Uncovering the properties of exotic nuclei via reactions with relativistic radioactive beams

Thomas Aumann
Institut für Kernphysik, Technische Universität Darmstadt, Schlossgartenstraße 9, 64289 Darmstadt, Germany
GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstraße 1, 64291 Darmstadt, Germany
E-mail: t.aumann@gsi.de

Abstract.
Measurements of reactions with relativistic radioactive beams provide powerful tools to extract properties of short-lived nuclei and nuclear matter. A brief overview is given by selecting a few examples with emphasis on knockout reactions and heavy-ion induced electromagnetic excitation. The latter is being utilized to extract the collective dipole response of exotic nuclei, e.g., to study the Pygmy dipole resonance which is related to the neutron skin in heavy neutron-rich nuclei. Knockout reactions are being used to study the shell structure of exotic nuclei. They give also access to investigate the role of nucleon-nucleon correlations in nuclei and nuclear matter as a function of neutron-proton asymmetry. A new technique based on a fully exclusive measurement of quasi-free knockout reactions in inverse kinematics is discussed.

1. Introduction
Since the discovery of the atomic nucleus via alpha-scattering experiments in 1911 by Rutherford [1], a tremendous knowledge on properties of stable nuclei and nuclear matter has been derived from reaction experiments. With the advent of high-energy beams of short-lived nuclei about 25 years ago, the science field of physics of exotic nuclei has experienced a boost. First reaction studies with relativistic radioactive beams have been carried out by Tanihata et al. [2] in 1985 at the BEVALAC measuring total interaction cross sections for stable and neutron-rich nuclei, observing surprisingly large cross sections for nuclei close to the neutron dripline [2, 3, 4], see Figure 1. The phenomenon has been explained by Hansen and Jonson [5] in a core plus valence-neutron picture, in which the wave function of the loosely bound neutrons has a large extension due to the weak binding and low centrifugal barrier. The low-density distribution of the neutrons extending considerably beyond the size of the core with normal nuclear density is called nuclear halo since then. In later years, experiments utilizing reactions with high-energy beams of short-lived nuclei have been developed at various laboratories towards constituting precision tools which facilitate extracting the properties of these exotic species. The $^{11}\text{Li}$ nucleus is a prime example, which we select to discuss a few observables in high-energy reaction experiments providing access to detailed nuclear-structure information.

Figure 2 shows a density distribution extracted from a precise measurement of elastic proton scattering on $^{11}\text{Li}$ at low momentum transfer in inverse kinematics. The effect of the extended neutron density is apparent. A consistent picture on the properties of $^{11}\text{Li}$ has emerged with
time by looking to different observables. The measurement of recoil-momentum distributions in high-energy knockout reactions gives direct access to the intrinsic momentum distribution of the knocked nucleon. An example is shown in Figure 3. The left panel displays the momentum distribution of the unbound $^{10}$Li nucleus after removal of a neutron from $^{11}$Li [8]. The distribution is quantitatively explained by a calculation assuming s- and p-wave components in the $^{11}$Li ground-state wave function with about equal weights, implying that the N=8 shell closure does not hold for $^{11}$Li. The large s-wave content in the wave function is responsible for the very extended halo-like structure of $^{11}$Li. The exclusive measurement with the LAND reaction setup at GSI allowed also for the observation of the $^{10}$Li decay in flight and for reconstructing its excitation-energy distribution (not shown) and the angular distribution of the decay products. The direction of the decay of $^{10}$Li into $^{9}$Li plus neutron with respect to the recoil direction exhibits a pronounced pattern, shown in the middle frame of Figure 3. The observed pattern is again a fingerprint of the structure of $^{11}$Li having its origin in the mixed-configuration wave function populating unbound s- and p-wave states in $^{10}$Li after neutron knockout. All observables (momentum distribution, $^{10}$Li excitation-energy spectrum, angular correlation) are consistently explained and quantitative information has been deduced by Simon et al. [8] on the configuration mixing in the $^{11}$Li ground-state wave function.

A redistribution of dipole strength compared to stable nuclei was observed in several neutron-rich light nuclei. For halo nuclei, a complete decoupling of the dipole response into the part related to the response of the halo neutrons and that of the core is observed. The neutron halo of a nucleus manifests itself in the dipole spectrum causing extremely large transition probabilities directly at the threshold at very low excitation energy. This part of the dipole strength is of non-resonant character and directly related to the properties of the halo wave function like its spatial extension and its single-particle characteristics. The measurement of the strength function thus can be used as a spectroscopic tool similar to the knockout reactions discussed above, see Ref. [9] for a more detailed discussion. A recent example is the measurement of the $^{11}$Li response at low excitation energy performed at RIKEN [10] shown in the right part of Figure 3. The neutron-neutron spatial correlations in the halo of $^{11}$Li enhances the dipole strength at low energies significantly providing access to exploring such correlations by measuring the dipole response. A similar observation and analysis was made for the two-neutron halo nucleus $^6$He [11]. From the Coulomb dissociation data, Nakamura et al. [10] quantified this spatial correlation of the two
halo neutrons in \(^{11}\text{Li}\) in terms of an average relative angle. The correlation of the two neutrons has consequences also on the charge radius of the nucleus. Assuming a three-body structure of \(^{11}\text{Li}\) consisting of a \(^{9}\text{Li}\) core plus two neutrons, the charge radius is expected to reflect that of the core nucleus but affected by the center-of-mass motion. A precise value for the charge radius of \(^{11}\text{Li}\) has been recently extracted from isotope-shift measurements performed at TRIUMF by Sanchez et al. [12]. The larger charge radius compared to \(^{9}\text{Li}\) is to a large extend explained by the correlations of the two neutrons in agreement with the Coulomb dissociation experiment.

There are many more experiments on \(^{11}\text{Li}\) and observables which have been studied in order to unravel the structure of the dripline nucleus \(^{11}\text{Li}\), which we cannot mention here. The development of the experimental tools in the past 20 years together with higher beam intensities allow nowadays to study the structure of light drip-line nuclei and even nuclear systems beyond the drip-line in a rather precise manner, which we can mention here only in passing. A recent example from experiments with the LAND neutron detector are the unbound heavy Li [13] and He isotopes. The kinematically complete measurement of the two-neutron decay of, e.g., \(^{10}\text{He}\) allowed for a detailed study of correlations in the decay of the continuum states of \(^{10}\text{He}\) [14]. It has been demonstrated, that the correlations allow for disentangling contributions from overlapping resonances and for assigning their quantum numbers.

We will discuss in the next two sections two types of experiments with high-energy radioactive beams both related not only to the nuclear-structure aspects but also to the properties of neutron-rich nuclear matter and astrophysics. These are the heavy-ion induced electromagnetic excitation to study the collective dipole response of heavier exotic nuclei, and the exclusive measurement of quasi-free knockout reactions to study the role of nucleon-nucleon correlations as a function of isospin.

2. The dipole response of exotic nuclei
Electromagnetic excitation of exotic nuclei is a very powerful tool to explore the evolution of collective phenomena like giant resonances, especially the giant dipole resonance (GDR) as a function of isospin asymmetry. At beam energies in the range of few hundred MeV/nucleon, cross sections for dipole excitations are large, in the order of barn, and the excitation energies transferred reach up to around 20 MeV [15]. The so called Pygmy Dipole Resonance (PDR) has attracted particular interest, an excitation mode which is related directly to the neutron-excess. A cumulation of dipole strength at low excitation energy well below the Giant Dipole Resonance

\[\text{Figure 3. Left panel: Momentum distribution of }^{10}\text{Li after one-neutron knockout from }^{11}\text{Li at 264 MeV/nucleon measured at the LAND setup at GSI [8]. Middle panel: Angular correlation in the decay of }^{10}\text{Li produced in one-neutron knockout reactions from }^{11}\text{Li from the same experiment [8]. Right panel: Coulomb dissociation cross section of }^{11}\text{Li measured at 70 MeV/nucleon at RIKEN [10].}\]
(GDR) has been observed in several unstable neutron-rich nuclei [16, 17, 18, 19] just above the neutron threshold. An example is given in the left frame of Figure 4, where the excitation spectra of $^{130}$Sn and $^{132}$Sn are shown as derived from a kinematical complete measurement of the neutron decay after electromagnetic excitation at around 500 MeV/nucleon at GSI [17]. A structure at around 10 MeV excitation energy has been observed in addition to the GDR, which has been interpreted as a Pygmy dipole excitation.

There are several measurements of dipole excitations in stable nuclei [20, 21, 22, 23, 24, 25, 26, 27] reporting a cumulation of strength below the particle separation threshold, which has been discussed in the context of PDR excitations as well. A comparison of the different measurements has been made by Klimkiewicz et al. [18], see middle panel of Fig. 4, suggesting a systematic growing of the integrated PDR strength with neutron excess. The comparison, however, is questionable due to several reasons. The data on Pygmy dipole excitations in stable nuclei and neutron-rich nuclei have been obtained with different methods and with different sensitivity. While the low-lying strength observed in neutron-rich nuclei is located above the neutron separation threshold around an excitation energy of 10 MeV, the strength in stable nuclei is found below the threshold between 6 and 8 MeV. In addition, the strength extracted from photon-scattering experiments for stable nuclei does not provide the full strength distribution but only contains the fraction which decays via one-photon emission to the ground state. It is still an open question how these two observations are related. New experiments have been proposed at various facilities both for stable and neutron-rich nuclei in order to solve this issue.

An important aspect of the collective response of nuclei is its relation to bulk properties of the nucleus and nuclear matter. The appearance of low-lying strength in exotic nuclei is particularly interesting from the nuclear-structure point of view since its occurrence is interpreted as a consequence of neutron-proton asymmetry and the evolution of skin effects. Similar as for the properties of the collective giant resonances, one can relate the PDR strength to bulk properties of nuclei and nuclear matter. It has been shown in microscopic calculations, that the density dependence of the symmetry energy close to saturation density is correlated with the low-lying dipole strength in neutron-rich nuclei [28, 29], very similar to the neutron-skin thickness in heavy neutron-rich nuclei [30]. A first attempt to extract the parameters describing the neutron-proton asymmetry part of the equation of state for nuclear matter from the measured low-lying dipole strength has been made by Klimkiewicz et al. [18] and later by Carbone et al. [31]. Having those values determined, the neutron-skin thickness is fixed as well. The neutron-skin thicknesses for $^{130,132}$Sn from the analysis of Klimkiewicz et al. [18] are compared to values deduced from GDR measurements in stable tin nuclei by Krasznahorkay et al. [32] in the right part of Figure 4. The deduced values for the symmetry energy and its density dependence as well as the neutron-skin thicknesses are consistent with other methods. The systematic uncertainties of such an approach, however, has still to be explored in detail. It has been suggested that the dipole polarizability might be a more robust observable [33, 29] with less model dependences. The sensitivity, however, is largest for the low-energy dipole response [29].

Clearly, the measurement of dipole-strength functions for neutron-rich nuclei using heavy-ion induced electromagnetic excitation at high beam energies looks very promising for deriving the necessary information for the understanding of the neutron-capture nucleosynthesis processes as well as for constraining the equation of state for neutron-rich matter, which is fundamental for the understanding of the properties of neutron stars. The experimental situation concerning the pygmy dipole response of exotic and even stable nuclei is, however, far from being clear. It is mandatory that measurements of exotic nuclei are performed which are sensitive to the full strength function below and above the threshold including a measurement of the $\gamma$ branching ratios. In addition, the quality of the data in terms of statistics and experimental response will be improved in the future. But even for stable nuclei, the situation is not clear, as discussed above. Important part of the strength decaying by cascades has not been measured. First
with sufficient counting statistics could be accumulated for separation threshold, relevant in the present context, a resolution of neutron number (upper row) and with even-neutron number (bottom row). The solid lines show results for neutron number. The energy-differential Coulomb cross sections were obtained. reactions (deduced from a measurement with a carbon target) without target) and after subtracting contributions from nuclear systematics of stable nuclei (see, e.g., Ref. [17]. The main emphasis of the present Rapid Communication displays the remaining dipole strengths.

Figure 4. Left panel: Coulomb excitation (left frames) and photo-absorption cross sections (right frames) for neutron-rich tin nuclei [17]. Middle panel: Integrated low-lying dipole strength as a function of neutron-proton asymmetry. Values for stable nuclei (open symbols) have been derived from photon-scattering experiments and reflect only the strength below threshold for states decaying by one-photon emission back to the ground state. The data for radioactive nuclei (filled symbols) contain only the strength above the neutron threshold. The figure is taken from Ref. [18]. Right panel: Neutron-skin thickness of tin isotopes derived from GDR excitations with an isoscalar probe for the stable isotopes [32], and from PDR excitations in $^{130,132}$Sn [18].

We find good agreement with model predictions. The experimental evidence that indeed a substantial part of the strength particularly close to the threshold is missing has been obtained [34, 27] recently.

3. Quasi-free knockout reactions with radioactive beams

The measurement of quasi-free nucleon-knockout reactions have proven in the past to constitute a quantitative tool to provide information on the single-particle structure of nuclei. From electron-induced proton-knockout reactions spectral functions and momentum distributions of nucleons inside the nucleus have been deduced. Such measurements have revealed the role of correlations leading to a redistribution of the single-particle strength at the Fermi surface. Beyond the shell-model like correlations among valence nucleons and couplings to collective states, nucleon-nucleon correlations have been identified leading to high-momentum components and to a depletion of the occupancy of single-particle states. From such measurements, it has been concluded that about 20% reduction of spectroscopic factors should be attributed to such short-range correlations [35]. In total, a typical occupancy of single-particle states in the order of 60% has been established [35]. Recent (e,e’p) experiments performed at JLAB [36] have measured proton knockout reactions at high momentum transfer detecting a 2nd correlated nucleon in coincidence. The authors have concluded from such measurements, that the nucleon-nucleon correlations inside a nucleus causing the high-momentum components of nucleons are related mainly to neutron-proton pairs, and to a much less degree to p-p or n-n pairs. This conclusion is, however, not yet established. It would be of course extremely interesting to probe such correlations for neutron-proton asymmetric nuclei, where a change of the importance of the different kind of correlations is expected, as it is the case for asymmetric nuclear matter [37]. The amount of correlations in neutron-rich matter has significant influence on the properties of neutron stars. Radioactive beams potentially provide the possibility to probe the role of nucleon-nucleon correlations in nuclei as a function of neutron-proton asymmetry.

Nucleon-knockout reactions from high-energy radioactive beams using light targets (usually Be or C) have been extensively used in the past decade to probe the shell structure of exotic nuclei. It has been demonstrated that this reaction is well understood by the Eikonal reaction.
theory and that spectroscopic factors for valence nucleons can be deduced with rather good accuracy and less ambiguities as it is the case, for instance, for transfer reactions at lower energies. The method has been recently also applied to knockout of more deeply bound nucleons, and strongly reduced cross sections have been found if compared to calculated single-particle cross sections [38]. Gade et al. [38] have published a systematic investigation, where they plot the ratio of experimental-to-theoretical single-particle cross sections as a function of the difference of separation energies of neutrons and protons, i.e., the difference in the Fermi energies. The surprising result was, that proton knockout from a neutron-rich nucleus yields to a much larger reduction of this ratio, i.e., a ratio of only 0.3. Similarly, a neutron knockout from a neutron-deficient nucleus, while the factor approaches unity for weekly bound nucleons, and about 0.6 for symmetric cases, as established from the (e,e’p) experiments. This has raised the question of isospin effects of the correlations, but also a debate on the experimental method and observable and their interpretation. The role of correlations as a function of asymmetry has been studied theoretically in the context of neutron-rich matter [37]. Also in nuclei, the effect of correlations on single-particle occupancies is predicted to depend on neutron-proton asymmetry, see the work of Barbieri [39] and Jensen et al. [40]. The effect, however, is much smaller then discussed above. In contrast to an electron-induced knockout reaction, the reaction with a beryllium or carbon target leads to a localization of the reaction on the surface of the nucleus. The reaction probes only the tail of the wave function. The fraction of the density to which the reaction is sensitive to depends strongly on the separation energy. In the extreme case of a weekly bound neutron, i.e., knockout of a halo neutron, this fraction is rather large, e.g., in the order of 50% for knockout of the 2s neutron from $^{11}$Be. The higher the separation energy and the larger the angular momentum, the smaller this fraction becomes approaching few % for the cases where the large reduction has been found.

Since electron-induced knockout reactions cannot be realized at present with short-lived nuclei, proton-induced knockout is the most attractive alternative. High beam energies have the advantage that the nucleon-nucleon cross section is small causing some transparency of the nucleus which makes the reaction more sensitive to the inner part of the nucleus. Quasi-free (p,2p) reactions have been used with stable nuclei and spectroscopic factors consistent with those derived from (e,e’p) have been extracted. The (p,2p) and (p,pn) reactions in inverse kinematics would thus provide an ideal tool to explore isospin effects of the single-particle character of nuclei and of correlations beyond mean field in asymmetric nuclei. The beam energies available at FAIR are ideally suited for quasi-free scattering and can be chosen so that the ‘incoming’ proton as well as the outgoing nucleons have large-enough energy (i.e. always above 200 MeV) in a range where the nucleon-nucleon cross section is minimal. This maximizes the transparency of the nucleus and minimizes final-state interaction. A typical beam energy would be around 600 MeV/nucleon leading to nucleon energies depending on angle between 150 and 450 MeV. The R$^{3}$B collaboration has carried out pilot experiments in this direction demonstrating the feasibility of the method to apply quasi-free knockout reactions in inverse kinematics [41, 42]. Quasi-free scattering events could be clearly identified as shown in Figure 5. The left two panels show the angular correlations of the two protons involved in the scattering process [41] from a measurement of (p,2p) knockout from the two-proton halo nucleus $^{17}$Ne. The strong correlations visible are those expected for quasi-free scattering. Proton knockout has been measured with a $^{12}$C beam constituting a bench mark experiment. The reconstructed excitation spectra after proton knockout from $^{12}$C exhibit the three states in $^{11}$B populated after knockout from the p-shell, as well as a broad bump around 20 MeV resulting from knockout reactions of the deeply bound 0s proton [42]. The excitation energy after knockout has been determined from a measurement of the photon and particle decays of $^{11}$B using the invariant-mass method. The right part of Figure 5 shows the fragments observed after a (p,2p) reaction on $^{12}$C, which have been used to reconstruct the excitation energy, and thus the binding energy of the knocked


Figure 5. Quasi-free scattering in inverse kinematics. Left and middle frames: Angular correlations of the two protons after a (p,2p) knockout reaction on \(^{17}\)Ne \([41]\). Right frame: Fragments produced after a (p,2p) knockout reaction on \(^{12}\)C \([42]\). (Preliminary data of the R\(^3\)B collaboration \([41, 42]\)).

nucleon.

The quasi-free scattering in inverse kinematics has an advantage compared to the normal previously used reaction in normal kinematics (and also to (e,e’p)). This is the fact, that the heavy residue after knockout can be observed, its recoil momentum and excitation energy determined, independent from the measurement of the nucleons. The same quantities might be extracted from the kinematics of the nucleons as well, of course. With this method, the single-particle structure of nuclei and the role of correlation can be explored systematically as a function of (N-Z) in (p,pn) and (p,2p) reactions. The method will also be utilized to investigate the cluster structure of exotic nuclei, e.g., the alpha clustering by (p,p\(^\alpha\)) knockout reactions. In the introductory section it has been already mentioned that the (p,2p) reaction is also ideally suited to populate continuum states, in particular states beyond the driplines.

4. Conclusion

Experiments with neutron-dripline nuclei have been possible so far only for the lightest nuclei up to oxygen. After the first experiments at the BEVALAC by Tanihata et al. \([2]\) 25 years ago which lead to the discovery of the neutron halo in \(^{11}\)Li \([5]\), tremendous experimental and theoretical progress has been made. The light dripline nuclei played a key role in the progressing understanding of nuclei with large neutron access and weak binding. Meanwhile exclusive multi-coincidence experiments of reactions with dripline nuclei have been realized. Precise experiments with light neutron-rich nuclei are still a major frontier due to the fact that predictions from ab-initio theory are possible for these light nuclei which can be contrasted to the experimental findings. In the past years, the experimental investigation of continuum states, in particular nuclear system beyond the neutron dripline have become possible with good precision and statistics. The effect of neutron-proton asymmetry on the collective response of nuclei will remain a research focus in the coming years. There are still many unanswered questions. A precise measurement of the dipole response of neutron-rich nuclei is an important issue not only in a nuclear-structure context, but is also important for the modeling of the r-process nucleosynthesis. The dipole response of neutron-rich nuclei may also give access to constraining properties of neutron-rich matter, which are poorly determined experimentally, but fundamentally important, e.g., for the understanding of astrophysical objects as neutron stars. In the same context, the role of nucleon-nucleon correlations as a function of neutron-to-proton asymmetry manifests itself in the properties of neutron-rich matter and asymmetric nuclei. The latter effects might be observable in reaction experiments with radioactive beams. The quasi-
free scattering in inverse kinematics looks to provide a quite promising tool. The quasi-free nucleon and cluster knockout will at the same time being an important reaction to study the evolution of shell structure, cluster structure, as well as to investigate nuclear states beyond the dripline. With the upcoming next-generation high-energy radioactive-beam facilities like FAIR such methods will be applicable to heavier neutron-rich nuclei which will in conjunction with modern nuclear theory provide the basis for a fundamental understanding of isospin-asymmetric nuclei and nuclear matter.

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