DIPOLE EXCITATIONS OF UNSTABLE NEUTRON-RICH NUCLEI*

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Coulomb breakup of high-energy secondary beams of unstable nuclei serves in nuclear structure investigations of neutron-rich isotopes. A summary of the respective research activities at GSI is presented, covering isotopes from helium to oxygen. The breakup is mediated through dipole excitations into the continuum. Non-resonant excitations into the continuum near the dissociation threshold deliver information on the single-particle ground-state structure. Resonant excitation into the giant resonance domain is also observed. In addition, a brief outlook on future activities at GSI is given.

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1. Introduction

Investigations of neutron-rich nuclei are at the forefront of present-day nuclear structure physics. Energetic ion beams of unstable nuclei are available at a number of laboratories all over the world, where secondary radioactive beams are produced in fragmentation reactions or fission of ^{238}U. At high bombarding energy, although of moderate intensity, the secondary beams can be used in nuclear reaction experiments. At present, under most circumstances, reaction experiments are yet restricted to exotic nuclei of masses below $A \approx 50$. At GSI a fragmentation facility exists with the synchrotron SIS-18 and an In-Flight separator (FRS) delivering secondary beams at kinetic energies of several hundred MeV/nucleon. During the past decade, the LAND Collaboration developed an apparatus for reaction studies with secondary beams for nuclear structure purposes. These devices have been used extensively to study, in particular, neutron-rich nuclei at or near the neutron drip line. Here, a summary is given covering isotopes

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from helium to oxygen. The reaction mechanisms relevant in nuclear structure investigations with high-energy beams are addressed in the subsequent section, emphasis is paid to Coulomb breakup. Section 3 illuminates the experimental concepts and techniques. Results are exemplified in Section 4, restricted to a discussion of the measured nuclear dipole response and the deduced nuclear structure information. In concluding, a brief outlook is given towards future activities at GSI.

2. High-energy reactions

Secondary beams of exotic nuclei produced in projectile fragmentation reactions and separated in flight are essentially of primary beam velocity. At GSI, secondary beams are produced with beam energies up to about 1 GeV/nucleon; the experiments described here use energies between 240 and 640 MeV/nucleon. Reaction mechanisms in this high-energy domain are required which are useful to study low-energy nuclear structure phenomena. Until now, nuclear or electromagnetic (in)elastic scattering and single (few) nucleon knockout reactions are most frequently applied for structure studies. The main general physics aspects of such high-energy reactions are:

The interaction time is short in comparison to the period of a nucleon bound in its orbit (in particular for weakly bound valence nucleons), *i.e.* the projectile-target interaction may be considered as a sudden process.

The short interaction time yields high collision Fourier frequencies, up to $\hbar\omega = 30$ MeV for heavy-ion Coulomb scattering at around 1 GeV/nucleon.

Between 200–500 MeV the elementary nucleon–nucleon cross section is lowest and thus re-scattering effects are minimal at such energies, multi-step processes are relatively small.

The transverse momentum transfer is small and the eikonal approximation may be applied, simplifying a theoretical description of some reactions.

The Coulomb field in a heavy-ion collision is essentially of transverse nature; large cross sections are obtained for dipole excitations. The nuclear optical potential, at energies around 500 MeV/nucleon, essentially becomes predominantly absorptive.

In the following, we restrict the discussion to electromagnetic excitation processes in the collision of two heavy ions. Here, the projectile excitation of exotic nuclei forming a secondary beam is of interest. As stated above, the short interaction time at high collision energies allows to excite high-lying states, even covering the domain of giant resonances. The excitation of the isovector giant dipole resonance with cross sections of the order of one barn is predominant. The electromagnetic excitation can be reliably described in semi-classical approximation and thus transition matrix elements can be deduced quantitatively. In neutron-rich nuclei with loosely bound valence neutron, non-resonant (dipole) transitions into the continuum are likely to occur with a sizeable cross section. In semiclassical approximation (1st order perturbation), such a 'direct breakup' process can be written as

$$\frac{d\sigma(I_c^\pi)}{dE^*} = \left(\frac{16\pi^3}{9\hbar c}\right) N_{\mathrm{E1}}(E^*) \sum_m C^2 S(I_c^\pi, nlj) \mid \langle q \mid \frac{Ze}{A} r Y_m^1 \mid \psi_{nlj}(r)\rangle \mid^2 . \tag{1}$$

This equation is obtained by expanding the nucleus ground-state wave function into a decomposition of a single-particle wave function coupled to the eigenstates of the residual nucleus and projecting onto a particular eigenstate. Here, $\frac{d\sigma(I_c^\pi)}{dE^*}$ denotes the partial cross section for observation of a neutron at excitation energy E^*, which equals the sum of its separation energy and its kinetic energy after being released, while I_c^π identifies the eigenstate of the residual nucleus after breakup. $N_{\mathrm{E1}}(E^*)$ describes the spectrum of virtual dipole photons due to the electromagnetic field of the collision partner which is computed in semi-classical approximation. The dipole matrix element in above equation involves the initial-state single-particle wave function ψ_{nlj} and the nucleon final state q in the continuum. Evidently, in case of weakly bound nucleons with a pronounced radial tail of its wave function, good matching conditions can be found with the outgoing wave of an appropriate wavelength, in general fulfilled at a rather low continuum energy near the particle separation energy. The outgoing wave may be approximated by a plane wave, but for a quantitative description the influence of wave distortions in the outgoing channel need to be considered. From above equation it is obvious that the measured Coulomb dissociation cross sections reveals information on the ground state configuration: The state of the residual nucleus can be observed experimentally through its de-exciting γ-ray transition(s). The orbital momentum l of the released nucleon is revealed in the energy (E^*) dependence of the cross section and, finally, the spectroscopic factor C^2S of the configuration determines the magnitude of the cross section.

3. Experimental techniques

Secondary beams of exotic nuclei are obtained with intensities much below that of stable-ion beams. At high beam energy, however, luminosity can be gained using thick targets of the order of one g/cm^2. A full solid angle coverage, moreover, of the disintegration products of the excited projectile is easily achieved due to their kinematical forward focussing. For the highly-penetrating particles, detection efficiencies close to unity can be realized since, if necessary, redundant measurements are possible. Altogether, reasonable count rates are obtained even at very low beam intensities; measurements reported here were performed typically at intensities of 10–1000 ions per second.

The main experimental tasks are:

Preparation of the secondary beam. For the experiments described in the subsequent section, primary beams of ^{18}O or ^{40}Ar were used from the SIS synchrotron at GSI. After fragmentation in a Be target, the secondary beams are separated in the FRS and transported to the experimental area. For the experiments discussed in this report, only a magnetic separation was implemented resulting in a secondary beam composed out of a number of different isotope species. All of them, however, exhibit a similar mass-to-charge ratio and thus could be of similar physics interest. The incident projectiles are identified on an event-by-event basis prior to hitting the interaction target. Energy-loss, time-of-flight, and magnetic rigidity are used for that purpose.

Detection of the projectile residues. After hitting the target (lead target in case of Coulomb breakup studies), the projectile residues (here the heavy fragment and ejected neutrons) pass a dipole magnet with a large gap. Position-sensitive Si diodes, scintillating fiber arrays, and a wall of organic scintillators subdivided into 34 modules serve to measure the trajectory, the nuclear charge (from energy loss) and the velocity of the fragment. From the combined information, the nuclear mass can be deduced. The momenta of ejected neutrons are measured in LAND, a position-sensitive time-of-flight spectrometer for energetic neutrons with an intrinsic detection efficiency around 90%.

Detection of γ-rays. Although γ-rays emitted from the projectile fragment are also boosted into forward direction, at least the forward hemisphere needs to be covered in order to achieve sufficient solid-angle coverage. Two devices are operated alternatively, the NaI Crystalball (160 elements) subtending almost a 4π solid angle, and a CsI array covering the forward hemisphere. The geometry of its 144 submodules of the CsI detector is chosen in order to minimize Doppler broadening effects. Yet, the Doppler broadening determines the γ-ray energy resolution amounting to typically 10 %.

The main observables deduced from such measurements are: the longitudinal and transverse momentum transfer; the excitation energy of the projectile or of the residual fragment by means of the invariant-mass method in case of continuum excitation or, in case of bound state excitation, from the observation of discrete γ rays; angular correlations giving access to spins and transition multipolarities.

4. Coulomb breakup experiments

Using the experimental setup as described above, a number of experiments were performed at GSI aiming at nuclear structure investigations of unstable neutron-rich nuclei. Here, results can only be exemplified.

Coulomb breakup studies were performed for neutron-rich isotopes ranging from ^{6}He to ^{23}O. Here we choose three examples to illustrate the potential of such measurements: Coulomb breakup of ^{6}He and its astrophysical aspect; Coulomb breakup and the single-particle ground state structure of ^{17}C; the giant dipole resonance in ^{20,22}O.

The radiative capture of two neutrons on ^{4}He was considered as a possible mechanism in bridging the mass instability gap at $A = 5$ for certain astrophysical nucleosynthesis scenarios [1, 2]. For the two-neutron capture, the predominant process is expected to be a two-step mechanism with formation of the ^{5}He ground state resonance as the first step followed by a non-resonant neutron capture and subsequent γ-deexcitation into the ^{6}He ground state. In a Coulomb breakup reaction, here induced by the electromagnetic interaction of ^{6}He with a lead target, the inverse process occurs, *i.e.*, ^{6}He is excited into its continuum followed by two-neutron decay. The Coulomb breakup cross section was measured; it can be converted into a $(\gamma, 2n)$ photoabsorption cross section [3]. For the above two-neutron capture mechanism, however, only that fraction of cross section is relevant which proceeds via the ^{5}He ground-state resonance as intermediate state. This fraction can be deduced from the measurement, reconstructing the relative energy between ^{4}He and one of the two neutrons as shown in the left-hand panel of Fig. 1. A comparison with a calculated phase space distribution in fact reveals a cross section enhancement at the energy of the ^{5}He ground state resonance. The respective photoabsorption cross section amounts to about 1.6 mb MeV; it is of the same order of magnitude as obtained from model calculations in [1].

The right-hand panel of Fig. 1 shows the relative energy between the two neutrons released in the breakup; the deviation from the calculated phase space distribution is is qualitatively in accordance with the known virtual state in neutron–neutron scattering.

As was outlined in Section 2, Coulomb breakup can be utilized to determine spectroscopic factors for single-particle ground-state configurations. Non-resonant dipole excitations into the continuum in close vicinity to the nucleon separation threshold bear the relevant nuclear structure information. As an example, we show result for ^{17}C in Fig. 2 [4]. The upper panel shows the sum-energy spectrum of $\gamma-$ray transitions in ^{16}C after Coulomb breakup of ^{17}C into ^{16}C and a neutron. For about two third of the breakup cross section, a coincident γ-ray transition from the ^{16}C(2^+) state is observed. The lower panel of Fig. 2 shows the differential Coulomb dissociation cross section with respect to the ^{17}C excitation energy and its analysis within the direct breakup model using the equation in Section 2, Using a plane-wave approximation for the outgoing neutron, spectroscopic factors of 0.23(8) and 0.6(4) are deduced for the ^{16}C$(2^+) \otimes \nu_s$ and ^{16}C$(2^+) \otimes \nu_d$ configurations of the ^{17}C ground state, for details see [4]. Similar conclusions were drawn from knockout reactions on ^{17}C performed at MSU [5].

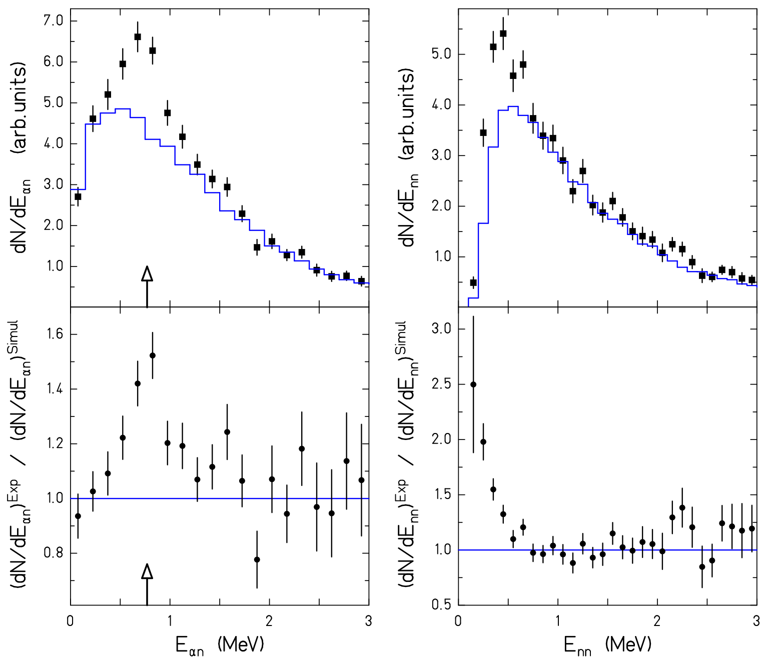

Fig. 1. Top: Relative energy spectra between ^{4}He and neutron (left) and two neutrons (right) after Coulomb breakup of ^{6}He. Solid lines show calculated phase space distributions. Bottom: Ratio between measured data and phase space distribution. From [3].

Recently, we studied the nucleus ^{23}O [6]. The preliminary analysis indicates a predominant ground-state configuration $^{22}\mathrm{O}(0^+) \otimes \nu_{s_{1/2}}$ and thus a ground-state spin $I^\pi = 1/2^+$. This appears to be in conflict with conclusions drawn from two-neutron knockout reactions studied at RIKEN [7]. There, a $(s_{1/2})^2 d_{5/2}$ configuration as a main component in the ^{23}O ground state was deduced and thus a different ground-state spin.

Similar studies were performed also for ^{11}Be and neutron-rich nitrogen and other oxygen isotopes [8]. The case of ^{11}Be served as a bench mark experiment since the resulting spectroscopic factors can be compared with that from conventional transfer reactions measured at GANIL [9]; very good agreement is obtained. It thus appears that non-resonant Coulomb dissociation delivers a quantitative tool for exploring the single-particle structure of exotic nuclei. In case of loosely bound valence nucleons occupying low orbital angular momentum orbits, the breakup cross sections are particularly large and thus serve well for rare-isotope beams.

As a last example, the giant dipole resonance will be considered. So far, only one giant resonance measurement for unstable nuclei was performed.

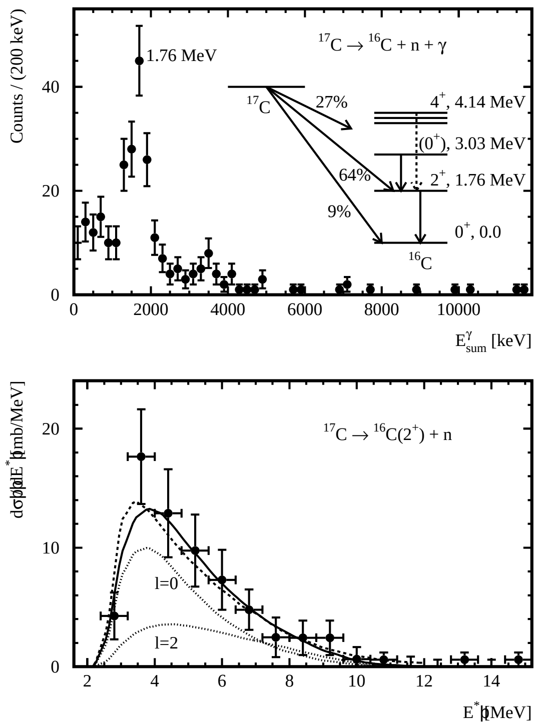

Fig. 2. Top: γ-sum energy spectrum after Coulomb breakup of ^{17}C. The inset shows a partial level scheme of ^{16}C. Bottom: Measured excitation energy spectrum of ^{17}C and calculations within the direct breakup model for $l = 0$ and $l = 2$ neutrons and the sum of both (solid line). From [4].

For ^{20,22}O isotopes, photoneutron cross sections $\sigma_{\gamma,xn}$ for x=1,2,3 could be extracted from heavy-ion induced Coulomb breakup [10]. The results are shown in Fig. 3, for comparison photoapsortion data for the doubly magic ^{16}O nucleus are also shown. The dipole strength of the neutron-rich isotopes appears strongly fragmented with a considerable fraction of strength at excitation energies clearly below the giant resonance domain as it is known for stable nuclei. If integrated up to 15 MeV excitation energy, the energy-weighted dipole strength amounts to about 10% of the Thomas–Reiche–Kuhn sum rule. The data shown in Fig. 3 are compared to shell-model calculations of Sagawa and Suzuki [11], the general trend is reasonbly well reproduced. More recently, (Q)RPA calculations were performed [12, 13]. According to the calculation [13], the lower-lying dipole transitions essentially are of single-particle type and a coherent motion of (part of) the neutrons outside the ^{16}O core seems not to occur; collective effects, however, should be expected in heavy nuclei.

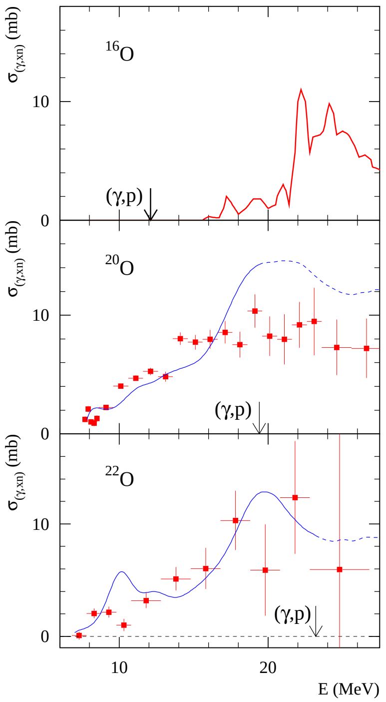

Fig. 3. Photoneutron cross sections in oxygen isotopes. From [10], see further references therein.

5. Outlook

In an attempt to move on to heavier nuclei, very recently the LAND/FRS group at GSI performed a measurement with a secondary beam of ^{132}Sn and neighboring isotopes. The beam was produced by in-flight fission of a primary ^{238}U beam at an intensity of about 10^9 ions per spill. Data were taken with lead and carbon targets and are currently analyzed. One of the goals is to determine the photoneutron cross sections. Low-lying components, if existing, could have impact on calculations for the nucleosynthesis r-process.

On a longer term, GSI plans for a future international facility that includes intense beams of exotic nuclei as one of its pillars. A Conceptual Design Report [14] was presented in 2002. Primary beam intensity will increase by several orders of magnitude in comparison to the present facility; for example, an intensity of 10^{12} ^{238}U ions per second is envisaged. A schematic layout of the exotic-nuclear-beam facility is shown in Fig. 4. The main components are a double-ring synchrotron SIS-100/200 (not shown), a superconducting fragment separator (Super-FRS) with large acceptance even for in-flight separated fission products of ^{238}U, two accumulator-storage-cooler rings with in intersecting electron storage ring, and advanced experimental equipment for high- and low-energy experiments. Colliding electron-ion beams would for the first time allow to perform electron scattering experiments off exotic nuclei; charge distribution measurements from elastic scattering or inelastic scattering to giant resonances should become feasible. Scattering experiments with light nuclei such as hydrogen or helium are foreseen at the heavy ion storage ring NESR equipped with gas-jet targets. The luminosity achieved there with stored unstable beams (up to about 10^{28} cm^{-2} s^{-1}) opens up another new field of reaction studies with exotic nuclei.

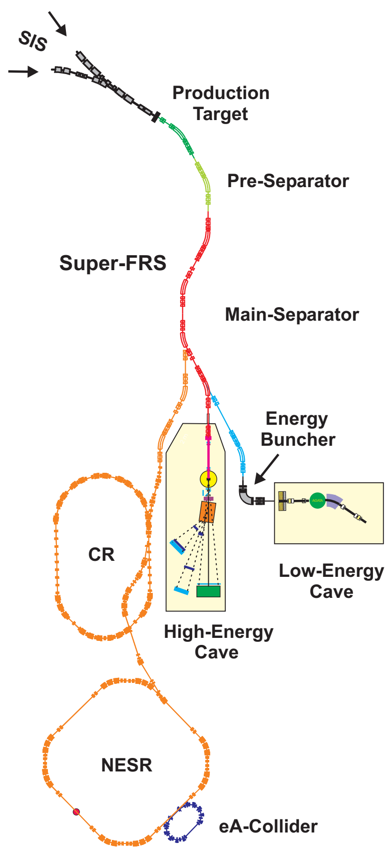

Fig. 4. Schematic view of the exotic-nuclear-beam facility planned at GSI. From [14].

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REFERENCES

[1] V. Efros *et al.*, *Z. Phys.* **A355**, 101 (1996).
[2] J. Görres *et al.*, *Phys. Rev.* **C52**, 2231 (1995).
[3] T. Aumann *et al.*, *Phys. Rev.* **C59**, 1252 (1999).
[4] U. Datta Pramanik *et al.*, *Phys. Lett.* **B551**, 63 (2003).
[5] V. Maddalena *et. al., Phys. Rev.* **C63**, 024613 (2001).
[6] K. Jones *et al.*, to be published.
[7] R. Kanungo *et al.*, *Phys. Lett.* **B512**, 261 (2001).
[8] R. Palit *et al.*, to be published.
[9] S. Fortier *et al.*, *Phys. Lett.* **B461**, 22 (1999).
[10] A. Leistenschneider *et al.*, *Phys. Rev. Lett.* **86**, 5442 (2001).
[11] H. Sagawa, T. Suzuki, *Phys. Rev.* **C59**, 3116 (1999).
[12] G. Colo, P.F. Bortignon, *Nucl. Phys.* **A696**, 427 (2001).
[13] D. Vretenar *et al.*, *Nucl. Phys.* **A692**, 496 (2001).
[14] `http://www.gsi.de/GSI-Future/cdr`