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Studies of light neutron-rich nuclei near the drip line

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Abstract. Coulomb breakup of neutron-rich Be, B, C, and O isotopes at relativistic energies (400–600 A MeV) was studied with kinematically complete measurements. The ground-state properties of these nuclei were deduced by comparing experimental data for Coulomb-dissociation cross-sections with direct-breakup model calculations. The dominant ground-state configurations of ^{15}C, ^{11}Be, ^{14}B, and ^{23}O were found to be $^{14}\mathrm{C}_{gs}(0^+) \otimes \nu_s$,$^{10}\mathrm{Be}_{gs}(0^+) \otimes \nu_s$, $^{13}\mathrm{B}_{gs}(3/2^+) \otimes \nu_{s,d}$, and $^{22}\mathrm{O}_{gs}(0^+) \otimes \nu_s$, respectively, and $^{16}\mathrm{C}(2^+) \otimes \nu_{s,d}$ for ^{17}C. The capture cross-section for ^{14}C(n,γ) ^{15}C relevant in astrophysical scenarios was measured indirectly through Coulomb dissociation.

PACS. 21.10.Jx Spectroscopic factors – 25.40.Lw Radiative capture – 26.30.+k Nucleosynthesis in novae, supernovae, and other explosive environments

1 Introduction

Recent developments in radioactive nuclear beam techniques have led to exciting discoveries in the field of nuclear structure. The neutron halo, the appearance of low-lying dipole strength, and the melting of closed shells are examples of new structural phenomena observed in light nuclei near the neutron drip line. Breakup reactions are an important source of information about the structure of exotic nuclei. Coulomb breakup is a particularly important mechanism due to its sensitivity to the tail of the wave function of loosely bound nuclei. In the present contribution we summarize the results of Coulomb-breakup measurements to study the single-particle ground-state properties of ^{15,17}C, ^{11}Be, ^{14}B, and ^{23}O, and an indirect measurements (through Coulomb dissociation) of the radiative-capture cross-section of the ^{14}C(n,γ)^{15}C reaction which is relevant in astrophysical scenarios.

2 Experimental details

Secondary beams of neutron-rich Be, B, C, and O isotopes at energies of 400–600 A MeV were produced by fragmentation of a ^{40}Ar beam. Those beams were separated in the FRS and transferred to a secondary-reaction target placed inside the LAND-ALADIN setup at GSI [1,2,3]. The ions were identified event by event by means of energy-loss and time-of-flight measurements. Neutrons from the decay of reaction products were kinematically forward focussed and detected by the large-area neutron detector, LAND. Decay γ-transitions of the fragments were measured to identify the core-excited states. Coulomb-dissociation cross-sections were obtained using a Pb target. Breakup data were also taken for a C target to determine the nuclear contribution, and for an empty target in order to deduce background reactions taking place in various detector materials. By measuring the momenta of all decay products after breakup, the excitation energies of the decaying nuclei were determined.

3 Results

3.1 Single-particle structure of light neutron-rich nuclei

The electromagnetic breakup of loosely bound nuclei in energetic heavy-ion collisions is dominated by dipole excitations. The non-resonant direct breakup cross-section

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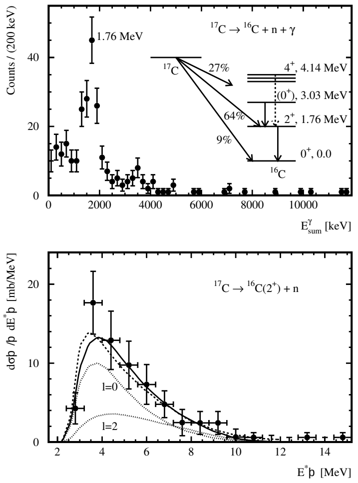

Fig. 1. Top: Sum-energy spectrum of γ transitions in ^{16}C after Coulomb breakup of ^{17}C. Bottom: Differential CD cross-sections as a function of excitation energy, E^*, of ^{17}C in coincidence with the 1.766 MeV γ transition ($^{16}\mathrm{C}(2^+ \rightarrow 0^+)$). The smooth curves are the cross-sections calculated using a direct-breakup model in plane-wave approximation for $l = 0$ and $l = 2$ neutrons (solid lines) and their sum (heavy solid curve). The dashed curve shows the result using the distorted-wave approximation [1].

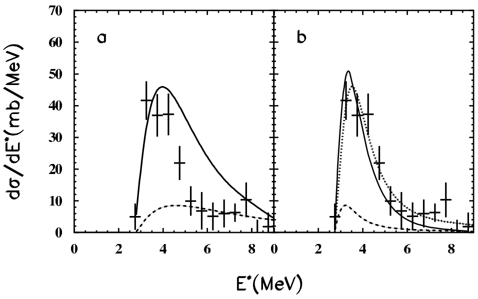

Fig. 2. Differential CD cross-sections for ^{23}O breakup into $^{22}\mathrm{O}(0^+)$ and neutron. In panel (a) and (b), respectively, the full (dashed) line shows the direct-breakup calculation assuming plane waves and distorted wave using an optical potential for the outgoing neutron and adopting a ground-state spin of $1/2^+$ ($5/2^+$) for ^{23}O. The dotted line in panel (b) is the result of the calculation within the effective-range approach for a ground-state spin of $1/2^+$. For details see [2].

Table 1. Capture cross-section (in μb) at $E_{cm} = 23$ keV

This expt	Direct [7]	Indirect [8]
4.3(10)	1.1(3)	2.6(9)

due to the Coulomb interaction, $\mathrm{d}\sigma/\mathrm{d}E^*(I_c^\pi)$, can be expressed as

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

ψ_{nlj} represents the single-particle wave function of the valence neutron in the projectile ground state, and $C^2 S(I_c^\pi, nlj)$ its spectroscopic factor with respect to a particular core state, I_c^π. The final-state wave function $\langle q \mid$ of the valence neutron in the continuum may be approximated by a plane wave, or, alternatively, by a distorted wave. The single-particle wave functions have been derived from a Woods-Saxon potential. $N_{E1}(E^*)$ is the number of equivalent dipole photons of energy E^*. For details see ref. [1]. Non-resonant low-lying dipole strength is observed in neutron-rich ^{15,17}C [1], ^{11}Be [3], ^{14}B and ^{23}O [2] isotopes which can be explained by the direct-breakup mechanism. Data analysis showed that after Coulomb dissociation (CD) of ^{15}C, ^{11}Be, ^{14}B, and ^{23}O, the respective cores are mainly populated in their ground states (to 90–70%), and that the valence neutrons occupy the $s_{1/2}$ orbital ($d_{5/2}$ in the case of ^{14}B). But the situation is very different in ^{17}C. Figure 1 (top) shows the partial CD cross-section of ^{17}C when different core states after Coulomb breakup are populated. The experimental data for CD [1] shows (fig. 1, bottom) that the predominant ground-state configuration of ^{17}C is $^{16}\mathrm{C}(2^+)\otimes\nu_{s,d}$. In ^{23}O, the analysis of the dipole-transition probability into the continuum allows us to infer a $^{22}\mathrm{O}(0^+)\otimes 2\nu s_{1/2}$ ground-state configuration with a spectroscopic factor of 0.77(10) and thus a ground-state spin $I^\pi(^{23}\mathrm{O}) = 1/2^+$, resolving earlier conflicting experimental findings [4,5]. It is evident from fig. 2 that final-state interactions are of significant influence in the case of the more tightly bound ^{23}O nucleus; an effective reduced scattering length for low-energy $p_{3/2}$ neutron scattering could be derived from the data [2].

3.2 Indirect measurement of capture cross-section

The radiative-capture cross-section of the $^{14}\mathrm{C}(\mathrm{n}, \gamma)^{15}\mathrm{C}$ reaction may play an important role in various astrophysical scenarios [6]. Beer *et al.* [7] measured this reaction cross-section directly at low energies and obtained a result different from the calculated one. However, a direct measurement of this reaction is very difficult due to the small cross-section (μb) and the use of a radioactive target. We measured the capture cross-section indirectly via CD and obtained an integrated cross-section of 360 ± 10 mb. Table 1 shows the (deduced) capture cross-section at $E_{cm} = 23$ keV for both direct and indirect measurements. Horvath *et al.* [8] also derived the same quantity from a CD measurement but at a much lower beam energy (35 A MeV); the dependence of their curve on relative energy appears to be different from our measurement. Both indirect measurements of capture cross-section at the astrophysical relevant energies were obtained from extrapolating the CD cross-sections.

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