Eur. Phys. J. A **20**, 95–96 (2004)
DOI 10.1140/epja/i2002-10329-8

THE EUROPEAN PHYSICAL JOURNAL A

Study of drip line nuclei through two-step fragmentation

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Received: 31 October 2002 /
Published online: 24 February 2004 – © Società Italiana di Fisica / Springer-Verlag 2004

Abstract. We have studied the structure of light neutron-rich nuclei around $N = 16$ by employing the in-beam γ-ray spectroscopy technique using the fragmentation of secondary beams of ^{25,26}Ne, ^{27,28}Na and ^{29,30}Mg isotopes. This secondary-beam "cocktail" was obtained by the fragmentation of a ^{36}S beam at 77.5 MeV $\cdot A$ by the SISSI/GANIL facility. By a second-step fragmentation, we have measured γ-ray–residue coincidences in $^{17-20}$C and ^{23,24}O and described the obtained levels in the framework of the shell model.

PACS. 23.20.Lv γ transitions and level energies – 21.60.Cs Shell model – 27.20.+n $6 \leq A \leq 19$ – 27.30.+t $20 \leq A \leq 38$

1 Introduction

In-beam γ-ray spectroscopy of nuclei formed in fragmentation reactions gives access to the structure of neutron-rich light isotopes which hardly could be obtained by other methods. Experiments at GANIL have successfully demonstrated the usefulness of this approach [1,2]. However, the primary-beam intensity has to be reduced to few enA in order to match the maximum counting rate that individual γ-ray detectors can withstand. To overcome this limitation for accessing nuclei close to the drip line, a new method has been employed in which the fragmentation of secondary neutron-rich beams is used. A "cocktail" of secondary beams of ^{25,26}Ne, ^{27,28}Na, ^{29,30}Mg, of mean rate of 10^5 pps, has been produced by the fragmentation of a high-intensity (400 pnA) ^{36}S beam at 77.5 MeV $\cdot A$ onto a carbon target (348 mg/cm^2) located in the SISSI device. The beam nuclei were selected through the ALPHA spectrometer and driven to a secondary target composed of a plastic scintillator sandwiched by two carbon foils. The plastic scintillator was used for time-of-flight and energy loss measurements in order to identify on an event-by-event basis the ions that have induced reactions in the secondary target. A γ-array, composed of 74 BaF$_2$ detectors was surrounding the secondary target in a 4π geometry, leading to 30% efficiency for a 1.3 MeV γ-ray. γ-rays were collected in coincidence with the tertiary fragments detected through the SPEG spectrometer. From the analysis of the γ-ray–fragment coincidences, γ-ray spectra from excited states in $^{17-20}$C, ^{23,24}O have been extracted and level schemes have been deduced and compared to shell model predictions (fig. 1).

2 Results

In the case of the odd nucleus ^{17}C, the experimental spectrum suggests that there is a low-lying triplet of levels. The energies of the two excited states are 207 and 329 keV, in relative accordance with shell model calculations involving the WBP interaction [3]. The ^{17}C ground state has a well-established $3/2^+$ spin [4], but the decisive spin assignement of the excited levels cannot be made. From the

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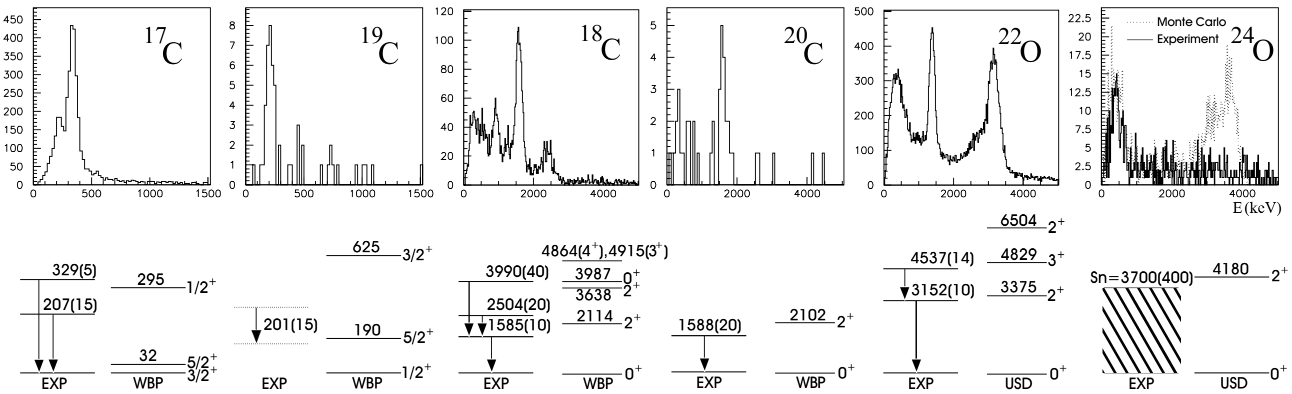

Fig. 1. Top: γ-ray spectra; bottom: experimental and shell model level schemes obtained for $^{17-20}$C with the WBP interaction [3] and for ^{22,24}C with Wildenthal USD Hamiltonian.

transfer reaction experiment of Fifield *et al.* [5], a level at 295(10) keV has been evidenced. It is not clear if it corresponds to that at 329(5) keV seen in our experiment, or if it is another excited state in ^{17}C. The structure of ^{19}C is poorly known. Results of mass measurements [6,7] and neutron breakup measurements [8–11] give conflicting evidence for spins and parities. The most probable ground-state spin, however, seems to be $1/2^+$ and we therefore suggest that the 201 keV transition observed in the present experiment is the $3/2^+ \to 1/2^+$ or the $3/2^+ \to 5/2^+$. A stretched $E2$ transition $5/2^+ \to 1/2^+$ at 201 keV to the ground state would imply a μs-range half-life. In such a case, the in-flight γ-decay of ^{19}C would have occurred downstream, out of the γ-array detection window. If the first excited state were $5/2^+$, then we suggest a $3/2^+ \to 5/2^+$ assignment to the 201 keV transition. We notice that the presence of an isomer could in principle explain the divergence of the results on ^{19}C mentioned above. The γ-lines at 1585(10) keV in ^{18}C and 1588(20) keV in ^{20}C are assigned to the 2^+-to-0^+ transition. These spectra have been obtained with a total of 5884 ^{18}C and 189 ^{20}C, leading to feeding intensities to the 2^+ state of 15% and 24%, respectively. These results extend the systematics of the 2^+ excitation energy up to $N = 14$ in the carbon isotopic chain. The 2^+ energy of ^{20}C is about a factor of two lower than for ^{22}O. A total number of 6671 ^{24}O has been produced during the experiment, which originate at 72% from the ^{26}Ne fragmentation and 28% from reaction channels which involved the removal of more than 2 nucleons. As shown in fig. 1 by the full-line spectrum of ^{24}O, no clear transition is observed. A compelling explanation is that the 2^+ excitation energy could be higher than the neutron separation energy S_n and therefore not bound. We performed a Monte Carlo simulation based on 7000 ^{24}O fragments excited to a supposed 2^+ at 3.7 MeV (the S_n value), emitting γ-rays into the BaF_2 array. Feeding probability to a 2^+ state in the fragmentation process has been deduced from the ^{22}O study. The result is shown in fig. 1 as an overlay. The contrast to the experimental spectrum supports the conclusion of an unbound 2^+ state, in accordance with the theoretically suggested value at 4.18 MeV. A total of 19620 residuals of ^{23}O was detected, but no transition identified. Using a similar analysis as for ^{24}O, we conclude that the first excited state of ^{23}O is also unbound, its energy is higher than the neutron separation energy of 2.74(12) MeV. The similarity of the 2^+ energies of the C and O isotopes up to $N = 12$ is striking. This is due to the dominance of the $(d_{5/2}+)^n J = 2$ configuration for both $Z = 6$ and $Z = 8$. However, a strong difference appears at $N = 14$. The high 2^+ state in ^{22}O is due to the large energy gap between $d_{5/2}$ and $s_{1/2}$ single-particle energies at $Z = 8$ and $N = 14$, the main shell model configurations for ^{22}O are $(d_{5/2})^6$ for the ground state and $(d_{5/2})^5$-$s_{1/2}$ for the 2^+ state. When one goes to $Z = 6$, it is known from the spectra of ^{17}O and ^{15}C that the $s_{1/2}$ neutron single-particle energy decreases relative to $d_{5/2}$ by 1.6 MeV. This decrease is accounted for by the spin-dependant proton-neutron ($\pi p_{j=1/2,3/2}$-$\nu d_{5/2}$) part of the WBP interaction. Thus, the energy of the 2^+ state is lowered in ^{20}C by roughly 1.6 MeV relative to ^{22}O and a $(d_{5/2}$-$s_{1/2})^6$ pairing-type structure dominates the ^{20}C ground state.

In conclusion, the study of the neutron-rich $^{17-20}$C and $^{22-24}$O nuclei has been performed by the in-beam γ-ray spectroscopy using the fragmentation reactions of radioactive beams. The 2^+ energy of ^{20}C is determined for the first time. Its low-energy value hints for a major structural change at $N = 14$ between C and O nuclei. Evidence for the non-existence of bound excited states in either of the ^{23,24}O nuclei has been provided, pointing to a large sub-shell effect at $N = 16$ in the O chain.

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