

Spectroscopy of ^{26}F

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The structure of the weakly bound $^{26}\text{F}_{17}$ odd-odd nucleus, produced from $^{27,28}\text{Na}$ nuclei, has been investigated at GANIL by means of the in-beam γ -ray spectroscopy technique. A single γ -line is observed at 657(7) keV in ^{26}F which has been ascribed to the decay of the excited $J = 2^+$ state to the $J = 1^+$ ground state. The possible presence of intruder negative parity states in ^{26}F is also discussed.

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The neutron-rich $^{26}\text{F}_{17}$ nucleus can be considered to be a *benchmark* in the study of nuclear forces for at least three reasons. Firstly, as its neutron binding energy amounts to only 0.80(12) MeV [1] its structure is likely to be influenced by drip-line phenomena. Secondly, it is only two nucleons off the $^{24}\text{O}_{16}$ doubly magic nucleus [2,3] which has a high energy 2^+ excited state at 4.47 MeV [4]. Therefore its nuclear structure at low excitation energy could be described by the interaction between a $d_{5/2}$ proton and a $d_{3/2}$ neutron on top of a closed ^{24}O core, leading to $J = 1, 2, 3, 4$ positive parity states. Thirdly, it could be used to track the evolution of the negative parity states (arising from the neutron $p_{3/2}$ or $f_{7/2}$ orbits) in the $N = 17$ isotones [5–8] and predict their role in the description of the unbound ^{25}O for which a broad resonance has been observed at 770 keV [9].

So far the ground state spin of ^{26}F has been found to be 1^+ , based on the observed β -decay branches to the 0^+ ground state and the 2^+ state in the ^{26}Ne nucleus [10]. Two candidates of bound excited states have been proposed at 468(17) keV and 665(12) keV by Elekes *et al.* [11] with confidence levels of 2.2 and 3.8σ , respectively. In Ref. [11] the ^{26}F nuclei were produced in interactions between a ^{27}F nucleus and a liquid hydrogen target at 40A MeV. Moreover, a neutron unbound state has been proposed by Frank *et al.* [12] about 270 keV above the neutron emission threshold. This state has been populated in interactions between a ^{26}Ne beam and a Be target at 86A MeV.

The present experimental work aims at studying bound excited states in ^{26}F , hereby clarifying the situation about their existence. The ^{26}F nuclei were produced in two-steps reactions. A primary beam of ^{36}S with an average intensity of 400 pnA

and an energy of 77.5A MeV was used to induce fragmentation reactions into a 398 mg/cm²-thick C target placed inside the SSSI device at the GANIL facility. Projectile-like fragments of interest were selected through the α spectrometer. A wedge-shaped, 130 mg/cm²-thick, Al foil was installed at the dispersive focal plane between the two dipoles of the spectrometer to provide an additional energy-loss selection. The magnetic rigidity of the α spectrometer was optimized for the transmission of secondary beam nuclei with energies of about 60A MeV, among which $^{27,28}\text{Na}$ were the main generators of ^{26}F . An “active” target composed of a plastic scintillator (103.5 mg/cm²) sandwiched between two carbon foils of 51 mg/cm² was used for identifying the nuclei of this cocktail beam through their time of flight values. This “active” target was also used to induce secondary reactions. The ^{26}F nuclei were subsequently selected and identified on an event-by-event basis through the SPEG spectrometer using the time of flight, energy loss, and focal-plane position information. The ^{26}F nuclei could be produced in the ground state, as well as in bound or unbound excited states. The short-lived (<1 ns) excited bound state decay by prompt in-flight γ emission, while (if existing) longer-lived or unbound states could not be observed in our work. To detect prompt γ rays, the “active” target was surrounded by an array of 74 BaF₂ detectors located in two hemispheres at a mean distance of 30 cm from the target. Doppler shift corrections were applied to the observed γ rays as a function of their detection angle to account for the momentum value of the emitting nuclei determined by the measurement of their position at the focal plane of SPEG located 22 m downstream to the BaF₂ array. The total photopeak efficiency of the BaF₂ array was about 42% (29%)

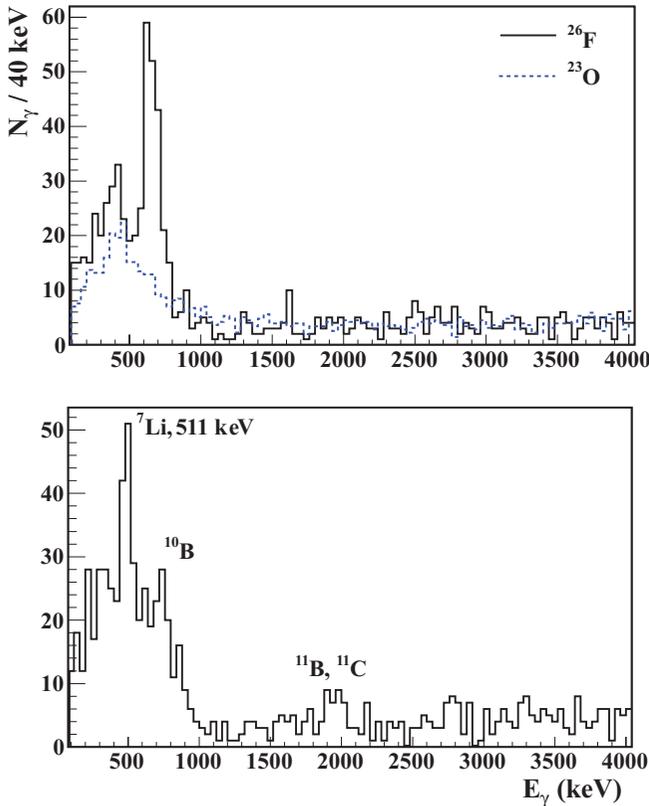


FIG. 1. (Color online) Top: Doppler corrected γ -ray spectrum obtained using the BaF₂ detectors for ^{26}F (full line), and for ^{23}O (dotted line). Bottom: Spectrum obtained for ^{26}F without applying the Doppler corrections. Labeled γ rays belong to target fragmentation.

for a γ ray of 600 keV (1300 keV). The energy resolution (σ), including the part provided by the Doppler broadening, amounts to about 10% of the γ energy at 500 keV. Low-energy γ transitions down to 100 keV were detected with an efficiency value of about 24%.

The Doppler-corrected γ spectrum obtained for ^{26}F is shown in the upper part of Fig. 1. It exhibits a clear peak at 657(7) keV, with a width $\sigma = 61(6)$ keV. The centroid energy of the peak matches, within the experimental value, the one tentatively proposed by Elekes *et al.* [11] at 665(12) keV. The low-energy structure seen around 400 keV [with $\sigma = 81(14)$ keV] is too broad to correspond to a γ ray emitted in flight. Indeed, known in-flight γ peaks observed at a similar energy during the present experiment have smaller widths: the γ peak at 478 keV in ^7Li has $\sigma = 51(2)$ keV while that at 320 keV in ^{11}Be has $\sigma = 36(1)$ keV. Moreover the same pattern appears around 400 keV in the ^{23}O nucleus (see dashed line in upper part of Fig. 1), which has no bound excited state [13]. Therefore this structure more likely corresponds to a γ transition arising from the fragmentation of the target nuclei. As these γ rays are emitted almost at rest, they are not suitably Doppler-corrected when using the velocity of the in-flight nuclei, leading to the broad structure in the γ -ray spectrum (upper panel of Fig. 1). Without applying any Doppler correction a thinner peak, belonging

TABLE I. Comparison between experimental and calculated energies in keV of the 1^+ to 4^+ states in ^{26}F . Calculations are made with shell model calculations using the USD [15], USDA, or USDB [16] interactions. The asterisk indicates energy extracted from Ref. [12], however the spin assignment is not known (see text for details)

J	1	4	2	3
Exp	0		657(7)	$\simeq 1070(120)^*$
USD	0	353	681	1604
USDA	0	850	850	1800
USDB	0	200	600	1600

to target excitations, appears at about 500 keV in Fig. 1 (lower panel) on top of a broader structure, caused by the 657 keV γ rays emitted in flight. The tentative γ ray at 468(17) keV proposed by Elekes *et al.* [11] may either be hidden in the background of our spectrum, or not be fed by the presently used reaction.

The structure of $^{26}\text{F}_{17}$ can be viewed simply by assuming a closed ^{24}O core to which a proton and a neutron are added. The ^{24}O nucleus has the properties of a doubly magic nucleus [2,3], with a first excited state above 4.47 MeV [4] and a neutron $N = 16$ shell gap of about 4.95(16) MeV. Following the normal filling of orbits, the odd valence proton occupies the $d_{5/2}$ orbit, while the odd valence neutron occupies the $d_{3/2}$ one. Their coupling leads to states $J = 1^+ - 4^+$. Guided by the rule of particle-particle couplings for a neutron and a proton having the same ℓ value on top of a closed core (see for instance [14]), a parabolic curve as a function of J is expected to be formed by the states in ^{26}F , the lowest spin $J = 1$ and highest spin $J = 4$ spin states having the largest binding energy, i.e., lowest excitation energy. This is what is found by the shell model calculations presented in Table I. The calculated configuration of these states is as much as 80–90% pure $\pi d_{5/2} \otimes \nu d_{3/2}$. Noteworthy is the fact that both the USD [15] and USDA/USDB [16] interactions predict the $J = 4$ state to be a β -decaying isomeric state, partly connected to the ground state by a delayed $M3$ transition. In all interactions, the $J = 3$ state is found to be unbound, at an excitation energy of about 1.7 MeV. Taking the value of 0.80(12) MeV for the neutron emission threshold, the $J = 3$ state is predicted to be unbound by about 0.9 MeV. Consequently, it is reasonable to discard the two possibilities of $J = 4$ and $J = 3$ for the observed excited state at 657(7) keV, the former being possibly long-lived isomer, the latter being likely unbound. We therefore ascribe the observed peak at 657(7) keV to arise from the decay of the $J = 2$ excited state to the $J = 1$ ground state.

Besides the “normal” positive parity states, low-lying negative parity states could be present in $^{26}\text{F}_{17}$. Indeed a $3/2^-$ intruder state has been discovered at 765 keV above the $3/2^+$ ground state in the $^{27}_{10}\text{Ne}_{17}$ isotone [5–7]. From the recent work of Ref. [8], it is confirmed that the $3/2^-$ state has a large $p_{3/2}$ component. Therefore the coupling of the $p_{3/2}$ neutron to the $d_{5/2}$ proton would lead to negative parity states $J = 1^- - 4^-$ in ^{26}F . The excitation energy of these negative parity states should be related to the energy difference between

the neutron $d_{3/2}$ and $p_{3/2}$ orbits, which is expected to be reduced in ^{26}F as compared to ^{27}Ne . This reduction comes from the fact that the removal of a proton from the $d_{5/2}$ orbit between ^{27}Ne and ^{26}F should weaken the binding energy of the $\nu d_{3/2}$ orbit relative to the $\nu p_{3/2}$ one. This owes to the fact that the $\pi 1d_{5/2} - \nu 1d_{3/2}$ monopole interaction (between orbits having the same number of nodes n , the same angular momentum ℓ and anti-aligned spin) is expected to be more attractive than the $\pi 1d_{5/2} - \nu 2p_{3/2}$ one (between orbits with different n and ℓ values, and aligned spin) [17]. It follows that a multiplet composed of negative parity states should be present at relatively low excitation energy in ^{26}F . The Hamiltonian WBP-M used in the $0s - 0p - 0d - 1s - 0f - 1p$ valence space in Ref. [8] predicts the lowest negative parity states in ^{26}F to be 2^- and 4^- around 1 MeV excitation. In order to produce these negative parity states, the projectile nuclei should contain a significant intruder configuration component [such as $(p_{3/2})^2$] added to the dominant $(d_{3/2})^2$ one. This is not likely in the present experiment, in which the ^{26}F nuclei were produced from $^{27,28}\text{Na}$, which lie outside of the island of inversion according to Ref. [18] and Fig. 9 of Ref. [16]. Energy-wise, the observed unbound state by Frank *et al.* [12] at about 270 keV above the 0.8 MeV neutron emission threshold would correspond to a 3^+ or $2^-, 4^-$ state. However it is again hard to conceive a favored feeding of negative parity states from a ^{26}Ne precursor nucleus, which is expected to contain a negligible fraction of $(2p_{3/2})^2$ component in its ground state. The 468(17) keV γ ray, tentatively observed by Elekes *et al.* [11] through the $^{27}\text{F}(-1n)^{26}\text{F}$ reaction, might correspond to the decay of a negative parity excited state. Indeed, hint for a significant intruder content of the ground state of ^{27}F

was derived from the large deformation length in the (p, p') reaction [11].

To summarize, the ^{26}F nuclei were produced in two-steps fragmentation reactions. Their in-flight γ decays were observed in a large efficiency detector array composed of 74 BaF₂ detectors. A single bound state is proposed from the observation of a 657(7) keV γ ray. Among the possible $J = 1^+ - 4^+$ spin values of the low energy states in ^{26}F predicted by shell model calculations, we propose a spin assignment $J = 2^+$ for this state. It is based on the facts that the $J = 4^+$ state is likely to be an isomer, and that the $J = 3^+$ state is predicted to lie above the neutron emission threshold. Further experimental investigations are needed to locate the $J = 4^+$ state and to conclude about the presence of negative parity (intruder) states in ^{26}F . The presence of negative parity states at low excitation energy would suggest a further reduction of the neutron $d_{3/2} - p_{3/2}$ spacing in ^{26}F , as compared to ^{27}Ne . If pursued, this reduction would manifest itself as a $p_{3/2}$ component at low energy in the ^{25}O isotone. To evidence the presence of $\ell = 1$ negative parity states in the ^{26}F and ^{25}O nuclei, further experiments should be carried out using the fragmentation of projectile nuclei (such as ^{31}Na) lying inside the island of inversion.

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