fusion and its mirror reaction $^3$He(d,p)$^4$He.


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Cluster configuration effects in the elastic scattering of Boron isotopes $^8B$, $^{10}B$, $^{11}B$ and $^{12}B$ on $^{58}Ni$ and $^{10}C$ on $^{208}Pb$.

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Correlations of the valence particles and the strong coupling with the continuum can significantly distort the shell structure as well as the collective properties of weakly bound exotic nuclei. Angular distributions for the elastic scattering process using these nuclei as projectiles may contain effects due to these exotic configurations [1]. For exotic nuclei, those processes introduce also characteristic dynamic polarizations (attractive or repulsive) in the optical potential, which are not present in the case of stable projectiles. In this contribution I will discuss on the cluster configuration effects in the angular distributions data for the elastic scattering at energies close to the barrier for boron isotopes $^8B$, $^{10}B$, $^{11}B$ and $^{12}B$ on $^{58}Ni$ target. The measurement for $^8B$ has been performed at University of Notre Dame, USA with the Twinsol [2,3], for $^{10,11}B$ at Tandar Laboratory, Argentina [4,5] and more recently $^{12}B+^{58}Ni$ at University of São Paulo, Brazil, using the RIBRAS system [6]. The discussion will be based on the optical potential and coupled channel calculation analysis, where the different configurations of the boron isotopes, $^8B=^7Be+p$, $^{10}B=^6Li+\alpha$, $^{11}B=^7Li+\alpha$ and $^{12}B=^{11}B+n$, have been considered.

Also, data on the elastic scattering of $^{10}C$ on $^{208}Pb$ target at energy close to the barrier, measured at Cyclotron Institute of the Texas A&M University (TAMU), USA, will be present. The $^{10}C$ nucleus is supposed to have a Brunnian (super-borromean) structure, where the four-body cluster configuration $p+p+\alpha+\alpha$ are associated to four rings interconnected [7].

Elastic scattering of polarized protons from $^6$He at 200 $\text{A}$ MeV


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Spin-dependent interactions play essential roles in nuclear structure and reactions. One of the best-known examples is the spin asymmetry found in nucleon elastic scattering, which is a direct manifestation of the spin-orbit interaction. Large spin asymmetry gave us hint on the strength of spin-orbit coupling in the world of atomic nuclei, leading to the establishment of the shell model. Since the spin-orbit interaction is expected to work in the surface region, it is natural to expect that such interaction could be strongly modified in neutron-skin or -halo nuclei that has exotic surface structure.

In order to investigate the radial shape of the spin-orbit term of optical potential between proton and a nucleus with diffuse surface, we measured the differential cross sections (d.c.s.) and vector analyzing powers ($A_Y$) of the proton elastic scattering from $^4$He at 200 $\text{A}$ MeV at RIBF SAMURAI beamline utilizing a spin-polarized proton target specially developed for the RI-beam experiments. The d.c.s. were obtained in the highest momentum-transfer region among the existing measurements. The data are found to be exclusively sensitive to the inner part of the $^4$He density distribution, confirming existence of a solid alpha core (neutron radius = proton radius) [1]. Preliminary results of the $A_Y$ will also be presented together with recent theoretical predictions and with the case of previous measurement at a lower energy of 71 $\text{A}$ MeV [2, 3] showing largely different behavior than the case of 200 $\text{A}$ MeV.

In addition, I will introduce the future perspectives of experimental programs using the polarized proton target, such as measurements of low-energy reactions (resonant scattering [4] and ($p,d$) transfer) and nucleon knockout reactions at an intermediate energy.

References
Possible signature of tensor interactions observed via $(p,dN)$ reaction at large momentum transfer


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We report observation of new evidence for tensor interactions from $^{16}$O$(p,dN)$ measurements at 392-MeV proton under quasi-free scattering kinematics but at scattering angle relevant to neutron pick up mechanism. In our earlier work [H. J. Ong, et al., Phys. Lett. B725, 277 (2013)], we reported observation of large components of high-momentum neutrons via inclusive $(p,d)$ scattering on $^{16}$O at high-momentum transfer, and showed the ratio of the cross sections populating different final states are consistent with model that includes tensor interactions.

To investigate isospin dependence of high-momentum component, an exclusive $(p,dN)$ reaction experiment was performed recently at RCNP. The out-going deuteron were momentum analyzed by the high-resolution spectrometer GrandRAIDEN. Recoiled nucleons $N$ [$p$ or $n$] were measured by plastic scintillator telescopes and the newly developed stacked neutron detector BOS$^4$[L. Yu, et al. Nucl. Inst. A866 (2017)118], which were placed opposite to the spectrometer at angles corresponding to the recoilless condition for residual $^{14}$N. Missing mass spectra were reconstructed using the detected deuteron and nucleon momenta. For $^{16}$O$(p,dp)^{14}$N channel, the good excitation energy resolution allows to resolve several final states of the residual nuclei in the excitation energy spectra. Among the low-lying states in residual $^{14}$N, strong suppression for the lowest $T=1$ state was observed, which were observed in similar amplitudes with $T=0$ states in the other reactions; electron induced deuteron knockout reaction $(e,ed)$ [R. Ent, et al., Nucl. Phys. A578(1994)93-133] and proton induced deuteron knockout $(p, pd)$ but at lower energy [J. Y. Grossiod et al., Phys. Rev. C15(1977)843]. The missing transition to $T=1$ states suggests that high-momentum-correlated $p$-$n$ pairs in nuclei are dominant $T=0$ nature. In neutron channel $(p,dn)$, the observed cross section was found to be strongly suppressed also in comparison with $(p,dp)$ $T=0$ channel. The observed clear isospin dependences can be understood by considering the tensor interactions at large-momentum transfer. Detailed reaction analysis will be discussed also.
A relativistic Eikonal model for the dissociation of one-neutron halo nuclei at high energy

Laura Moschini\textsuperscript{1} and Pierre Capel\textsuperscript{1}

During the last decades the improvement of experimental facilities worldwide has opened up the investigation of nuclear reactions at high energy [1–3]. Going to higher energy implies the necessity to include relativistic corrections to reaction models, which is a rather new aspect for nuclear reaction theory and only few works take into account a proper kinematic and dynamical relativistic description, e.g. [4,5].

In this work we focus on the breakup of one-neutron halo nuclei. These exotic nuclei are found close to the neutron drip-line and exhibit a much larger matter radius than their isobars. This peculiar property is qualitatively understood as due to their low binding energy of one neutron, which then can tunnel far into the classically forbidden region and hence form like a diffuse halo around a compact core.

Our purpose is to apply this model to the case of the breakup of \textsuperscript{11}Be, the archetypal one-neutron halo nucleus, which was measured at 520 AMeV on \textsuperscript{208}Pb and \textsuperscript{12}C targets at GSI [1]. This is a particularly interesting case because of a discrepancy in the \(\frac{d\mathcal{B}(E)}{dE}\) calculation extracted by this GSI experiment and a RIKEN measurement of the same reaction at 69 AMeV [6].

To model this process we first assume that our \textsuperscript{11}Be projectile, seen as an inert \textsuperscript{10}Be core plus a neutron, is initially bound in its ground state. Since the reaction occurs at relativistic energy, we assume the projectile follows a straight line and maintains a constant velocity during the whole collision. These assumptions are ideal conditions to apply an Eikonal model [7]. We also make the adiabatic approximation: the collision occurs in a very brief time and the internal projectile coordinates are frozen during the process. To avoid the usual divergence of the Coulomb breakup within the Eikonal approximation, we apply the correction suggested in [8,9]. To simulate the nuclear interaction between the projectile constituents and the target, we use the Optical Limit Approximation [10].

To include the relativistic effects we apply our model in the projectile-target center-of-momentum frame [11], then we make a boost to move to the projectile center-of-mass frame of reference, where we can calculate the projectile’s breakup cross section as a function of the dissociation energy [12]. The description of the \textsuperscript{11}Be structure is provided by Halo-EFT, fitting the same structure observables obtained by \textit{ab initio} calculations [13].

Our result for the cross section of the \textsuperscript{11}Be breakup on both targets is in good agreement with the GSI data [1], considering both experimental and theoretical uncertainties. In addition, the same \textsuperscript{11}Be structure model has been found to give a good description of the reaction measured at RIKEN at intermediate energy [6,14]. The \(\frac{d\mathcal{B}(E)}{dE}\) extracted from our \textsuperscript{11}Be Halo-EFT description is in excellent agreement with the RIKEN result [6] and the \textit{ab initio} calculations [13]. Since the \(\frac{d\mathcal{B}(E)}{dE}\) constitutes the major contribution of the breakup cross section on lead target, we assume that the one we obtain, and hence the one predicted by [13], is the correct one; this should solve the apparent discrepancy between the GSI and RIKEN estimation of this value from their breakup data.

So we can conclude that with the inclusion of relativistic corrections we are able to extend the description of nuclear reactions to higher energy, thus following the pace of experimental new studies. Given these promising results, we plan to apply our reaction model to other systems: in particular we have started to look at the \textsuperscript{13}C case, which has also been measured at RIKEN and GSI energies [2,15].

\textbf{References}

In recent years a series of experiments has been carried out at LNL by using heavy ion beams delivered in inverse kinematic on medium mass targets, with reaction products detected at forward angles with the large solid angle magnetic spectrometer PRISMA [1][2]. Main focus was on the study of nucleon-nucleon correlations [3][4][5] and on the production mechanism of heavy neutron rich nuclei [6][7]. Correlation properties have been studied by measuring transfer cross sections [8] far below the Coulomb barrier, making excitation functions down to very low energies and corresponding to very large distances of closes approach where the nuclear absorption is quite small. The transfer probabilities have been extracted for the closed shell \(^{40}\text{Ca}+^{96}\text{Zr}\) [3] and superfluid \(^{60}\text{Ni}+^{116}\text{Sn}\) [4] systems. The data have been compared with microscopic calculations that incorporate nucleon-nucleon correlations, essential for the population pattern of the single particle levels around the Fermi energy. For the (well Q-value matched) one and two neutron transfer channels in the system \(^{60}\text{Ni}+^{116}\text{Sn}\) the calculations very well reproduce the experimental data in the whole energy range, in particular, the transfer probability for two neutrons is very well reproduced, in magnitude and slope, as seen in Fig.1. 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 [5] in which PRISMA was coupled to the AGATA gamma array.

Such processes have been recently extended and investigated in the \(^{206}\text{Pb}+^{118}\text{Sn}\) system in a very challenging experiment, in order to probe whether and to what extent the effect of neutron-neutron correlations in the evolution of the reaction is modified in the presence of high Coulomb fields. The experiment made use of the presently heaviest mass beams delivered by the ALPI-PIAVE accelerator complex of LNL and exploited the highest performance of the PRISMA spectrometer.

The talk will focus on the main results from these studies critically addressing the new achievements, the present problems and new challenges. These studies are especially relevant for future investigations with radioactive beams, where the pairing strength is predicted to be modified.

Fig.1 Experimental (points) and microscopically calculated (lines) transfer probabilities for the one- and two-neutron pick-up channels plotted as a function of the distance of closest approach \(D\). Open circles correspond to the angular distribution in direct kinematics [5] while full points refer to the excitation function performed in inverse kinematics [4].

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The study of nuclei far from stability is one of the most active and challenging areas of nuclear structure physics. One of the most exotic neutron-rich nuclei currently accessible to experiment is $^{40}$Mg [1, 2], which lies at the intersection of the nucleon magic number N=28 and the dripline, and is expected to have a large prolate deformation similar to that observed in the neighboring lighter isotopes $^{32,38}$Mg [3]. In addition, the occupation of the weakly bound low-$l$ $p_{3/2}$ state may lead to the appearance of an extended neutron halo. $^{40}$Mg offers an exciting possibility and a rare opportunity to investigate the coupling of weakly bound valence particles to a deformed core, and the influence of near threshold effects on collective rotational motion.

We will discuss the results of an experiment carried out at RIBF RIKEN to study low-lying excited states in $^{40}$Mg produced by a 1-proton removal reaction from a $\sim 240$ MeV/u $^{41}$Al secondary beam. $^{40}$Mg and other final products were separated and identified using the Zero Degree Spectrometer, and prompt gamma rays were detected using the DALI2 array. Two low energy gamma rays were observed, reflecting an excitation spectrum that shows unexpected properties compared to systematics along the Z=12 Mg isotopes and available state-of-the-art theoretical model predictions. A potential explanation for the observed structure involves weak-binding effects and the influence of coupling to continuum states.


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In-Beam $\gamma$-ray Spectroscopy of $^{28-30}$Ne

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It is known that neutron magic number $N=20$ disappears in the region of $Z=10-12$. Study of nuclei in this region, called "island of inversion" is important for understanding the evolution of shell structure in neutron-rich region. Currently the south boundary of the "island of inversion" is not known because available experimental data on neutron-rich F and Ne is not sufficient.

We performed in-beam gamma-ray spectroscopy of the neutron-rich $^{29}$F, $^{28-30}$Ne generated by inelastic scattering and single-nucleon removal reactions on a liquid hydrogen target at the RIKEN RI Beam Factory. Secondary beams of $^{29}$F, $^{29,30}$Ne ($\sim 230$MeV/u), generated by projectile fragmentation of a $^{48}$Ca primary beam on a beryllium target, were impinged on 15cm thick liquid-hydrogen target provided by MINOS. The de-excitation gamma rays were detected with the NaI(Tl) scintillator array DALI2 arranged to surround the target. Outgoing particles were identified by SAMURAI spectrometer.

We investigated high-lying excited states based on $\gamma-\gamma$ coincidence analysis. In case of nucleon-removal reactions of $^{29,30}$Ne, partial cross sections have also been investigated. In this presentation, we discuss the nuclear structure of these nuclei based on the experimental results.
Excitation modes and rotational moment of inertia in triaxial nuclei

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Our goal is to construct a microscopic collective model to treat large-amplitude shape fluctuation and shape mixing in nuclei, which appear in a mass region of around 100, transitional region. To treat such a shape fluctuation, the five-dimensional quadrupole collective Hamiltonian as a function of quadrupole deformation parameters $\beta$ and $\gamma$ was constructed [1], consisting of the constrained Hartree-Fock-Bogoliubov (CHFB) for the collective potential and local quasiparticle random phase approximation (LQRPA) for the inertia functions in the kinetic terms with the pairing-plus-quadrupole force. Our goal is to perform CHFB + LQRPA with Skyrme energy density functionals in $(\beta, \gamma)$ deformation space. Therefore, we need to perform LQRPA calculations on triaxial shapes (finite $\gamma$). Recently, the finite amplitude method (FAM) has been proposed as an altanative method to QRPA [2,3]. Advantages of FAM are that (1) functional derivative of Hamiltonian in the residual interactions is replaced with a finite-difference form and (2) construction and diagonalization of a huge QRPA matrix are avoided by using an iterative method. These advantages considerably reduce the computational cost, expecially for deformed nuclei [4].

With the help of FAM, we have constructed FAM with Skyrme functionals in three-dimensional coordinate [5] and have performed FAM calculations for triaxially deformed superfluid nuclei within an efficient computational cost. Then, we apply our method to local FAM at each $(\beta, \gamma)$-constrained HFB state to calculate rotational moment of inertia [6], shown in Fig. 1. In this contribution, we will present those results and discuss the phenomena of shape fluctuations in transitional nuclei.

This work was funded by ImPACT Program of Council for Science, Technology and Innovation (Cabinet Office, Government of Japan).

FIG. 1: Thouless-Valatin rotational moment of inertia $J_{TV}^{I}(\beta, \gamma)$ by local FAM.

Magnetic moment of $^{75m}\text{Cu}$ measured with a highly spin-aligned beam

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The nuclear magnetic dipole moment is one of the fundamental observables a nucleus intrinsically has, as well as allows us to catch a glimpse into the nuclear structure in terms of the wave function. A technique to orient the nuclear spin is necessary for the magnetic moment measurement. Recently a scheme of the two-step projectile fragmentation for the production of spin alignment (rank-two orientation) in RI beams was proposed [1]. The two-step scheme was employed in the magnetic moment measurement of the isomeric state of the neutron-rich nucleus $^{75m}\text{Cu}$ ($^{75m}\text{Cu}$), where low-lying states of the Cu isotopes exhibits an intriguing behavior involving the shell evolution.

The magnetic moment measurement was carried out at RIKEN RIBF. The spin alignment as large as 30% was achieved in $^{75m}\text{Cu}$ by the two-step scheme incorporating an angular-momentum selecting proton removal from $^{76}\text{Zn}$, which made it possible to measure the magnetic moment of $^{75m}\text{Cu}$.

In this presentation, the production of the spin-aligned beam will be introduced and the experimental results will be shown. Discussion on the nuclear structure of Cu isotopes, analyzed with the Monte-Carlo shell model calculation, will also be given.

Shape transition in light short-lived actinides and
the absence of Z=92 sub-shell closure

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Light short-lived actinides were produced via the fusion-evaporation reactions \(^{40}\text{Ar} + ^{187}\text{Re/186W}\), separated using the gas-filled recoil separator SHANS and implanted in a double sided silicon strip detector, where the implantation and subsequent \(\alpha\)-decay were recorded. Short-lived \(\alpha\)-radioactivities with half-lives down to tens of \(ns\) were resolved by using the fast digital pulse processing technique. Two new short-lived isotopes \(^{223,224}\text{Np}\) were identified, and the \(\alpha\)-decay chains of their short-lived daughters \(^{219,220}\text{Pa}\) were established for the first time \([1,2,3]\). The absence of the \(Z = 92\) subshell closure near \(N = 126\) is supported by the trend in the proton separation energy of \(N=130\) isotones up to \(Z=93\). Fine structure in the \(\alpha\)-decay of \(^{223}\text{U}\) was observed and the \(\alpha\)-particle energy for the ground-state to ground-state transition was revised. Onset of octuple deformation was found to emerge in \(N=131\) isotones from \(Z=88\) and shape co-existence was proposed in the \(N=129\) isotones \(^{215}\text{Rn}\) and \(^{217}\text{Ra}\) \([4]\). The systematics of the reduced \(\alpha\)-decay width along the \(N=131\) isotonic chain can be interpreted in terms of the asynchronous shape/structure evolution along the \(N=129\) and 131 isotonic chains \([4]\).

References:
Systematic investigation of nucleon knockout around $^{132}$Sn.

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Fission of $^{238}$U and fragmentation of $^{132}$Xe projectiles at relativistic energies have been used at GSI to produced medium-mass nuclei around $^{132}$Sn. The first section of the Fragment Separator made it possible the unambiguous identification of those nuclei, while the second section was used to identify the residual nuclei produced in proton and neutron knockout reactions induced on a beryllium target installed at the intermediate image plane of the separator.

The one neutron knockout cross sections are in good agreement with recent measurements at RIKEN for $^{134}$Sn[1]. They show a clear reduction at N=84 explained by the N=82 closed shell. All measured cross sections are rather well explained by model calculations based on hole excitations on independent particle shell model configurations.

The proton knockout cross sections are much lower than expected from the same calculations but are in agreement with previous observations [2,3]. The observed reduction in the proton knockout cross sections for N=83 nuclei ($^{132}$Sn and $^{134}$Sb) is explained as due to the N=82, while the relative difference between those two nuclei is attributed to the shell Z=50. The overall low proton knockout cross sections and the coincident values obtained for nuclei below N=82 is not yet fully understood, although the role of short-range correlation effects is under investigation.

Impact of Uncertainties in Nuclear Reaction Cross Sections on Nucleosynthesis Beyond Fe

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Low-energy reaction cross sections are required to determine astrophysical reaction rates and to constrain the production of nuclides in various astrophysical environments. Even along stability not all rates can be constrained experimentally and combinations of experimental data and nuclear theory have to be used. Furthermore, off stability only theoretically predicted reaction rates are used in nucleosynthesis calculations, both for neutron-rich and proton-rich nuclides. In the first part of my talk I will briefly outline some open problems in theoretical predictions for neutron-, proton-, and $\alpha$-induced reactions on intermediate and heavy nuclei, close to and off stability, and impacting nucleosynthesis beyond Fe.

In the second part of the talk I will address an important question in the context of astrophysical applications: how uncertainties in nuclear cross sections and rates propagate into the final isotopic abundances obtained in nucleosynthesis models. This information is important for astronomers to interpret their observation data, for groups studying the enrichment of the Galaxy over time with heavy elements, and in general for disentangling uncertainties in nuclear physics from those in the astrophysical modelling. We developed a new method based on a Monte Carlo (MC) method to allow large-scale studies of the impact of nuclear uncertainties on nucleosynthesis. The MC framework PizBuin can perform postprocessing with large reaction networks of trajectories obtained from a variety of nucleosynthesis sites. Temperature-dependent rate uncertainties combining realistic experimental and theoretical uncertainties are used. This is necessary because experiments can only constrain ground state contributions to the stellar rates. From detailed statistical analyses uncertainties on the final abundances are derived as probability density distributions. Furthermore, based on rate and abundance correlations an automated procedure to identify the most important reactions in complex flow patterns from superposition of many zones or tracers is used. This method is superior to visual inspection of flows and manual variation of limited rate sets.

The method so far was already applied to a number of processes: the $\gamma$ process ($p$ process) and the $\nu p$ process in core-collapse supernovae, the production of $p$ nuclei in white dwarfs exploding as thermonuclear (type Ia) supernovae, the weak $s$ process in massive stars, and the main $s$ process in AGB stars. Especially the studies of nucleosynthesis in thermonuclear supernovae and for the $\nu p$ process were computationally very demanding and necessitated the use of the HPC system DiRAC in the UK. The full reaction network containing about 3000 nuclides had to be run several $10^7$ times. Highlights from these results and from those for the other processes will be presented, demonstrating the impact of current nuclear rate uncertainties on astrophysical simulations.
Compact stars with strange interactions in a modified quark meson coupling model (MQMC)

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Abstract

With the increase of baryon density towards center of neutron stars, chemical potentials of neutrons become high so that neutrons at Fermi surfaces are changed to hyperons via strangeness non-conserving weak interactions. This hyperon mixing to neutron star matter gives rise to the hyperon puzzle. The recent detection of the gravitational-wave signal from merging neutron-star binaries, GW170817 [1], has provided new insight on the range of radii of neutron stars within a stringent limit of $9.9 < R_{1.4} < 13.6$ km for a $1.4M_{\odot}$ mass neutron star. Confining the quarks inside a baryon through a phenomenological average potential in an equally mixed scalar-vector harmonic form $U(r) = \frac{1}{2}(1 + \gamma^0)V(r)$, with $V(r) = (ar^2 + V_0), a > 0$ (hence forth called the MQMC model [2], [3]) and making appropriate corrections due to spurious center of mass, the pionic correction for restoration of chiral symmetry and the short-distance one-gluon exchange contribution, we realize the mass of the baryon and study its dynamics inside the neutron star matter through the exchange of $\sigma$, $\omega$, and $\rho$ mesons. Since these are nonstrange they couple only to the $u$ and $d$ quarks, while the $s$ quark remain as spectators. It is expected that with increasing density, the hyperons interact with the strange mesons $\sigma^*$ and $\phi$ hence modifying its effective mass $M^*$. Further, incorporation of $\sigma^*$ and $\phi$ mesons gives us a scope to study the effect of SU(3) on the equation of state of the neutron star matter. With the inclusion of the hyperon matter, the hyperon puzzle becomes conspicuous and the radius increases. To address this we include a non-linear $\omega - \rho$ coupling term in the Lagrangian. The equation of state is developed using the isoscalar and vector-meson couplings to the octet baryons in SU(3) symmetry and a comparison is made to those of the SU(6) calculations. A maximum mass of $1.90 M_{\odot}$ with the corresponding radius being 11.28 km is found while the radius corresponding to the canonical mass $1.4 M_{\odot}$ is 13.1 km which is within the limits predicted from the GW170817 studies.

References

Excitation of baryon resonances in isobaric charge-exchange reactions of medium-mass nuclei

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Nucleonic excitations play an important role in many and diverse facets of nuclear science such as the definition of three body forces \cite{1}, the quenching of the Gamow-Teller strength \cite{2}, or the description of relativistic heavy-ion collisions by using transport codes \cite{3}. Recently, it has been also pointed out the direct role of the lowest-energy nucleon excitations, the so-called -isobars, in the composition of neutron stars \cite{4}. Recent constraints of the symmetry energy at saturation density and its density derivative favor the appearance of Δ-isobars in β-stable nuclear matter at densities around three times the saturation density, even below the limit for hyperon formation.

In this work, isobaric charge-exchange reactions induced by tin projectiles in thin targets of C, CH\textsubscript{2}, Cu, and Pb at energies of 1\textit{A} GeV were used to investigate the baryon-resonance production. These reactions were measured by using the fragment separator spectrometer FRS \cite{5} at GSI (Darmstadt). The excellent momentum resolution of the FRS allowed to obtain with high accuracy the missing-energy distributions of the residual nuclei, in particular, for the (p,n) and (n,p) charge-exchange channels. These missing-energy distributions show two components corresponding to the quasi-elastic and inelastic charge-exchange channels, which are used to extract information about the produced resonances (widths, masses, production cross sections, etc), as well as information about in-medium nuclear matter effects.

Finally, the new ideas for the investigation of baryon resonances at the Super-FRS/FRS will be presented, in particular, the experiments of 2019/2020.

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Delta matter in neutron stars in a relativistic quark model

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Abstract

We study the formation of $\Delta (1232)$ isobars ($\Delta^-, \Delta^0, \Delta^+, \Delta^{++}$) in neutron star matter in a relativistic quark model [1], [2] which is based on a confining relativistic independent quark potential model to describe the baryon structure in vacuum. We begin by considering baryons as composed of three constituent quarks confined inside the hadron core by a phenomenological flavor-independent potential, $U(r)$ with equal mixture of scalar and vector parts in harmonic form, $U(r) = \frac{1}{2}(1 + \gamma^0)V(r)$, with $V(r) = (ar^2 + V_0)$, and $a > 0$. Here $(a, V_0)$ are the potential parameters determined by fitting the nucleon mass and the proton charge radius. Corrections due to spurious center of mass motion as well as those due to other residual interactions, such as the one gluon exchange at short distances and quark-pion coupling arising out of chiral symmetry restoration, have been considered in a perturbative manner to obtain the baryon mass in vacuum. The baryon-baryon interactions are realized by making additional quark couplings to $\sigma$, $\omega$, and $\rho$ mesons through mean-field approximations. The relevant parameters of the interaction such as the quark meson couplings are obtained self-consistently while realizing the saturation properties of nuclear matter including the binding energy, pressure, symmetry energy and compressibility.

Due to lack of microscopic constraints on the coupling of the $\Delta$ baryon with $\omega$ and $\rho$ mesons and from theoretical studies indicating weaker coupling of the isoscalar mesons to the $\Delta$ isobars we scale the $\Delta-\omega$ coupling with the value of $x_{\omega,\Delta} = 0.7$. The equation of state including the nucleons and the $\Delta$ isobars for the nuclear matter in $\beta$-equilibrium is determined and the Tolman-Oppenheimer-Volkoff equations are solved to obtain the mass and radius of the star. We find that $\Delta^-$ appears at a density of $\rho_B = 0.39$ fm$^{-3}$ followed by $\Delta^0$ at $\rho_B = 0.71$ fm$^{-3}$. The maximum mass of the neutron star is found to be $1.98$ M$_\odot$ with the corresponding radius $12.0$ km. The radius for the canonical neutron star is $13.6$ km. We also study the dependance of the radius on the strength of coupling of the $\Delta$ baryon with $\omega$ and $\rho$ mesons and find a strong dependance on the meson-baryon coupling constants.

REFERENCES

Study of the $E_\alpha = 395$ keV resonance of the $^{22}\text{Ne}(\alpha,\gamma)^{26}\text{Mg}$ reaction at LUNA

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Abstract. The $^{22}\text{Ne}(\alpha,\gamma)^{26}\text{Mg}$ is the competitor of the $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ in AGB stars. The $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ is an efficient source of neutrons for s-process in medium masses AGB. There is significant uncertainty in the $^{22}\text{Ne}(\alpha,\gamma)^{26}\text{Mg}$ thermonuclear reaction rate. This has been clearly remarked by the presence of this particular reaction in the COST Action called ChETEC (CA16117) that includes the $^{22}\text{Ne}(\alpha,\gamma)^{26}\text{Mg}$ among the nuclear reactions with great impact on stellar nucleosynthesis. At the energies of the LUNA400kV accelerator a narrow resonance in the $^{22}\text{Ne}(\alpha,\gamma)^{26}\text{Mg}$ reaction has been claimed. This resonance should be at energy $E_\alpha = 395$ keV and it has been studied only with indirect methods leading to a range of possible values for its resonance strength from $10^{-9}$ to $10^{-15}$ eV. At LUNA (Laboratory for Underground Nuclear Astrophysics) this resonance can be studied directly, thanks to a high efficiency setup, composed by a $4\pi$-BGO detector and a windowless gas target filled with neon gas enriched in the $^{22}\text{Ne}$ isotope to 99.99%. This setup has been already used in a previous experiment for the study of the $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ reaction, and in April-June 2018 a new measurement campaign will be performed. Thanks to its position inside the Laboratory of Gran Sasso, LUNA already benefits from a reduced background and in particular a factor one thousand for the neutron component. Still this remains the most important source of background in the region of interest for the $^{22}\text{Ne}(\alpha,\gamma)^{26}\text{Mg}$. A new borated polyethylene shielding will be implemented to reduce the neutron contamination due to the environmental background in order to reduce this contribution by an additional order of magnitude.

Keywords: underground measurements, resonant strength, gamma spectroscopy
First Measurements of $^{19}\text{F}(\alpha,p)^{22}\text{Ne}$ and $^{19}\text{F}(p,\alpha)^{16}\text{O}$ Reactions at Astrophysical Energies: Implication for Stellar Nucleosynthesis

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Cosmic origins of fluorine are still uncertain. Indeed its sole stable isotope, the $^{19}\text{F}$, is produced in stars through a very complicated network of reactions and it can be easily destroyed by both proton- and $\alpha$-captures [1]. Asymptotic Giant Branch (AGB) stars have been proven to be sites of $\text{F}$ production through spectroscopy observations by several authors ([2] and references therein). However, it is not clear whether these stars might account for fluorine abundance of the Galaxy and, in particular, of the solar neighborhood, for which the contribution from type-II supernovae has been definitively excluded by [3]. Very recently the two main channels for $^{19}\text{F}$ destruction in AGB stars, namely the $^{19}\text{F}(p,\alpha)^{16}\text{O}$ and $^{19}\text{F}(\alpha,p)^{16}\text{O}$ reactions, have been studied via the Trojan Horse Method [4, 5, 6, 7] in the energy range of interest for astrophysics, not completely accessible by direct methods. In both cases experimental results have shown the presence of resonant structures below 500 keV never observed before, hinting to an enhancement in efficiency of fluorine destruction by stellar H- and He- burning. In particular the $^{19}\text{F}(p,\alpha)^{16}\text{O}$ reaction rate at $T_\alpha \leq 0.2 \text{K}$ turns out to be increased up to a factor of 1.7 while the $^{19}\text{F}(\alpha,p)^{16}\text{O}$ is enhanced more than a factor of 4 at $0.1 \leq T_\alpha \leq 0.25$.

We present here a re-analysis of the role of AGB stars as fluorine galactic source by comparing stellar observations with predictions of AGB nucleosynthesis (with masses from 1.5 to 5$M_\odot$) computed by employing in state-of-the-art models ([8, 9] and references therein) the THM reaction rates for $^{19}\text{F}$ destruction.

References

Experiments probing nuclear symmetry energy at supra-saturation densities

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Recent observation of gravitational waves from a merger of two neutron stars (GW170817)\(^1\) once again reminds us how little we know about the nuclear equation of state (nuclear EoS) at supra-saturation densities to account for this spectacular phenomenon. Symmetry energy, which dictates isospin dependence of the thermodynamical character of nuclear matter, is the least known in the EoS. In order to constrain the symmetry energy in a high density domain we, SπRIT (Samurai Pion Reconstruction and Ion Tracker) collaboration, started preparing for a series of experiments measuring mainly charged πs from central unstable-nucleus-nucleus collisions at RIBF, RIKEN in 2004. We had designed and constructed a large time projection chamber (TPC)\(^2\) with a rectangular field cage of 86(W)\(\times\)134(L)\(\times\)50(H) cm\(^3\). Induced signals on 12096 pads of the TPC were processed with the newly developed Generic Electronics for the TPC (GET)\(^3\).

In May 2016, the first two series of physics experiments to measure isospin multiplex ratios of not only \(\pi^-/\pi^+\) but also \(n/p\) and \(t/^{3}\text{He}\) from \(^{108}\text{Sn}+^{112}\text{Sn}\) (neutron poor), \(^{112}\text{Sn}+^{124}\text{Sn}\) (normal), \(^{124}\text{Sn}+^{112}\text{Sn}\) (normal) and \(^{132}\text{Sn}+^{124}\text{Sn}\) (neutron rich) reactions at 270 MeV/nucleon have been performed at RIBF. Current status of the data analysis will be presented in this talk.

This work is supported in part by the US Department of Energy under grant No. DE-SC0004835 and Japanese MEXT KAKENHI (Grant-in-Aid for Scientific Research on Innovative Areas) grant No. 24105004.

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In my talk, I will present the efforts on the way of reliable constraints of symmetry energy from heavy ion collisions. Reliable constraints on the symmetry energy from HICs depend on the progress of experiment and theory. In theoretical side, we improve the description of nucleon-nucleon collisions and got a progress on the reliable of transport models, through the code comparison collaboration project with the different authors. Secondly, the influence of impact parameter smearing, which has been ignored in many studies of isospin physics, are also investigated for understanding the uncertainties caused by it. Finally, I will show our recent efforts on constraints of symmetry energy and Skyrme Energy density functional in 5-dimension parameter surface, based on a new version of ImQMD where the ‘realistic’ Skyrme energy density functional can be used. Based on it, we have some got a preliminary result on the Skyrme EDF and symmetry energy, the cross check from the nuclear structure or neutron star studies are on the way.
Hadron-quark phase transition - the QCD phase diagram and stellar conversion *

Débora P. Menezes 1, Kauan D. Marquez 1, Clebson A. Graeff 2 and Constança Providência 3

The complete understanding of the quantum chromodynamics (QCD) phase diagram represents a challenge in both theoretical and experimental physics. While many of the features it aims to describe can be tested in heavy-ion collision experiments, other aspects related to matter under extreme conditions can only be inferred from results of lattice QCD (LQCD) [1] or from observational results of astrophysical objects.

Effective models remain a good source of information about regions of the QCD phase diagram inaccessible by terrestrial experiments or by LQCD methods, providing qualitative results and theoretical insights. The present work intends to help in advancing our knowledge towards some of the regions of the QCD phase diagram through this strategy. Different extensions of the Nambu-Jona-Lasinio model [2], known to satisfy expected QCD chiral symmetry aspects, are used to investigate a possible hadron-quark phase transition at zero temperature and to build the corresponding binodal sections.

Considerations on the phase transition at zero temperature have already been done in many works [3], [4], [5], [6], [7], [8], but we do believe the formalism we present in the present work is more adequate, because the effective models employed here exhibit chiral symmetry in both hadronic and quark phases, which is demanded to take seriously the appearance of the quarkyonic phase. The models to be used here are all included in the Nambu–Jona-Lasinio (NJL) model framework [2] in order to naturally describe the chiral characteristics of QCD matter. For the description of the hadronic matter, the model developed in [9] is utilized and the description of quark matter is done with the inclusion of a vector interaction both in its su(2) [10] and su(3) [11] versions, depending on the context.

We have shown that the transition point is very parameter dependent and that both pressure and chemical potential increase drastically with the increase of the vector interaction strength in the quark sector. β-equilibrium and charge neutrality are also incorporated to the models so that the investigation can be extrapolated to stellar matter. In this case, two different scenarios are analyzed, both constrained to the fact that the conversion is restricted to a situation where there is no strangeness in the hadronic star matter, but it is incorporated in the quark star matter. The same conclusions drawn before with respect to the coexistence pressure and chemical potentials are reinforced, but we have checked that even if a transition from a metastable hadronic star to a quark star is thermodinamically possible, it is either energetically forbidden or gives rise to a balckhole. It is shown that the vector interaction can be strong enough to inhibite the softening of the equation of state when the s-quark sets in.

REFERENCES

Neutron-proton dynamics and pion production in heavy-ion collisions by the AMD+JAM approach

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It is one of the important subjects in nuclear physics and astrophysics to determine the nuclear symmetry energy at various densities. In central heavy-ion collisions at several hundred MeV/nucleon, the maximum density around $2\rho_0$ is reached when the system is compressed in an early stage of the reaction. The ratio $N/Z$ of the neutron and proton densities in the compressed part is naturally sensitive to the nuclear symmetry energy at high densities. Since the $N/Z$ ratio in the high density region is not a direct observable, the $\pi^-/\pi^+$ ratio has been proposed to be a good probe to constrain the high-density behavior of the symmetry energy [1]. Therefore, it is necessary to understand the relation between the $\pi^-/\pi^+$ ratio and the nucleon dynamics such as the $N/Z$ ratio in order to deduce the information on the symmetry energy.

For this purpose, we have studied the pion production in central collisions of neutron-rich nuclei $^{132}\text{Sn} + ^{124}\text{Sn}$ at 270 and 300 MeV/nucleon using an approach [2] that combines antisymmetrized molecular dynamics (AMD) [3] and a hadronic cascade model (JAM) [4]. The dynamics of neutrons and protons is solved by AMD, and then pions and $\Delta$ resonances in the reaction process are handled by JAM. AMD calculations were performed for several cases with and without cluster correlations, and with two effective interactions corresponding to different density dependences of the symmetry energy. These different cases of AMD calculation yield different dynamics of neutrons and protons. Recently, the Sr\textit{R}IT experiments of $^{132}\text{Sn} + ^{124}\text{Sn}$ and $^{112}\text{Sn} + ^{108}\text{Sn}$ at 270 MeV performed at RIBF/RIKEN.

As the results, we found the mechanism how the $\Delta$ resonance and pions are produced reflecting the dynamics of neutrons and protons. We also investigated the impacts of cluster correlations as well as of the high-density symmetry energy on the nucleon dynamics and consequently on the pion ratio. In addition, we found that Pauli blocking plays some important role on the pion observables.

References

Title: Probing the Equation of State of Asymmetric Nuclear Matter with Heavy Ion Collisions

Speaker: Zbigniew Chajecki (Assistant Professor, Western Michigan University)

Abstract:
The equation of state (EOS) is a fundamental property of nuclear matter, important for studying the structure of systems as diverse as the atomic nucleus and neutron stars. Understanding the physics of neutron stars is becoming even more important recently because of the observation of gravitational waves from the neutron star merger.

Nuclear reactions involving heavy-ion collisions in the laboratories can produce the nuclear matter similar to those contained in neutron stars. The density and momentum dependence of the EOS of asymmetric nuclear matter, especially the symmetry energy term, is widely unconstrained. Collisions of neutron-deficient and neutron-rich heavy ions studied in the laboratory already provide initial constraints on the EoS of neutron-rich matter at sub-saturation densities.

Finding appropriate constraints, especially at higher densities, requires new experimental measurements as well as advances in theoretical understanding of nuclear collisions and neutron stars. We present the results from the recent experiment performed at the National Superconducting Cyclotron Laboratory focused on studying the EOS through the observables involving charged particles and neutrons (e.g. neutron to proton spectral ratios). We show the comparison of experimental results to different transport model calculations with the main focus on their sensitivity to both the density and momentum dependence of the nuclear symmetry potential and their importance to understanding the EOS of neutron star mergers.
Collective flow at neutron rich Sn + Sn collisions with 270MeV/u

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Investigation of nuclear Equation of State (EoS) is one of the most attractive topics not only for nuclear physics but also astrophysics since the neutron star merger was discovered with the gravitational wave.

Nuclear EoS indicates large uncertainty in theory, because of lack of information above the normal nuclear density. Neutron rich heavy ion collisions are suitable to investigate isospin symmetry dependence of nuclear EoS at supra-saturation. A neutron-proton differential collective flow would be sensitive for the isospin symmetry potential because it could minimize influence of the isoscalar potential. Ref(PRL85,4221).

The first experiment was performed at RIKEN-RIBF-SAMURAI in 2016 using SAMURAI Pion-Reconstruction and Ion-Tracker-Time-Projection Chamber (S\textpi RIT-TPC). The nuclear collisions with $^{132}\text{Sn}$ and $^{108}\text{Sn}$ beams at 270MeV/u on $^{124}\text{Sn}$ and $^{112}\text{Sn}$ targets were utilized for the systematic study.

In this talk, the recent results of collective flow obtained by S\textpi RIT-TPC experiment will be shown and discussed.

This work is supported by the U.S. Department of Energy under Grant Nos. DE-SC0004835, DE- SC0014530, DE-NA0002923, US National Science Foundation Grant No. PHY-1565546, the Japanese MEXT KAKENHI (Grant-in-Aid for Scientific Re- search on Innovative Areas) grant No. 24105004, and the Polish National Science Center (NCN), under contract Nos. UMO- 2013/09/B/ST2/04064 and UMO- 2013/10/M/ST2/ 00624.
Electromagnetic Interaction Model Calculation of the Very Forward Neutron Transverse Single Spin Asymmetry in Polarized Proton + Nucleus Collision at RHIC

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RIKEN/RBRC

A strikingly strong atomic mass dependence was discovered in the single spin asymmetry of the very forward neutron production in transversely polarized proton-nucleus collision at $\sqrt{s} = 200$ GeV in PHENIX experiment at RHIC. Such a drastic dependence was far beyond expectation from predictions based on Regge theory regardless of its successful calculation of corresponding asymmetries in proton+proton case. A theoretical attempt is made to explain the A-dependence within the framework of the electromagnetic effect using the Mainz unitary isobar (MAID2007) model to estimate the asymmetry. The resulting calculation well reproduced the new neutron asymmetry data in combination of the asymmetry induced by the strong force. The present electromagnetic interaction calculation is confirmed to give consistent picture with the existing asymmetry results in $p+Pb \rightarrow \pi^0+p+Pb$ at Fermilab.
Recent results from the strong interaction program of the NA61/SHINE experiment and physics plans beyond 2020

Roman Planeta
for the NA61/SHINE Collaboration

Abstract:

The exploration of the QCD phase diagram ($T$-$\mu_B$) particularly the search for a phase transition from hadronic to partonic degrees of freedom and the QCD critical point is one of the most challenging theoretical and experimental tasks in present heavy ion physics. Unfortunately the QCD predictions are to a large extent qualitative, as QCD phenomenology at finite temperature and baryon number is one of the least explored domains of the theory.

To achieve these goals the NA61/SHINE experiment scans of a broad region of the QCD phase diagram ($T$-$\mu_B$) by varying the momentum (13A-158A GeV/c) and the size of colliding systems (p+p, p+Pb, Be+Be, Ar+Sc, Xe+La, Pb+Pb).

New NA61/SHINE results on particle spectra and event-by-event fluctuations in p+p, Be+Be and Ar+Sc collisions will be discussed together with previous NA49 results. The evolution of non-monotonic structures in pion and strangeness production as a function of system size and energy will be addressed. The obtained results reflect very interesting features and might be related to the onset of deconfinement as well as to the onset of formation of large clusters of strongly interacting matter.

Recently, the experimental setup of the NA61/SHINE facility was supplemented with a Vertex Detector which was motivated by the importance and the possibility of the first direct measurements of open charm mesons in heavy ion collisions at SPS energies. The presentation will also focus on the physics motivation behind the open charm measurements at the SPS energies and will provide information on future plans of charm flavor measurements in NA61/SHINE experiment.
Rapidity decorrelation from hydrodynamic fluctuations and initial fluctuations

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Fluctuations have been playing an important role in understanding observables in high-energy nuclear collisions. For example, event by event initial fluctuations of transverse profiles are discussed to understand higher harmonics of azimuthal angle distributions. Recently, thermal fluctuations during hydrodynamic evolution (i.e. hydrodynamic fluctuations) of the QGP fluids in the intermediate stage are studied to understand the rapidity decorrelation (decorrelation of event plane angle in the rapidity direction) [1]. On the other hand rapidity decorrelation could appear also from event-by-event initial fluctuations of rapidity profiles [2]. In this presentation, we analyze the effect of both thermal fluctuations and initial fluctuations on rapidity decorrelation.

We employ an integrated dynamical model [3,4] which combines full three-dimensional relativistic hydrodynamics with Monte-Carlo version of the Glauber model for event-by-event initialization and the hadronic cascade model in the late rescattering stage.

By using this model, we first adjust initial parameters and transport coefficients to reproduce pseudorapidity distribution, $dN_{ch}/d\eta$, and centrality dependence of integrated elliptic flow parameter, $v_2$, in Pb+Pb collisions at the LHC energy. We next analyze the $n$-th order factorization ratios, $r_n(\eta)$, which quantify rapidity decorrelations [5] by switching on and off hydrodynamic fluctuations in the hydrodynamic stage. From this analysis, we see how hydrodynamic fluctuations and initial fluctuations break longitudinal correlations.

References
Dynamically integrated transport model
for high-energy nuclear collisions at $3 < \sqrt{s_{NN}} < 30$ GeV

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To explore the structure of the QCD phase diagram in high-baryon density domain, several high-energy nuclear collision experiments in a wide range of beam energies, such as BES programs in RHIC, the NA61/SHINE experiment at SPS, the CBM experiments at FAIR, MPD at NICA, JINR, and J-PARC-HI at J-PARC, are currently performed or planned. In these experiments search for a first-order phase transition and the QCD critical point is one of the most important topics. To find the signature of the phase transition, experimental data should be compared to appropriate dynamical models which quantitatively describe the process of the collisions. In higher-energy collisions at LHC and RHIC, hydrodynamical models have been successful in explaining various experimental observables such as hadron spectra and collective flow coefficients.

However, for lower-energy collisions where the high baryon density matter is created, the model should be extended to include a non-equilibrium transport model to describe the pre-hydrodynamical stage. Here we develop a new dynamical model on the basis of non-equilibrium microscopic transport model JAM and 3+1D hydrodynamics by utilizing a dynamical initialization method. We implement spacetime-dependent core-corona separation of the system between hot regions and the other parts. We show that the new model describes multiplicities and mean transverse mass for a beam energy region of $3 < \sqrt{s_{NN}} < 30$ GeV. Good agreement of the beam energy dependence of the $K^+ / \pi^+$ ratio is obtained, which is understood by the partial thermalization of the system in our core-corona approach.