EPJ Web of Conferences **194**, 03001 (2018) https://doi.org/10.1051/epjconf/201819403001
NSRT18

Symmetries in mirror nuclei ^{31}S and ^{31}P

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Abstract. Excited states in mirror nuclei ^{31}S and ^{31}P were populated in the 1n and 1p exit channels, respectively, of the reaction ^{20}Ne + ^{12}C. The beam of ^{20}Ne, with an energy of 33 MeV, was delivered for the first time by the Piave-Alpi accelerator of the Laboratori Nazionali di Legnaro. Angular correlations of coincident pairs and Doppler-shift attenuation lifetime measurements in ^{31}S and ^{31}P were performed using the multidetector array GASP in conjunction with the EUCLIDES charged particle detector. A comparison of the determined B(E1) strengths of the analog mirror $7/2^{-} \rightarrow 5/2^{+}$ transitions indicates the presence of a violation of isospin symmetry.

1 Introduction

Investigations of nuclei in A=31 mass region attract considerable interest during the last years, both from the point of view of nuclear structure and from astrophysics. Information for reaction details in this mass region brings important data for nucleosynthesis in the $A \geq 30$ region for ONe novae [1,2]. This information sheds light on the nova thermometers, nova mixing meters, and the identification of candidate pre-solar nova grains in terrestrial laboratories. Our interest is inspired by the nuclear structure investigation of symmetries in A=31 mirror nuclei. The study of mirror nuclei along the N=Z line is of considerable interest since it directly addresses the validity of the charge symmetry of the nuclear forces and the role of the Coulomb effects on nuclear structure. If the nuclear force is charge symmetric, then in the limit of long wavelengths, the E1 transition operator is purely isovector and therefore E1 transitions are forbidden in N=Z nuclei between states of equal isospin and they have equal strength in mirror nuclei. An approach to check the isospin symmetry breaking is to observe experimental deviations from the two rules above. The aim of our experiment was to verify whether the transition strengths of the E1 transitions depopulating the $7/2^{-}$ analog states in the mirror couple ^{31}S and ^{31}P are equal. Using the same reaction as in Ref. [3] the level schemes of ^{31}S and ^{31}P were obtained and a difference of the branching ratios of the analog transitions depopulating the $7/2^{-}$ state was observed (see Fig. 1). In such a case it is reasonable to check whether the different patterns of the decay of the $7/2^{-}$ to the $5/2^{+}$ states in both nuclei lead correspondingly to different B(E1) values. And the way to answer this question is to measure the lifetimes of the two states and the M2/E1 mixing ratios of the transitions. Lifetimes of the analog $7/2^{-}$ states of interest in ^{31}S and ^{31}P [4] were measured with the Doppler shift attenuation method (DSAM), the data being analyzed using gates from below and making some hypothesis for the unknown feeding, an approach which is generally limited by intrinsic uncertainties. The purpose of the present experiment is to extract precise lifetime values of the excited states in the mirror A=31 pair using advanced methods, together with performing angular correlation analysis in order to determine the multipole mixing ratios of the transitions of interest. Using reliable branching ratios, multipole mixing ratios and lifetimes of excited nuclear states we could compare B(E1) strengths of the analog states in both mirror nuclei and to conclude correctly about the structure of ^{31}S and ^{31}P.

2 Experiments and data analysis

Excited states in ^{31}S and ^{31}P were populated using the 1n and 1p exit channels, respectively, of the reaction ^{20}Ne + ^{12}C. The beam of ^{20}Ne, with an energy of 33 MeV, was delivered for the first time for our experiment by the Piave-Alpi accelerator of the LNL. The new accelerator center in Sofia, Bulgaria will also open new possibilities to investigate the structure of light nuclei and nuclear reaction mechanism [5]. To prepare a thick Carbon target

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for a good DSAM experiment it is not a trivial task. In order to obtain such a thick Carbon target needed for a DSAM measurement we used a two steps procedure. The first step was to evaporate a 10 mg/cm^2 gold layer on a 0.6 mg/cm^2 ^{12}C foil. In the second step 0.15 mg/cm^2 ^{12}C were evaporated onto the carbon foil in order to reach 0.75 mg/cm^2 final thickness. We note that this was the maximum Carbon thickness we could reach keeping at the same time a high quality of the target. The deexciting γ rays were registered with the GASP array [6] in its configuration II.

Charged particles were detected with the EUCLIDES silicon ball [7]. Gain matching and efficiency calibration of the Ge detectors were performed using ^{152}Eu and ^{56}Co radioactive sources. The data were sorted into coincidence γ - γ matrices whereby the detection of protons was required to construct the matrices for ^{31}P, since it is 1p exit channel of the reaction.

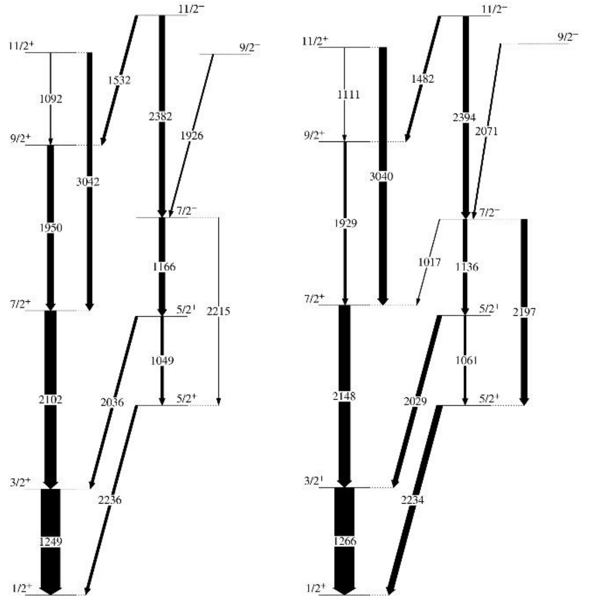

Figure 1. Partial level schemes of the mirror couple ^{31}S and ^{31}P from Ref. [3], showing mainly the yrast cascades. The different pattern of the decay of the $7/2^-$ states in the mirror couple is clearly seen in the picture.

Next to necessity of a precise determination of the branching rations and lifetimes of excited nuclear states it is very important to determine the multipole mixing ratios. Our approach for their determination is presented below.

The angular correlation function $W(\theta_1,\theta_2,\phi)$ for a cascade of two successive transitions from oriented states is presented by:

$$W(\theta_1,\theta_2,\phi) = \sum_{\lambda_1,\lambda,\lambda_2} B_{\lambda_1}(I_1) A_{\lambda}^{\lambda_1\lambda_2}(\gamma_1) A_{\lambda_2}(\gamma_2) H_{\lambda_1,\lambda,\lambda_2}(\theta_1,\theta_2,\phi)$$

This function depends on the spins of the initial, intermediate, and final states, on the multipolarities of the transitions as well as on the two multipole mixing ratios of the two coincident transitions. The first γ transition is detected at an angle θ_1 with respect to the beam axis, the second γ transition at an angle θ_2, and ϕ is the difference of the azimuthal angles of the corresponding detectors. The term $B_{\lambda 1}$ (I_1) describes the orientation of the upper nuclear state, the term $A_{\lambda}^{\lambda_1\lambda_2}(\gamma_1)$ the orientation of the intermediate state due to emission of γ_1, and $A_{\lambda_2}(\gamma_2)$ the emission of γ_2. With the $H_{\lambda_1,\lambda,\lambda_2}(\theta_1,\theta_2,\phi)$ is denoted the angular function. It is reduced to an ordinary Legendre polynomial if any of the λ's vanish. Detailed information about the angular correlation function $W(\theta_1,\theta_2,\phi)$ is presented in Ref. [8].

The symmetries of the coincident radiation event of the two γ rays lead to symmetries of the function W. They can be used to establish the independent angular correlation groups for a given setup. The coincidence efficiency can be represented to a good approximation as a product of the efficiencies of the two detectors. For the angular correlation analysis, we used the code CORLEONE [9]. The relative efficiencies of the detector groups were adjusted by requiring a reasonable reproduction of the properties of clearly known $4_1^+ \rightarrow 2_1^+ \rightarrow 0_1^+$ cascades of the even-even nuclei: ^{24}Mg, ^{28}Si and ^{30}Si, well populated in the present experiment.

The good quality of the experimental data as well as the excellent agreement with the theoretical predictions of the computer code CORLEONE is shown for the cases of ^{24}Mg (Fig. 2) and ^{30}Si (Fig. 3).

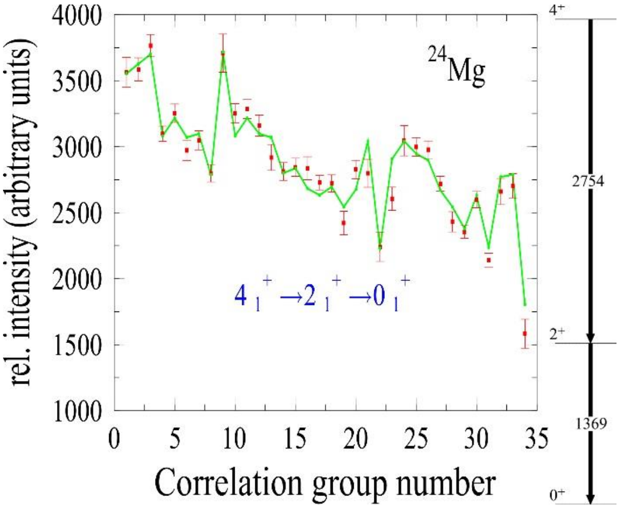

Figure 2. Angular correlation pattern for the cascade involving $4_1^+ \rightarrow 2_1^+ \rightarrow 0_1^+$ transitions of ^{24}Mg. For this spin hypothesis, the best fit shows clearly the pure E2 character of the transitions investigated. The transition energies are indicated on the right hand side of the figure.

For a given spin hypothesis, the data analysis consists of fitting the intensity of the cascade by adjusting the parameter σ characterizing the distribution of the magnetic sub-states *m* of the spin of the first oriented level and the multipole mixing ratios δ_1 and δ_2 of the two successive transitions. Usually, the analysis is simpler if the spins of the cascade are known and we concentrate our work on the determination of the δ_1 and δ_2. This procedure was successfully used to derive the multipole mixing ratios for the transitions depopulating the $7/2^-$ analog states in ^{31}P and ^{31}S. Due to the good statistics of the experiment we constructed 34 detector correlation groups, which ensures very precise determination of the multipole mixing coefficients.

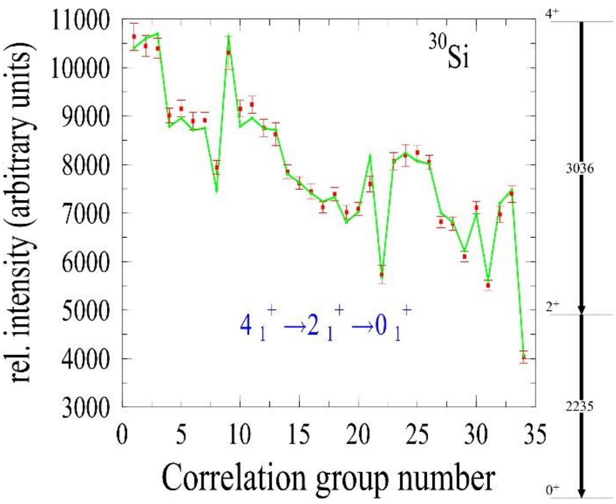

Figure 3. Angular correlation pattern for the cascade involving $4_1^+ \rightarrow 2_1^+ \rightarrow 0_1^+$ transitions of ^{30}Si. For this spin hypothesis, the best fit shows clearly the pure E2 character of the transitions investigated. The transition energies are indicated on the right hand side of the figure.

The next step in our analysis was to derive precisely the lifetimes of the $7/2^-$ states of interest. Since the lifetimes are in the femtosecond region of interest a DSAM measurement was utilized. For the purposes of such a measurement, the information on the detection angles of the γ rays is of primary importance because the Doppler shifts of their energies depend on the angle between the direction of the recoil velocity and the direction of observation. Therefore the Ge detectors of GASP were grouped into rings corresponding to approximately the same polar angle with respect to the beam axis. In both cases of ^{31}P and ^{31}S the statistics allowed to use γ-γ matrices where the angular information was conserved on both axes of the matrix, i.e., the events represented the registration of two coincident γ rays by the detectors of two particular rings.

In order to determine a lifetime in a DSAM measurement we need to know exactly the velocity histories of recoiling nuclei when they are slowing down in the target and stopper, until the moment they stop. The best way to obtain this information is to perform a Monte-Carlo (MC) simulation. For the MC simulation of the slowing-down histories of the recoils we used a modified [10,11] version of the program DESASTOP [12] created by G. Winter. In this version, the time-evolution of the recoil velocities in the target and stopper is followed in three dimensions. A crucial point for the correct MC procedure is to determine precisely the stopping powers. In some cases the uncertainty of the final value of the lifetime could be about 10-20 %, coming from the error of determination of the stopping powers. In the present analysis, the electronic stopping powers used were obtained from the Northcliffe and Schilling tables [13] with corrections for the atomic structure of the medium along the lines discussed in Ref. [14]. As suggested in Ref. [15], an empirical reduction of $f_n = 0.7$ was applied to down-scale the nuclear stopping power predicted by the theory of Lindhard, Scharff and Schiøtt [16]. According to the calculations performed, the mean velocity of the recoils when leaving the target was about 3.7 % of the velocity of light, and they needed in average 1.1 ps to come to rest. The evaporation of charged particles, which is of importance for the velocity distribution of light residual nuclei, was taken into account in the MC simulation and led to better fits of the spectra. The database of about 10 000 velocity histories was additionally randomized with respect to the experimental setup by taking into account the exact position of the GASP detectors and their finite size. Complementary details on our approach for Monte-Carlo simulation can be found in Refs. [10,11,17,18].

The strength of the ^{31}P and ^{31}S reaction channels and the good quality of the data made it possible to apply the newly developed procedure for analysis of coincidence DSAM data, where the gate is set on the shifted portion of the line shape of a transition directly feeding the level of interest [11]. Within this approach, the timing quality of the gated line shape is improved compared to the case where the gate includes also fully stopped events because they do not bring lifetime information. Moreover, gating from above allows the elimination of the uncertainties related to the unobserved feeding of the level of interest which perturbs singles measurements and coincidence measurements where the gate is set on a transition deexciting a level fed by the level of interest.

Fits of the line shapes obtained using the approach [11] and applied to determine the lifetime of the $3/2_1^+$ states in ^{31}P and ^{31}S are presented correspondingly in Figs. 4 and 5. (See also the captions to Figs. 4 and 5.)

We estimate the uncertainty due to the imprecise knowledge of the stopping powers to be 10 % and include it in the final errors of the lifetimes. It should be noted that the derivation of lifetimes in ^{31}S and ^{31}P in the same experiment makes the determination of the ratios of the corresponding transition strengths very precise since uncertainties related to the stopping powers nearly cancel.

3 Results and discussion

Following the procedure described in the previous section and using the code CORLEONE written by I. Wiedenhöver [9] we succeeded to derive the multipole mixing ratios for the transitions depopulating the $7/2-$ states in both mirror nuclei. We checked how the approach works by an investigation of already known and reported δ values in Ref. [19]. A very good agreement with the reported results was found.

The results for the transitions $7/2^- \rightarrow 5/2_2^+$ in both mirror nuclei show dominantly an E1 character. In the frame of the error of the δ values determined we could state that the transitions could be accepted as pure E1 ones. In the present contribution we report this result for the first time. The exact values for the multipole mixing ratios will be reported in a forthcoming publication [20].

As a test of our lifetime approach we determined some lifetimes in ^{31}P which are already known and published. The values we derived are in a very good agreement with the results from earlier measurements [19, 21]. For example we could compare the value of the lifetime of the $3/2_1^+$ state reported in the literature [21] $\tau = 745(35)$ fs with the value derived by us $\tau = 736(24)$ fs. The agreement is perfect, but in our measurement due to the excellent statistics the error is smaller. The quality of the data is well seen in Fig. 4.

Different statistics for the two cases presented in Figs. 4 and 5 is due to the different portion on which the gates on the feeding transitions were set. Due to close transition energies in the mirror nuclei the gates should be chosen very carefully in order not to include any contamination from the mirror nucleus.

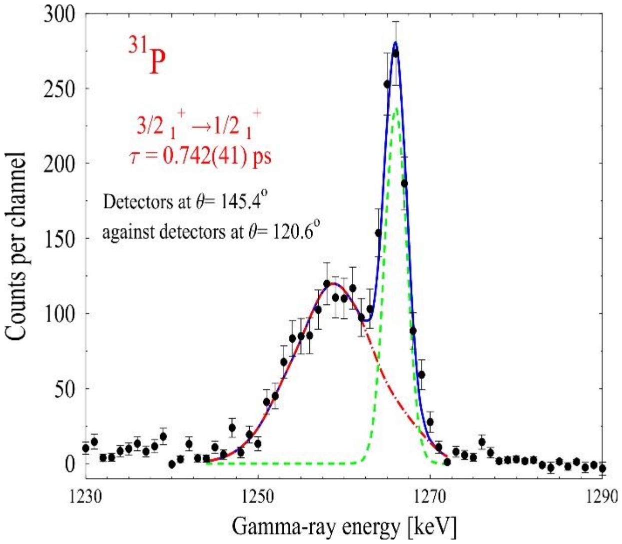

Figure 4. Illustration of the line-shape analysis of the 1264 keV γ-ray transition and determination of the lifetime of the $I_\pi = 3/2_1^+$ in ^{31}P. The spectrum measured with the detectors of ring 7, the fit (full line), the DSA portion of the fit (dotted line), and the unshifted portion (dashed line) are presented.

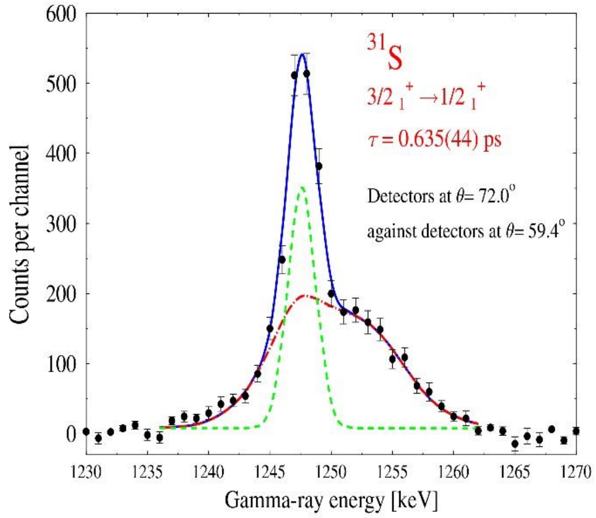

Figure 5. Illustration of the line-shape analysis of the 1249 keV γ-ray transition and determination of the lifetime of the $I_\pi = 3/2_1^+$ in ^{31}S. The spectrum measured with the detectors of ring 3, the fit (full line), the DSA portion of the fit (dotted line), and the unshifted portion (dashed line) are presented.

The lifetimes previously measured in ^{31}S were obtained with an experimental setup which contained only one detector and have been analyzed with a gate from below [22]. Often, due to the fact that the side feeding is not exactly determined, the lifetime values are overestimated. The lifetime of the $3/2_1^+$ state in ^{31}S is reported to be 720(180) fs [19].

With significantly better statistics and using much more detectors and a procedure with a gate from above we derived a shorter lifetime value of 624(24) fs for the $3/2_1^+$ level in ^{31}S. Then within the frames of the errors the lifetimes of the analog states in both nuclei are the same.

As it is for the cases of A = 47 [17] and A = 51 [23] mirror pairs, most of the lifetimes in the nucleus with one proton more have shorter lifetimes. This is the conclusion also for the $3/2_1^+$ levels in the A = 31 mirror couple.

The quality of the data from the present experiment is good enough in order to determine the lifetime values of the $7/2^-$ state in both mirror nuclei, using a gate on the shifted component of a feeding transition. The lifetime values determined from the present experiment are with smaller errors than previously determined and allow us to distinguish a difference in the B(E1) values of the analog transitions in ^{31}P and ^{31}S.

For the $7/2^-$ excited state of ^{31}P we obtained a value which is not different from that reported in the literature [19,21], but its error is four times smaller. The value derived by us for the $7/2^-$ state of ^{31}S is different from that reported in Ref. [4]. It is about twice shorter than 1.03(21) ps.

4 Conclusions

Using precisely determined branching ratios, multipole mixing ratios and lifetimes we could compare corresponding B(E1) values for the analog transitions depopulating the $7/2^-$ state of the A=31 mirror couple. The B(E1) value derived by us for the $7/2^-$ state of ^{31}S is about two times larger than the already known B(E1) value characterizing the analog state in ^{31}P. The significant difference observed between the B(E1) values is an indication for a symmetry violation component. Such behavior was observed in the mirror couples A = 35 [24] and A = 67 [25] and it was explained by the presence of a large isoscalar component. This component provides evidence for a coherent contribution to isospin mixing, probably involving the isovector giant monopole resonance [25]. The presence of a large (induced) isoscalar component could be the reason for the different B(E1) values in the case of ^{31}P and ^{31}S [26,20].

D.T. express his gratitude to Ivanka Necheva and Jordanka Toneva for their outstanding support. Thanks to the PIAVE-ALPI accelerator staff of LNL-INFN, Legnaro for their perfect work for our experiment. This research has been supported by the Bulgarian Science Fund under Contract No. 08/6, 13.12.2016.

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