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# Characterizing neutron-proton equilibration in nuclear reactions with sub-zeptosecond resolution

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We study neutron-proton equilibration in dynamically-deformed atomic nuclei created in nuclear collisions. The two ends of the elongated nucleus are initially dissimilar in composition and equilibrate on a sub-zeptosecond timescale following first-order kinetics. We use angular momentum to relate the break-up orientation to the timescale of the breakup. The extracted rate constant is  $3 \text{ zs}^{-1}$ , which corresponds to a mean equilibration time of 0.3 zs. This technique enables new insight into the nuclear equation of state that governs many nuclear and astrophysical phenomena leading to the origin of the chemical elements.

The description of atomic nuclei as microscopic liquid drops, proposed in 1935 [1], described the masses of a broad range of nuclides with a simple concept. Subsequently, many liquid-like properties were discovered. For example, viscous forces were seen to play an important role in fission [2] and a boiling transition was observed when nuclei were moderately excited [3]. These and other discoveries motivated the investigation of the nuclear equation of state (nEoS), which describes the relationships between the thermodynamic state variables for a system of strongly interacting dilute nuclear matter ( $\rho \geq 10^{11} \text{ g/cm}^3$ ). The nEoS governs many aspects of astrophysics such as neutron star physics and nucleosynthesis during the explosive death of stars [4–7]. In terrestrial environments, the nEoS is integral in explaining the neutron skin thickness of heavy nuclei, collective excitations of nuclei, and the dynamics of heavy-ion collisions [8–10].

The energy associated with an imbalance of neutrons and protons is termed the symmetry energy, and its density dependence is largely unconstrained. A refined understanding of nuclear material with extreme neutron-proton ratios is necessary, for example, to understand the origin of the elements and characterize the structure and composition of neutron stars. Nuclear scientists across many subfields have contributed to expanding our understanding of the nEOS of neutron-rich and neutron-poor material [12, 13]. One method to constrain the symmetry energy involves multi-nucleon exchange between nuclei leading to neutron-proton (NZ) equilibration. Although there has been significant work focused on measuring the asymptotic composition of the nuclei [14–17], some experiments have probed the timescale of the NZ equilibration process. Important efforts in the 70s and 80s [18–23] established the timescale is in the range of 0.1-1.0 zs (1 zeptosecond is  $10^{-21}$  seconds). This was achieved by measuring isotopic composition of fragments as a function of either the energy dissipation or the separation orientation. The dissipation is related to the interaction time and can be estimated through a model. A recent measurement of a broad range of isotopes and energy dissipation is consistent with this timescale [24]. Similarly, the separation angle is proportional to the interaction time and can be calibrated via angular momentum. Re-

cent measurements by Hudan et al. [25–28] employing this technique reported certain fragment compositions explicitly as a function of time, indicating the persistence of the equilibration process for as long as 4 zs, though the majority of the equilibration takes place within 1 zs.

In this letter, we report direct evidence of NZ equilibration between nuclei on a sub-zeptosecond timescale. Equilibration chronometry is made possible by applying the method pioneered by Hudan et al. [25–28] to experimental data with near-complete angular coverage and excellent isotopic resolution. With the present data, this technique allows us to examine the detailed evolution of the NZ composition of both reaction partners in 0.1 zs time slices.

In the experiment, a beam of  $^{70}\text{Zn}$  nuclei was accelerated to 35 MeV/nucleon by the K500 cyclotron at the Texas A&M University Cyclotron Institute. The beam was focused onto a thin foil of  $^{70}\text{Zn}$  (95% pure). The nuclear reaction products were measured in NIMROD (Neutron Ion Multidetector for Reaction Oriented Dynamics) [29], which provides nearly complete geometrical coverage ( $3.6^\circ$  to  $167.0^\circ$  relative to the beam axis). NIMROD provides excellent isotopic identification of charged particles up to  $Z=17$  in most detectors, and up to  $Z=21$  in some detectors [30]. Elemental identification is achieved up through  $Z=30$  (atomic number of beam). The combination of the isotopic resolution and the full geometric coverage are crucial to observing the time-dependence of the NZ equilibration with high-resolution. In contrast to previous work where lighter fragment of a binary split was measured and interpreted as demonstrating equilibration with its heavier partner, in this work we make the simultaneous measurement of both reaction partners of a binary split, conclusively demonstrating observation of the equilibration process.

Heavy-ion reactions in this energy regime produce an excited projectile-like fragment (PLF\*) and an excited target-like fragment (TLF\*). As the PLF\* and TLF\* begin to move apart after colliding, a neck of nuclear material is formed between them as illustrated in figure 1a. The system is strongly elongated by the collision dynamics, and is stretched beyond the capabilities of the attractive nuclear force to hold it together. As a result, the neck ruptures and the emerging PLF\*

and TLF\* are typically strongly deformed along their axis of separation ( $\vec{v}_{CM}$ ) [31–33]. Figure 1b depicts the deformation of the two fragments shortly after the neck rupture and prior to subsequent breakup. Due to the deformation, the PLF\* and TLF\* are likely to break up promptly along the deformation axis. These types of breakups, referred to as dynamical decay, exhibit a characteristic angular distribution peaked along the beam direction [33–35]. Because our detectors are optimized to measure the fragments of the PLF\* with high efficiency, we focus on the PLF\* decay with the understanding that the same process occurs for the TLF\* [32]. Since the fragments of the TLF\* are not measured, they are represented as gray in the cartoon. The coloring of the PLF\* reflects the measured composition, which will be discussed later.

In order to focus on the dynamical decay of the PLF\*, we selected events in which at least two charged particles were measured in NIMROD. Fragments were sorted by their atomic number with charge-identical fragments sorted by mass number. We refer to the fragment with the largest atomic number as the heavy fragment (**HF**) and the fragment with the second largest atomic number as the light fragment (**LF**). The **HF** was required to have an atomic number of  $Z_H \geq 12$ , and **LF** was required to have an atomic number of  $Z_L \geq 3$ . We also require a total measured charge of  $21 \leq Z_{tot} \leq 32$ , which includes  $Z_H$ ,  $Z_L$ , and all other charged fragments measured. These requirements maximize the likelihood that these two fragments are the heaviest two daughters of the PLF\*. Finally, we require that both **HF** and **LF** be isotopically identified. Evidence that both **HF** and **LF** originate from the PLF\* is seen in the velocity distributions: both fragments are centered above mid-velocity as illustrated in figure 1, and consistent with previous work [33].

To examine the strong alignment expected from dynamical decays of a deformed PLF\*, we look at the distribution of the alignment angle  $\alpha = \text{acos}(\frac{\vec{v}_{CM} \cdot \vec{v}_{REL}}{\|\vec{v}_{CM}\| \|\vec{v}_{REL}\|})$ . The velocity vectors represent the two-fragment center-of-mass velocity  $\vec{v}_{CM} = (m_{HF}\vec{v}_{HF} + m_{LF}\vec{v}_{LF}) / (m_{HF} + m_{LF})$  and the relative velocity  $\vec{v}_{REL} = \vec{v}_{HF} - \vec{v}_{LF}$ . These quantities are illustrated in figure 1b. After the neck rupture, and as they move apart along their separation axis (the direction of  $\vec{v}_{CM}$ ) the PLF\* and TLF\* continue to rotate and their shapes continue to evolve. A later point in time is shown in panel b when the PLF\* is about to split into two fragments (**HF** and **LF**). The lifetime of the PLF\* after breaking from the TLF\* and before breaking into **HF** and **LF** is correlated with the rotation angle  $\alpha$  (depicted in panel b). Thus the equilibration chronometry technique utilizes  $\vec{v}_{CM}$  and  $\vec{v}_{REL}$  to define the orientation of the PLF\* at those two critical points in time, and the angle made by these vectors can then be related to its lifetime. By this definition,  $\alpha=0^\circ$  corresponds to  $t=0$  with **LF** emitted in the backward direction relative to **HF**, and larger rotations correspond to longer time.

Selected angular distributions,  $\cos(\alpha)$ , are shown in figure 2. The upper left panel of figure 2 ( $Z_H=14$ ,  $Z_L=5$ ) shows a large peak near  $\cos(\alpha)=1$ . The peak extends with significant yield out to  $\cos(\alpha)=0.5$ . Beyond this, the yield becomes rel-

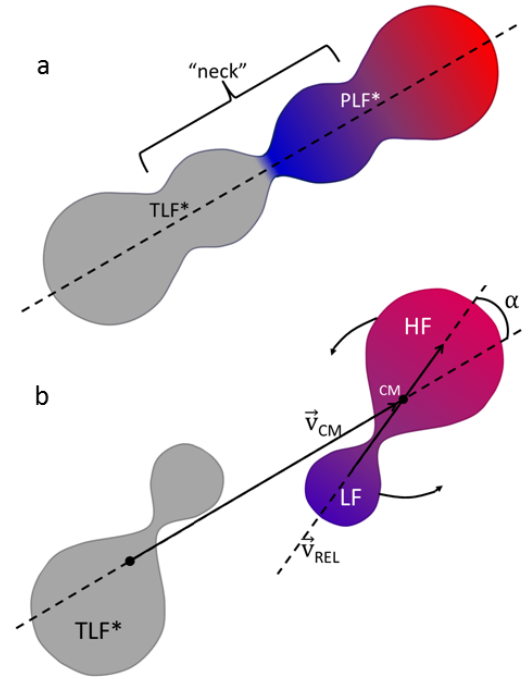


FIG. 1. Illustration of dynamical deformation and decay. Panel a shows the deformed PLF\* and TLF\* system before rupture of the neck. Panel b shows a later time after the PLF\* and TLF\* system has separated. The PLF\* has rotated relative to the TLF\* separation axis ( $\vec{v}_{CM}$ ) and is itself about to break up into two fragments (**HF** and **LF**). The time the PLF\* lives before breaking up is measured by the angle  $\alpha$ . The color denotes the composition with blue indicating neutron richness and red indicating relative neutron deficiency.

atively flat, but displays a slight excess near  $\cos(\alpha)=-1$ . This trend is seen as well in the other three panels ( $Z_H=14$ ,  $Z_L=7$ ;  $Z_H=12$ ,  $Z_L=5$ ; and  $Z_H=12$ ,  $Z_L=7$ ). These pairings were selected to examine the impact of varying  $Z_H$  and  $Z_L$  independently. Forty-three pairings were analyzed, with  $Z_H$  ranging from 12 to 19 and  $Z_L$  ranging from 3 to 11. Those shown represent a good compromise between a significant variation in ( $Z_H, Z_L$ ) and high statistics, and are representative of the entire set. The similarities for the angular distributions indicate the same basic reaction dynamics.

To understand the observed yield we consider two mechanisms of production: statistical decay and dynamical decay. For statistical decay from a non-rotating source, the angular distribution should be flat as a function of  $\cos(\alpha)$ . With rotation, the distribution evolves to have increased yield at  $\cos(\alpha)=\pm 1$  due to the tendency to decay in the plane perpendicular to the angular momentum vector. The larger the angular momentum, the greater the yield at  $\cos(\alpha)=\pm 1$ , though symmetry about  $\cos(\alpha)=0$  would be maintained. The observed yield for  $\cos(\alpha)<0$  may therefore be due primarily to statistical decay. The effect of the measurement device on the symmetry of the angular distribution was investigated using the statistical model GEMINI++ [36]. The simulation was filtered with a NIMROD array simulation environment. The granularity, resolution, and thresholds of the detection device

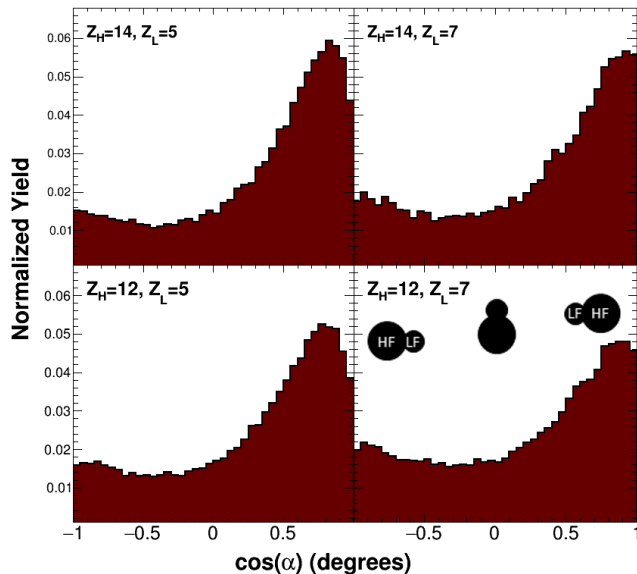


FIG. 2. Normalized angular distributions for select  $Z_H$  and  $Z_L$  pairings. Emission of the lighter charged fragment in the backward direction (toward the target) corresponds to  $\cos(\alpha)=1$ .

preserve the symmetry of the angular distribution for statistical decay. Hence, the larger yield for  $\cos(\alpha)>0$  seen in figure 2 cannot be ascribed to purely statistical decay.

The excess yield for  $\cos(\alpha)>0$  is consistent with dynamical decay: the breakup of the PLF\* tends to occur aligned with the separation axis of the PLF\*-TLF\* breakup. The angular distribution is therefore peaked for the most aligned configuration,  $\cos(\alpha)=1$ , and decreases in yield with decreasing alignment. This excess yield is largest and most strongly aligned for the most asymmetric splits (figure 2 left panels:  $Z_H=14, Z_L=5$ ; and  $Z_H=12, Z_L=5$ ). For more symmetric pairings, the preference for strongly aligned backward emission decreases slightly, as seen by the decrease in the peak value of the normalized yield and slight broadening of the distribution from (top left panel:  $Z_H=14, Z_L=5$ ) to (bottom right panel:  $Z_H=12, Z_L=7$ ), in agreement with previous studies of dynamical decay [33]. This may be understood in terms of a large collectivity and larger potential barrier slowing the symmetric splits and decreasing their likelihood. This provides support that **HF** and **LF** are produced dynamically. The timescale of dynamical decays of the PLF\*, evident in figure 2, is short relative to PLF\* rotation time. Less aligned decays represent longer times. This is the basis for using the rotation of the di-nuclear system as a clock.

For each pairing of  $(Z_H, Z_L)$ , the asymmetry  $\langle\Delta\rangle = \langle\frac{N-Z}{A}\rangle$  was calculated as a function of the alignment angle  $(\alpha)$  for both **HF** and for **LF**. Figure 3 shows  $\langle\Delta\rangle$  distributions for the same  $(Z_H, Z_L)$  pairings shown in figure 2. The large number of angular bins afforded by the experimental configuration allows the evolution of  $\langle\Delta\rangle$  to be examined in detail. For **LF**, a large initial  $\langle\Delta_L\rangle$  value is seen (at  $\alpha=0^\circ$ ,  $t=0$ ), followed by a sharp

decrease in  $\langle\Delta_L\rangle$  for small angles of rotation. After the initial decrease,  $\langle\Delta_L\rangle$  levels off. Complementarily,  $\langle\Delta_H\rangle$  starts at a small value, initially rises, and slows its ascent at a rate similar to that of  $\langle\Delta_L\rangle$ . The evolution of  $\langle\Delta_L\rangle$  and  $\langle\Delta_H\rangle$  with alignment appears exponential, suggesting first-order kinetics. The evolution of the composition is illustrated by the inset in figure 3 and by the coloring in figure 1, using blue to indicate a neutron abundance and red to indicate a relative neutron deficiency.

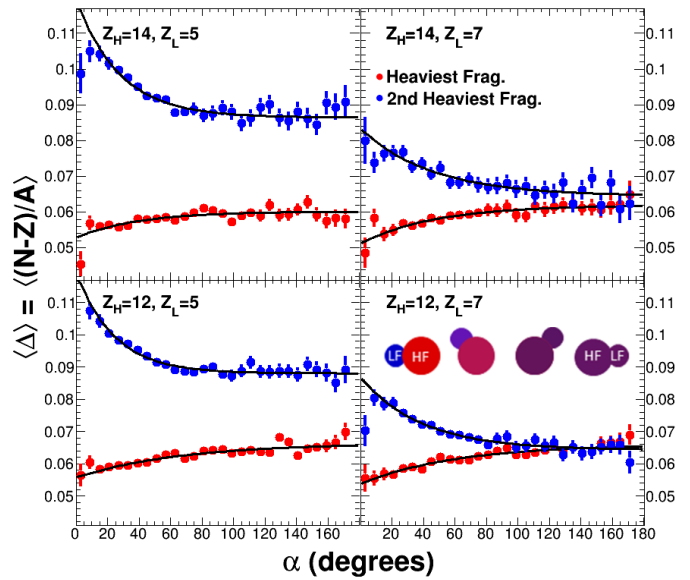


FIG. 3. Composition as a function of decay alignment showing equilibration. As the angle of rotation increases ( $\alpha$  increases from  $0^\circ$  to  $180^\circ$ ), the  $\langle\frac{N-Z}{A}\rangle$  initially decreases rapidly for  $Z_L$  and increases for  $Z_H$  before plateauing. The majority of equilibration occurs between  $0^\circ$  and  $80^\circ$ .

To understand the origin of these features, consider the dynamical mechanism. Due to dynamical deformation of the PLF\* and presence of a velocity gradient, the PLF\* tends to quickly break into two pieces along the direction of deformation. The material near mid-velocity, i.e. the neck connecting the PLF\* and TLF\*, is neutron-rich due to preferential flow of the neutrons to this region of low density [37]. This flow occurs as the system seeks to minimize the symmetry energy. If very prompt decay occurs then the composition of **LF**, which originates near the neck region, will be neutron rich, and **HF** will be neutron poor to compensate. However, the attractive nuclear force has a chance to delay or even prevent dynamical decay; surface tension drives the strongly deformed PLF\* toward sphericity. While these regions of the PLF\* are in contact, their densities may evolve toward each other, allowing their asymmetries to do likewise. Thus a slower decay (farther from  $\alpha=0^\circ$ ) ought to exhibit more similar values of  $\langle\Delta_H\rangle$  and  $\langle\Delta_L\rangle$ .

The plateau values seen in figure 3 are not necessarily equal. The thermodynamic equation of state indicates that **HF** and **LF** should approach a common chemical potential

rather than a common composition. The chemical potentials are dependent on variations in internal energy, density and ground-state binding energies; the conversion from composition to chemical potential is not trivial. The composition is directly measurable and model independent.

We explored the effects of secondary decay within GEMINI++. Secondary decay causes a modest decrease of the  $\Delta$  values, and a slight reduction in the range of  $\Delta$ . However, the exponential trend is neither created nor destroyed by secondary decay, and the rate constant of the exponential is not affected within experimental uncertainty.

The change in  $\langle\Delta_L\rangle$  is larger than the change in  $\langle\Delta_H\rangle$  (figure 3) due to mass conservation. Since  $Z_H$  is larger, exchanging nucleons affects  $\langle\Delta_L\rangle$  more than  $\langle\Delta_H\rangle$ .

To study the equilibration kinetics, the dependence of  $\langle\Delta_H\rangle$  and  $\langle\Delta_L\rangle$  on  $\alpha$  was parameterized by the form  $\langle\Delta\rangle=a+b \cdot \exp(-c\alpha)$ . The results of the fits are shown as the black curves in figure 3. The exponential form describes the experimental data well, confirming first-order kinetics. The parameter  $c$  is a surrogate for the equilibration rate constant. It is a direct measure of the exponential slope of the composition with respect to rotation angle. The rate constants for all eight curves shown in figure 3 are equal within experimental uncertainty. This consistency holds true for all 43 pairings analyzed. The average rate constant was  $0.02 \pm 0.01$  per degree for **HF** and  $0.03 \pm 0.01$  per degree for **LF**. The rate constant for **HF** is independent of  $Z_L$ , and the rate constant for **LF** is independent of  $Z_H$ . The agreement of rate constants within experimental uncertainty indicates that the force driving the equilibration is independent of the size of both partners, and only depends on the difference in asymmetry, or, more accurately, on the difference in chemical potential.

If the correlation between rotation angle and decay time is monotonic (i.e. decay time is short relative to rotation period), then  $c$  is a good surrogate for the rate constant. Strong evidence of this exists in the angular anisotropy seen in figure 2; if decay time were not significantly shorter than rotational period, the angular distribution would appear isotropic. By making the assumption that the correlation between rotation angle and decay time is linear, then  $c$  can be used to find a true rate constant in units of inverse time rather than inverse angle. The timescale is determined through  $t=\alpha/\omega$ , where  $t$  is time and  $\omega$  is angular frequency. The angular frequency is dependent on the angular momentum ( $J$ ) and moment of inertia ( $I_{eff}$ ):  $\omega=(J\hbar)/I_{eff}$ . The moment of inertia is calculated for a system of two touching spheres **HF** and **LF** rotating around their common center of mass:  $I_{eff}=m_H r_{CM,H}^2 + \frac{2}{5}m_H r_H^2 + m_L r_{CM,L}^2 + \frac{2}{5}m_L r_L^2$ . Here,  $r_H$  is the radius of **HF**,  $r_L$  is the radius of **LF**,  $r_{CM,H}$  is the distance from the center of **HF** to the two-fragment center-of-mass, and  $r_{CM,L}$  is the distance from the center of **LF** to the two-fragment center-of-mass. The masses of **HF** and **LF** are denoted by  $m_H$  and  $m_L$  respectively. The moment of inertia ranged from  $2.8-9.9 \times 10^{-42} \text{MeV}\cdot\text{s}^2$  for different combinations of **HF** and **LF**, but contributes little uncertainty for any given

pairing.

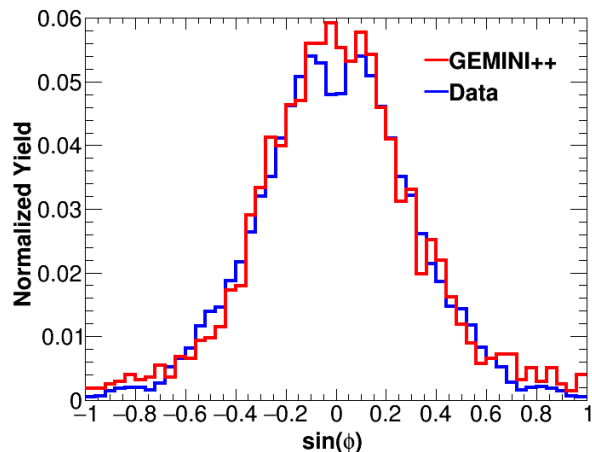


FIG. 4. Out-of-plane  $\alpha$ -particle distribution comparing experimental data and the GEMINI++ model to evaluate the spin ( $22\hbar$ ).

The angular momentum was determined using the width of the out-of-plane  $\alpha$ -particle distribution. Fission studies [38] have shown the out-of-plane fragment distribution width is proportional to the angular momentum of the parent nucleus. In this case, the parent is the combined **HF** and **LF** system. The spin axis is perpendicular to the reaction plane, defined by the beam axis and the two-fragment center-of-mass velocity vector  $\vec{v}_{CM}$ . For alpha particles measured in coincidence with any **HF** and **LF** pair, the angle  $\phi$  relative to this reaction plane is calculated. Figure 4 shows the experimental distribution of  $\sin(\phi)$  in blue. The width of the measured distribution, 0.28, is sensitive to the angular momentum of the parent. The detector efficiency impacts the central four bins, but doesn't impact the width of the distribution. The distribution has only negligible variation for different ( $Z_H, Z_L$ ) combinations. Comparison of the distribution of forward emitted alpha particles to figure 4 indicates that our assessment of  $J$  is robust with respect to strong deformation of the PLF\*. We use the GEMINI++ model to assess the angular momentum. The experimental distribution may be reproduced for a variety of angular momenta and excitation energies. A spin of  $10\hbar$  can reproduce the width of  $\sin(\phi)$  for low excitation energy ( $E^*/A=0.8\text{MeV}$ ). A spin of  $50\hbar$  can reproduce the width of  $\sin(\phi)$  for higher excitation ( $E^*/A=1.2\text{MeV}$ ). Beyond this range, it is difficult to justify higher angular momentum transfer or lower excitation energy. Taking the geometric mean of the extremes of the range in spin, we obtain  $22\hbar$  with a factor of 2.2 systematic uncertainty. The resulting angular distribution at  $22\hbar$  from GEMINI++ is shown by the red line in figure 4. From this, we calculate rotational periods ranging from 1 to 4 zs, with an average of  $3 \pm 1^6$  zs. The calculated timescales, rate constants and mean lifetimes are shown in table 1.

We have examined binary decay of deformed, out-of-equilibrium nuclei. The composition of the daughters exhibits a smooth evolution over time. The timescale is directly probed

$Z_H, Z_L$ Pairing	Period (zs)	$k_H$ (zs <sup>-1</sup> )	$k_L$ (zs <sup>-1</sup> )	$\tau_H$ (zs)	$\tau_L$ (zs)
12,5	$2 \pm_1^5$	$3 \pm_1^3$	$7 \pm_4^9$	$0.4 \pm_{0.2}^{0.7}$	$0.1 \pm_{0.1}^{0.3}$
12,7	$3 \pm_1^6$	$2 \pm_1^3$	$4 \pm_2^4$	$0.5 \pm_{0.2}^1$	$0.3 \pm_{0.1}^{0.6}$
14,5	$2 \pm_1^5$	$4 \pm_3^5$	$6 \pm_3^7$	$0.3 \pm_{0.1}^{0.6}$	$0.2 \pm_{0.1}^{0.4}$
14,7	$3 \pm_1^7$	$3 \pm_2^3$	$3 \pm_2^3$	$0.4 \pm_{0.2}^{0.9}$	$0.4 \pm_{0.2}^{0.8}$
Average	$3 \pm_1^6$	$3 \pm_2^4$	$4 \pm_2^4$	$0.3 \pm_{0.2}^{0.7}$	$0.3 \pm_{0.1}^{0.6}$

TABLE I. Extracted parameters quantifying the rate of NZ equilibration.

with the angular distribution by taking advantage of the fact that the decay occurs on a fraction of the rotation timescale. With this measurement, we demonstrate the power of this experimental technique for measuring NZ equilibration in action. The examination of the time-dependence of the equilibration provides a direct connection to the nuclear equation of state. A previously unobserved consequence of the nuclear equation of state is now demonstrated using this technique: namely that the equilibration of neutrons and protons in nuclear matter follows first-order kinetics. The rate constant is around  $3 \text{ zs}^{-1}$ , which corresponding to a mean lifetime of 0.3 zs.

In 2004, Tsang et al. [14] published nucleon transport simulations that displayed sensitivity of NZ equilibration to the form of the density dependence of the symmetry energy employed in the model. A plot of the composition of the reaction partners changing in time illustrated that equilibration depends on the contact time, the potential driving equilibration, and relative NZ asymmetry of the reaction partners. Subsequent research focused on how the final-state nuclear compositions might be used to constrain the equation of state rather than on measuring the time dependence of the equilibration. However, the time dependence carries more information about the nEoS than the final-state values, and our current results demonstrate that this can be observed with the proper tools. This new data, and the new avenue of experimental research it opens up, will guide theoretical developments in nuclear science. These advances promise to deepen our understanding of the fundamental interactions of nuclear material.

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- [1] C.F.v. Weizsäcker. Zur Theorie der Kernmassen. *Zeitschrift für Physik*, 96:431, 1935.
  - [2] K.T.R. Davies et al. Effect of viscosity on the dynamics of fission. *Phys. Rev. C*, 13:6, 1976.
  - [3] V. Viola and K. Kwiatkowski. How to boil a nucleus. *American Scientist*, 86:449–455, 1998.
  - [4] P.B. Demorest et al. A two-solar-mass neutron star measured using Shapiro delay. *Nature*, 467:1081, 2010.
  - [5] A.W. Steiner et al. Isospin asymmetry in nuclei and neutron stars. *Phys. Rept.*, 411:325, 2005.
  - [6] J.M. Lattimer and M. Prakash. Neutron star structure and the equation of state. *Astrophys. J.*, 550:426, 2001.
  - [7] J.M. Lattimer and M. Prakash. The physics of neutron stars. *Science*, 304:536–542, 2004.
  - [8] U. Garg et al. The giant monopole resonance in the Sn isotopes: why is tin so fluffy? *Nucl. Phys. A*, 788:1–4, 2007.
  - [9] V. Baran et al. Mass and isospin dependence of the dipole response in a microscopic transport approach. *AIP Conf. Proc.*, 1645:267, 2015.
  - [10] X. Roca-Maza et al. Neutron skin of radius experiment. *Phys. Rev. Lett.*, 106:252501, 2011.
  - [11] P. Danielewicz et al. Determination of the equation of state of dense matter. *Science*, 298:1592, 2002.
  - [12] C.J. Horowitz et al. A way forward in the study of the symmetry energy: experiment, theory, and observation. *J. Phys. G*, 41:093001, 2014.
  - [13] M.B. Tsang et al. Constraints on the symmetry energy and neutron skins from experiments and theory. *Phys. Rev. C*, 86:015803, 2012.
  - [14] M.B. Tsang et al. Isospin diffusion and the nuclear symmetry energy in heavy ion reactions. *Phys. Rev. Lett.*, 92:062701, 2004.
  - [15] D.V. Shetty et al. Density dependence of the symmetry energy and the nuclear equation of state: A dynamical and statistical model perspective. *Phys. Rev. C*, 76:024606, 2007.
  - [16] Z.Y. Sun et al. Isospin diffusion and equilibration for Sn+Sn collision at E/A=35 MeV. *Phys. Rev. C*, 82:051603, 2010.
  - [17] L. May. *Isospin Equilibration in Fermi-Energy Heavy-Ion Nuclear Collisions*. PhD thesis, Texas A&M University, 2015.
  - [18] J. Galin et al. The transition between quasi elastic and completely damped collisions studied in the <sup>40</sup>Ar (280MeV)+<sup>58</sup>Ni reaction. *Z. Physik A*, 278:347–352, 1976.
  - [19] J.V. Kratz et al. Charge-asymmetry equilibration in the reaction of <sup>129,132,136</sup>Xe with <sup>197</sup>Au near the Interaction Barrier. *Phys. Rev. Lett.*, 39:984, 1977.
  - [20] L.G. Moretto and R.P. Schmitt. Deep inelastic reactions: a probe of the collective properties of nuclear matter. *Rep. Prog. Phys.*, 44:533, 1981.
  - [21] E.S. Hernandez et al. Quanta dynamics of charge equilibration in damped nuclear collisions. *Nuc. Phys. A*, 361:483, 1981.
  - [22] G.J. Matthews et al. <sup>20</sup>Ne-induced reactions with Cu and <sup>197</sup>Au at 8.6 and 12.6MeV/nucleon. *Phys. Rev. C*, 25:300, 1982.
  - [23] H. Freisleben and J.V. Kratz. N/Z-equilibration and nucleon exchange in dissipative heavy-ion collisions. *Phys. Rep.*, 106:1, 1984.
  - [24] G.A. Souliotis et al. Isoscaling of heavy projectile residues and N/Z equilibration in peripheral heavy-ion collisions below the Fermi energy. *Phys. Rev. C*, 90:064612, 2014.

- [25] S. Hudan et al. Tracking saddle-to-scission dynamics using N/Z in projectile breakup reactions. *Phys. Rev. C*, 86:021603, 2012.
- [26] K. Brown et al. Timescale for equilibration of N/Z gradients in dinuclear systems. *Phys. Rev. C*, 87:061601, 2013.
- [27] K. Stiefel et al. Symmetry energy dependence of long-timescale isospin transport. *Phys. Rev. C*, 90:061605, 2014.
- [28] S. Hudan and R.T. deSouza. Timescale for isospin equilibration in projectile breakup. *Eur. Phys. J. A*, 50:36, 2014.
- [29] S. Wuenschel, K. Hagel, R. Wada, J.B. Natowitz, S.J. Yennello, Z. Kohley, C. Bottosso, L.W. May, W.B. Smith, D.V. Shetty, B.C. Stein, S.N. Soisson, and G. Prete. NIMROD-ISiS, a versatile tool for studying the isotopic degree of freedom in heavy ion collisions. *NIMA*, 604:578, 2009.
- [30] Z. Kohley, L.W. May, S. Wuenschel, M. Colonna, M. Di Toro, M. Zielinska-Pfabe, K. Hagel, R. Tripathi, A. Bonasera, G.A. Souliotis, D.V. Shetty, S. Galanopoulos, M. Mehlman, W.B. Smith, S.N. Soisson, B.C. Stein, and S.J. Yennello. Investigation of transverse collective flow of intermediate mass fragments. *Phys. Rev. C*, 82:064601, 2010.
- [31] C.P. Montoya et al. Fragmentation of necklike structures. *Phys. Rev. Lett.*, 73:3070, 1994.
- [32] J. Colin et al. Dynamical effects in multifragmentation at intermediate energies. *Phys. Rev. C*, 67:064603, 2003.
- [33] A.B. McIntosh et al. Short-lived binary splits of an excited projectile-like fragment induced by transient deformation. *Phys. Rev. C*, 81:034603, 2010.
- [34] F. Bocage et al. Dynamical effects in nuclear collisions in the Fermi energy range: aligned breakup of heavy projectiles. *Nucl. Phys. A*, 676:391, 2000.
- [35] B. Davin et al. Fragment production in noncentral collisions of intermediate-energy heavy ions. *Phys. Rev. C*, 65:064614, 2002.
- [36] R.J. Charity. N-Z distributions of secondary fragments and the evaporation attractor line. *Phys. Rev. C*, 58:1073, 1998.
- [37] D. Theriault et al. Neutron-to-proton ratios of quasiprojectile and midrapidity emission in the  $^{64}\text{Zn}+^{64}\text{Zn}$  reaction at 45 MeV/nucleon. *Phys. Rev. C*, 74:051602, 2006.
- [38] R. Vandenbosch and J.R. Huizenga. Nuclear Fission. 1973.