Continuum spectroscopy of exotic nuclei

Thomas Aumann

Gesellschaft für Schwerionenforschung (GSI)
Planckstrasse 1, D-64291 Darmstadt, Germany

Abstract

The dipole response of unstable short-lived nuclei has been probed experimentally by utilizing the electromagnetic excitation process with high-energy secondary beams at around 500 MeV/u. Differential cross sections with respect to excitation energy have been extracted from an exclusive measurement of the neutron-decay channel. Light neutron-rich nuclei, e.g. the halo nucleus ^{11}Be and the oxygen isotope chain ranging from A=17 to A=23 were investigated systematically. A quantitative analysis of low-lying threshold strength indicates that the characteristics of the dipole strength is directly related to the ground-state single-particle structure of the projectile.

1 Introduction

Nuclear and electromagnetic inelastic scattering of radioactive beams in inverse kinematics opens up the possibility of studying the multipole response of exotic nuclei. Theory predicts considerable changes of the excitation spectra for neutron-proton asymmetric nuclei in comparison to what is known from stable nuclei. For neutron-rich nuclei different types of calculations predict pronounced effects, in particular a redistribution of the strength towards lower excitation energies well below the giant resonance region [1, 2, 3]. The predicted strength functions depend strongly on the effective forces used in the calculations [2] and thus, in turn, the measurement of the multipole response of exotic nuclei can yield information on the isospin dependent part of the in-medium nucleon-nucleon interaction. A first systematic experimental investigation of the dipole response of neutron-rich nuclei was carried out utilizing electromagnetic excitation at high energies, i.e. at several hundred MeV/u [4, 5, 6]. One aspect here is the threshold strength as observed for halo nuclei, which characteristically depends on the single-particle configurations of the ground state. A systematic investigation of this effect was carried out in order to establish the exclusive measurement of differential one-nucleon removal cross sections for electromagnetic excitation as a spectroscopic tool to investigate the ground-state structure of short-lived nuclei.

2 Experimental method

The radioactive beams were produced by fragmentation of a primary ^{40}Ar beam delivered by the synchrotron SIS at GSI, Darmstadt. The settings of the Fragment Separator FRS [7] and the beam line to the experimental area were chosen to accept secondary fragments with a magnetic rigidity corresponding to a certain mass-over-charge ratio. This mixed secondary beam contained several isotopes, which were identified uniquely according to their nuclear charge and mass number on an event-by-event basis by utilizing energy-loss and time-of-flight measurements. In a similar manner, the fragments produced in the reaction target are identified by measuring energy loss, time-of-flight and the magnetic rigidity. The latter is accomplished by three position measurements in order to determine the trajectory through a large-gap dipole magnet placed behind the target. Neutrons emitted from the excited projectile or excited projectile-like fragments are kinematically focused in the forward direction and detected with high efficiency (90%) in the LAND neutron detector [8], which was placed at zero degrees about 11 m downstream from the target. The gap of the dipole magnet allowed an angular acceptance for the neutrons of about ±80 mrad in both horizontal and vertical planes. The angular range for fragments and neutrons covered by the detectors corresponds to a 4 π measurement of the breakup in the rest frame of the projectile for fragment-neutron relative energies up to 5 MeV (at 500 MeV/u beam energy). Gamma-rays were detected by the 4 π Crystal Ball spectrometer surrounding the target. The excitation energy prior to decay is obtained by reconstructing the invariant mass. In order to extract the electromagnetic excitation cross section from the measurement with the lead target, the nuclear contribution was determined from a measurement with a carbon target and scaled accordingly.

3 Results and discussion

3.1 Dipole-strength function of neutron-rich oxygen isotopes

In a first attempt to study giant resonances and lower lying modes in exotic nuclei, we investigated systematically the dipole-strength distributions of all neutron-rich oxygen isotopes up to ^{23}O. ^{16}O is a strongly bound doubly magic nucleus with a neutron separation energy $S_n = 16$ MeV, while for the heavier isotopes the separation energy decreases to $S_n \approx 7$ MeV for the even isotopes with A=18 to 22, and $S_n \approx 4$ MeV for the odd isotopes. One may expect therefore a decoupling of the valence neutrons from the inert ^{16}O core and the appearance of a collective soft-dipole excitation.

The deduced $\sigma_{(\gamma,xn)}$ for ^{20,22}O are shown in Figure 1 in comparison with the stable nucleus ^{16}O. Evidently, the dipole response changes significantly due to the presence of the valence neutrons. Most noticeable is the sizeable dipole absorption cross section below the giant dipole resonance (GDR) energy region. A clear separation into two energy domains associated with GDR excitations of the core and a soft dipole mode involving valence neutrons is not observed. The data are compared to a large-scale shell-model calculation [3] after convolution with the experimental resolution (solid curves). Qualitatively, the shell-model calculations reproduce the experimental observation of a redistribution of the E1 strength towards excitation energies below the GDR compared to that of the doubly magic nucleus ^{16}O.

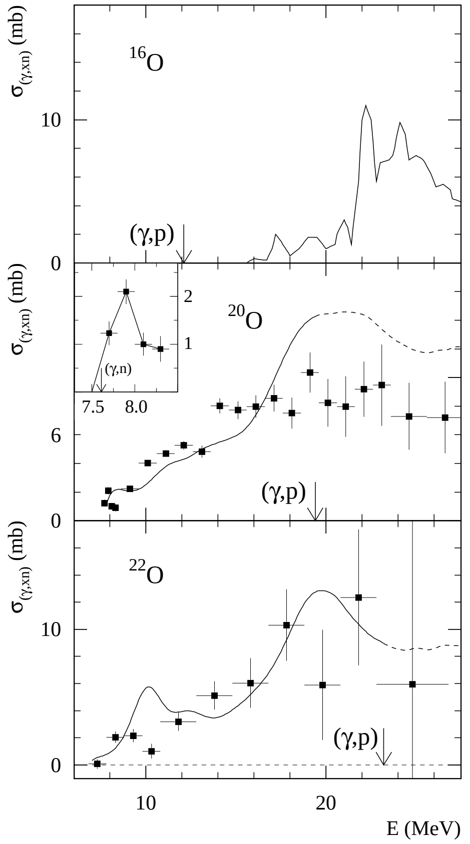

Fig. 1: Photo-neutron cross sections $\sigma_{(\gamma,xn)}$ for the stable nucleus ^{16}O as measured with real photons [10] (upper panel), and for the unstable isotopes ^{20,22}O [4] (lower panels) as extracted from the measured electromagnetic excitation cross section by applying semi-classical calculations [9]. Neutron multiplicities up to $x = 3$ are included. The thresholds for decay channels involving protons (which were not observed in the present experiment) are indicated by arrows. For ^{20,22}O, the data are compared to large-scale shell-model calculations by Sagawa and Suzuki [3] using the Warburton-Brown interaction [11]. Adapted from [4].

3.2 Low-lying dipole transitions as a spectroscopic tool

One characteristic property of halo nuclei is the very large electromagnetic dissociation cross section peaking at low excitation energies. This low-lying 'threshold' strength is interpreted to originate from direct, non-resonant transitions into the continuum. The transition matrix element can be written as

$$\frac{dB(E1)}{dE^*}(I_c^\pi) = \sum_{nlj} CS^2(I_c^\pi, nlj) \sum_m |\langle q|(Ze/A) r Y_m^1 |\psi_{nlj}(\vec{r})\rangle|^2. \tag{1}$$

The ground state is described by the single-particle wave function $\psi_{nlj}(\vec{r})$ with $\vec{r}$ being the relative distance between the core and the valence or halo neutron. The final state is represented by a distorted wave describing the neutron in the continuum. As one can see from above equation, the E1-strength distribution is very sensitive to the spatial extension of the single-particle wave function. A pronounced halo like tail of the wave function leads to large transition probabilities at very low relative energies. The shape of the strength distribution is thus sensitive to the angular momentum of the valence neutron. This characteristic behavior can be utilized to probe the ground-state single-particle structure by measuring the differential electromagnetic dissociation cross section: the l value of the valence nucleon is determined by the shape of the distribution, the core state I_c^π to which the nucleon is coupled can be identified by the characteristic γ decay (in case of excited states), while the associated spectroscopic factors $CS^2(I_c^\pi, nlj)$ can be deduced from the absolute cross sections.

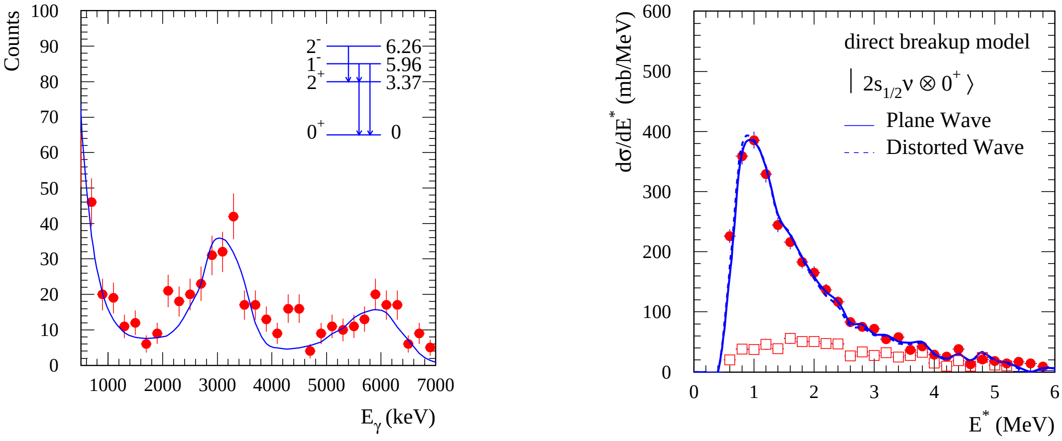

Fig. 2: Doppler corrected γ sum-energy spectrum (left) and excitation energy spectrum (right) for the breakup of ^{11}Be (520 MeV/u) on a lead target.

As an example, the results obtained for the halo nucleus ^{11}Be are shown in Figure 2. The γ-spectrum as recorded in coincidence with ^{10}Be fragments and a neutron (left panel) reveals contributions to the breakup cross section involving the 2^+ first excited state but also higher lying states at around 6 MeV. The latter result from removal of core neutrons from the p shell populating 1^- and

2^- states. The right panel shows the differential cross section after subtraction of excited states contributions. The data are well described by the sum (solid curve) of a nuclear contribution (open symbols) and a calculation (equation 1) for a *s*-wave neutron coupled to the ^{10}Be ground state. A preliminary analysis yields a spectroscopic factor of about 0.6-0.7 for this configuration.

For ^{17}O ($J^\pi = 5/2^+$) the Coulomb breakup reaction yields the ^{16}O core mainly in the ground state as expected. The comparison of the differential cross section (Figure 3) with ^{11}Be (Figure 2) shows that the distribution is much broader and the peak cross section is much smaller (by about two orders of magnitude!). Obviously, this reflects the fact that the valence neutron of ^{17}O is well bound in a $l = 2$ state, while ^{11}Be has a well pronounced halo structure. It clearly demonstrates the tremendous sensitivity of the Coulomb breakup cross section to a halo-like tail of the wave function. Our preliminary analysis yields a spectroscopic factors of 0.8(1), very close to the expected value of 1 and also to the result of S = 1.04(10) obtained from an electron scattering experiment [12], thus giving confidence that Coulomb breakup can be utilized to extract quantitative nuclear-structure information.

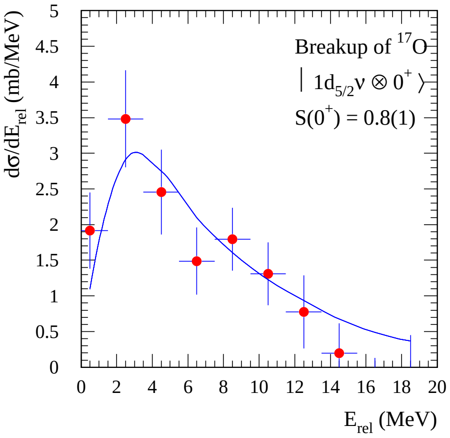

Fig. 3: Differential cross section $d\sigma/dE_{rel}$ as a function of relative energy between ^{16}O(0^+) and the neutron for Coulomb breakup of ^{17}O populating the ground state of ^{16}O. Nuclear and excited states contributions are subtracted. The shape of the experimental spectrum (symbols) is well reproduced by the plane-wave calculation for a $1d_{5/2}$ neutron coupled to the ^{16}O ground state with a spectroscopic factor 0.8 (solid curve).

4 Summary and conclusion

The dipole response of neutron-rich nuclei was investigated via a kinematically complete measurement of the neutron-decay after electromagnetic projectile excitation to the continuum. Low-lying dipole strength was observed as being a general phenomenon for these light, neutron-rich nuclei. Although the cross sections are much smaller for the non-halo nuclei with comparatively large separation energies, the shape of the cross section as well as the absolute magnitude is well reproduced by the direct-breakup model. The enormous sensitivity of the cross section to the tail of the wave function makes Coulomb breakup one of the most efficient spectroscopic methods to extract quantitative structure information on the ground-state configuration of weakly bound nuclei even with very low beam intensities. In this context we finally mention a recently performed experiment studying ^{23}O breakup reactions. A ground-state spin assignment of $J^\pi = 1/2^+$ could be made and a spectroscopic factor was deduced [13] from the differential Coulomb breakup cross section measured with a ^{23}O beam intensity of about 1 ion/sec only.

Acknowledgment

The experiments discussed in this article are the result of a collaborative effort. The author likes to thank all members of the LAND collaboration: P. Adrich, K. Boretzky, D. Cortina, U.D. Pramanik, Th.W. Elze, H. Emling, M. Fallot, H. Geissel, A. Grünschloß, M. Hellström, K.L. Jones, L.H. Khiem, J.V. Kratz, R. Kulessa, Y. Leifels, A. Leistenschneider, E. Lubkiewicz, G. Münzenberg, C. Nociforo, R. Palit, P. Reiter, H. Simon, K. Sümmerer, and W. Walús.

References

[1] I. Hamamoto and H. Sagawa, Phys. Rev. C **53** (1996) R1492; F. Ghielmetti, G. Col, P.F. Bortignon, and R.A. Broglia, Phys. Rev. C **54** (1996) R2143; D. Vretenar, N. Paar, P. Ring, and G.A. Lalazissis, Phys. Rev. C **63** (2001) 047301; Nucl. Phys. A **692** (2001) 496;

[2] P.G. Reinhard, Nucl. Phys. A **649** (1999) 305c;

[3] H. Sagawa and T. Suzuki, Phys. Rev. C **59** (1999) 3116;

[4] A. Leistenschneider *et al*, Phys. Rev. Lett. **86** (2001) 5442;

[5] U. Datta Pramanik *et al*, Phys. Lett. B **551** (2003) 63;

[6] R. Palit *et al.*, GSI scientific report 2001, ISSN 0174-0814 (2002) 19;

[7] H. Geissel *et al.*, Nucl. Instr. and Meth. B **70** (1992) 286;

[8] T. Blaich *et al.*, Nucl. Instr. and Meth. A **314** (1992) 136;

[9] C.A. Bertulani and G. Baur, Phys. Rep. **163** (1988) 299;

[10] E.G. Fuller, Phys. Rep. **127** (1985) 187; A. Vessire *et al.*, Nucl. Phys. A **227** (1974) 513; B.L. Berman, At. Data Nucl. Data Tables **15** (1975) 319;

[11] B.A. Brown, Progr. in Part. and Nucl. Phys. **47** (2001) 517;

[12] S. Burzynski *et al.*, Nucl. Phys. A **399** (1983) 230;

[13] K.L. Jones *et al.*, in preparation.