Investigating the dependence of collective dynamics on n/p asymmetry for light nuclei

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The dynamics present in the fusion of neutron-rich nuclei is explored through the comparison of experimental cross-sections at above-barrier energies with measurements of the interaction cross-section at relativistic energies. The increase of fusion dynamics with increasing neutron excess is clearly demonstrated. Experimental cross-sections are compared with the predictions of a Sao Paulo model using relativistic mean field density distributions and the impact of different interactions is explored.

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Nuclei are extremely interesting quantal systems, which despite a limited number of constituent particles, manifest collective dynamics. This collective dynamics is observed in many forms including the giant dipole resonance [1, 2], shape coexistence [3], and fission [4, 5]. Although typically associated with the structure and reactions of mid-mass and heavy nuclei, collectivity for very light nuclei has recently been reported [6]. Nuclear fusion and nuclear fusion provide examples in which collective degrees of freedom undergo substantial change as the reaction proceeds. Of particular interest is the role of collectivity for neutron-rich nuclei as for these nuclei the dependence of the dynamics on the asymmetry between the neutron and proton densities can be probed. Fusion reactions provide a powerful means to assess the response of neutron-rich nuclei to perturbation. As fusion involves the interplay of the repulsive Coulomb and attractive nuclear potentials, by examining fusion for an isotopic chain one probes the neutron density distribution and how that density distribution evolves as the two nuclei approach and overlap [7, 8]. In the following manuscript we propose a novel perspective for investigating the role of collective dynamics in fusion. Moreover, using this new perspective we elucidate the dependence of the fusion dynamics on n/p asymmetry for the first time including the indication that for light nuclei fusion dynamics is enhanced with increasing neutron number.

Measurement of the interaction cross-section, $\sigma_{\text{int}}$, in high energy collisions is an effective means to investigate the spatial extent of the matter distribution [9]. The interaction cross-section in these measurements is simply defined as the total nuclear reaction cross-section resulting in a change of either the atomic number (Z) or mass number (A) of the projectile. Systematic comparison of these cross-sections for lithium isotopes revealed the halo nature of $^{11}\text{Li}$ [10, 11]. Presented in Fig. 1 are the interaction cross-sections of carbon isotopes with a carbon target. Measurements for A≥12 were made at E/A ~ 900 MeV at GSI-Darmstadt and utilized the high-resolution fragment separator FRS to resolve the reaction products [12, 13]. These data, represented as solid symbols in Fig. 1 are supplemented by the results of earlier measurements at the LBL Bevalac indicated by open symbols [4]. The overall trend observed is an approximately linear increase in $\sigma_{\text{int}}$ with neutron excess, (N-Z). At the high incident energy that these experiments were conducted at, one expects the sudden approximation to be valid. Hence, the measured interaction cross-section, $\sigma_{\text{int}}$ provides a direct measure of the extent of the matter distribution. Through comparison with a Glauber model, the rms matter radii of these nuclides has been extracted [14].

Closer examination of Fig. 1 provides an indication of the impact of shell structure on $\sigma_{\text{int}}$. The dependence of $\sigma_{\text{int}}$ on neutron excess for 12≤A≤14 is weak as is the dependence for 16≤A≤18. Between $^{14}\text{C}$ and $^{16}\text{C}$ one observes a jump in $\sigma_{\text{int}}$ from a value of ~850 mb to ~1050 mb. This increase reflects the completion of the 1p$_{\text{1/2}}$ with N=8 and the population of the 1d$_{5/2}$ shell. This observation is significant as it indicates that the shell structure of the neutron-rich isotopes is accessible through measurement of $\sigma_{\text{int}}$ for an isotopic chain.

Juxtaposed with the measured interaction cross-sections in Fig. 1 are the results of calculations of the...
FIG. 1. Comparison of the interaction cross-section $\sigma_{\text{int}}$ for various carbon isotopes with the prediction of the average fusion cross-section at above-barrier energies using a RMF-SP model. See text for details.

fusion cross-section at energies just above the fusion barrier. These calculations were performed at energies of $E_{\text{CM}} = 1-2$ MeV/A and utilize the Sao Paulo model for calculating the fusion cross-section \[15\]. In this model the density distributions of the colliding nuclei are assumed to be frozen during the fusion process thus the calculated cross-sections reflect the size of the colliding nuclei. Moreover, use of a common target nucleus allows one to assess the change in the size of the projectile nucleus with increasing neutron excess. The density distributions used in the Sao Paulo calculations were determined using a relativistic mean field (RMF) model \[16\] \[17\]. In order to investigate the sensitivity of the calculated cross-sections to the interaction used in the RMF calculations, the RMF calculations were performed using two sets of interactions FSUGOLD and NL3 \[18\]. In contrast to the widely used NL3 interaction, the FSUGOLD corresponds to a softer interaction \[19\]. To facilitate the comparison of the fusion cross-sections predicted by the RMF-SP model with $\sigma_{\text{int}}$, we have calculated the average fusion cross-section over the interval $14 \text{ MeV} \leq E_{\text{CM}} \leq 17$ MeV and designate this quantity $<\sigma_{\text{fusion}}>$\[14\]. Although the calculations with the FSUGOLD interaction manifest a consistently larger fusion cross-section, nonetheless both RMF-SP calculations exhibit a similar dependence on neutron number. For $N < Z$ the value of $<\sigma_{\text{fusion}}>$\[14\] is approximately constant while for $N > Z$ it increases approximately linearly with $(N-Z)$. The slope of the predicted cross-sections for the two interactions shown is to first order the same indicating that while the absolute size of the nucleus depends on the interaction used in the RMF model, the increase in size with increasing N is relatively insensitive to the interaction utilized. Moreover for $N > Z$, the slope of the predicted above-barrier fusion cross-section is very similar to that for $\sigma_{\text{int}}$. This similarity of the two slopes arises from the fact that the $\sigma_{\text{int}}$ measures the size of the nucleus and the RMF-SP with the frozen density distributions is intrinsically related to the same quantity. As such, the quantity $\sigma_{\text{int}}$ provides a key reference from which to examine fusion dynamics.

In Fig. 2 the density distributions for neutrons predicted by the RMF model for the various carbon isotopes are displayed. The density distributions for $N \neq Z$ are compared with that of $^{12}$C for reference. As expected, the tail of the neutron density distribution extends further for the more neutron-rich the isotope. The value of calculating these neutron density distributions for an isotopic chain lies in the ability to examine the systematic dependence on neutron number. The evolution of the nuclear size on neutron number may have different sensitivity to the model uncertainties as compared to the absolute size. Presented in Fig. 3 are the density distributions for protons predicted by the RMF model for the different isotopes of carbon. While the distributions are all quite close as might be expected, as the isotope becomes more neutron-rich the tail of the proton distri-
distribution extends slightly further out. This change in the proton distribution is due to the attractive nuclear force of the valence neutrons. The dependence of the charge radii on neutron number for the carbon isotopic chain has recently been determined through measurement of the charge changing cross-section [14].

To investigate the evolution of fusion dynamics with increasing neutron number we examine the fusion cross-section for $^4\text{C} + ^{12}\text{C}$ at near barrier energies. Using a novel active target approach the fusion excitation functions for these reactions was measured by the ANL group [22]. This active target approach is particularly well suited to studying reactions with low intensity beams and allowed measurement of the fusion excitation function with beam intensities as low as 500 ions/s. Depicted in Fig. 4 (both columns) are the fusion cross-section data for $^{10-15}\text{C}$. The data for $^{10,15}\text{C}$ have been taken from [22]. Using the same approach though at higher beam intensity, $^{12,14}\text{C}$ cross-sections were also measured [20, 21] and are shown in Fig. 4. The fusion excitation functions observed for $^{12,13}\text{C} + ^{12}\text{C}$ are in good agreement with those published in the literature [24, 25]. The measured excitation functions manifest the expected dependence indicative of a barrier driven process. The experimental data are compared with the results of a RMF-SP model using FSUGOLD and NL3 interactions depicted in the left and right columns respectively. While in the case of $^{10}\text{C}$ the models overpredict the experimental results, in the remainder of the cases the agreement is reasonable. Close comparison of the left and right columns indicates that the calculations with FSUGOLD consistently predict larger cross-sections than those with NL3, consistent with the observation in Fig. 2. It is noteworthy though that this increase in the cross-section for FSUGOLD as compared to NL3 is typical of the entire above-barrier regime. In Fig. 4, the blue bar indicates the value of the average cross-section as well as the energy interval over which the average was calculated. For $^{12-15}\text{C}$ the average cross-section is clearly representative of the above-barrier cross-section. In the case of $^{10}\text{C}$, however there is significant variation in the measured cross-sections and the average cross-section calculated is more sensitive to the choice of energy interval.

In Fig. 5 the average above-barrier fusion cross-sections...
for the carbon isotopic chain are compared with $\sigma_{\text{int}}$. One observes that for $^{12}\text{C}$ the fusion cross-section and $\sigma_{\text{int}}$ are essentially the same. For $N>Z$ however, the fusion cross-section depends more strongly on neutron excess than $\sigma_{\text{int}}$ does. Since the dependence of $\sigma_{\text{int}}$ on increasing neutron number indicates the inherent growth in the size of the neutron density distribution with increasing neutron number, the cross-section in the case of fusion, above that of $\sigma_{\text{int}}$, reflects the impact of dynamics in the fusion process. The quantity $\langle <\sigma_{\text{fusion}}^{14}_{17} - \sigma_{\text{int}} \rangle \rangle$ can be viewed as a measure of the fusion dynamics. Moreover, the increase in this quantity, dictated by the larger slope for fusion as compared to $\sigma_{\text{int}}$, indicates that this dynamics evolves with increasing neutron excess.

It is also instructive to compare the behavior of the fusion data with the results of the RMF-SP model. The experimental data indicates a stronger dependence on neutron excess than the RMF-SP model independent of the interaction chosen. This comparison thus also indicates an increased role for dynamics with increasing neutron excess. Thus, the increased role of fusion dynamics with neutron excess is realized in two independent ways. Juxtaposition of the $<\sigma_{\text{fusion}}^{14}_{17}$ with $\sigma_{\text{int}}$, namely a data to data comparison, indicates enhanced fusion dynamics with increasing neutron excess. This result is supported by the comparison of $<\sigma_{\text{fusion}}^{14}_{17}$ with the cross-sections predicted by the RMF-SP model.

Although the span of neutron excess for the fusion data presented is presently limited, the new generation of radioactive beam facilities allows one to extend these measurements to even more neutron-rich carbon isotopes. Measurement of fusion with beams of $^{16,17}\text{C}$ and possibly $^{18,19}\text{C}$ at FRIB [26] is envisoned. Similar measurement for the oxygen isotopic chain extending nearly to the neutron-drip line is also possible.

Examination of the fusion cross-section at above-barrier energies for an isotopic chain is a powerful tool. Comparison of fusion cross-sections just above the barrier with the interaction cross-section, $\sigma_{\text{int}}$, at high energies where the sudden approximation is valid allows extraction of not just the fusion dynamics but the dependence of the dynamics on neutron excess. Investigating this dynamics for the most neutron-rich nuclei accessible could provide valuable insight into the dynamics of extremely asymmetric nuclear matter.

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[1] F. E. Bertrand, Ann. Rev. Nucl. Sci. 26, 457 (1976).
[2] T. Kobayashi et al., Phys. Lett. B 232, 51 (1989).
[3] K. Heyde and J. Wood, Rev. of Mod. Phys. 83, 1467 (2011).
[4] L. Meitner and O. R. Frisch, Nature 143, 239 (1939).
[5] R. Vandenbosch and J. R. Huizenga, Nuclear Fission (Academic Press, Inc., New York, NY, 1973).
[6] C. Morse et al., Phys. Lett. B 780, 227 (2018)
[7] Varinderjit Singh, J. Vadás, T. K. Steinbach, B. B. Wiggins, S. Hudan, R. T. deSouza, Zidu Lin, C. J. Horowitz, L. T. Baby, S. A. Kuvina, Vandana Tripathi, I. Wiedenhöver, and A. S. Umar, Phys. Lett. B 765, 99 (2017)
[8] J. Vadás, V. Singh, B. B. Wiggins, J. Huston, S. Hudan, R. T. deSouza, Z. Lin, C. J. Horowitz, A. Chbihi, D. Ackermann, M. Famianno, and K. W. Brown, Phys. Rev. C 97, 031601(R) (2018)
[9] A. Ozawa et al., Nucl. Phys. A 608, 63 (1996).
[10] I. Tanihata et al., Phys. Lett. B 160, 380 (1985).
[11] I. Tanihata et al., Phys. Rev. Lett. 55, 2676 (1985).
[12] A. Ozawa et al., Nucl. Phys. A 691, 599 (2001).
[13] A. Ozawa, T. Suzuki, and I. Tanihata, Nucl. Phys. A 693, 32 (2001).
[14] R. Kanungo et al., Phys. Rev. Lett. 117, 102501 (2016).
[15] L. R. Gasques, L. C. Channon, D. Pereira, M. A. G. Alvarez, E. S. Rossi, C. P. Silva, and B. V. Carlson, Phys. Rev. C 69, 034603 (2004).
[16] B. D. Serot and J. D. Walecka, Adv. Nucl. Phys. 16, 1 (1986).
[17] P. Ring, Prog. Part. Nucl. Phys. 37, 193 (1996).
[19] F. J. Fattoyev, C. J. Horowitz, J. Piekarewicz, and G. Shen, Phys. Rev. C 82, 055803 (2010).

[20] S. Almaraz-Calderon et al., EPJ Web of Conferences 96, 01001 (2015).

[21] P. Carnelli, Ph.D. thesis, Universidad Nacional De General San Martin, Comision Nacional de Energia Atomic. Buenos Aires, Argentina (2014).

[22] P. F. F. Carnelli et al., Phys. Rev. Lett. 112, 192701 (2014).

[23] P. F. F. Carnelli et al., Nucl. Instr. Meth. A 799, 197 (2015).

[24] D. G. Kovar et al., Phys. Rev. C 20, 1305 (1979).

[25] R. A. Dayras, R. G. Stokstad, Z. E. Switkowski, and R. M. Wieland, Nucl. Phys. A 265, 153 (1976).

[26] FRIB, Facility for Rare Isotope Beams, Michigan State University, USA.