1 Challenges for Nuclear Reaction Theory

The INT Program "Interfaces Between Structure and Reactions for Rare Isotopes and Nuclear Astrophysics" was held on August 8 to September 2, 2011. One of the goals of this Program was to identify specific problems in the area of reaction theory for rare isotopes and propose paths for their solutions. The Program began with an overlap with the 7th ANL/JINA/MSU annual FRIB workshop on "Interfaces between Nuclear Reactions and Structure" (August 8-12, 2011). The talk-intensive workshop had a large input from experimentalists, who were encouraged to formulate charges and challenges to nuclear structure and reaction theory that could both influence and benefit experimental nuclear physics research programs. The experimental talks included the topics of one-nucleon transfer and knockout reactions; two-particle transfer, two-particle knockout and two-particle decay; charge-exchange reactions and their connections to nuclear astrophysics; and medium to high energy heavy-ion reactions. The Workshop and Program were successful in illuminating the theoretical problems that need to be solved for understanding the rich nuclear landscape from stable to neutron-rich nuclei and their implications for nuclear astrophysics.

This report introduces some of the areas discussed and presents some of the specific issues and problems that were raised. Contributors to this report include Alex Brown, Pierre Capel, Pawel Danielewicz, Wim Dickhoff, Charlotte Eslter, Henning Esbensen, Filomena Nunes, Ian Thompson, Jeff Tostevin and Remco Zegers.

2 Transfer Reactions

The primary tools addressed here are theoretical direct reaction models/codes for use in nuclear spectroscopy and in studies of one- and two-nucleon particle and hole strengths using reactions that add (pickup) or remove (strip) nucleons from the exotic nucleus of interest. These tools are used to interpret experimental results and also to validate the effectiveness of developments of shell, mean field and many-body structure models and their derived observables into more extended regions of the nuclear chart – with applications and implications for nuclear astrophysics. The emphasis here is on the capabilities of readily available codes and their effectiveness. Specifically, major users are (i) practitioners of light-ion induced one and two nucleon transfer reactions, such as (d,p) and (p,t), usually and optimally carried out at near Coulomb barrier energies (the topic covered in the remainder of this section), and (ii) practitioners exploring methods using one- and two-nucleon removal reactions from fast fragmentation beams on light nuclear targets (the topic covered in the next section). Brief mention will be made of the more general capabilities of transfer codes, e.g. for reactions between light heavy-ions and for calculations of breakup observables of weakly-bound (halo) systems.

A chronology of transfer/coupled channels code developments can be found at Reference [1]. Basic aspects of distorted-wave Born approximation (DWBA) transfer codes are finite-range (FR) treatments of transfer vertices using exact integration (EFR) or Local Energy

Approximation (LEA/ZR) corrections to zero-range (ZR) methods. Beyond the DWBA, treatments of breakup effects, particularly for (d,p) and its inverse, use the adiabatic (AD) [2] or the discretized coupled channels (CDCC) methodologies [3]. The ability to treat nucleon transfers to unbound (UB) final states is becoming a more general requirement especially for exotic nuclei. For two nucleon transfers (TNT) (treated other than as transfer of a dinucleon cluster) then two-step (TS) or multi-step transfers (MST) need to be implemented, with the necessary non-orthogonality terms and issues. In some applications the inclusion of remnant terms (RT) in the transition interaction [4] may also be needed. Overarching all of these methods, a clear and flexible capability to specify the parameters of, or to read in numerical form, the complex optical potentials of the practitioner's choice is essential.

Documented codes are available for most of these tasks. For one-step DWBA and AD model transfers DWUCK4 (LEA/ZR) and DWUCK5 (EFR) are available [5]. DWUCK4 allows for UB final states, treated using the Vincent-Fortune method [6]. FRESCO, developed by Thompson [7] is a very general direct and coupled-reaction channels code with DWBA, EFR, LEA/ZR, CDCC, AD, RT, TS, and MST capability. UB final states can be approximated using its discretized continuum capability. Essentially all physical inputs are user-specified (few defaults) with a large overhead for novice/first-time users. Ancillary codes include SFRESCO, with potential and coupling parameters search capability and XFRESCO, a graphical interface that helps users to create and modify input files interactively [7]. A post-processor bundle is also available for FRESCO (CDCC) for the calculation of three-body breakup observables [8] in either individual projectile fragment or their c.m. and relative motion variables [9].

The Surrey version of TWOFNR [10], like the DWUCK4 code, has DWBA, AD, LEA/ZR capability. Moreover, an interactive front-end/pre-processor exists to generate data sets, that includes phenomenological (nucleon, d, p, t) global, JLM (nuclear matter G-matrix plus LDA) [11] nucleon potentials and also the auto-generation of AD potentials if needed. Observables in inverse/regular kinematics are computed. Though a less sophisticated code, this utility has allowed inexperienced practitioners to plan proposals and readily assess reaction sensitivities. Given the generality of the capability of FRESCO, and the investment therein, only modest effort could provide dedicated front-end processors for reactions of choice, with default choices and/or theoretical recommendations for applicable potential sets. This should include microscopic theoretical interactions such as JLM where applicable, to extend the reach beyond the existing phenomenology. Making these options readily available could lead rapidly toward a better assessment of their effectiveness for asymmetric systems. New phenomenological global potentials and theoretically-driven projectile- or energy-specific potential developments, e.g. from the use of the dispersive optical model approach [12], can also be readily incorporated, as they become publicly available, into such reaction code-specific tools, encouraging their wider use and assessment against new data.

Again, at a modest cost, there is scope within such such front-end processing to provide estimates (where available, and references to relevant work) for the expected level of accuracy of the user-selected approximations and/or combinations of selected parameters to guide/inform users. E.g., in the case of (d,p) and (p,d) reactions, such information on e.g.

FR, AD aspects, could include recent Refs. [13, 14].

3 Fast Removal (Knockout) Reactions

Here the codes used remain more developmental. The methods used are the sudden and eikonal approximations. Observables are inclusive with respect to target final states and computed based on the absorptive/diffractive elastic S-matrices of nucleons and ions with a nuclear target. Like transfer, codes rely on complex two-body interactions at the energy of interest. $t\rho\rho$ approximations are used and there is scope for improved ion-ion interaction input at the lowest energies (if significantly less than 100 MeV/u) used by some practitioners. In common with transfer reactions, nuclear structure information is in the form of particle overlap functions. A rather general package for calculations of cross sections and residue momentum distributions for one-nucleon removal is provided by MOMDIS [15], with a number of in-built interaction options. A code bundle (modular) for two-nucleon removal cross section calculations, see e.g [16], is available and documentation is in preparation. The two-nucleon removal codes structure interface is to shell model amplitudes. Development requires structure theory practitioners to make available microscopically-derived two-nucleon overlaps as and when available. The documented primary sensitivity to orbital rms radii simplifies this task. Code for two-nucleon momentum distributions is advanced, is being exploited for spectroscopy, e.g. [17], and is under further development.

Needs are for theoretical resource for extensions toward deformed systems. Developments of fragmentation facilities (RIBF, GSI, FRIB) toward higher energies ($\geq$250 MeV/u) do not suggest the need or value of major investment toward a new non-sudden/eikonal machinery. Nevertheless, further studies of the accuracy of these reaction model ingredients, and the uncertainties associated with the spectator-core, eikonal and sudden approximations used, are necessary if one wishes to attach *theoretical errors* to calculated observables. These ongoing evaluations require the continued experimental commitment to high-precision and also test-case experiments, e.g. [18], to challenge the model expectations.

4 Charge-Exchange Reactions

Charge-exchange reactions at intermediate energies (100-300 MeV/u) are widely used to study the spin-isospin response of nuclei (see e.g. [19]). One of the main goals is to extract Gamow-Teller transition strengths, but other types of isovector excitations and (giant) resonances are the subject of intense experimental and theoretical work as well. In recent years, the experimental communities at various facilities have started programs using charge-exchange reactions on unstable nuclei, or using unstable probes to isolate specific types of isovector channels. Aside from providing fundamental information about microscopic and macroscopic properties of nuclei, charge-exchange experiments provide input for a wide variety of applications, for example related to astrophysics and neutrino

physics.

Given the opportunities (that will be) provided by new rare-isotope beam facilities, the experimental groups focusing on charge-exchange reactions have developed a variety of new tools and measurement techniques. However, it has also become clear that renewed efforts in theoretical approaches are required. Such efforts would not only be beneficial to new types of experiments with unstable beams, but also allow researchers to extract more detailed information from traditional experiments with stable beams. In particular, the need for improved descriptions of the charge-exchange reaction mechanism has become apparent.

Two widely used reaction codes for charge-exchange reactions, are **DW81**, which is the main code for nucleon-induced charge-exchange reactions [(p,n) and (n,p)] and **FOLD**, which is mainly used for charge-exchange reactions with composite probes. Both employ the effective interaction by Love and Franey [20, 21], which were fitted to the nucleon-nucleon (NN) data availabe at the time (specfically SP84 of the VPI phase shift analysis) at selected NN c.m. energies ranging from 50 MeV to 1 GeV. Over the last 25 years the NN data base increased substantially. In addition, in the 1990s the socalled 'high-precision' potentials by the Nijmegen group [23], the charge-dependent Bonn NN potential [24], and the Argonne V18 [25] NN potential fitting the NN observables with a χ^2 of about one were developed. Current nuclear structure calculations often employ a chiral potential of order N3LO [26] describing the NN data base with the same quality. Thus it is highly desirable to upgrade current charge-exchange codes so that those reaction calculations can take advantage of the investments the NN community made in improving the description and understanding of the nucleon-nucleon interaction.

In the case of **FOLD**, the NN-interaction is folded over the transition densities of the projectile and target systems. Exchange terms are currently treated in a short-range approximations and are only included for the central terms. Therefore, aside from the use of an outdated NN-interaction, additional uncertainties are due to this approximation [22]. For the nucleon-induced calculations, the situation is better: **DW81** calculates exchange contributions exactly, but still relies on the outdated NN-interaction.

The general structure of the NN amplitudes is given by the Wolfenstein respresentation [27], and any of the above mentioned NN interactions can calculate the scattering amplitude in this form. Love and Franey [21] further filter out singlet and triplet contributions and then parameterize a t-matrix obtained from the scattering matrix in terms of potential-like Yukawa functions. The NN t-matrix obtained in this fashion still consists of operators multiplied by scalar functions of magnitudes of momenta. Those scalar functions are in the original Love-Franey implementation Fourier transforms of r-space Yukawa functions. The parameters of the Yukawa functions are given in Ref. [20].

A workable suggestion for implementing modern NN interactions in the code **FOLD** for charge-exchange reactions is, to keep the operator structure of the nn t-matrix, but calculate the scalar functions from microscopic NN potentials. This will involve

1. A code to calculate the scattering amplitude in Wolfenstein form, Eq. (2) of Ref. [21]. Elster and Weppner have such a code, obtaining Wolfenstein amplitudes from codes that solve the partial wave Lippmann-Schwinger equation in momentum space for the above given potentials. (To be specific, Nijmegen and AV18 are still in check-mode.)

2. A code either manipulating the Wolfenstein amplitudes from Eq. (2) of Ref. [21] into the operator structure of Eq. (14) in Ref.[21] or summing up the partial wave on-shell t-matrix elements to directly obtain the required scalar functions.

3. A modification of the reaction code **FOLD** so that the currently hard-wired Yukawa functions are replaced by the reading in of scalar functions as numerical values.

4. Once all tests are carried out, some code work will be needed for smooth interfaces between different code pieces.

It is important to assess early in the project the applicability of this procedure to performing reactions calculations with composite probes, as the improvement of the NN-interaction will be much more valuable if it can also be applied to such studies.

5 Breakup Reactions

Breakup reactions are another set of tools to study nuclear structure far from stability. They are mostly used to study the structure of loosely-bound projectiles such as halo nuclei. These nuclei exhibit a strongly clusterized structure and are rather well described as a core, which contains most of the nucleons, to which one or two light fragments are loosely-bound. In (elastic) breakup, the fragments dissociate from the core through their interactions with a target, hence revealing the internal structure of the projectile. This type of reaction differs from knockout (discussed above) as in the present exclusive final state case all the projectile fragments can be detected in coincidence and the target remains in its ground state.

Significantly, breakup reactions have been measured on heavy targets and interpreted using first order perturbation theory [28], simulating the projectile-target motion by a classical (Coulomb) trajectory and the nuclear interaction by means of an impact-parameter cut-off. Unfortunately, higher-order effects (e.g. couplings inside the continuum) and nuclear-Coulomb interferences are not negligible [32, 29, 30, 31]. Therefore breakup reactions cannot be reliably analysed within perturbation theory and one must consider more elaborate models to infer structure information from experimental data. Various models have been developed to interpret data on one-nucleon halo nuclei, i.e. two-body projectiles. Review articles on breakup models can be found in Refs. [34, 33].

Probably the best known reaction model is the Continuum Discretised Coupled Channel model, or CDCC [35, 36]. As mentioned in the section on transfer reactions, Thompson has developed the code FRESCO that implements this model. The code is freely available

online [7] and a clear manual with simple examples ready to use can be found in Ref. [37]. In CDCC, the projectile-target wave function is expanded over the basis of the projectile eigenstates, leading to the resolution of a set of coupled equations. However, such an expansion requires a discretisation of the continuum of the projectile. It is purely quantal and naturally includes both Coulomb and nuclear interactions on the same footing. The CDCC is computationally expensive, in particular at high beam energy. Other models, less computationally demanding, have been developed to study breakup reactions.

Many groups have developed time-dependent models (TD) [38, 39, 40, 41]. These models rely on a semiclassical approximation in which the projectile-target relative motion is approximated by a classical trajectory, which leads to the resolution of a time-dependent Schrödinger equation. Unlike in the aforementioned perturbation theory, it is solved exactly (i.e. numerically) by applying iteratively an approximation of the time-evolution operator to the initial bound state of the projectile. This method can include Coulomb and nuclear interactions on the same footing [42]. Due to its semiclassical nature, it cannot account for the quantum interferences that are observed in CDCC angular distributions. However, it produces excellent angular-integrated observables, such as energy distributions. None of these codes have been made public.

Another set of breakup models is based on the eikonal approximation (see the section on knockout reactions). The usual eikonal approximation, relying on an adiabatic—or sudden—approximation, is valid only for light targets and diverges in Coulomb-dominated collisions [43]. In order to avoid this divergence and deal with heavy targets as well, one can avoid making the adiabatic approximation. This leads to the Dynamical Eikonal Approximation (DEA) [44, 45]. This approximation leads to the resolution of an equation mathematically equivalent to a time-dependent Schrödinger equation but for straight-line trajectories. It can thus be solved using any of the algorithms developed for the TD method [38, 39, 40, 41]. However, being fully quantal, the DEA naturally includes diffractive patterns observed in angular distributions. It therefore generalizes the TD technique. Moreover, including dynamical effects, it can handle properly both light and heavy targets, which improves the usual eikonal model. At sufficiently high energy (e.g. 70AMeV), it reproduces very well CDCC calculations with smaller computational overheads. Being built on the eikonal model, the DEA lacks Coulomb deflection and hence fails at describing low-energy reactions (i.e. below 40AMeV).

It is also possible to include the Coulomb interaction in the eikonal model using first order perturbation theory [46, 47, 43]. This Coulomb-Corrected Eikonal model (CCE) reproduces fairly well DEA calculations with smaller computational times [43]. It has thus been used to extend reaction models to three-body projectiles, e.g. two-neutron halo nuclei like ^{6}He [48]. Plans are made to extend the CCE to more microscopic descriptions of the projectile. Similar progress has already been made within CDCC. An extended version of the model (XCDCC) has been developed to include excitations of the core [49, 50]. Efforts are also made to include three-body projectiles [51, 52, 53]. However, the computational cost of such an extension has up to now limited the model to include three-body breakup channels in elastic-scattering calculations.

The development of accurate reaction models has enabled a better understanding of the mechanism of breakup. It is now clear that relying on a simple perturbative description of the reaction is unreliable and can lead to misinterpretations of experimental data. However, most of these models still rely on a crude description of the projectile: a valence nucleon loosely-bound to an inert core through an effective interaction. To improve the study of loosely-bound nuclear systems from breakup measurements, reaction models including more microscopic descriptions of the projectile will have to be developed. Efforts have already been made within the CDCC framework. However, due to the computational cost of this model, extensions of other models should be considered. In particular, the CCE, DEA, and/or TD techniques seem promising in that respect due to their relatively low computational cost.

6 Breakup and Fusion

There is a strong need for realistic optical potentials that can be used without much difficulty in the analysis of breakup reactions of weakly bound nuclei. A global, empirical nucleon-nucleus optical potential has been available for some time up to 65 MeV [54] and new (global and local) potentials have been developed up to 160 MeV [55] and 200 MeV [56]. This is very fortunate because the latter potentials cover the energy range of interest to most radioactive beam facilities. At very high energies on can use a simplified description in terms of the free t-matrix interaction and nucleon-nucleon profiles functions, combined with Glauber theory [57], but there is still a gap in energy where Glauber theory does not apply and optical potentials are not available. The Glauber theory has anyway been used down to very low energies, where it may not be so realistic. There are also microscopic optical potentials, generated by effective g-matrix interactions but they are in general rather complicated to construct [58] and are not readily available to practical applications in calculations of breakup reactions.

Systematic studies of optical potentials for nucleus-nucleus scattering (i. e., the core-target interaction in breakup reactions) are also needed. The empirical potentials that are used are usually local, i. e. they have been constructed to describe scattering data for a particular projectile-target combination and at a particular energy, and some extrapolation is therefore often needed to the case of interest. The potentials can also be constructed by the double-folding technique from effective nucleon-nucleon interactions but they should in general be tested against scattering data before they are applied with confidence in calculations of breakup reactions. In this connection, it would be extremely valuable if the core-target (elastic) scattering were measured separately, whenever a breakup experiment was performed.

The structure models that are used in calculations of break reactions of weakly bound nuclei are usually based on a simplified two- or three-body description. They often employ a Woods-Saxon potential which is adjusted to describe certain desirable features, such as the separation energy and energies of known resonances in the nucleus of interest. The simplified nature of these models is necessary when higher-order processes must be considered in the

breakup process. However, as microscopic structure models improve and are able to predict the ground state properties of nuclei far from stability, it becomes very attractive to apply these predictions in reaction calculations. This is possible when the reaction mechanism is simple and direct, and higher-order processes do not play any role. This is the case at very high energy, where the sudden approximation or Glauber theory applies. An example is the calculation of the scattering and reaction of ^{6}He at very high energy [59].

It is also of interest to include explicit excitations of the core nucleus in breakup reactions, both in the initial state (as in the Nilsson model) and during the breakup due to interactions with the target nucleus. Implementing these features will improve the quality of the spectroscopic information that can be extracted from measurements, for example, of gamma-rays measured in coincidence with the breakup fragments. Attempts have been made to implement core excitations [49] but the reaction code has not yet been fully utilized.

The static and dynamic ion-ion potentials that are used to calculate low-energy heavy-ion fusion and scattering cross sections are also uncertain. The potentials can be obtained by the double-folding technique from simplified, effective g-matrix interactions, whereas the dynamic potential is generated by coupled-channels calculations. This approach usually provides a very good description of the height of the Coulomb barrier but the potential is uncertain for overlapping nuclei. The latter problem is particularly critical in the description of fusion reactions at extreme sub-barrier energy, where it is necessary to modify the potential for overlapping nuclei in order to explain the data [60]. The analysis of fusion data suggests that the empirical interaction must produce a fairly shallow pocket in the entrance channel potential, with a minimum that is far above the ground state of the compound nucleus. Important questions are what causes the shallowness of this pocket and how does it relate to the quasi-molecular resonances that were observed in light-ion scattering more than 50 years ago [61]. In the empirical work of Ref. [60] it is explained by the nuclear incompressibility. It is very interesting that recent TDHF calculations seem to confirm the existence of such a shallow potential [62, 63].

Improved coupled-channels calculations of low-energy, heavy-ion reactions should also be pursued. One could utilize the form factors and transition densities that are obtained in microscopic theory, in particular, for those transitions that are poorly known experimentally. This would improve the predictive power of coupled-channels calculations and make the extrapolation of cross sections to very low energies more reliable. A recent example is the fusion of carbon isotopes which is sensitive to excitations of high-lying states that are poorly known experimentally. By applying the structure information of the shell model, it is possible to make a more realistic prediction and provide an upper limit for the ^{12}C+^{12}C fusion cross section at very low energy [64], which is of great interest to nuclear astrophysics.

In order to understand the influence of breakup on the complete and incomplete fusion of weakly bound nuclei, one would need to go beyond the conventional, coupled-channels approach. It would be necessary to include continuum states of the weakly bound nucleus, in order to be able to describe the fusion of each of the fragments from the breakup. That should be feasible in CDCC calculations but it would require some developments.

7 Linking reactions and structure with the dispersive optical model

(Dickhoff)

An attractive and reliable approach to link nuclear reactions, that can be analyzed with nucleon optical potentials as input, with the intended nuclear-structure information that one aims to extract, is provided by the dispersive optical model (DOM) pioneered by Mahaux [65]. In addition to providing a good representation of elastic nucleon scattering, this approach is capable of describing bound-state data either above or below the Fermi energy that includes overlap functions and spectroscopic factors linking the different energy domains by a (subtracted) dispersion relation. Recent implementations have concentrated on $Z = 20, 28, 50$ and 82 isotopes as well as isotones with $N = 28$ and 50 [66]. This paper also reports on elastic neutron-scattering experiments performed on ^{48}Ca that yielded information concerning the neutron surface absorption as a function of nucleon asymmetry. Extensions to a truly global version of these potentials are currently under consideration.

An illustration of the power of the method is documented in Ref. [67] where the DOM ingredients (potentials and overlap functions) were introduced in the analysis of transfer reactions using the finite-range ADWA method [2]. Results indicate that extracted spectroscopic factors become less dependent on deuteron beam energy and are typically comparable to those generated from $(e, e'p)$ reactions unlike traditional procedures to determine spectroscopic factors that rely on global optical potentials and standard Woods-Saxon overlap functions. For the rare isotope ^{132}Sn similar conclusions are obtained. More work is necessary to clarify the role of excitations in the case of ^{208}Pb.

Recent extensions of the DOM have aimed at increasing the scope of the applications to include more experimental data that describe properties of the ground state of the target like*e.g.* the charge density [12]. The introduction of nonlocal binding potentials (as opposed to energy-dependent local potentials) is a requirement for such an implementation and leads to a proper determination of the spectral strength distribution below the Fermi energy that can be constrained by $(p, 2p$ and $(e, e'p)$ and other knockout data. The calculation of spectroscopic factors and occupation numbers at large nucleon asymmetry is accordingly placed on a more secure footing and leads to intriguing predictions for proton $g_{9/2}$ removal from rare Sn isotopes [66], documenting a strong reduction of the spectroscopic factors of the minority species when the continuum of the majority species is nearby.

Future extensions of the DOM method will rely on recent insights obtained from a comparison with *ab initio* nucleon self-energy calculations that emphasize long-range correlations as in the FRPA [68] and short-range correlations [69]. Based on these comparisons it appears critical to analyze nuclear potentials with nonlocal imaginary components as these are essential to link the DOM with *ab initio* methods to provide further insights into the physics of rare isotopes. This paradigm changing conclusion represents a computational challenge that is under close scrutiny.

8 Central Intermediate-Energy Collisions

Central collisions at intermediate energies populate wide angles with large numbers of different nuclear species, from nucleons, through alphas to IMF fragments ($Z \geq 3$). 4π arrays are generally used to characterize the impact parameters and to reconstruct the reaction plane from the emitted particles. More sophisticated detection systems are used to study the isospin degrees of freedom. Besides single-particle spectra and multiplicities, two- and more-particle correlations are also investigated. Dedicated global observables are constructed for specific purposes such as studies of flow and stopping. Selected observables are used for controlling the reactions, e.g. filtering the reaction centrality or for assessing the orientation of a reaction plane. Observables from central reactions tend to exhibit smooth dependencies on control parameters and studies of those reactions concentrate on the determination of bulk nuclear properties at varying nuclear densities and temperatures, as well as on understanding of the reaction dynamics. The sought-after bulk properties include the nuclear equation of state, both for symmetric matter and the symmetry energy, as well as the transport properties for the matter such as isospin diffusion and stopping. Knowledge derived from central collisions about the equation of state at supra-saturation densities can provide a unique contribution to the understanding of dense matter within neutron stars.

A significant role in arriving at conclusions from observables is played by the comparisons of data to the results of collision simulations within nuclear transport models. That role is underscored by the fact that, in modeling, the central reactions progress through stages that each tends to impact the reaction observables. For efficiency in advancing the conclusions, the simulation codes need to be available to experimentalists. An ability to change, in a simple manner, basic physics parameters associated with the code should be built in. These parameters should include those tied to the dependence of the equation of state on density, momentum dependence of mean fields and to the in-medium dependence of elementary cross sections, affecting stopping in the reactions. When predictions are made in the literature, version of the code used to generate those predictions should be retained to make later inspections possible, if deemed necessary, to clarify details of the predictions.

One problem plaguing transport codes is some level of divergence regarding predictions, for the same basic physics inputs. Those divergencies depend on selected observable and many of them tend to grow with a decrease in the beam energy. Efforts to identify the source of problems through meetings of transport practitioners specialized workshops should be commended. Eventually, a set of simplified test situations needs to be developed for assessing the codes by different authors, with benchmark calculations that could be performed in each code to assess the influence of different choices of physics input, of different choices of transport theoretical descriptions and of different methods of solving the underlying transport equations.

Given the abundance of light clusters coming out from central collisions, algorithms for producing those clusters in transport simulations need to be improved. In parallel, construction of observables that are weakly sensitive to the deficiencies in the description

of cluster production needs to be advanced. Identification of isospin sensitive observables is also important. To improve perspectives for narrowing uncertainties in the equation of state of symmetric matter and for learning about the symmetry energy, uncertainties in the in-medium elementary cross sections need to be narrowed down. The inclusion nuclear structure aspects in the initialization of the collisions and possible influence of the geometry of the collisions should be considered.

At higher incident energies, the production of mesons play an increasingly important role in the collision dynamics. The production rates for pions and kaons have been identified as promising observables for constraining the equation of state. However, some of the predictions for the sensitivity of these production rates to the equation of state do not agree. In order to allow constraints on the density dependence of the symmetry energy and on the equation of state from these observables, the origins for these discrepancies need to be identified and the discrepancies need to be resolved.

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