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Intruder configurations in neutron-rich ^{34}P

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Extensions to the yrast and near-yrast decay sequences of the neutron-rich nucleus $^{34}_{15}P_{19}$ have been established through an analysis of the γ deexcitation of fragments produced in deep-inelastic processes which occur when 230-MeV ^{36}S ions interact with a thick target of ^{176}Yb. The highly sensitive GASP array of escape-suppressed Ge detectors was used to measure the resulting γ-ray deexcitations of both projectilelike and targetlike fragments. Previously unobserved excited states in ^{34}P were observed at 3351, 6236, 2320, and (4723) keV. Several states above an excitation energy of 2.3 MeV involve intruder configurations from the $f_{7/2}$ shell. The investigation of negative parity intruder states on the periphery of the "island of inversion" has an important role to play in our understanding of the evolution of nuclear structure as the island of inversion is approached.

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I. INTRODUCTION

The experimental properties of neutron-rich nuclei are currently of major interest in nuclear structure physics. Such nuclei are expected to reveal new aspects of nuclear structure that challenge established theoretical models. One such region encompasses neutron-rich nuclei around the shell-model magic numbers of $N = 20$ and 28 where measured properties have been found to be inconsistent with shell closure. Early experimental evidence for these inconsistencies came from mass measurements [1,2] of neutron-rich Mg and Na isotopes at CERN ISOLDE; the two-neutron separation energies at neutron number 20 revealed a discontinuity. Measurements of the excitation energy of the first 2^+ excited state of ^{32}Mg [3] revealed that it was much lower than expected for a closed-shell nucleus. Several measurements of $B(E2; 0^+ \rightarrow 2^+_1)$ for ^{32}Mg have been reported [4–7]. While one of these measurements disagrees with the other three, the values nevertheless point to a large quadrupole deformation for the first 2^+ state of ^{32}Mg ($\beta_2 \sim 0.5$). These observations are inconsistent with shell closure at $N = 20$.

The "anomalies" in the $N = 20$ region can be understood within shell-model calculations [8] that consider the promotion of neutrons from the *sd* (lower shell) to the *fp* (upper) shell. This leads to low-lying intruder states due to residual neutron-proton interactions which lower the energy of configurations with neutrons in the $f_{7/2}$ subshell and protons in the $d_{5/2}$ subshell. While it is of current interest to study the shell structure of nuclei within this so-called island of inversion, the investigation of nuclei on the periphery of this tightly circumscribed region also has an important role to play in our understanding of the evolution of nuclear structure as a function of neutron and proton numbers and, in particular, of the role of negative parity intruder states. In the present work we focus on the role of intruder configurations in the structure of yrast levels of $^{34}_{15}P_{19}$, which lies near the island of inversion. Measurements of the level structure of moderately neutron-rich nuclei such as $^{34}_{15}P_{19}$ also provide data which may be compared with the results of state-of-the-art shell-model calculations. The production of nuclei in this region is difficult because of the limitations of traditional experimental techniques. The study of nuclei that are even moderately neutron rich adds to our understanding of nuclear structure in this "difficult to study" region. The deep-inelastic process has become a reliable way to populate such nuclei, whose properties can be studied by γ-ray spectroscopic techniques [9,10].

II. EXPERIMENTAL METHODS

The combination of Tandem-XTU and ALPI accelerators at the INFN Legnaro Laboratory, Italy, was used to deliver

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a beam of ^{36}S ions at an energy of 230 MeV (6.39 MeV/u) onto a target of ^{176}Yb. The target was isotopically enriched to 97.8% and was of thickness 14 mg cm^{-2} with an isotopically enriched ^{208}Pb (98.7%) backing of thickness 35 mg cm^{-2}. ^{36}S ions entered the ^{208}Pb backing with an energy of 160 MeV (4.4 MeV/u). The backing was sufficiently thick to stop all forward-moving reaction fragments. In the present experiment the v/c values of projectilelike species resulting from deep-inelastic processes is around 10%. For excited nuclear states with lifetimes less than the slowing-down time of the recoiling nuclei in the thick composite target (~1 ps), Doppler effects result in very wide photopeaks which, in a low statistics experiment, cannot be observed. Our experiment is therefore sensitive to the study of the γ decay of excited nuclear states with lifetimes in excess of ~1 ps. The GASP array was used to measure the emitted γ rays from the deexciting targetlike and projectilelike fragments populated in the deep-inelastic processes. The array is composed of 40 high-purity (HP) Ge Compton-suppressed detectors and an inner ball of 80 bismuth germanate (BGO) crystals that can act as a calorimeter. The total photopeak efficiency of the Ge array is about 3% at a γ-ray energy of 1332 keV (^{60}Co), and the mean peak to total ratio is about 60–65% at 1332 keV for the Compton-suppressed γ-ray spectra [11]. The electronic trigger conditions were set such that if three or more Ge signals (unsuppressed) and two or more BGO signals were in time coincidence, then the event was accepted by the acquisition system and subsequently written to tape. Data were collected during six days of beam time. Gain matching of the detectors and data sorting were performed off-line, and a $\gamma\gamma\gamma$ cube with no conditions was constructed. Analysis of this cube was undertaken using the RADWARE code [12]. Yields from deep-inelastic processes are small, typically ranging from about 10 mb to submillibarns, and this can increase the experimental difficulties in studying γ deexcitations using this type of reaction. In the present experiment, the fusion-fission process dominates the processes resulting from the interaction of projectile and target nuclei.

Both the projectile and target involved in this experiment are neutron rich, increasing the probability of producing neutron-rich species. Furthermore, during the deep-inelastic process, nucleons flow across the neck joining the two nuclei to equilibrate the N/Z ratio between targetlike and projectilelike fragments [13]. The N/Z ratios of the target (1.51) and projectile (1.25) used here will tend to favor neutron flow toward the projectile, thus further increasing the probability of populating neutron-rich projectilelike species.

III. RESULTS AND DISCUSSION

Studies of the β^- decay of ^{34}P by Goosman *et al.* [14] determined a J^π value of 1^+ for the ground state of ^{34}P. The first study of the excited states of ^{34}P was made by Ajzenberg-Selove *et al.* [15] using the ^{34}S$(t,^3$He$)^{34}$P reaction. Excited states at 423, 1605, 2225, 2309, and (3345) keV were observed. Although no J^π assignments were made, the authors speculated that the states of excitation energies of 2.225 and 2.309 MeV have a $(\pi s_{1/2} \times \nu f_{7/2})$ configuration with J^π values of 3^- and 4^-. The ^{34}Si β-decay studies of Nathan and Alburger [16] identified excited states in ^{34}P at 429 and 1608 keV and tentatively assigned J^π values of 2^+ and 1^+, respectively. Further studies by Fornal *et al.* [17] using deep-inelastic reactions resulting from the interactions of a beam of ^{37}Cl ions with a target of ^{160}Gd revealed an excited state at 2305 keV that deexcites by a γ ray of energy 1876 keV to the previously known first excited state. The authors associated this state with the 2309 ± 10 keV level populated in the $(t,^3$He) work of Ajzenberg-Selove *et al.* [15] and adopted their suggested J^π values of 3^- and 4^-. The first two excited yrast states were thus established at 429 and 2305 keV. The states of ^{34}P have, more recently, been studied by Pritychenko *et al.* [18] using intermediate-energy Coulomb excitation. The authors suggest that a previously unobserved 627 keV γ-ray connects the 2225 ± 10 keV level with the 1607.6-keV ($J^\pi = 1^+$) level observed by Ajzenberg-Selove *et al.* [15] and by Nathan and Alburger [16]. Nathan and Alburger [16] suggested that the 1607.6-keV level has a configuration $\pi(d_{3/2})\nu(d_{3/2})^{-1}$, and Pritychenko *et al.* [18] further proposed that the states reported in [15] at 2225 and 2309 keV are other members of the multiplet with possible J^π values of 0^+, 2^+, and 3^+. Since the 2225-keV state is populated directly in the intermediate energy Coulomb excitation experiment by an $E2$ transition, its suggested J^π value is 2^+. More recently, Asai *et al.* [19] studied nanosecond isomers in neutron-rich $N \approx 19$ nuclei produced by deep-inelastic collisions initiated by 9-MeV/u ^{37}Cl ions incident on a target of ^{198}Pt. Multipolarities of γ transitions were determined through an in-plane to out-of-plane γ-ray anisotropy analysis. For ^{34}P, the half-life of the 2305-keV state was measured as $0.3 < t_{1/2} <$ 2.5 ns. The γ-ray anisotropy analysis established the 1876-keV transition (2305 → 429 keV) as a stretched quadrupole in nature. These measurements resulted in the assignment of an $M2$ multipolarity, and consequently a J^π assignment for the 2305-keV state as 4^-. The J^π assignment of 0^+ or 3^+ for this state proposed by Pritychenko *et al.* [18] would now appear to be incorrect while the earlier proposed configuration [15], namely $\pi(s_{1/2})\nu(f_{7/2})$, is consistent with the J^π assignment of Asai *et al.* [19]. The suggested configuration of $\pi(s_{1/2})\nu(f_{7/2})$ made by Ajzenberg-Selove *et al.* [15] for the 2225-keV state is also inconsistent with the probable $J^\pi = 2^+$ assignment.

In the present work we have been able to extend the yrast decay scheme by setting a double gate on the two previously established transitions at 429 and 1876 keV. Figure 1(a) shows the resulting γ-ray energy spectrum, which displays a photopeak at an energy of 1046 keV which has not previously been reported. The γ decay of the associated fragments contributes to the "background" in the spectrum. We are unable to observe significant population of rotational sequences within the odd-Z complementary Lu isotopes, presumably as a consequence of fragmentation of population strength across the yrast and near-yrast rotational sequences. The figure also reveals a weak photopeak at an energy of 2885 keV. This γ-ray transition can be seen much more clearly in the spectrum of Fig. 1(b), which corresponds to a double gate on the 1046- and 429-keV photopeaks. Furthermore, when a single gate is set on the 2885-keV photopeak, we can clearly see the 429-, 1876-, and 1046-keV photopeaks (see Fig. 2).

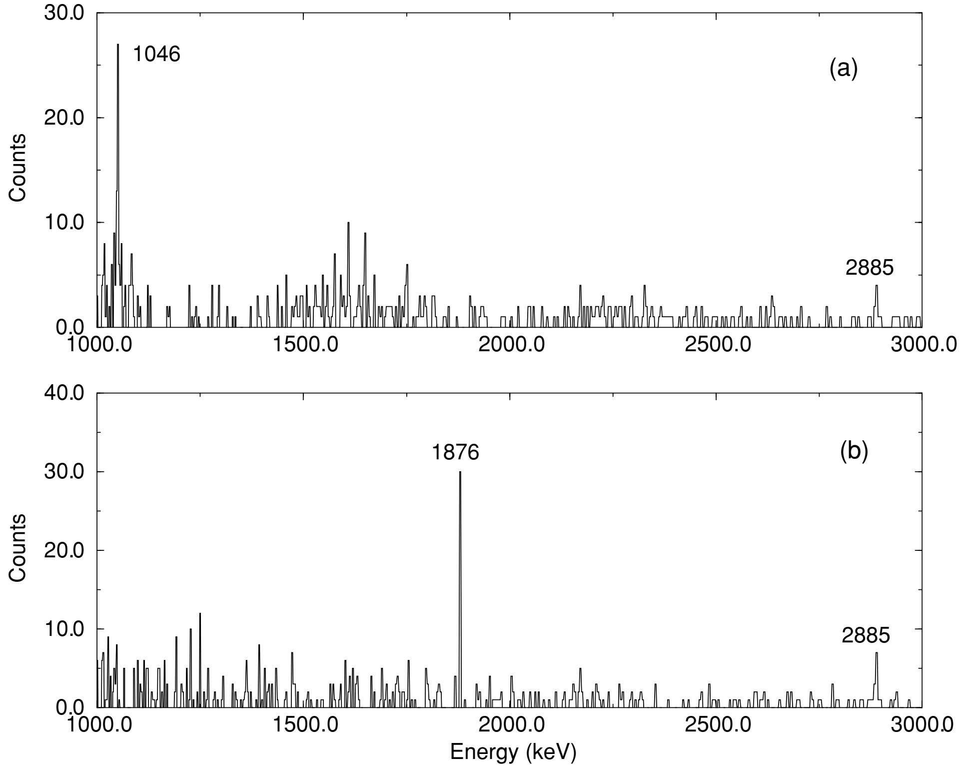

FIG. 1. γ-ray energy spectrum produced by double gating on transitions (a) at 429 and 1876 keV and (b) at 429 and 1046 keV.

These results confirm that the γ-ray transitions at 1046 and 2885 keV are indeed part of the decay sequence associated with ^{34}P. In the present work, we are unable to use the associated fragment coincidence technique to identify transitions in ^{34}P since, as explained earlier, the population of yrast and near-yrast decay sequences in Lu isotopes is heavily fragmented. We are therefore unable to measure the relative intensities of all the γ-ray transitions in ^{34}P by gating on γ rays from the associated targetlike fragment. Ordering of the new transitions was achieved by measuring the relative γ-ray intensities of the 1046- and 2885-keV photopeaks in the spectrum produced by a double gate at energies of 429 and 1876 keV. The results, after detector efficiency corrections, are presented in Table I. The relative intensities show the ordering of the two new transitions; the 2885-keV transition corresponds to the decay of the 6236-keV excited state to the 3351-keV state which subsequently decays with the emission of a γ ray of energy 1046 keV to the 2305-keV state.

Recent experimental work by Liang *et al.* [20] used the EUROBALL γ-ray array to study the γ deexcitation of fragments from deep-inelastic processes resulting from

TABLE I. The relative intensities of the two new transitions in ^{34}P. See text for comments on spin and parity values.

E_γ (keV)	Relative intensities	Initial state spin I_i	Final state spin I_f
1046	257(36)	(5^-)	4^-
2885	72(30)	(7^+)	(5^-)

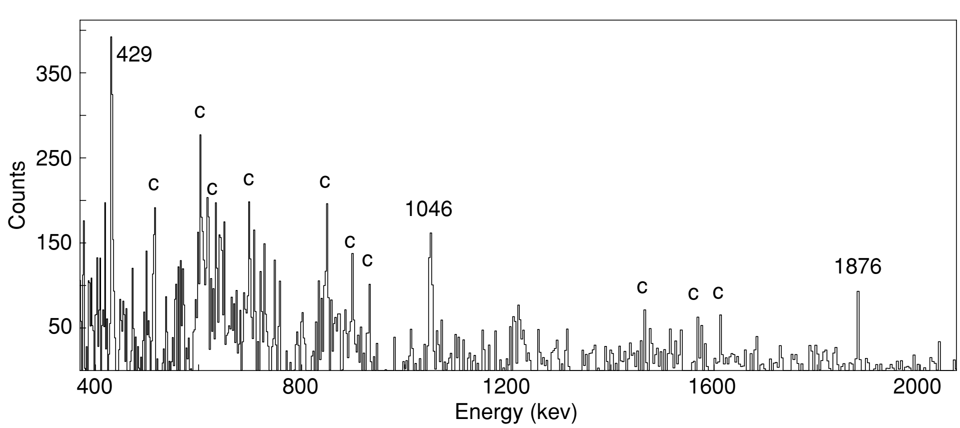

FIG. 2. γ-ray energy spectrum produced by gating on the γ-ray photopeak of energy 2885 keV. The peaks labeled C are contaminants of unknown origin brought in by the single gate.

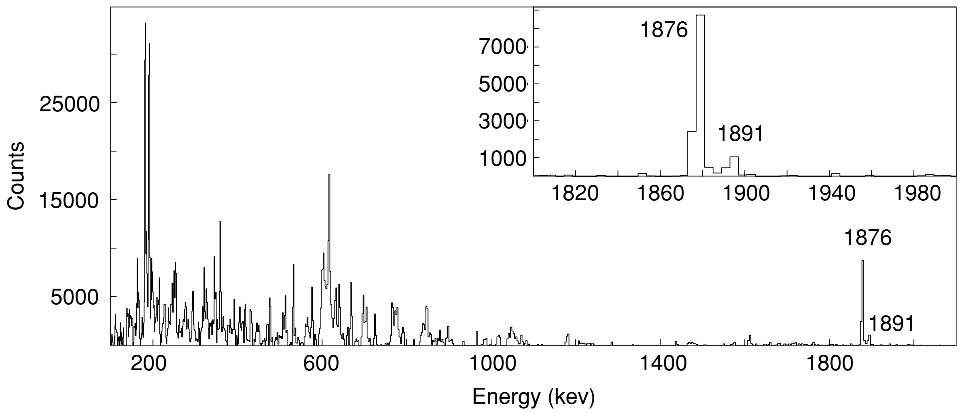

FIG. 3. γ-ray spectrum produced with a single gate at 429 keV.

the interaction of 234-MeV ^{37}Cl ions with a Pb-backed (40 mg cm^{-2}) ^{160}Gd target of thickness 12 mg cm^{-2}. This work has yielded evidence of a further excited state in ^{34}P at an energy of 2320 keV which deexcites to the first excited state at 429 keV with the emission of a γ ray of energy 1891 keV. In the present work a single gate was set on the photopeak at 429 keV. The resulting spectrum is shown in Fig. 3. This figure clearly shows the photopeak at 1876 keV as well as a smaller peak at 1891 keV corresponding to the deexcitation of the 2320-keV excited state established by Liang [20]. Furthermore, in the present work a double gate at 1891 keV and at 429 keV has provided tentative evidence for an additional transition of energy 2403 keV [see Fig. 4(a)]. The 1891-keV photopeak is observed weakly in the spectrum corresponding to a double gate at 429 and 2403 keV [Fig. 4(b)], and the 429-keV photopeak is weakly observed in the spectrum corresponding to a double gate at 1891 and 2403 keV [Fig. 4(c)].

These new transitions can now be placed into the decay scheme of ^{34}P (Fig. 5). The figure also presents the previously published level schemes from the work of Ajzenberg-Selove *et al.* [15], Nathan and Alburger [16], Fornal *et al.* [17], Pritychenko *et al.* [18], and Asai *et al.* [19]. Also shown in this figure are the results of the *sd* shell-model calculations of Brown [21]. We note here that the processes of intermediate

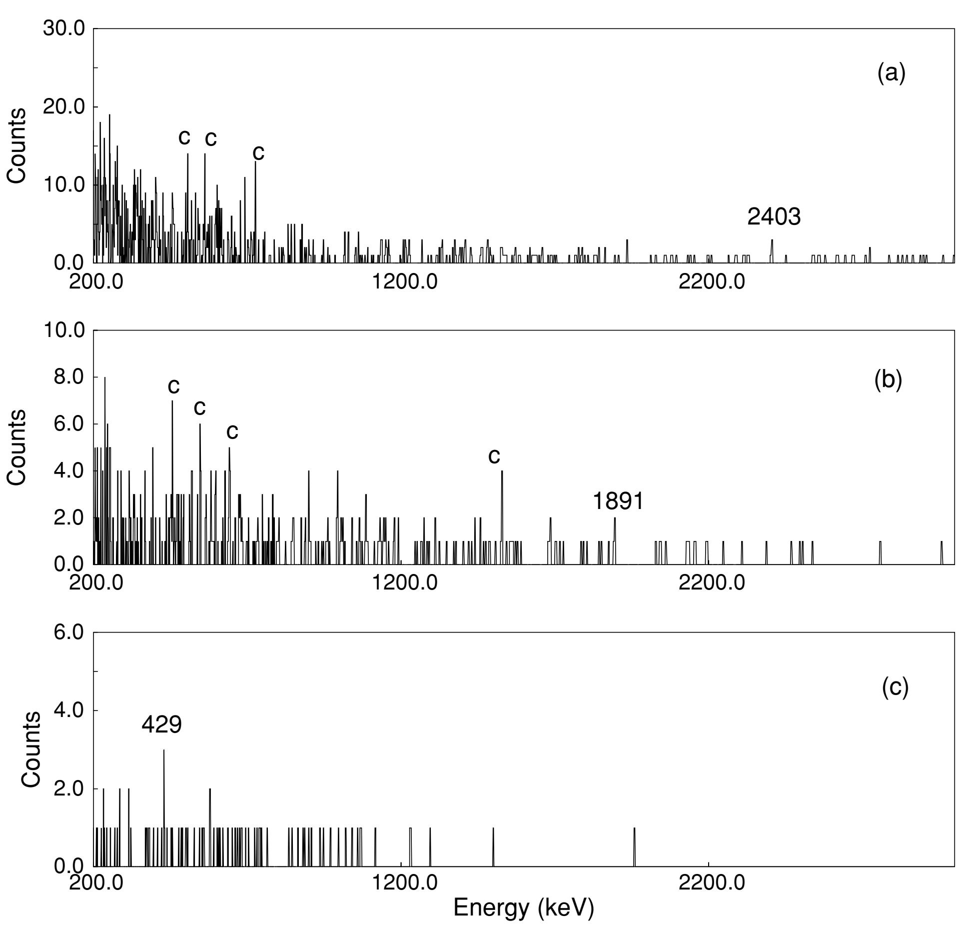

FIG. 4. γ-ray spectra produced by double gating on γ-ray transitions of energy (a) 429 and 1891, (b) 429 and 2403, and (c) 1891 and 2403 keV.

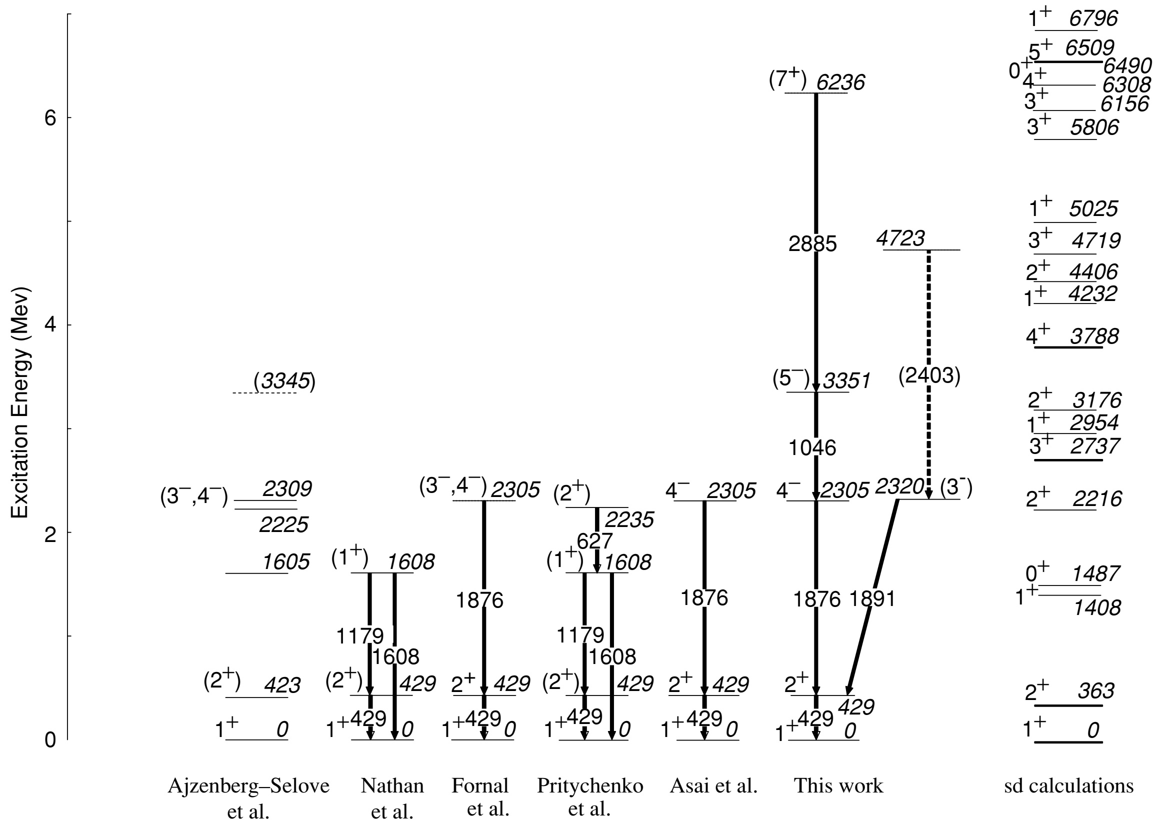

FIG. 5. Experimental level schemes of ^{34}P from Refs. [15–19] and from the present work. Also seen here are results from *sd* shell-model calculations [21] with yrast states highlighted with bold lines.

energy Coulomb excitation and deep-inelastic collisions do not populate the same subset of states in ^{34}P. The deep-inelastic process populates yrast and near-yrast states, while intermediate energy Coulomb excitation populates states connected to the ground state by significantly large $B(E2\uparrow)$ values. In the work of Pritychenko *et al.* [18], the 2225-keV ($J^\pi = 2^+$) level is the only state to be fed directly in ^{34}P; this is consistent with the shell-model value of 9.6 e^2 fm^4 for the transition from the ^{34}P ground state to the $J^\pi = 2^+$, 2216-keV shell-model state. These calculations reproduce the first three excited states found experimentally in ^{34}P, including the state at 1608 keV with a predicted J^π of 1^+ [15,18].

We now comment on the structure of the levels of ^{34}P presented in Fig. 5. Within the context of the shell model we expect the dominant configuration of the ground state and the first excited state to be $\pi(s_{1/2})\nu(d_{3/2})$. The lack of direct population of the 429-keV state in intermediate energy Coulomb excitation [18] is consistent with the 1^+ and 2^+ states being members of the $\pi(s_{1/2})\nu(d_{3/2})^{-1}$ multiplet. The shell-model prediction for the $B(E2\uparrow)$ value corresponding to the excitation of the 429-keV state is 0.3 e^2 fm^4. As noted earlier, the 1608-keV ($J^\pi = 1^+$) and 2225-keV ($J^\pi = 2^+$) states have a proposed configuration of $\pi(d_{3/2})\nu(d_{3/2})^{-1}$. The results of the *sd* shell-model calculations [21] are able to accurately reproduce these four states but not higher-lying yrast states. The $J^\pi = 0^+$ and 3^+ members of the multiplet, which shell-model calculations predict at excitation energy of 1487 and 2737 keV, respectively, have not been identified experimentally. The 2305-keV, $J^\pi = 4^-$, excited state has a proposed configuration of $\pi(s_{1/2})\nu(f_{7/2})$ and is the lowest energy intruder state of ^{34}P. The 3^- member of the doublet was previously incorrectly associated with the 2225-keV state which, from the Coulomb excitation work of Pritychenko *et al.* [18], is now believed to have a J^π value of 2^+. We suggest here that the 2320-keV state observed in the present work may be the $J^\pi = 3^-$ member of the doublet. This would be consistent with its weak population in the deep-inelastic process and also consistent with the systematics of the $J^\pi = 3^-$ states in the even-*A* P isotopes (Fig. 6). We speculate that the 4723-keV state has $J > 3$. We also advance arguments in the following paragraphs that the 3351- and 6236-keV states, observed here for the first time, have stretched configurations $\pi(d_{3/2})\nu(f_{7/2})$ ($J^\pi = 5^-$) and $\pi(f_{7/2})\nu(f_{7/2})$ ($J^\pi = 7^+$), respectively. We note here that the population of the 429- and 2305-keV states of ^{34}P in the ^{34}P$(t,{}^3$He) reaction [15] is consistent with the configurations proposed here for these states.

The systematics of the level structures of $N = 15$, 17, 21 P isotopes and of ^{34}P from the present work are shown in Fig. 6. The 4^- and 3^- excited states can be seen here to decrease in energy as the *sd* shell is filled. The $J^\pi = (3^-)$ assignment of the excited state at 249 keV in the ^{36}P level scheme, first reported in charge exchange reactions by Drumm *et al.* [22], was based on

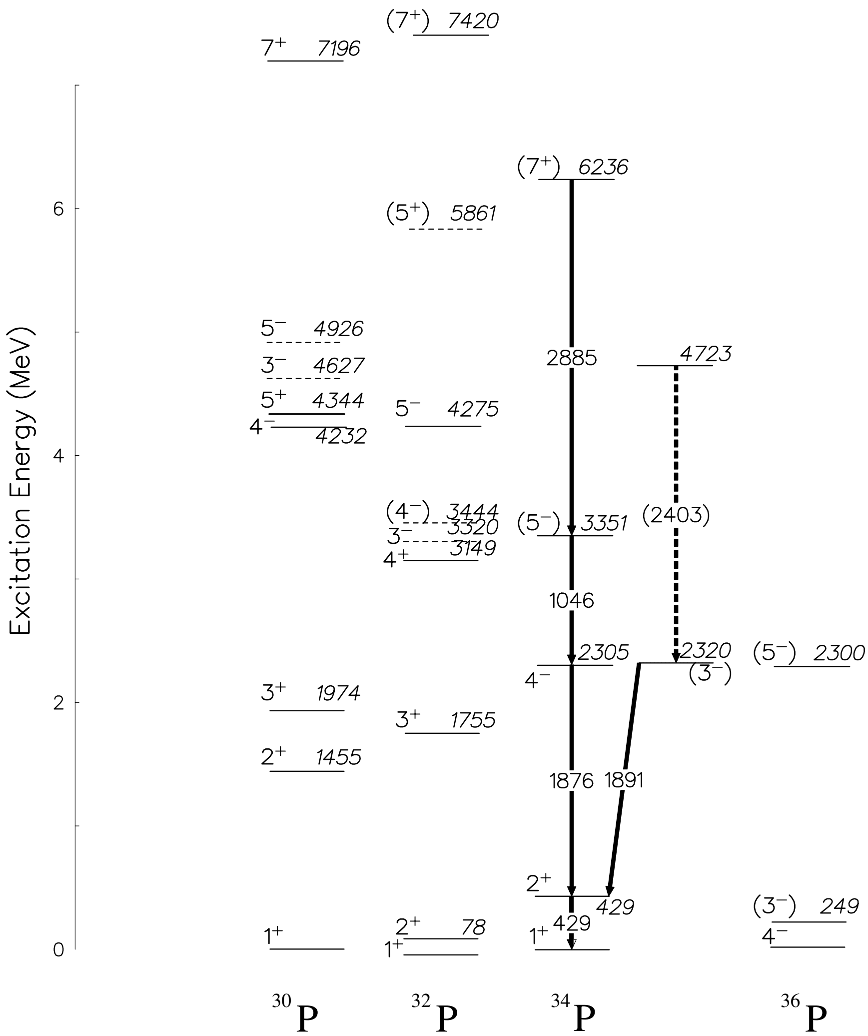

FIG. 6. Yrast-level structures for $N = 15, 17, 21$ P isotopes together with the level scheme of ^{34}P from the present work. Nonyrast states in ^{30,32}P of relevance to possible counterparts in ^{34}P are shown as dashed levels.

a comparison to results of "SDPF interaction" calculations by Warburton and Becker [23]. Similarly, the 2300-keV excited state in ^{36}P, observed by Orr *et al.* [24] in the ^{37}Cl(^{13}C,^{14}O) reaction, is a possible candidate for the $J^{\pi} = 5^-$ state when compared with results of "SDPF" shell-model calculations [24]. Based on the systematics of the 5^- state in ^{30}P and ^{32}P, we tentatively suggest that the state in ^{34}P at 3351 keV also has $J^{\pi} = 5^-$ with a probable dominant configuration of $\pi(d_{3/2})\nu(f_{7/2})$. The weak population of this state in the ^{34}S(t,^{3}He) reaction [15] presumably reflects the presence of a small $2p$-$2h$ component $\pi(d_{3/2})^2\pi(s_{1/2})^{-2}$ in the ^{34}S ground state. The ^{34}S(d,^{3}He)^{33}P proton pickup studies of Thorn *et al.* [25] do indeed provide experimental evidence for such a two-particle–two-hole component in the ^{34}S ground state; $d_{3/2}$ proton pickup was observed with a total spectroscopic strength of $C^2S \simeq 0.5$.

A state of ^{30}P at $E_x = 7196 \pm 6$ keV, assigned $J^{\pi} = 7^+$ $(5^+, 6^+)$, which γ decays to the 5^+ state at 4343 keV was reported in the ^{28}Si($\alpha, d\gamma$)^{30}P work of Vermeulen *et al.* [26]. This state, at a measured excitation energy of 7231 $\pm$ 50 keV, had previously been populated by $L = 6$ np transfer in the ^{28}Si(α, d)^{30}P work of Del Vecchio *et al.* [27] and assigned a J^{π} value of (7^+). Baumann *et al.* [28], who studied the states of ^{30}P populated in the pn channel of the ^{16}O $+^{16}$O fusion evaporation reaction, verified the existence of this excited state at $E_x = 7200$ keV, which was identified as a possible candidate for the $J^{\pi} = 7^+$ state. A possible candidate for the 7^+ state in ^{32}P was observed at $E_x = 7420 \pm 50$ keV in the ^{30}Si(α, d) reaction [27]. Population in the (α, d) reaction takes place through the transfer of a $\pi(f_{7/2})\nu(f_{7/2})$ pair in stretched configuration. This excited state was also observed in the work of Baumann *et al.* using the ^{18}O + ^{16}O fusion evaporation reaction [28]. In the present work we have identified a possible candidate for the 7^+ excited state in ^{34}P consistent with the systematics shown in Fig. 6. The observed transition at 2885 keV probably corresponds to the γ deexcitation of the proposed $J^{\pi} = 7^+$ state at 6236 keV to the proposed $J^{\pi} = 5^-$ state at 3351 keV. These conclusions are also based on the experimental observations [20,29,30] that the deep-inelastic process leads to the population of yrast states of the projectilelike and targetlike fragments.

Figure 7 shows the np separation energy $S(np)$ as a function of mass number for the 4^-, 5^-, and 7^+ yrast states of the phosphorus isotopes with $A = 30$–36. For ^{36}P, the ground state

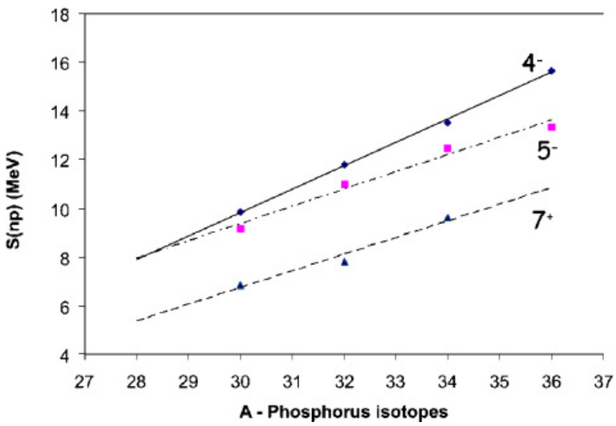

FIG. 7. (Color online) Graph of *np* separation energy for 4^-, 5^-, and 7^+ yrast states of the P isotopes versus mass number A.

($J^\pi = 4^-$) and the 249-keV [$J^\pi = (3^-)$] and the 2300-keV [$J^\pi = (5^-)$] states are known. The proposed stretched configurations of the $J^\pi = 4^-, 5^-$, and 7^+ states are $\pi s_{1/2}\nu f_{7/2}, \pi d_{3/2}\nu f_{7/2}$, and $\pi f_{7/2}\nu f_{7/2}$, respectively. The states of ^{34}P observed in the present work at 2.305, 3.351, and 6.236 MeV, assigned above as $J^\pi = 4^-, (5^-)$, and (7^+), respectively, are also included in Fig. 7. The linear dependence of $S(np)$ with mass number, which has previously been discussed within the context of the Bansal-French [31] model, provides further evidence of common configurations for the three stretched states and for the proposed J^π assignments of the three states of ^{34}P.

The observed linear behavior is also consistent with previous observations in relation to two-nucleon high-spin stretched states [32,33]. From the linear dependence of Fig. 7, we can predict the excitation energy of the $7^+(\pi f_{7/2}\nu f_{7/2})$ state of ^{36}P to be 4.83 MeV. A prediction can also be made for the excitation energies of the $4^-, 5^-$, and 7^+ states of ^{28}P and these are 7.47, 7.86, and 10.01 MeV, respectively.

IV. CONCLUSIONS

The results of the present experimental work have provided additions to the previously published yrast level scheme of the neutron-rich nucleus ^{34}P. Two new transitions have been identified at 1046 and 2885 keV which, it is proposed, correspond to the decay of excited states with $J^\pi = 5^-$ (3351 keV) and 7^+ (6236 keV), respectively. In addition, new states have been observed at 2320 keV [$J^\pi = (3^-)$] and tentatively at 4723 keV ($J > 3$). The structures of the negative parity states with $J^\pi = 4^-$ and (5^-) and of the (7^+) intruder state are discussed within the context of stretched configurations involving the $f_{7/2}$ neutron shell. In this paper we focused much of the discussion on the role of negative parity intruder states; the investigation of such states in the close proximity of the island of inversion, where the fp shell has a profound effect on the properties of nuclear states, has an important role to play in our understanding of the evolution of nuclear structure as a function of neutron and proton numbers.

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