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Neutron-unbound states in ^{25,26}F

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Neutron-unbound states in ^{25}F and ^{26}F were populated via the reactions ^{9}Be(^{26}Ne,^{24}F + n) and ^{9}Be(^{26}Ne,^{25}F + n), respectively. A resonance close to the neutron separation energy in ^{25}F was identified with a decay energy of 28 ± 4 keV. This resonance corresponds to an excited state in ^{25}F at 4249 ± 116 keV assuming it decays to the ground state of ^{24}F. Guided by shell-model calculations, a spin and parity of $1/2^-$ can be assigned to this state. In the spectrum of ^{26}F, which was produced in a nucleon-exchange reaction, there are indications for an excited state with a decay energy of ∼270 keV.

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There are no bound oxygen isotopes past $N = 16$ while bound fluorine isotopes extend out to at least $N = 22$. Understanding the change in nuclear structure that underlies this difference has been the focus of considerable theoretical work. This change has been attributed to the spin-isospin component of the nucleon-nucleon force [1] which results in a larger energy gap between the $\nu(1s_{1/2})$ and $\nu(0d_{3/2})$ orbitals in oxygen isotopes [2]. At the same time, the gap between the $\nu(0d_{3/2})$ orbital and the pf shell decreases as the number of protons increases from $Z = 8$ to $Z = 14$ [3]. While the anomaly in the location of the oxygen dripline is not reproduced by shell-model calculations based on microscopic two-nucleon forces, it was recently demonstrated that the inclusion of three-nucleon forces provides a microscopic explanation [4]. The smaller shell gap enhances the possibility for cross-shell excitations. The Monte Carlo shell model with SDPF-M effective interactions (MCSM), which includes cross-shell excitations [5,6], reproduces data in the region of the "island of inversion" [7]. This region of the nuclear chart includes neutron-rich Ne, Na, and Mg nuclei whose low-lying structure is dominated by neutron particle-hole excitations across the $N = 20$ shell gap ([7,8] and references therein).

Indications for cross-shell excitations have also been observed in neutron-rich fluorine isotopes [9]. While the first excited state in both ^{25}F and ^{26}F can be explained within the sd-shell-model space using the USD interaction, neutron $2p2h$ excitations in the MCSM calculation are necessary to reproduce the energy of the first excited state in ^{27}F. The situation in the fluorine isotopes is even more complicated because of possible proton cross-shell excitations from the p to the sd shell. For example, the second excited state in ^{17}F, ^{19}F, and ^{21}F is a $1/2^-$ level originating from proton p-shell intruder configurations. Similarly, it has been speculated that the second excited state in ^{25}F and ^{26}F, as well as an additional bound state in ^{27}F, could be due to simultaneous proton-neutron cross-shell excitations [9].

In a recent analysis of the two-proton removal reactions from ^{26}Ne, aimed at the study of neutron-unbound states in ^{23}O [10,11], decay energy spectra were also obtained for ^{25}F and ^{26}F. Here we present evidence for resonances in ^{25,26}F.

The experiment was performed at the National Superconducting Cyclotron Laboratory at Michigan State University. A secondary beam of 86 MeV/u ^{26}Ne was produced by the Coupled Cyclotron Facility and the A1900 fragment separator [12] from a 140 MeV/nucleon ^{40}Ar primary beam. Neutron-unbound states of ^{25}F and ^{26}F were populated in proton removal and nucleon-exchange reactions, respectively, induced by the ^{26}Ne beam on a 721 mg/cm^2 thick beryllium target. The resulting fragments (^{24}F and ^{25}F) were recorded in a set of charged-particle detectors after being deflected by the large-gap Sweeper Magnet [13]. Beam velocity neutrons were detected in coincidence near zero degrees with the Modular Neutron Array (MoNA) [14]. The setup, detector calibration, and procedure to extract the decay energy spectra were the same as in the analysis of the ^{23}O decay [10,11]. The present data were recorded simultaneously with ^{23}O data.

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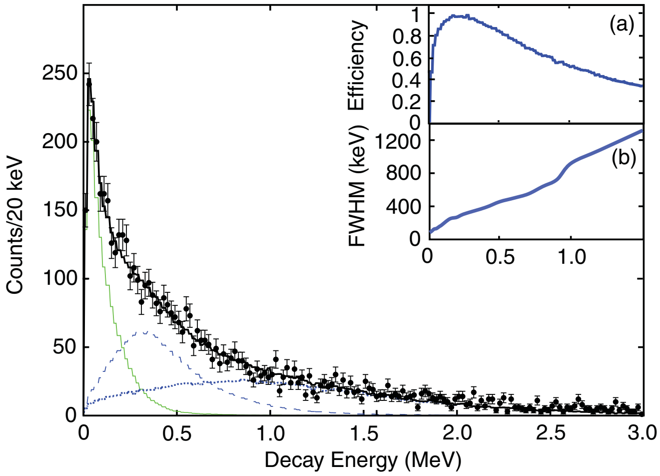

FIG. 1. (Color online) The decay energy spectrum for ^{25}F as produced in the reaction $^{9}Be(^{26}Ne,^{24}F + n)$. The data (black points with error bars) are compared to the results of Monte Carlo simulations (thick solid line). The calculation is the sum of three resonances at 28 keV (thin solid line), 350 keV (dashed line), and 1200 keV (dotted line). The insets display the efficiency (a) and resolution in full width at half maximum (FWHM) (b) as a function of decay energy.

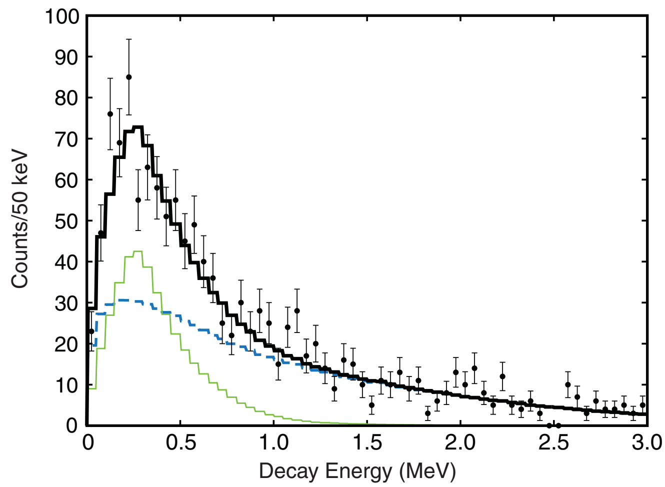

FIG. 2. (Color online) The decay energy spectrum for ^{26}F as produced in the reaction $^{9}Be(^{26}Ne,^{25}F + n)$. The data (black points with error bars) are compared to the results of Monte Carlo simulations (thick solid line). The calculation is the sum of a single 270-keV resonance (thin solid line) and a nonresonant background (dashed line).

Decay energy spectra were calculated from the difference of the invariant masses of $^{25,26}F$ and the sum masses of the neutron and $^{24,25}F$, respectively. The invariant masses were derived event by event using the measured relativistic four-momentum vectors of the neutrons and fragments in the laboratory frame. The mass excess of ^{24}F [7560(72) keV] from Ref. [15] and mass excesses of ^{25}F [11410(90) keV] and ^{26}F [18 680(80) keV] from Ref. [16] were used to calculate decay and separation energies. The decay energy spectrum of ^{25}F (see Fig. 1) exhibits a sharp peak at low decay energies while a broader peak at ∼200 keV is seen for ^{26}F (see Fig. 2).

Monte Carlo simulations including secondary beam characteristics, target thickness, nuclear reaction parameters, and detector acceptances and resolutions were performed to extract resonance energies. The overall efficiency and resolution as a function of decay energy are shown in the insets of Fig. 1. Nuclear reaction parameters were chosen to reproduce the neutron and fragment energy and angle spectra as described in Ref. [11]. ^{25}F was assumed to be produced in a direct one-proton removal reaction, and a Glauber reaction model was used in the simulation [17]. Based on the assumption that ^{26}F was produced via a nucleon-exchange reaction [8], a two-body reaction model was used. Owing to their intrinsically narrow widths compared to the experimental resolution, the resonances were simulated with l-independent Breit-Wigner line shapes [10]. The noticeable change in the resolution just below 1 MeV is due to perpendicularly emitted neutrons starting to completely miss MoNA, as noted in Ref. [18].

The data for $^{24}F + n$ coincidences can be described with three resonances. The lowest-lying resonance was found at a decay energy of 28 ± 4 keV. Due to the experimental resolution only an upper limit of 20 keV could be extracted for the width. No detailed fits were performed for the higher-lying resonances because several levels could be present that cannot be resolved with the present resolution. Although there should be few background events from the single-proton removal reaction [19], a small contribution from quasifree neutron knockout from the target may be present. Any such background is expected to be relatively featureless and would not influence the results presented here. The overall shape of the spectrum can be reproduced with resonances at 350 keV ($\Gamma = 190$ keV) and 1200 keV ($\Gamma = 1000$ keV).

Shell-model calculations were performed to examine the observed narrow peak in ^{25}F just above the neutron separation energy. The code Nushell@MSU [20] was used with the WBP interaction [7] within the $spsdpf$ model space. The calculation allowed for 2p2h sd-pf cross-shell neutron excitations and proton excitations from the p to the sd shell.

The results of these calculations are shown in Fig. 3 together with the observed unbound resonance and previously reported bound states [9,21]. The overall agreement of the calculations with the measurements up to 3500 keV is fairly good. All states are reproduced within 200 keV with the exception of the state at 1753 keV. Elekes *et al.* [9] speculated that this state may be a negative parity state due to proton cross-shell excitations, but concluded that any negative parity state would have to be at higher excitation energy. Thus the spin and parity of this state are still unassigned.

Figure 3 shows that there are several positive parity states and one negative parity state close to the neutron separation energy. Only the $1/2^-$ level at 4296 keV has a large spectroscopic factor of 1.40 for one proton removal from ^{26}Ne, corresponding to the removal of a proton from the $\pi(0p_{1/2})$ orbital. The spectroscopic factor for the nearby positive parity states in contrast is smaller than 0.05. Thus the observed 28 ± 4 keV resonance can most likely be assigned to the $1/2^-$ state at an excitation energy of 4249 ± 116 keV

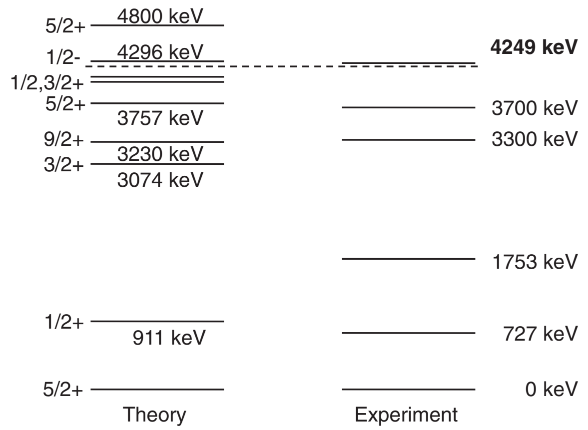

FIG. 3. Comparison of theoretical (left) and measured states (right) for ^{25}F. The measured states are from this work (bold) and Refs. [9,21]. The dashed line indicates the one-neutron separation energy [16].

using the recently measured one-neutron separation energy of 4221 ± 115 keV [16].

This assignment assumes that the resonance decays to the ground state of ^{24}F. However, two bound excited states have been observed in ^{24}F [22], and because no γ-ray detection was available in the present experiment the resonance may decay to one of these excited states.

Several more negative parity states are predicted at higher excitation energies but the resolution of the current experimental setup does not allow for a detailed comparison of the 350- and 1200-keV resonances with these states. However, the large widths deduced for these resonances are consistent with the single-particle widths of $l = 1$ states ($\Gamma_{sp} \sim 200$ keV for a 350-keV resonance and $\sim$800 keV for a 1200-keV resonance) that we expect to be strongly populated in this experiment.

We also observed neutrons in coincidence with ^{25}F. They were interpreted as resulting from neutron emissions from unbound states in ^{26}F which can be produced via nucleon-exchange reactions. This process has been previously observed in this mass region [8]. The data shown in Fig. 2 show no distinct features or sharp resonances. Similar to the proton removal reaction, little background contributions resulting directly from this reaction are expected. The shell model predicts several unbound states above the neutron separation energy which would not be resolved in the present experiment. Instead of describing the data with a combination of resonances, the decay energy spectrum was compared to a flat distribution reflecting essentially the efficiency distribution (dashed line in Fig. 2). The enhancement at low decay energies was then fit with a single resonance with $E_{decay} = 271 \pm 37$ keV. This would correspond to a state at an excitation energy of 1072 ± 120 keV in ^{26}F assuming it decays to the ground state of ^{25}F.

In conclusion, neutron-unbound states have been observed in ^{25,26}F produced by one-proton removal and nucleon-exchange reactions, respectively. The 28 ± 4 keV resonance, corresponding to an excitation energy of 4249 ± 116 keV in ^{25}F, may be assigned as the first $1/2^-$ state using comparisons with shell-model predictions. Neutrons in coincidence with ^{25}F exhibited a possible resonance at $\sim 271 \pm 37$ keV corresponding to an excitation energy of 1072 ± 120 keV in ^{26}F. The assignments of these excitation energies in ^{25,26}F assume direct decays to the ground states of the respective daughter nuclei.

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