

Nuclear structure investigations in the $A \approx 30$ mass region

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Abstract. Experimental results for the structure of nuclei in the mass region $A \approx 30$ are presented. The first part of the paper is dedicated to the mirror nuclei ^{31}S and ^{31}P . In the second part we focus on the structure of the $N=Z$ nucleus of ^{30}P . Excited states in the ^{30}P , ^{31}P and ^{31}S were populated in the same experiment as the $1p_n$, $1p$ and $1n$ exit channels of the reaction $^{20}\text{Ne} + ^{12}\text{C}$, respectively. The ^{20}Ne beam accelerated to an energy of 33 MeV was delivered by the Piave-Alpi accelerator of the Laboratori Nazionali di Legnaro. Results for branching ratios measurements, angular correlations analysis of coincident γ -rays as well as Doppler-shift attenuation lifetime measurements are reported. The γ -rays were detected using the multi-detector array GASP with the EUCLIDES charged particle detector. The isospin symmetry in $A=31$ mirror nuclei was investigated using the Equation of Motion method based on a chiral potential and including two- and three-body forces. The level scheme and branching ratios for the positive parity band in the $N=Z$ nucleus of ^{30}P are well reproduced by the shell model calculations.

1 Introduction

The nuclei in the mass region $A \approx 30$ attract interest, both from a theoretical and experimental point of view. One of our subjects of interest, lifetime measurements in $A=31$ mirror nuclei offer possibilities for the investigation of the isospin symmetry [1] in light nuclei in comparison to heavier nuclei [2] and the role of the Coulomb effect on the nuclear structure

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[3]. In the light nuclei deformation and super-deformation effects are also interesting features for investigation [4].

2 Experiment and Data analysis

The experiment has been done at the Laboratori Nazionali di Legnaro using the GASP spectrometer. The reaction is the same $^{20}\text{Ne} + ^{12}\text{C}$ for the ^{30}P , ^{31}P and ^{31}S . They are products of the $1p1n$, $1p$, $1n$ exit channels of the reaction, respectively. The details of the experiment are well described in the works [1,5]. We need to underline that for the first time PIAVE-ALPI accelerator provided a ^{20}Ne beam and the fact that it is difficult to obtain a 0.75 mg/cm^2 thick carbon target, which at the same time has a high homogeneity. We report three types of analyses in the present paper. The first one is precise determination of the branching ratios for all the three nuclei. The GASP detectors were grouped into 7 rings corresponding to approximately the same polar angle with respect to the beam axes, namely, ring 0 (34.6°), ring 1 (59.4°), ring 2 (72°), ring 3 (90°), ring 4 (108°), ring 5 (120.6°), and ring 6 (145.4°). In order to reduce the uncertainty due to angular correlation effects we analyse only spectra obtained by the GASP detectors positioned at 120.6° . The gates were set in a coincidence matrix ($120.6^\circ, \Sigma$), where the axis (Σ) corresponds to the detection of γ -rays by every GASP detector. An efficiency correction was applied using the results of the calibration with a ^{152}Eu source. The approach we have used has also been presented in the works [5,6]. An example which illustrates the good statistics of the data when analysing ^{30}P , is shown in Figure 1. This spectrum is obtained by gating of the transition $4_1^- \rightarrow 3_3^+$ at the energy of 1392 keV. The 4_1^- state and correspond linking transitions to the positive parity band are shown in Figure 2.

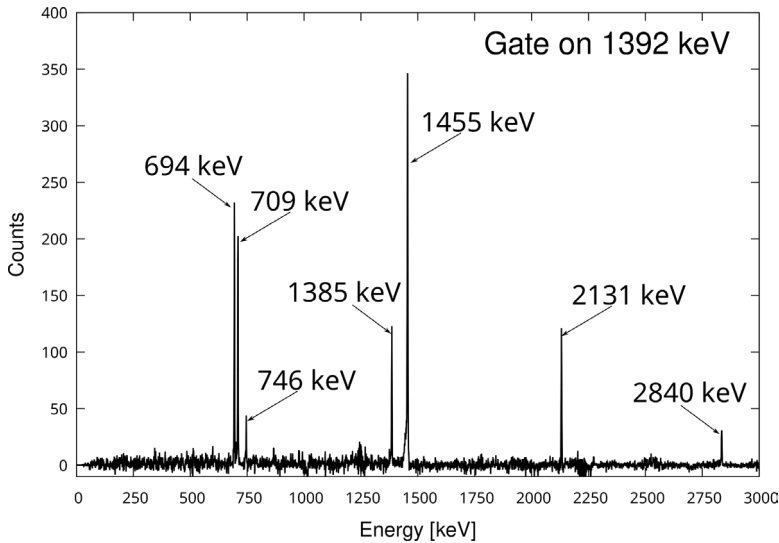


Fig. 1. Gated γ -ray spectrum of the $N=Z$ nucleus of ^{30}P . The gate is set on the 1392 keV transition, connecting the 4_1^- state with the 3_3^+ state. See also Figure 2. Peaks of interest from the positive parity band are shown in the picture.

The same approach has been used to obtain the branching ratios for the $A=31$ mirror transitions. The angular correlation analysis has been used to determine the multipole mixing ratios for the transitions of interest. We used the computer code CORLEONE introduced by Wiedenhoever et al. in the work [7]. In order to check the reliability of the method we have analysed the data for the even-even nuclei of ^{24}Mg and ^{30}Si [1]. In both nuclei we have

investigated the cascades $4_1^+ \rightarrow 2_1^+ \rightarrow 0_1^+$, where the transitions of interest are known to show E2 character. They are strongly populated and the results obtained have shown that the angular correlation approach is working successfully and allow us to adjust the relative efficiencies. The good quality of the data allows us to form 34 detector correlation groups and this condition guarantees the reliable and precise determination of the M2/E1 multiple mixing ratios for the $7/2_1^- \rightarrow 5/2_2^+$ transitions in ^{31}P and ^{31}S .

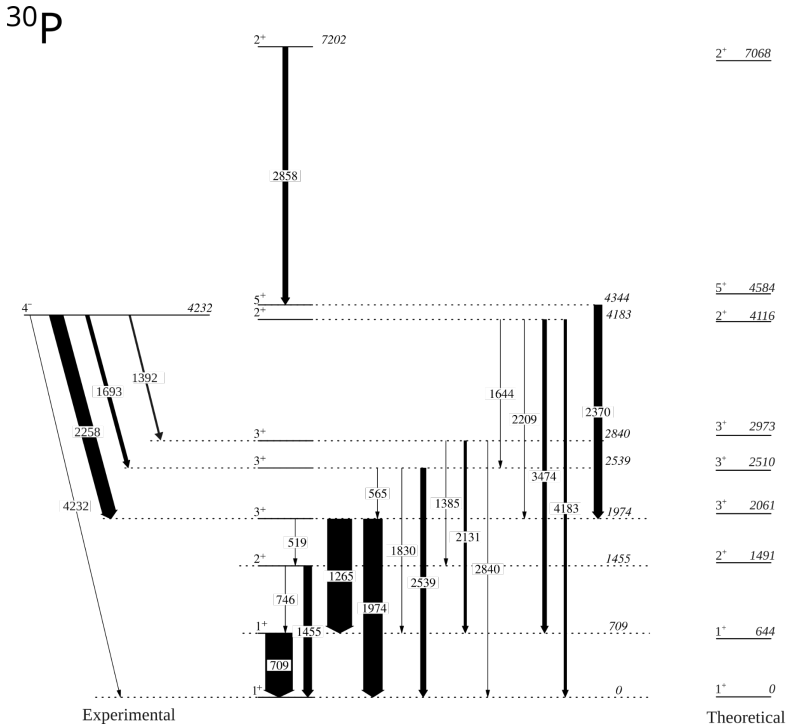


Fig. 2. Partial level-scheme of the ^{30}P obtained in the present work. The width of the arrows indicates their intensity. On the right hand side the shell model predictions are indicated.

The third type of analysis we have used was the improved Doppler-shift method for the determination of lifetimes in the subpicosecond time region. The best way to calculate the time evolution of the velocity distribution of the recoils is to perform a Monte-Carlo (MC) simulation of the process of creation of the recoils, followed by a slowing-down in the target and the stopper. In order to reproduce well the lineshape we have simulated 10 000 individual velocity histories, a data set, which contains three projections of every velocity history in time, additionally randomized with respect to the GASP setup by considering the exact position of the detectors and their finite size [8,9]. It is important to underline that we are using a MC procedure, which includes the process of evaporation of light particles from the compound nucleus and different ways of describing the stopping power of the projectiles in the target and stopper. The effect of the evaporation of charged particles from the compound nucleus is crucial for describing the lineshape and respectively the lifetime of excited states. In the case of light nuclei, not considering this effect could bring up to 70% error to the lifetime determined [3]. The gate is set on the shifted portion of the feeding transition, which avoids the possibility to include into the analysis signal from the unobserved feeding. The partial gate on the shifted component of the feeding transitions are also carefully checked for the absence of the contaminations in the peak of interest. Here we underline that to fulfil such a condition is not so easy, since the corresponding mirror transitions are with close energies.

An illustration of the lifetime analysis is shown in Figure 3, used for the determination of the lifetimes of the $3/2_1^+$ state in both mirror nuclei ^{31}P and ^{31}S .

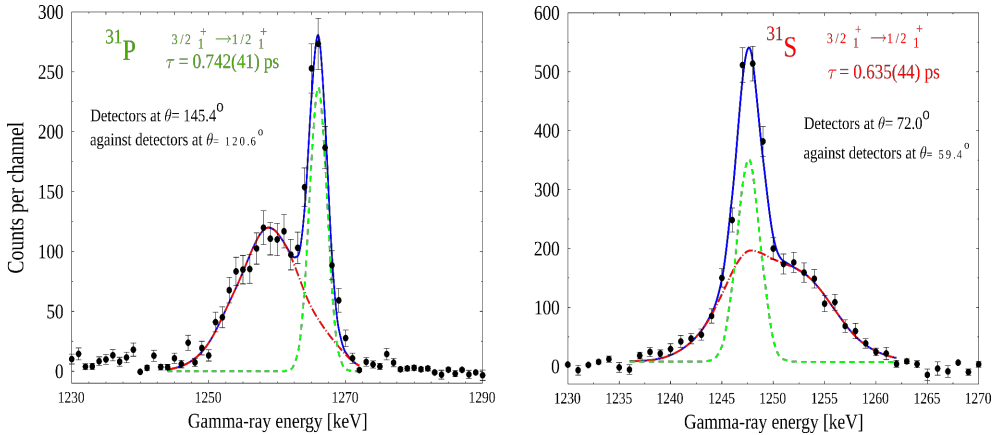


Fig. 3. Illustration of the lifetime analysis using an improved procedure for Doppler-shift attenuation method in the ^{31}P (left hand side) and ^{31}S (right hand side). The unshifted peaks are indicated with a dashed line, the shifted one with a dot-dashed line, while the fit is indicated with a full line. The spectra are used to determine the lifetime of the $I^\pi = 3/2_1^+$ state in the $A=31$ mirror nuclei.

A partial level scheme of the mirror nuclei ^{31}P and ^{31}S based on Ref. [10] is shown in Figure 4. The different pattern of the decay of the $7/2_1^-$ states in the mirror nuclei is clearly seen.

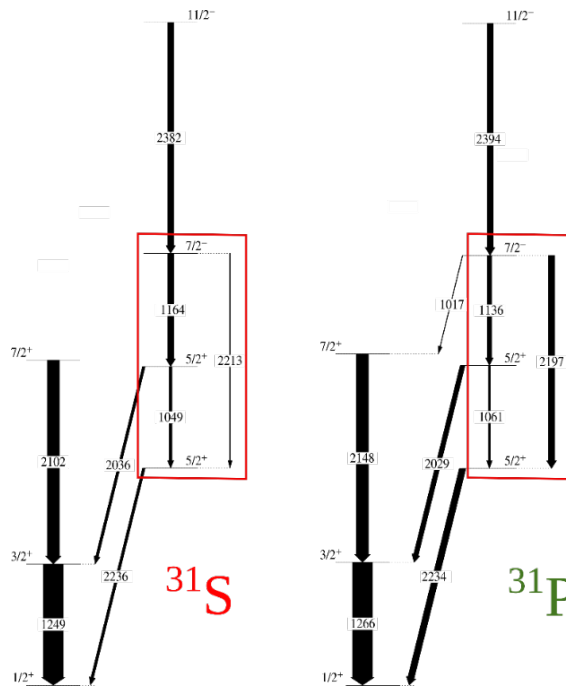


Fig. 4. Partial level-schemes of the mirror nuclei ^{31}P and ^{31}S up to $11/2^-$ state based on Ref [10]. The width of the arrows is proportional to the relative intensities of the transitions. The different pattern of the decay of the $7/2_1^-$ states in the mirror nuclei is clearly seen (levels surrounded by rectangles).

3 Results

In Ref. [1] we have reported the multipole mixing ratios for the transitions $7/2_1^- \rightarrow 5/2_2^+$ in ^{31}P and ^{31}S , which are $\delta = -0.03(3)$ and $\delta = -0.07(8)$ respectively. For the lifetimes of the states $3/2_1^+$ and $7/2_1^-$ in ^{31}P we have determined 736(35) fs and 597(45) fs correspondingly Ref. [1]. In the case of ^{31}S – they are 624(32) fs for the $3/2_1^+$ state and 543(49) fs for the $7/2_1^-$ Ref [1]. Our data are with the smallest uncertainty, and they allow us to obtain precise B(E1) transition probabilities.

A partial level scheme of ^{30}P has been reported in the work of Ray et al. [11]. Here we are showing only a positive parity band and the 4_1^- state from the negative parity band. We confirm all the transitions reported in the work [11]. The branching ratios obtained by us for the transitions depopulating the levels of the positive parity bands in the ^{30}P nucleus are given in Table 1. They are compared with the values obtained in previous measurements [12] as well as with the shell model predictions.

The level scheme is investigated and published in the Refs. [11,13] using the reactions $^{16}\text{O} + ^{16}\text{O}$ and $^{29}\text{Si}(p,\gamma)^{30}\text{P}$, respectively. We are currently working on angular correlation analysis and lifetime analysis for the excited levels of the nucleus of ^{30}P . The ^{30}P is the strongest channel in the experiment we have performed and the first results for the life-times and correlation analysis are very promising. They will be published in a forthcoming work.

Table 1. Comparison of the experimental and calculated branching ratios in ^{30}P . The first column indicates the initial and final level of the transition, the second one shows the corresponding transition energy, the third one - determined by our experiment branching ratios with an error, the fourth one – reported in NNDC values [12] and the last column shows the calculated values published in Ref. [11].

$J_i^\pi \rightarrow J_f^\pi$	E_γ [keV]	Present BR	Previous BR [12]	Theory BR [11]
$2_1^+ \rightarrow 1_2^+$	746	5.0 ± 0.3	4.6 ± 0.4	2.4
$2_1^+ \rightarrow 1_1^+$	1455	100	100 ± 0.4	100
$3_1^+ \rightarrow 2_1^+$	519	3.8 ± 0.3	< 7.2	3.8
$3_1^+ \rightarrow 1_2^+$	1265	100	100 ± 0.6	100
$3_1^+ \rightarrow 1_1^+$	1974	72 ± 5	81.8 ± 0.6	71.1
$3_2^+ \rightarrow 3_1^+$	565	0.9 ± 0.2	0.41 ± 0.11	0.7
$3_2^+ \rightarrow 1_2^+$	1830	4.0 ± 0.3	3.11 ± 0.21	4.3
$3_2^+ \rightarrow 1_1^+$	2539	100	100 ± 0.6	100
$3_3^+ \rightarrow 2_1^+$	1385	65 ± 5	55 ± 4	62.3
$3_3^+ \rightarrow 1_2^+$	2131	100	100 ± 4	100
$3_3^+ \rightarrow 1_1^+$	2840	41 ± 4	34 ± 4	9.6

4 Discussion

From the determined branching ratios, multipole mixing ratios and lifetimes in the mirror nuclei ^{31}P and ^{31}S we were able to determine the $B(E1)$ strengths of the analogue transitions linking the $7/2_1^- \rightarrow 5/2_2^+$ states. From the experimental findings we have determined $B(E1) = 2.7(2) \times 10^{-4} \text{ e}^2\text{fm}^2$ for ^{31}P and $B(E1) = 7.2(7) \times 10^{-4} \text{ e}^2\text{fm}^2$ for ^{31}S . The extracted $B(E1)$ values show that there is a big difference in the strengths of the transitions of interest, which underlines a breaking of the isospin symmetry. In order to describe the experimental observables, we have utilized the Equation of Motion Phonon Method [14,15]. The calculated values are respectively - $B(E1) = 2.2 \times 10^{-4} \text{ e}^2\text{fm}^2$ for ^{31}P and $B(E1) = 7.9 \times 10^{-4} \text{ e}^2\text{fm}^2$ for ^{31}S , and they are in a very good agreement with the experimental ones. The breaking term could be expressed by introducing an “induced” isoscalar part in the E1 transition matrix elements. It is clearly seen that the difference of the $B(E1)$ values for the analogue transitions in both mirror nuclei shows a violation of the isospin symmetry manifested by the presence of a large induced isoscalar component. Such a difference for the $B(E1)$ values is observed in the mirror nuclei $A=35$ [16] and for the heavier one $A=67$ [2] which shows an opposite phase ($B(E1)_{T_z = 1/2} < B(E1)_{T_z = -1/2}$).

For the positive parity band of the $N=Z$ nucleus ^{30}P , the shell model calculations reported in the Ref. [11] show an excellent agreement with experiment, as could be seen in Figure 2. The obtained precise branching ratios for the same band are compared with the shell model predictions published in the work [11]. They are in a good agreement with the previously measured values, but with smaller uncertainty. Comparison with the shell model predictions in mass region $A=30$ [17,18] show also a reasonable agreement, with few exceptions.

5 Conclusion

We have presented two data sets which are used to elucidate the structure of the mirror nuclei ^{31}P and ^{31}S and $N=Z$ nucleus of ^{30}P . All the data are obtained in the same experiment using different channels of the reaction $^{20}\text{Ne} + ^{12}\text{C}$, with the GASP spectrometer and PIAVI-ALPI accelerator at LNL.

The precise and reliable $B(E1)$ of the analogue transitions linking $7/2_1^- \rightarrow 5/2_1^+$ states show a violation of the isospin symmetry in mirror nuclei ^{31}P and ^{31}S . It could be explained with a coherent contribution to isospin mixing which probably involves the isovector giant monopole resonance [2]. The self-consistent theoretical predictions using the NNLO_{sat} and Equation of Motion Phonon Model are working well when describing the experimental observables.

The very good agreement of the theoretically predicted values for the excitation energies and branching ratios of the positive parity band in ^{30}P with the experimental ones proves that the shell model is working well in the mass region $A=30$.

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