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Nuclei in the vicinity of 'island of inversion' through the fusion reaction

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Abstract. The level structures of $N \sim 19$ nuclei such as ^{32,34}P have been investigated using the ^{18}O(^{18}O,$xnyp$) and ^{18}O(^{16}O,$xnyp$) reactions at an incident beam energy of about 34 MeV. The de-exciting γ-transitions were recorded using an array of clover detectors. These detectors have the dual advantage of higher efficiency at $E_\gamma \geq 2$ MeV, and are capable of providing information on the linear polarization of the observed γ-transitions. These polarization measurements when coupled with the angular correlations help us to assign uniquely the spin parity for the observed levels. The experimental results have been compared with the predictions of the spherical shell model. The shell-model calculations are able to reproduce the observed energy levels to a reasonable degree. However, the observed transition probabilities are not reproduced by the calculations. Hence there is a need to re-visit these calculations using more detailed and microscopic effective interactions.

Keywords. Nuclear structure; measured E_γ; γ–γ-coin; γ-ray polarization; coincidence angular anisotropy; ^{34,35}P deduced high-spin levels; J^π; comparison with shell model predictions.

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1. Introduction

The study of properties of nuclei under extreme conditions of spin, temperature and isospin is an area where intense experimental and theoretical investigations have been undertaken with the advent of heavy-ion accelerators and large detector arrays.

The interest in the properties of nuclei with a considerable N/Z ratio has been stimulated by intriguing observations such as (i) the presence of skin or halo structures and (ii) presence of deformed structures at relatively lower excitation energies contrary to the conventional expectations. The latter observation in particular has challenged the validity of the shell model which is the very basis of our understanding of the nucleus.

The vanishing of the traditional magic numbers has been investigated in detail in nuclei with $N \sim 20$. This has been established following the observation of anomalous behaviour in the binding energies of these nuclei, and the onset of deformation in this region, which is referred to as the 'island-of-inversion' [1]. These observations are attributed to the reduced shell gap between the $d_{3/2}$ and $f_{7/2}$ orbitals. The interactions between the orbitals within the major shell also has a pronounced effect on the single particle energies.

Hence the region of nuclei with Z near the bottom of sd shell and N near the top of the shell (which is likely to be influenced easily by the occupation of intruder-dominated configurations) belong to a highly transient region of nuclear structure. sd–pf nuclei such as ^{34,32}P in the vicinity of the island of inversion are ideal candidates from the aforementioned viewpoint.

2. Experimental results

Spectroscopy of nuclei in and around the 'island-of-inversion' has been undertaken using non-equilibrated reaction mechanisms such as transfer/deep-inelastic reactions [2]. These reactions are limited in terms of populating the higher angular momentum states. This difficulty could be circumvented using the conventional fusion reaction. The ^{18}O(^{18}O,$xnyp$) and ^{18}O(^{16}O,$xnyp$) reactions allow us to populate the difficult-to-access $N \sim 20$ nuclei using the fusion reactions at an incident beam energy around 35 MeV.

^{34}P ($N = 19$) was populated following ^{18}O(^{18}O,1p2n) reaction at an incident beam energy of 34 MeV. The ^{18}O beam was delivered by the BARC-TIFR 14 UD Pelletron Accelerator at Mumbai. A seven-clover detector array was employed to detect the de-exciting γ-rays. The high-spin states in ^{32}P, which lies in the pathway to the 'island-of-inversion' were investigated using the ^{18}O(^{16}O,1p2n) reaction. The ^{16}O beam at 34 MeV was provided by the 15 UD Pelletron Accelerator at IUAC, New Delhi. The near complete Indian National Gamma Array, comprising of 18 clover detectors, was used to detect the de-exciting γ-rays. The tantalum oxide (Ta_2O_5) target had about 50 mg/cm^2 of Ta and ~1.6 mg/cm^2 of ^{18}O on both sides of the Ta foil.

The use of composite detectors demands detailed pre-sorting to ensure that all on-line drifts are carefully corrected, prior to an accurate calibration. The data sorting software IUCSORT [3,4] ensured that the data were carefully pre-sorted and calibrated before generating the individual add-back spectra and the symmetric and angle-dependent E_γ–E_γ matrices, which were analysed using the RADWARE software [5].

The placement of the observed γ-transitions in the level sequence is only half the job accomplished. The complete level sequence is developed, only after the spin parity assignment for the individual levels is completed. This is achieved from the analysis of the observed coincidence intensity anisotropy and linear polarization measurements.

Figure 1 depicts the projection spectra from both the experiments. As is evident from the figure, high-spin states in these nuclei are accessible using the fusion evaporation reactions.

The spin and parity for the level is obtained from the multipolarity of the γ-transition de-exciting the level. The multipolarity assignment comprises essentially of (i) determining the change in angular momentum between the initial and final

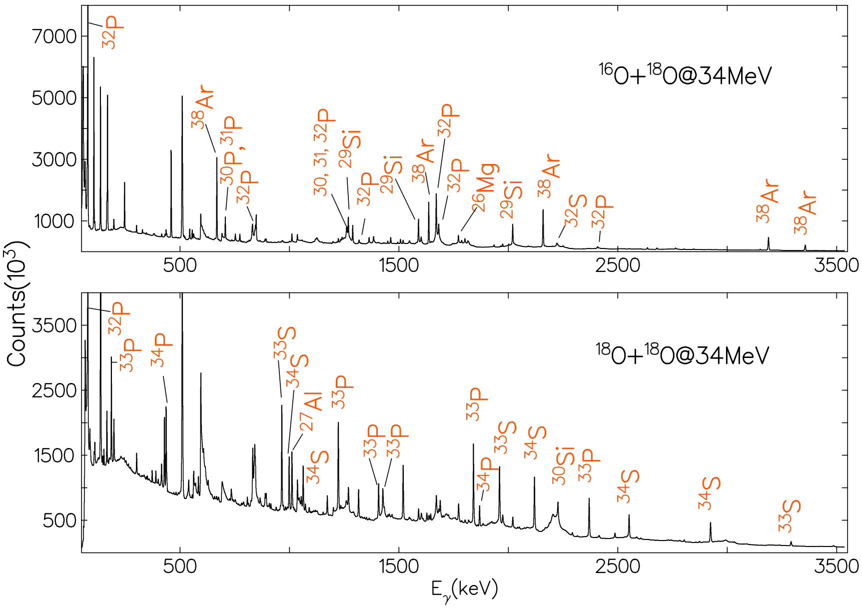

Figure 1. Projection spectra from ^{16}O + ^{18}O and ^{18}O + ^{18}O experiments at a beam energy of 34 MeV.

level and (ii) electromagnetic nature of the associated γ-transition. The observed coincidence intensity anisotropy is used to infer the spin difference between the initial and final levels connected by the γ-transition. The intensity ratios were obtained from angle-dependent γ–γ matrices, and the experimental anisotropy ratio is defined as

$$R_{\rm DCO} = \frac{I_{\gamma 1}\ (\text{at } \theta \text{ gated by } \gamma_2 \text{ at } 90^\circ)}{I_{\gamma 1}\ (\text{at } 90^\circ \text{ gated by } \gamma_2 \text{ at } \theta)}. \tag{1}$$

It is possible to qualitatively distinguish between the $\Delta J = 1$ and 2 transitions from the above procedure as is depicted in figure 2 where the $R_{\rm DCO}$ values as determined from gates on quadrupole transitions are plotted.

The above procedure is valid only for pure stretched transitions. For mixed transitions this procedure results in a qualitative information regarding the dominant multipolarity for the transition of interest. The predicted $R_{\rm DCO}$ values were obtained from the code ANGCOR [6], wherein the width of the m-state distribution (σ/J) was chosen to be 0.4.

Use of clover detector facilitated linear polarization measurements which allow us to establish the electromagnetic nature of the transitions following their preferential scattering either along the parallel (magnetic) or perpendicular (electric) direction with respect to the reaction plane. Hence, we wish to record the polarization asymmetry defined as [7]

$$\Delta_{\rm IPDCO} = \frac{aN_\perp - N_\parallel}{aN_\perp + N_\parallel}\ , \tag{2}$$

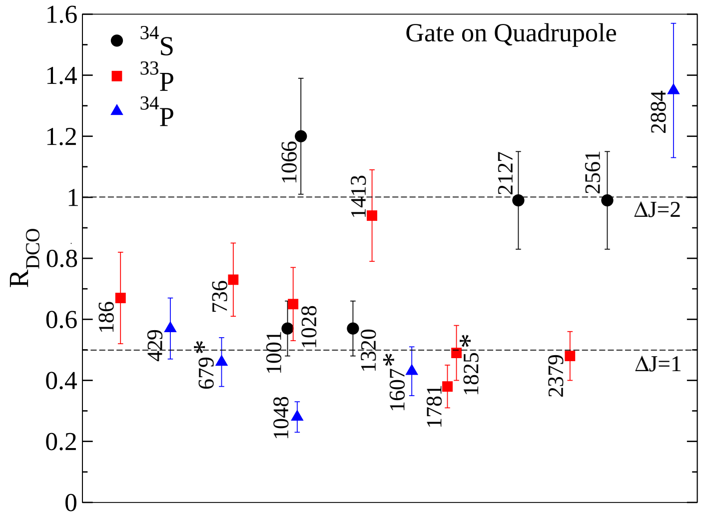

Figure 2. The experimental $R_{\rm DCO}$ values for transitions in ^{33,34}P and ^{34}S following the ^{18}O(^{18}O,$xnyp$) reaction, when the gate is on a quadrupole transition. The newly assigned γ-rays are marked with an asterisk.

where $N_{\perp}$ and $N_{\|}$ correspond to the number of photons with a given energy scattered along the direction perpendicular and parallel to the reaction plane, respectively, in the detectors placed at $\sim 90^{\circ}$ and in coincidence with another photon detected in at least another detector in the array. a denotes the correction due to the asymmetry in response of the clover segments. A positive value for the experimental asymmetry is indicative of an electric nature, while a negative value is attributed to a magnetic nature of the transition. A near-zero value is an indication for a mixed transition.

From the experimental asymmetry we could then obtain the linear polarization since

$$\Delta_{\rm IPDCO} = PQ(E_{\gamma}), \qquad (3)$$

where the polarization sensitivity, $Q(E_{\gamma})$, is dependent on the incident γ-ray energy and the geometry of the polarimeter, and its values were obtained for a similar set-up as reported by Palit *et al* [8]. The theoretical estimates for the polarization could be obtained if one knows the width of the m-state distribution and the mixing ratio, δ. These are obtained from a simultaneous and consistent analysis of both the $R_{\rm DCO}$ and $\Delta_{\rm IPDCO}$ values. A comparison between the predicted and the experimental polarization asymmetry is presented in figure 3. As seen from the figure the agreement between the two is reasonable.

The emphasis of this measurement was to ascertain the multipolarity of the 1876-keV transition de-exciting the 2305 keV level in ^{34}P. The measured $R_{\rm DCO}$ for this transition establishes it to be a mixed ($L = 2$ and $L' = 3$) transition. This is also evident from the difference between the 429-keV gated perpendicular and parallel scattering spectra (figure 4), where the number of counts under 1876 keV peak is nearly zero.

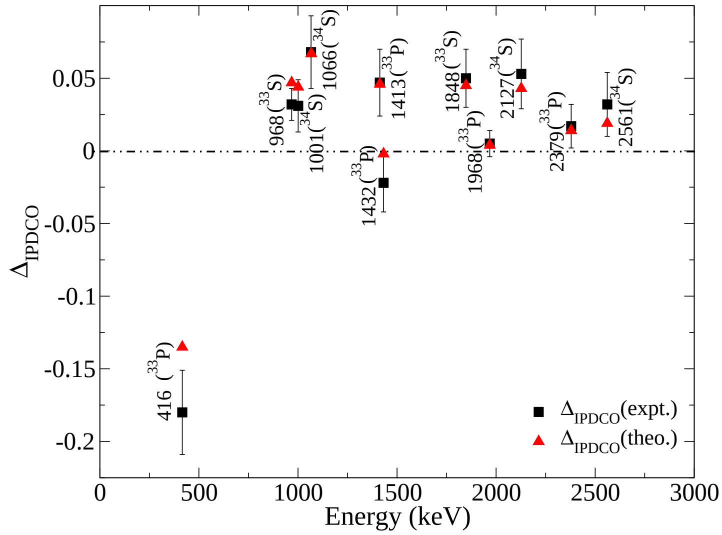

Figure 3. Theoretical and experimental Δ_{IPDCO} as a function of γ-ray energy.

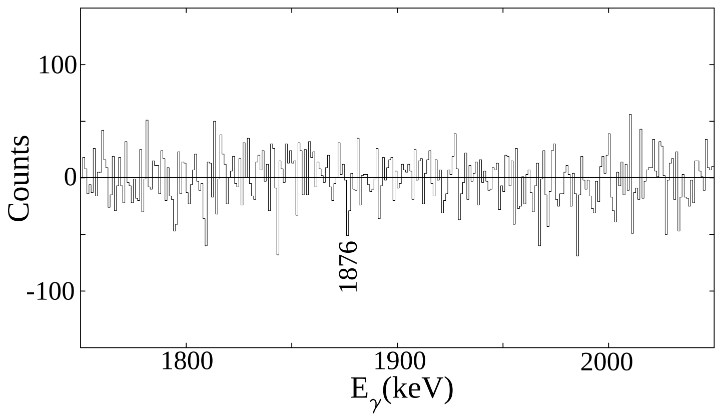

Figure 4. Background-subtracted difference spectrum of perpendicular and parallel scattered events when gated by 429 keV transition in ^{34}P. Absence of a clear positive or negative peak at 1876 keV is indicative of its mixed nature.

However, the polarization measurements could not unambiguously determine the nature of the transition as $M2/E3$ or $E2/M3$ as seen from figure 5. Further, the lifetime for the level is reported to be 0.3 ns $\leq t_{1/2} \leq$ 2.5 ns [9]. From the lifetime measurements and the mixing ratio determined from our linear polarization measurements, the experimental reduced transition probabilities assuming both $M2/E3$ and $E2/M3$ mixing were obtained. These calculations rule out an $E2/M3$ admixture due to unacceptable $M3$ strengths [10]. This supports an $M2/E3$ assignment for the 1876-keV transition and $J^\pi = 4^{(-)}$ assignment for the 2305 keV level in ^{34}P. The level scheme for ^{34}P is depicted in figure 6.

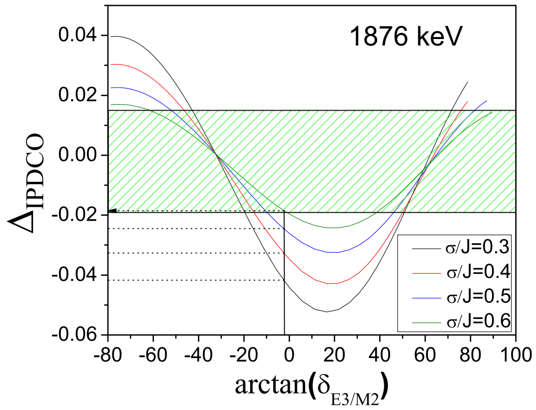

Figure 5. Plot of theoretical $\Delta_{\rm IPDCO}$ as a function of mixing ratios at different σ/J for 1876 keV ($4^- \rightarrow 2^+$) in ^{34}P considering a $M2/E3$ distribution. The shaded area represents the range of experimentally measured $\Delta_{\rm IPDCO}$. The shell-model predicted mixing ratio and the corresponding $\Delta_{\rm IPDCO}$ values are marked by the vertical and the horizontal dotted lines respectively.

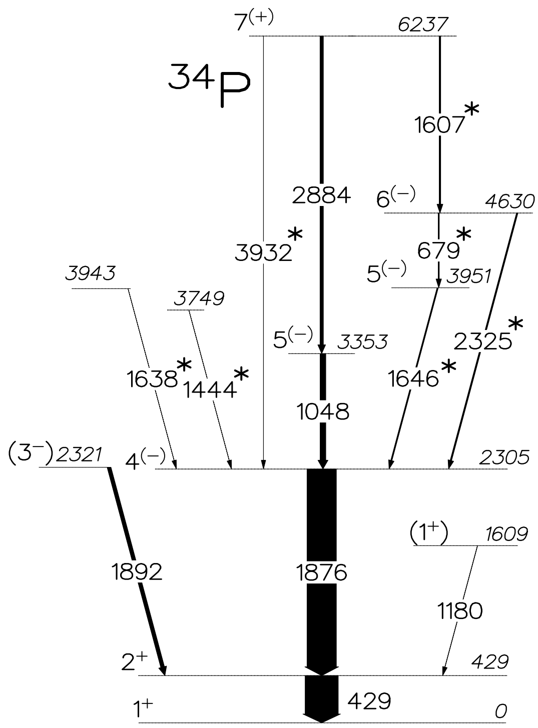

Figure 6. Level scheme of ^{34}P. The newly assigned γ-rays are marked with an asterisk.

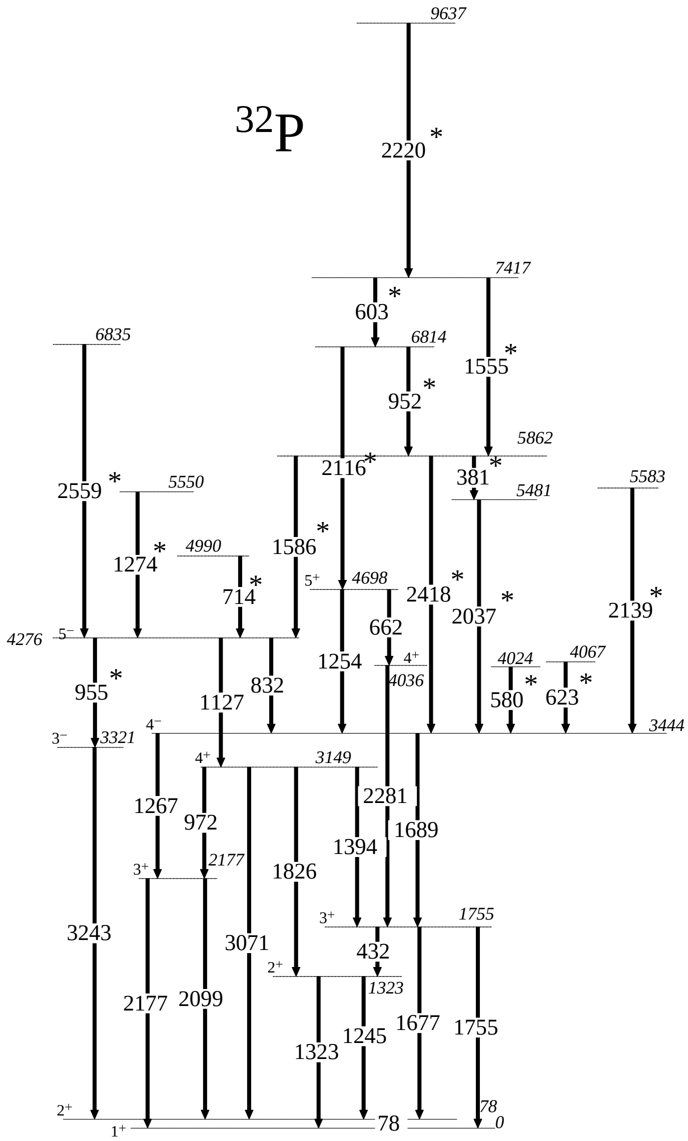

Figure 7. Preliminary level scheme of ^{32}P. The newly assigned γ-rays are marked with an asterisk.

The level scheme of ^{32}P (figure 7) has been considerably extended due to the observation of ~15 new transitions which have been placed in the level scheme. The analysis of the observed coincident angular intensity anisotropy and the coincidence linear polarization is in progress.

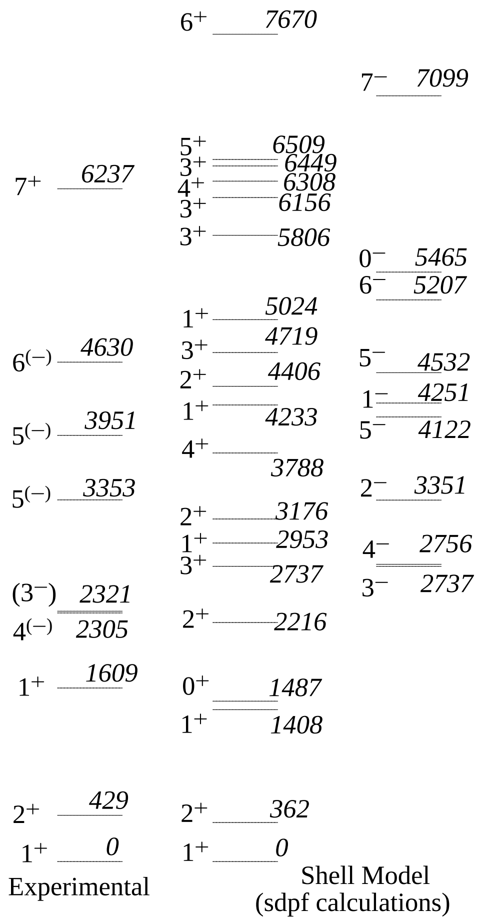

Figure 8. Comparison between experimental and shell-model predicted levels in ^{34}P.

3. Spherical shell-model predictions

Spherical shell-model calculations were carried out using Nushell@MSU [11] within the *sdpf* model space outside a ^{16}O core. The effective Hamiltonian was chosen to be the Warburton–Becker–Millener–Brown (WBMB) *sd-pf* shell Hamiltonian [12] that consists of Wildenthal matrix elements for the *sd* shell, McGrory's *fp* shell Hamiltonian for the *fp*-shell matrix elements [13], and a modification of the Millener–Kurath interaction for the cross-shell components [14].

In this region one expects the low-spin positive-parity states to be dominated by pure *sd* configurations and indeed the $0\hbar\omega$ calculations in both ^{34,32}P nuclei could reasonably reproduce the observed excitation energies. Excitation of nucleons from the *sd* shell into the *fp* shell is essential to generate the observed negative-parity states. Accordingly, $1\hbar\omega$ calculations were attempted for these nuclei. The calculations reproduced the energy level systematics for the low-lying negative parity

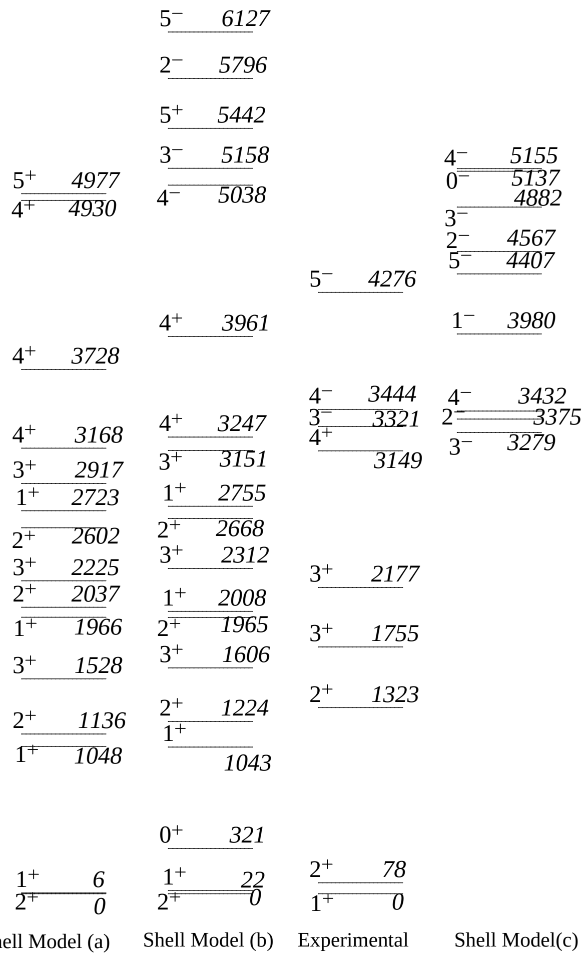

Figure 9. Comparison between the observed and calculated states in ^{32}P. Shell model (**a**) depicts the results of $0\hbar\omega$ calculations. Shell model (**b**) depicts the results of $1d_{5/2}^{(9-12)}1d_{3/2}^{(0-8)}2s_{1/2}^{(0-4)}1f_{7/2}^{(0-1)}$ calculations. Shell model (**c**) depicts the results of calculations after lowering the SPE for $1f_{7/2}$ and $1p_{3/2}$ orbitals.

states in ^{34}P (figure 8). However, these calculations were not feasible for ^{32}P due to computational limitations. This prompted us to perform the calculations for the negative-parity states in ^{32}P within a truncated valence space, where the $1d_{5/2}^{(9-12)}1d_{3/2}^{(0-8)}\ 2s_{1/2}^{(0-4)}1f_{7/2}^{(0-1)}$ sub-shell restrictions were imposed. The comparison between the experimental excitation energies and theoretical predictions is illustrated in figure 9.

It is worth mentioning that the calculations were carried out without lowering the single particle energies (SPE) for the $1f_{7/2}$ and $1p_{3/2}$ orbitals. It is a conventional practice to lower these SPE in this region, as there are indications that the energy

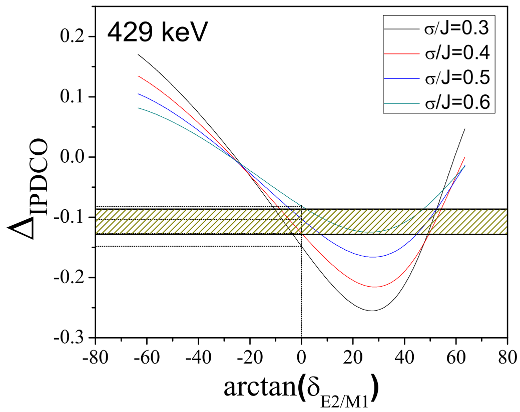

Figure 10. Plot of theoretical $\Delta_{\rm IPDCO}$ as a function of mixing ratios at different σ/J for 429 keV ($2^+ \rightarrow 1^+$) in ^{34}P. The shaded area represents the range of experimentally measured $\Delta_{\rm IPDCO}$. The shell-model predicted mixing ratio and the corresponding $\Delta_{\rm IPDCO}$ values are marked by the vertical and the horizontal dotted lines respectively.

gap between the sd and fp shells is lowered with an increase in the neutron number, especially around $N = 20$.

Having reasonably reproduced the energy levels, we decided to test the wave functions by obtaining the transition probabilities and extracting the mixing ratios. The $0\hbar\omega$ calculations for ^{34}P predicted a mixing ratio of $\delta = -0.0024$, for the 429-keV ($2^+ \rightarrow 1^+$) transition, which is well within the deduced experimental range. Figure 10 depicts the theoretical asymmetry curves for $2^+ \rightarrow 1^+$, $M1/E2$ radiation as a function of mixing ratio, at different values of σ/J.

The shaded area represents the experimental dispersion in $\Delta_{\rm IPDCO}$ of the 429-keV γ-ray. At $\sigma/J = 0.4$, the theoretical values are consistent with experimental $\Delta_{\rm IPDCO}$ values over the range $-8^\circ \leq \arctan(\delta) \leq 0^\circ$ and $49^\circ \leq \arctan(\delta) \leq 54^\circ$. However, as seen from figure 10, the mixing ratio predicted by the shell model limits the value to the former range.

Further, the $1\hbar\omega$ shell-model calculations for ^{34}P failed to predict the mixed nature of the 1876-keV transition, and it predicted an almost pure nature for this transition, as depicted in figure 5.

Hence, it seemed interesting to explore theoretically the situation in the neighbouring $N = 19$ isotones. Similar mixed transitions have indeed been reported in ^{35}S (1911 keV; $J^\pi = 7/2^- \rightarrow 3/2^+$) and in ^{37}Ar (1611 keV; $J^\pi = 7/2^- \rightarrow 3/2^+$). Our shell-model calculations for these nuclei also predict very little mixing, contrary to the experimental observations.

Recently, Bender *et al* [15] have reported their shell-model calculations for ^{32,34}P, wherein the SPE for the $1f_{7/2}$ and $1p_{3/2}$ orbitals have been lowered by 1.8 and 0.5 MeV respectively. In the case of ^{34} P, these predictions are very much similar to our results for both the excitation energies as well as the predicted pure $M2$ nature for the 1876-keV transition.

Further, the predictions of Bender and co-workers for ^{32}P (figure 9) are qualitatively a notch better than our preliminary shell-model results for the observed excitation energies. In view of the results from our Nushell calculations and those by Bender and co-workers for these nuclei, it is of interest to revisit the need for lowering the SPE while performing shell-model calculations for these nuclei, and explore the need and significance for this lowering.

4. Conclusion

The level structures of the difficult-to-access ^{32,34}P nuclei have been considerably extended by the use of heavy-ion fusion reaction which has resulted in the population of high-spin states that were generally not accessible using the methods employed in the earlier investigations. The shell-model calculations could successfully reproduce qualitatively the observed energy levels in ^{32,34}P. However, the experimental mixing ratio for the crucial 2305 keV level in ^{34}P could not be reproduced in these calculations. Clearly, there is a need to perform these calculations with a better Hamiltonian encompassing a realistic cross-shell interaction, and/or with a more complete wave function incorporating configurations arising from multiparticle excitations into the fp orbitals. This may also shed some light on the need to tweak the single-particle energies for the $f_{7/2}$ and $p_{3/2}$ orbitals which determine the energy gap between the sd and pf major shells as a function of the nucleon number.

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