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Giant Resonances in Unstable Oxygen Isotopes

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Electromagnetic and nuclear breakup of the neutron-rich Oxygen isotopes ranging from \(A = 17\) to \(A = 22\) is studied experimentally in reactions at energies around 600 MeV/u. The beams were produced in fragmentation reactions and separated by the GSI Fragment Separator FRS. By measuring the four-momenta of all decay products after inelastic scattering and neutron decay of the projectile, the excitation energy is determined. From the differential cross sections \(d\sigma/dE^*\) for electromagnetic excitation, the E1-strength distributions can be deduced. For \(^{18,20,22}\text{O}\), low-lying dipole strength is observed, exhausting about 5% of the Thomas Reiche Kuhn sum rule for energies up to 5 MeV above the continuum threshold.

1. INTRODUCTION

The multipole continuum response of nuclei near the driplines is expected to change considerably in comparison to what is known from stable nuclei. An intense theoretical activity has developed in the last years in order to understand this phenomenon. One effect which shows up in all calculations for neutron-rich nuclei is the additional strength below the normal giant resonance region, predicted for different multipolarities (see for example [1-4] and refs. given therein). If the binding energy approaches zero, coupling to the continuum becomes very important. Threshold strength characteristic of the specific

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ground state single-particle structure [5], and new collective modes were discussed [6]. But also the giant modes are expected to change considerably in neutron- (proton-) rich nuclei [1,7]. In addition, the coupling to doorway states can change in comparison to stable nuclei [1,9]. The predictions for the strength functions depend strongly on the effective forces used in the calculations. Thus, measurements of the multipole continuum response of exotic nuclei can yield important information on the isospin and density dependent parts of the effective interactions, as well as on the damping processes. For a detailed discussion we refer to the various theoretical papers presented during this conference [7–12]. Experimental information on multipole strength functions of exotic nuclei, including the giant resonances, are not available up to now, an exception being the threshold strength observed in some halo nuclei (see below). In the present paper we present a description and preliminary results of a first experiment going in that direction, with emphasis on the E1 strength function, utilizing electromagnetic excitation and neutron decay of secondary beams at relativistic energies.

Experimentally, low-lying dipole strength was observed for the halo nuclei 6He [13], 11Li [14–16], and 11Be [17]. For 6He and 11Li, e.g., about 10% of the Thomas-Reiche-Kuhn dipole sumrule was found below an excitation energy of 5 MeV [13,16]. In case of 6He, experimental evidence was also reported for low-lying multipole strength other than dipole [13]. In the present experiment, the Oxygen isotope chain in the mass range $A = 17$ to $A = 22$ is investigated. Utilizing the electromagnetic excitation process at high energies ($\approx 600$ MeV/u) the E1 strength distribution can be studied up to the energy region of the giant dipole resonance (GDR). For light nuclei, however, the GDR is located at relatively high excitation energies ($E^\ast \approx 25$ MeV), which are suppressed by the electromagnetic excitation process due to the adiabatic cut-off. Electromagnetic excitation was also applied recently at lower bombarding energies at MSU, where the E1 response of 11Be was studied in ($\gamma, \gamma'$) reactions, as reported on this conference by Beene [18]. The $\gamma$ decay is a weak branch and amounts for the GDR typically to less than $10^{-2}$ determined by the time scale associated with the damping of the collective motion and the E1 matrix element. The results of the present experiment studying the neutron decay together with a ($\gamma, \gamma'$) experiment as planned at MSU for 20O [19], would allow for a comparison of neutron- and $\gamma$-decay also for the low-lying part of the E1 strength. With the experimental technique presented here, also other multipolarities than E1 can be studied in principle by nuclear excitation processes using light targets. In addition, by measuring the $\gamma$-rays originating from excited fragments after knockout reactions, spectroscopic information on unstable nuclei can be deduced.

2. ELECTROMAGNETIC EXCITATION AT RELATIVISTIC ENERGIES

Electromagnetic excitation and neutron decay of relativistic projectiles at energies around 600 MeV/u was very successfully applied by the LAND group at GSI in experiments performed to study the two-phonon Giant Dipole Resonance (GDR) in heavy stable nuclei [20]. The cross sections for exciting the GDR are very large in this case, of the order of barn. It has been shown [21] that the measured differential cross section with respect to excitation energy can be reproduced without any free parameters by calculating the electromagnetic excitation probability using the semiclassical approach [22] and
known photoabsorption cross sections as an input. One advantage of the electromagnetic excitation process is the direct relationship between the observed cross section and the B(E1) distribution. Similar to photoabsorption, electromagnetic excitation in fast heavy ions is mostly sensitive to electric dipole transitions with small E2 contributions. For example, 10% of the energy weighted sumrule for E1 and E2 transitions at an excitation energy of 12 MeV leads to electromagnetic excitation cross sections of 75 and 3.8 mb, respectively (1 GeV/u $^{16}$O on a Pb target). In Fig. 1 the photonuclear $(\gamma, n)$ cross section is shown for $^{18}$O [23]. In contrast to $^{16}$O several peaks are visible at energies below the

![Figure 1. Upper frame: Photonuclear $(\gamma, n)$ cross sections for $^{18}$O. The curve is a rough adaptation to the data of Woodworth et al. [23]. Lower frame: Semiclassical calculation of the cross section $d\sigma/dE$ for electromagnetic excitation and neutron decay of $^{18}$O on a Pb target at beam energies of 250 MeV/u (dotted curve) and 1 GeV/u (solid curve), using the $(\gamma, n)$ cross sections shown above.](image)

GDR (located at 26 MeV) carrying a considerable fraction of the strength. Note that the low-lying component decays exclusively by neutron emission and is absent in the $(\gamma, p)$ cross section [23]. To our knowledge, this is the only case in a stable nucleus, where this is observed. The lower part of the figure shows a semiclasical calculation for electromagnetic excitation on a Pb target at two different beam energies using the experimental E1 strength distribution. One clearly sees the sensitivity to the low-lying E1 strength, which is of particular interest in the present context. The higher excitation energies are suppressed due to the adiabatic cut-off [22]. For light nuclei, where the GDR is located at relatively high excitation energies, beam energies around 1 GeV/u or higher are therefore needed to excite also the GDR with a considerable cross section. The integrated cross sections are typically several tens of mbarn, thus in the same order as the nuclear few neutron removal channels. The experiments therefore need to distinguish the different processes in order to extract the B(E1) distribution. This will be discussed in the next section.
3. EXPERIMENTAL METHOD AND REACTION MECHANISMS

The radioactive beams were produced in a fragmentation reaction of a primary $^{40}$Ar beam, delivered by the synchrotron SIS at GSI, Darmstadt, impinging on a beryllium target. The fragments were separated using the Fragment Separator FRS [24]. In two settings, a degrader was inserted in the midplane of the FRS. In these cases only $^{17,18}$O and $^{19,20}$O were transported to the experimental area, respectively. In a third setting without degrader and optimized for $^{20}$O, the beam contained various isotopes with similar $A/Z$ ratio ranging from Be up to O, which were identified uniquely by means of energy-loss and time-of-flight measurements. The trajectory of the incident ions was measured by a multiwire proportional chamber and a position sensitive Si pin-diode. Behind the target, the fragments were deflected by a large-gap dipole magnet. By means of energy-loss and time-of-flight measurements, as well as position measurements before and behind the dipole magnet, the nuclear charge, velocity, scattering angle, and the mass of the fragments are determined. The neutrons stemming from the excited projectile or excited projectile-like fragments are focussed to forward directions and detected with high efficiency in the LAND neutron detector [25], placed at zero degree about 11 m downstream from the target and covering an angular range of about 90 mrad. To detect the $\gamma$-rays, the target was surrounded by the 4$\pi$ Crystal Ball spectrometer, consisting of 160 NaI detectors.

In Fig. 2, the mass distribution for fragments with nuclear charge $Z_f = 8$ (upper frame) and $Z_f = 7$ (lower frame) in coincidence with at least one neutron is shown for an $^{20}$O beam after reacting in C and Pb targets. The distributions obtained with the Pb target

![Figure 2](image-url)

are scaled to that obtained with the C target for $Z_f = 7$ (lower frame in Fig. 2). For
$Z_f = 7$, the two histograms coincide, thus showing no contributions from electromagnetic excitations in case of the Pb target. Contrary, for the Oxygen fragments (upper panel) with $A_f = 19$ and $A_f = 18$, corresponding to the $1n$ and $2n$ removal channels, an enhancement is observed for the Pb target compared to the C target. The fact that, under these conditions, the $1n$ removal channel is suppressed in case of nuclear reactions can be understood by inspecting the different reaction mechanisms. The dominant process in case of nuclear fragmentation is knock-out of at least one nucleon and subsequent evaporation from the excited pre-fragments. Since only neutrons in the projectile-rapidity domain are within the acceptance of LAND, neutrons originating from the first step (knock-out or abrasion), which are scattered to large angles, are not detected (see [16] for a detailed discussion in the context of fragmentation of halo nuclei). Thus, even though the cross sections for few-neutron removal by nuclear and electromagnetic interactions are of similar magnitude, the electromagnetic part can be separated experimentally. Note that also for the $2n$ channel a similar reduction as for the $1n$ channel can be obtained by requiring exactly two neutrons detected in LAND.

4. CONTINUUM EXCITATIONS

As discussed in the previous section, the nuclear contribution to the cross section measured with the lead target can be reduced to a 10-20% level under certain experimental conditions. Then, the measured differential cross section is directly connected to the B(E1) distribution. For $^{18}$O, we obtain about 5% of the TRK energy weighted sum-rule by integrating the deduced strength up to 5 MeV above the continuum threshold, consistent with photo-absorption measurements [23]. For $^{20}$O and $^{22}$O we find a similar exhaustion of the sumrule in the respective energy region, while the maximum of the cross section shifts towards lower excitation energies going from $^{18}$O to $^{22}$O. The odd Oxygen isotopes are presently analyzed. In a future analysis also the nuclear excitation will be investigated. The reaction mechanism of nuclear excitation can be experimentally disentangled from knock-out processes in a similar manner as the electromagnetic excitation for the Pb target.

In order to illustrate the capability of the method we show some results, reported earlier, for the continuum excitation of the halo nucleus $^6$He from an experiment performed by the S135 collaboration [13,26] using the same experimental technique. The measured cross sections $d\sigma/dE^*$ are shown in Fig. 3 for $^6$He, deduced from the invariant mass of the $\alpha + n + n$ decay channel, obtained with Pb (upper frame) and C (lower frame) targets at 240 MeV/u. A dominant peak is visible at 1.8 MeV in the spectrum obtained with the C target, coinciding with the energy of the known 2+ resonance in $^6$He with a width of 110 keV. The observed width of the peak is dominated by the experimental resolution and agrees very well with our simulations. A second 2+ resonance was predicted by 3-body models at 4.3 MeV [4], but no evidence is found in the experimental spectrum. The higher lying continuum strength can be a mixture of various multipolarities, e.g. soft monopole and dipole strength is expected in addition to quadrupole contributions [4]. The angular distributions are expected to show substantial differences for the different multipole excitations [27], and can therefore be used to disentangle the multipole composition of the observed strength. An analysis of the differential cross section with respect to scattering
Figure 3. Excitation energy ($E^*$) spectra of $^6$He deduced from the invariant mass of the $\alpha+n+n$ decay channel, obtained with the Pb target (upper frame) and the C target (lower frame) at 240 MeV/u bombarding energy. The spectra are corrected for detection efficiency and solid angle acceptance, but are not deconvoluted with respect to resolution in $E^*$. In case of the Pb target, the dotted curve represents the calculated electromagnetic cross section using the $dB(E1)/dE^*$ distribution from the three-body model of [4] and a semi-classical perturbative calculation. The solid curve is obtained by convoluting the dotted curve with the instrumental response. The dashed curve represents calculated cross sections using the $dB(E1)/dE^*$ distribution from the three-body model of [28], including convolution with the instrumental response. The excitation energies of a known ($E^* = 1.80$ MeV) and a predicted ($E^* = 4.3$ MeV, [4]) $I^* = 2^+$ resonance are indicated by arrows. From [13], preliminary data.

angle of $^6$He (reconstructed from the momenta of fragment and neutrons) is in progress. In addition, angular correlations in the decay can be helpful to get access to the multipolarity of the observed strength. Low-lying strength other than dipole and quadrupole is indicated.

For the Pb target the dominant contribution comes from electromagnetic excitation (see section 3). The experimental data are compared to semiclasical calculations based on the strength distributions as predicted by different 3-body models [4] (solid curve), [28] (dashed curve). The experimental response is taken into account. The calculation using the B(E1) distribution of [4] is shown in addition without experimental filter (dotted curve) for comparison. Both calculations reproduce the absolute cross section and the peak position fairly well, the agreement with the model predictions of [4] is somewhat better. According to a calculation in eikonal approximation [29] we expect about 20 % nuclear contribution to the cross section. At 1.8 MeV a small peak is visible, which is more pronounced in the correlation function obtained by dividing the experimental spectrum by a randomized one (see Ref. [13,26]). The ratio of the extracted cross section for this peak to the cross section of the $2^+$ resonance obtained with the C target agrees well with the scaling for the diffraction cross section as predicted by the calculation [13,29]. The electromagnetic contribution to the excitation of the $2^+$ resonance can be neglected, it is less than 1 mb if B(E2) values are taken from the 3-body models, or as derived from the cross section with the C target. After subtracting the small nuclear contribution to the cross section, the B(E1) distribution can be deduced. 10% of the TRK sumrule is exhausted for excitation energies below 5 MeV. This corresponds to 40% of a cluster
sumrule, where the strength is splitted into dipole strength associated to the core, and E1 strength associated to the relative motion of valence neutrons and the core. Integrating up to 10 MeV excitation energy, the cluster sumrule is fully exhausted.

5. SPECTROSCOPY

The experimental method allows also for \(\gamma\)-spectroscopy of unstable nuclei. An example is given in Fig. 4, where the \(\gamma\) sum-energy spectra are shown for fragments \(^{18}\)O (upper frame) and \(^{19}\)O (lower frame) produced in reactions of \(^{20}\)O in a Pb target. The first two excited states in these two nuclei are clearly visible. In this case these states are known, but it demonstrates that the fragmentation reactions at high energies are suitable to perform \(\gamma\)-spectroscopy of exotic nuclei. By measuring the partial cross sections for one-nucleon knock-out reactions feeding the ground- and excited states, spectroscopic factors can be deduced [30] as well.

![Figure 4. \(\gamma\) sum-energy spectra as measured in the fragmentation of 600 MeV/u \(^{20}\)O in a Pb target, yielding the excited fragments \(^{19}\)O (lower frame) and \(^{18}\)O (upper frame). The peaks correspond to the known energy levels at 1.47 MeV and 3.16 MeV in \(^{19}\)O, and 1.98 MeV and 3.56 MeV in \(^{18}\)O.](image)

6. SUMMARY

The electromagnetic and nuclear fragmentation of secondary neutron-rich Oxygen beams at energies of 600 MeV/u has been studied. We have shown that the experimental technique allows for an extraction of the electromagnetic excitation cross section, even though the cross sections for competing nuclear processes in peripheral reactions are of similar magnitude. The aim of the experiment is, in the first place, to extract the dipole strength function from electromagnetic excitation cross sections. Low-lying dipole components were observed in all neutron-rich Oxygen isotopes carrying about 5 % of the energy-weighted dipole sumrule for excitation energies up to 5 MeV above the threshold, while the maximum of the cross section shifts to lower energies going from \(^{18}\)O to \(^{22}\)O. Coincident measurements of fragments and \(\gamma\)-rays after nuclear fragmentation, in particular
knock-out processes, provide spectroscopic information on exotic nuclei. The experimental technique is also applicable to study the continuum response in nuclear reactions as demonstrated for the $^6$He halo breakup. Since the measurement is kinematically complete in the projectile rapidity domain, differential cross sections (with respect to scattering angle) for inelastic electromagnetic or nuclear scattering can be deduced as well. The availability of higher beam intensities in the near future at GSI makes a continuation of this experimental study to the dripline nucleus $^{24}$O feasible, where the additional two neutrons occupy the 1s state, as well as an extension of such investigations to heavier exotic nuclei.

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