EMMI RRTF: Nuclear physics confronts relativistic collisions of isobars

Optimal species to maximize the impact of collider runs

On June 1^{st}, 2022, the Task Force met to discuss the physics opportunities offered by potential future collider runs with new nuclear species. A window to perform collisions with new ions may be opened in future, in particular at the Large Hadron Collider (LHC). The Task Force has, thus, worked on the identification of nuclear species that would maximize the scientific outcome of such runs. More precisely, one could select nuclear species that, besides permitting to address some targeted issues of the high-energy nuclear physics program, would in addition permit to:

- Exploit the known low-energy structure of the colliding ions to access more efficiently the targeted high-energy features;
- Allow us to to extract some important information about the structure of the colliding ions that would complement the effort of low-energy experiments;
- Reveal features of the low-energy structure of the colliding ions that are not accessible via conventional nuclear structure experiments, and that would have a significant impact on low-energy nuclear structure models.

The discussion lead to the identification of three science cases that may readily lead to breakthrough observations via relativistic collision experiments. They involve nuclides belonging, respectively, to the mass regions $A \sim 20$, $A \sim 40$, and $A \sim 150$.

1. Stress-testing small-system collectivity with ^{20}Ne

The nucleus neon-20 presents the most extreme ground state of all stable nuclides. It is a strongly-deformed object made of five α-clusters. The geometry is that of two tetrahedrons stuck together on one side. In terms of the common quadrupole deformation coefficient, the ground state has $\beta_2 \approx 0.7$, the highest of all stable ground states. It should be appreciated that these features are robustly understood, i.e. several different nuclear structure frameworks provide a consistent description of its ground- and excited-state properties.

The deformation of this nucleus is so large that its effects are expected to survive the prominent event-by-event fluctuations that characterize the initial states of collisions of small ions (driven by the small nucleon numbers). Our idea is to exploit the extreme geometry of this nuclide to perform nontrivial tests of the initial-state modeling and the hydrodynamic response in small systems. This is akin to the motivation that lead to running ^{238}U nuclei at the BNL Relativistic Heavy Ion Collider (RHIC), where the large deformation of such ion could be used to, e.g., produce quark-gluon plasmas at a higher temperature, depending on the relative orientation of the two ions, compared to ^{197}Au+^{197}Au collisions. Here, one can compare ^{20}Ne+^{20}Ne collisions with ^{16}O+^{16}O collisions, as ^{16}O nuclei are essentially spherical. Thanks to this *spherical baseline*, the case for ^{20}Ne+^{20}Ne collisions appears to be very compelling, as we detail below.

1. First, any understanding of upcoming ^{16}O+^{16}O data will be plagued by large model uncertainties, related, in particular, to the transport properties of the created medium. The reason is that this is the only nucleus-nucleus system available in the mass region $A \sim 20$. Any predictions for bulk observables in the soft sector will result mostly from an extrapolation from much larger collision systems, which are well-described within the effective relativistic hydrodynamic framework. As it has been fully established in the past three

years or so, the situation changes entirely if more than one system is available in the same mass region. The reason is that, by looking at relative variations between two systems, one can construct observables that are independent of transport properties, and access an information that is model-independent. Having data from ^{20}Ne+^{20}Ne collisions will permit, hence, to maximize the scientific output of the ^{16}O+^{16}O run (and vice versa).

2. If a large statistics of ultra-central ^{20}Ne+^{20}Ne collisions is recorded, then one could use it to investigate nontrivial effects of energy loss of hard probes in such systems. In particular, one should look for path-length-dependent effects via event-shape selection techniques. One has to select events that present an abnormally large v_2 (or v_3), and then look for the angular dependence of the suppression of jet yields. If modifications appear with respect to the spherical baseline provided by ^{16}O+^{16}O systems, that would lead to model-independent evidence of energy loss effects for a system with $N_{\rm part} \sim 40$. Once again, this is not possible if a single collision system is available.
3. A gas of ^{20}Ne ions can be readily injected (and has been already injected) in the SMOG system of the LHCb detector. This implies that, while collecting ^{20}Ne+^{20}Ne collisions in collider mode at $\sqrt{s_{\rm NN}} \approx 7$ TeV, one can at the same time record ^{20}Ne+^{20}Ne collisions in fixed-target mode at a center-of-mass energy that is smaller by two orders of magnitude ($\sqrt{s_{\rm NN}} \approx 70$ GeV). This would provide a unique window onto the beam-energy dependence of the initial state, the dynamics and longitudinal structure of small systems.
4. On the side of nuclear structure theory, having data on ^{20}Ne+^{20}Ne collisions would have unique implications. Indeed, this nucleus presents strong collective correlations, contrarily to the weakly-correlated ^{16}O. For this reason, ^{20}Ne can be regarded as a prototype of the many complex nuclei that are found later on in the nuclear chart and that challenge our theoretical description. Very recently, complementing more phenomenological frameworks, *ab initio* approaches have been able to access light deformed systems like ^{20}Ne. In these approaches, nuclear deformation emerges from genuine n-body (up to A-body) correlations in the wavefunction, themselves generated by inter-nucleon interactions linked to QCD via an effective field theory. Precise data from fluctuation observables in ^{20}Ne+^{20}Ne collisions would permit, then, to test the effectiveness of such *ab initio* calculations in capturing many-body correlations in nuclei. We stress that no such tests are really feasible via low-energy nuclear experiments.

⟶ **Collisions to perform:** ^{20}Ne+^{20}Ne

2. Measuring the neutron skin of ^{48}Ca

While the distribution of electric charge in atomic nuclei is (or can be) known precisely and in a model-independent way from electron-nucleus scattering experiments, our knowledge of the neutron distributions remains scarce. A quantity that is commonly used to investigate the distribution of neutrons is the thickness of the neutron shell that populates the surface of all nuclei presenting a neutron excess. This goes under the name of *neutron skin*. This is a quantity of fundamental interest. It is related to the so-called *symmetry energy*, one of the key parameters entering the equation of state of nuclear matter. The symmetry energy is in turn a key factor in explaining the stability of neutron stars, and for this reason is extensively discussed and investigated in low-energy nuclear physics and nuclear astrophysics.

The neutron skin is formally defined as the difference between the root-mean square (rms) neutron radius and the rms proton radius:

$$\delta_{np} = \sqrt{\langle r^2 \rangle_n} - \sqrt{\langle r^2 \rangle_p}. \tag{1}$$

A nucleus whose neutron skin has been subject of much work in the low-energy nuclear physics community is ^{48}Ca. The reason is that this is a nearly-spherical doubly-magic nucleus presenting a considerable neutron excess. Its sphericity and relatively small size makes it accessible to cutting-edge *ab initio* theoretical frameworks. Over the past decade, a dedicated experiment at Jefferson Lab, the CREX experiment, has been devoted to measuring the neutron skin of ^{48}Ca. The results of the experiment have been discussed at 2021 April Meeting of the APS Nuclear Physics Division. They are not yet published in a journal.

It turns out that providing a robust estimate of the neutron skin of ^{48}Ca in high-energy nuclear collisions is rather straightforward. The isotopic chain of calcium features two doubly-magic nuclei. One is ^{48}Ca, the other is ^{40}Ca. The latter has the same number of protons and neutrons ($Z = 20$). As a consequence, its neutron skin is much smaller[1] than that of ^{48}Ca. However, experiments reveal that ^{48}Ca and ^{40}Ca have the same charge radius (a unique feature of this isotopic chain) such that neutrons only determine the differences in size between these two isotopes. Experimental data from high-energy collisions of isobars at RHIC has demonstrated that, for collisions of nuclei that are close in size, one can robustly access the neutron skin difference between the two species. For instance, isobar data clearly shows that

$$\delta_{\rm np}(^{96}{\rm Zr}) - \delta_{\rm np}(^{96}{\rm Ru}) \approx 0.06 \pm 0.02 \text{ fm}. \tag{2}$$

If $\delta_{\rm np}(^{48}{\rm Ca}) \gg \delta_{\rm np}(^{40}{\rm Ca}) \approx 0$, then via high-energy collisions one could isolate

$$\delta_{\rm np}(^{48}{\rm Ca}) - \delta_{\rm np}(^{40}{\rm Ca}) \simeq \delta_{\rm np}(^{48}{\rm Ca}). \tag{3}$$

This quantity can be accessed unambiguously with an uncertainty of about 0.02 fm. Any significant deviations of such result from the expectations of low-energy theories or experiments should be ascribed to some novel effect related to the high-energy dynamics of nucleons.

$\longrightarrow$ **Collisions to perform:** ^{40}Ca+^{40}Ca, ^{48}Ca+^{48}Ca

3. Imaging the $^{144-154}$Sm isotopic chain: The ultimate nuclear shape experiment

Quite remarkably, for certain species it is enough to add a single neutron and move along neighboring isotopes to engender dramatic changes in the overall nuclear shapes. While this occurs mainly away from the stability line (such as in the chain of zirconium, Zr, isotopes) there exists in nature one isotopic chain of stable ground states that features a transition from nearly-spherical to well-deformed nuclei with increasing neutron number. This is the chain of samarium isotopes, Sm ($Z = 62$). In particular, low-energy nuclear physics tells us that ^{144}Sm is as spherical as ^{208}Pb ($\beta_2 \approx 0.07$), while ^{154}Sm is very strongly deformed ($\beta_2 \approx 0.35$), i.e., significantly more deformed than ^{238}U. It is of fundamental interest to see whether the addition of a single neutron has the same phenomenological implications in both low-energy experiments and high-energy collisions. At high energies, this could be readily quantified by extracting at the differences in quadrupole deformations among these isotopes, by comparing, say , $^{\rm x}$Sm+$^{\rm x}$Sm collisions with $^{\rm x+1}$Sm+$^{\rm x+1}$Sm collisions.

Much more important, though, in high-energy heavy-ion collisions one can directly access *dynamical* nuclear deformations that originate from many-body correlations beyond the mean field. This means that the *dynamical* octupole, β_3, and hexadecapole, β_4, deformations of the samarium isotopes can be precisely accessed via collisions at high energy. None of these nuclides is characterized by excitation spectra that suggests the presence of static octupole or hexadecapole deformations, meaning that low-energy experiments tell us little about them. However, such deformations would become visible essentially by eye in collider experiments, as one moves from ^{144}Sm to ^{154}Sm. This would showcase the unique capability of high-energy nuclear collisions to

---

[1] In fact, due to Coulomb repulsion between protons a *proton* skin is likely to appear for this nucleus.

probe many-body correlations in the ground state of nuclei, and pose new experimental constraints for future *ab initio* calculations of such nuclei, as well as challenge in an unprecedented way state-of-the-art energy-density functional and shell-model calculations.

$\longrightarrow$ **Collisions to perform:** As many ^{x}Sm+^{x}Sm as possible ($144 \leq x \leq 154$)