STUDY OF NEUTRON RICH NUCLEUS ^{25}F VIA SINGLE-STEP FRAGMENTATION*

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The structure of nucleus ^{25}F was studied by use of in-beam γ-ray spectroscopy of the fragmentation of a ^{36}S beam. The emitted γ rays were detected by BaF_2 detectors. In the γ-ray spectrum obtained a wide bump between 3 and 4.5 MeV energy was observed corresponding to a set of γ rays, including their first and second escape peaks. In order to resolve the peaks and to determine the high-energy structure of ^{25}F, the experimental spectra were compared to Geant4 simulations taking the complex line shape into account. The observed decomposition of the bump is in good agreement with the results of the two-step fragmentation experiment [Zs. Vajta *et al.*, submitted to *Phys. Rev.* **C**]. Furthermore, an additional transition was observed at 2140(30) keV.

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1. Introduction

At first glance, the fluorine isotopes are expected to possess a simple structure. In a naive picture, their energy spectrum can be described by use of *sd* single proton states coupled to the ground and excited states of the neighbouring semi-magic oxygen nuclei. However, the fluorine isotopes intrigued us in many cases. ^{19}F has a deformed ground state and a very low-lying negative-parity state which shows a clear multi-particle–multi-hole nature according to the shell model. In the case of ^{27}F, two bound excited states have been observed [1] contrary to the expectation of the *sd* shell model [2]. In addition, ^{31}F [3] was proved to be bound which can only be interpreted assuming multi-particle–multi-hole configurations [4], suggesting that states with intruder configuration may exist in ^{25}F, too.

As a part of our in-beam γ-spectroscopic studies of neutron rich nuclei around the $N = 28$ [5–7], $N = 20$ [8, 9] and $N = 16$ [10, 11] subshell closures, we investigated the structure of the neutron-rich nucleus ^{25}F. From the preliminary results [9, 12, 13], four γ rays at 750, 1700, 3300 and 3700 keV energies have been known. The existence of the two low-energy lines at 727 and 1753 keV have been confirmed by the two-neutron knock-out results [1]. In the present paper, we report on the precise analysis of the high-energy part of the γ-ray spectrum of ^{25}F obtained via fragmentation of a stable beam.

2. Experimental methods

In the experiment performed at Ganil, a ^{36}S beam of 77 MeVA energy and 15 *e*nA intensity was fragmented on a Be target of 2.76 mg/cm^2 thickness. The emerging fragments were detected by the SPEG spectrometer. Ionization and drift chambers, as well as a plastic scintillator were placed at the SPEG focal plane, providing information on the energy loss, total energy and time-of-flight for identification of the fragments. During the experiment about 78×10^3 ^{25}F nuclei were collected. These nuclei were produced partly in excited states. In order to measure the emitted γ-rays 74 BaF_2 detectors were mounted around the Be target.

During the off-line analysis the γ spectra were corrected for the Doppler-shift caused by the large fragment velocity ($v/c = 0.34$). After the correction, a full width at half maximum of about $\sim 12\%$ was achieved for the BaF_2 setup, which had a total photopeak efficiency of $\sim 20\%$ at 1.3 MeV energy. The γ rays could easily scatter from one detector to another. To decrease the background caused by the scattered photons, we used the array in add-back mode. Unfortunately, the cut-off energy in the spectrometer was set at a relatively high energy (above 600 keV), which made the add-back method ineffective for the annihilation γ rays.

In the γ spectra observed in this experiment, a relatively high background can be seen originating from different processes. In the experiment, the neutrons evaporated by projectile-like fragments were focused in forward direction and caused background mainly in the detectors placed at angles below 40°. The next component of the background arose from the neutrons directly knocked out by the target nuclei from the projectiles. They scattered to backward direction in the center of mass system, and covered a large angular range in the laboratory frame. The BaF_2 crystals also detected target-like evaporated neutrons, which produced a continuous background in their spectra. In addition, statistical γ rays were also observed from the massive breakup of the projectile. Furthermore, the neutrons induced $(n,\ n'\gamma)$ reactions in the various Ba isotopes of the BaF_2 crystals. This neutron-induced γ background in the BaF_2 detectors is smeared out in energy after summing all Doppler-corrected energies of individual crystals creating another increasement of the background. As a result, an exponential background was observed. A more detailed description of the background in the γ spectra observed can be found in Ref. [14].

3. Experimental results

The obtained γ-ray spectrum of ^{25}F is presented on the left-hand side of Fig. 1. In the spectrum, three well-separated γ peaks are observed at 750, 1720 and 2140 keV in addition to a wider, slightly structured bump visible between 3 and 4.5 MeV.

To resolve the wide bump in the γ spectrum, we first analyzed the energy dependence of the peak widths using single lines observed in other reaction channels. In the analysis, an almost linear energy dependence was observed.

To get a reasonable line shape, the response function of the BaF_2 array was simulated by use of the Geant4 package. In the simulation, the energy dependence of the peak width, the cut-off energy, the Doppler shift and the Doppler broadening were taken into account. For γ rays having energy higher than ~ 1.5 MeV, in addition to the photo and Compton effect the pair production also starts playing an important role. From the simulation it was found that the intensity of the single escape peak is about half of the photo-peak intensity at ~ 3.5 MeV. Using the simulated line shapes the region between 3 and 4.5 MeV γ energy could be well described by four γ rays at 3120(40), 3440(60), 3770(65) and 4120(130) keV energy.

In the multiplicity equal to 2 ($M = 2$) spectrum shown on the right-hand side of Fig. 1 the situation is cleaner, three significant γ peaks can be identified at 770, 1720 and 2140 keV and the high-energy bump is much more compressed. Fitting this region with four lines and assuming an exponential background with the same exponent as in the total spectrum, one can see

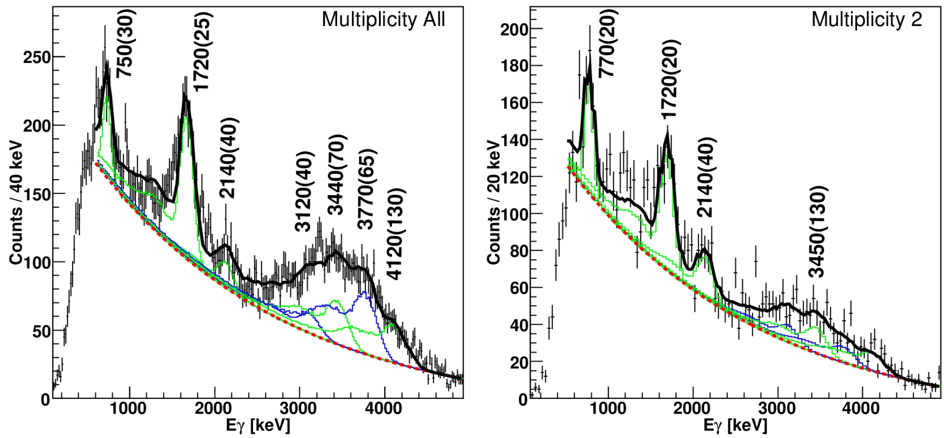

Fig. 1. Doppler-corrected γ-ray spectra of ^{25}F. The dots with error bars are the experimental values with statistical uncertainties. The grey (green) and dark grey (blue) solid curves correspond to the separate lines obtained by Geant4 simulation of the complex line shapes. The solid thick black line shows the final fit obtained by summing the peak curves and an exponential background (dashed line). Only the energy of significant γ peaks are indicated in the spectra.

that only the 3450 keV line is significant with 3.6σ confidence level. The fact that the traces of the 3120, 3770 and 4120 keV peaks appear in the $M = 2$ spectrum means that they are observed in coincidence with the neutrons emitted in the reaction feeding directly the high-energy states lying close to the separation energy ($S_n = 4.36(12)$ MeV). The stronger lines in the $M = 2$ spectrum are assumed to be in coincidence with at least one other line. The 770 and 2140 keV γ rays appear with their whole intensity in the $M = 2$ spectrum, thus, they likely decay to excited states. The 1720 keV γ line seems to be a doublet, as only about half of its intensity is present in the $M = 2$ spectrum. Hence, one member of this doublet is assumed to decay to the ground state directly, while the other one connects excited states.

On the basis of the present analysis the following γ transitions are assigned to ^{25}F: 760(15), 1720(15), 2140(30), 3120(40), 3440(60), 3770(65) and 4120(130) keV. Compared to the preliminary results, the weaker lines at 2140, 3120 and 4120 keV could be identified and the doublet nature of the 1720 keV transition could be revealed. The energy values for γ rays present with at least 2σ confidence level in both spectra shown in Fig. 1 were deduced as their weighted average. These energies are in a reasonable agreement with the values obtained in a two-step fragmentation experiment [15].

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