Lifetime measurements in mirror nuclei $^{31}\text{S}$ and $^{31}\text{P}$: A test for isospin mixing

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Abstract. Using the $^{20}\text{Ne} + ^{12}\text{C}$ fusion-evaporation reaction at $E_{20}\text{Ne} = 33$ MeV and the multidetector array GASP in conjunction with the EUCLIDES charged particle detector, angular correlations of coincident pairs of $\gamma$ transitions and lifetimes in mirror nuclei $^{31}\text{S}$ and $^{31}\text{P}$ have been measured at the Piave-Alpi accelerator of the Laboratori Nazionali di Legnaro. 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
The investigation 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 charge symmetry of the nuclear force is exact, 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 investigate the isospin symmetry breaking is to observe experimental deviations from the two rules above. The aim of the present experiment
is to verify whether the transition strengths of the E1 transitions depopulating the 7/2− analog states in the mirror couple 31S and 31P are equal. Using the same reaction in Ref. [1] the level schemes of 31S and 31P were obtained and a difference of the branching ratios of the analog transitions depopulating the 7/2− state was observed (see Fig. 1). Can the different pattern of the decay of the 7/2− to the 5/2+ states in both nuclei lead correspondingly to different B(E1) values? In order to answer this question we need to know the lifetimes of the two states and the M2/E1 mixing ratios in the transitions. Lifetimes of the analog 7/2− states in 31S and 31P [2] were recently investigated 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 more advanced methods, together with performing angular correlation analysis in order to determine the multipole mixing ratios of the transitions of interest.

2. Experiment and data analysis
Excited states in 31S and 31P were populated using the 1n and 1p exit channels, respectively, of the reaction 20Ne + 12C. The beam of 20Ne, with an energy of 33 MeV, was delivered for the first time by the Piave-Alpi accelerator of the LNL. In order to obtain a thick Carbon target needed for a DSAM measurement we used a two steps procedure. The first step was to evaporate a 10 mg/cm² gold layer on a 0.6 mg/cm² 12C foil. In the second step 0.15 mg/cm² 12C were evaporated onto the carbon foil in order to reach 0.75 mg/cm² 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 [3] in its configuration II.

Charged particles were detected with the EUCLIDES silicon ball [4]. Gain matching and efficiency calibration of the Ge detectors were performed using 152Eu and 56Co radioactive sources. The data were sorted into coincidence γ - γ matrices whereby the detection of protons was required to construct the matrices for 31P.

The angular correlation function W(θ1, θ2, φ) for a cascade of two successive transitions from oriented states is presented by

![Figure 1. Partial level-schemes of 31S and 31P from Ref. [1]. The different pattern of decay of the 7/2− state in both nuclei is illustrated by different arrow thickness.](image-url)
\[ W(\theta_1, \theta_2, \phi) = \sum_{\lambda_1, \lambda_2} B_{\lambda_1}(I_1) A_{\lambda_1 \lambda_2}^1(\gamma_1) A_{\lambda_2}^2(\gamma_2) H_{\lambda_1, \lambda_2}(\theta_1, \theta_2, \phi) \]  

(1)

This function mainly depends on the spins of the initial, intermediate, and final states, on the multipolarities of the transitions as well as on the two multiple mixing ratios of the two coincident transitions. The first \( \gamma \) transition is detected at an angle \( \theta_1 \) with respect to the beam axis, the second \( \gamma \) transition at an angle \( \theta_2 \), and \( \phi \) 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 \( A_{\lambda_1 \lambda_2}^1(\gamma_1) \) the orientation of the intermediate state due to emission of \( \gamma_1 \), and \( A_{\lambda_2}(\gamma_2) \) the emission of \( \gamma_2 \). With the \( H_{\lambda_1, \lambda_2}(\theta_1, \theta_2, \phi) \) is denoted the angular function. It is reduced to an ordinary Legendre polynomial if any of the \( \lambda \)'s vanish. Detailed information about the angular correlation function \( W(\theta_1, \theta_2, \phi) \) is presented in Ref. [5]. The symmetries of the coincident radiation event of the two \( \gamma \) 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 [6]. The relative efficiencies of the detector groups were adjusted by requiring a reasonable reproduction of the properties of known \( 4_1^+ \rightarrow 2_1^+ \rightarrow 0_1^+ \) cascades of the even-even nuclei: \( 24 \text{Mg} \), \( 28 \text{Si} \) and \( 30 \text{Si} \). The quality of the experimental data as well as the excellent agreement with the theoretical predictions of CORLEONE is shown for the cases of \( 24 \text{Mg} \) (Fig. 2) and \( 30 \text{Si} \) (Fig. 3).

![Figure 2. Angular correlation pattern for the cascade involving \( 4_1^+ \rightarrow 2_1^+ \rightarrow 0_1^+ \) transitions of \( 24 \text{Mg} \). For this spin hypothesis, the best fit shows clearly the pure E2 character of the investigated transitions.](#)

![Figure 3. Angular correlation pattern for the cascade involving \( 4_1^+ \rightarrow 2_1^+ \rightarrow 0_1^+ \) transitions of \( 30 \text{Si} \). For this spin hypothesis, the best fit shows clearly the pure E2 character of the investigated transitions.](#)

For a given spin hypothesis, the data analysis consists of fitting the intensity of the cascade by adjusting the parameter \( \sigma \) characterizing the distribution of the magnetic sub-states \( m \) of the spin of the first oriented level and the multiple mixing ratios \( \delta_1 \) and \( \delta_2 \) 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 \( \delta_1 \) and \( \delta_2 \). This procedure was successfully used to derive the multiple mixing ratios for the transitions depopulation the \( 7/2^- \) analog states.
in the $^{31}$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 multiple mixing coefficients.

The next step in our analysis was to derive precisely the lifetimes of the states of interest. For this reason a DSAM measurements was utilized. For the purposes of a such measurement, the information on the detection angles of the $\gamma$ rays is of primordial 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 $\gamma-\gamma$ matrices where the angular information was conserved on both axes of the matrix, i.e., the events represented the registration of two coincident $\gamma$ 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 [7, 8] version of the program DESASTOP [9] written by G.Winter. In this version, the time-evolution of the recoil velocities in the target and stopper is followed in three dimensions. The electronic stopping powers used were obtained from the Northcliffe and Schilling tables [10] with corrections for the atomic structure of the medium along the lines discussed in Ref. [11]. As suggested in Ref. [12], 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 [13]. 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 10000 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. [7, 8, 14, 15].

The strength of the $^{31}$P and $^{31}$S reaction channels 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 [8]. 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 perturb 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 [8] and applied to determine the lifetime of the $3/2^+$ states in $^{31}$P and $^{31}$S are presented correspondingly in Figs. 4 and 5. (See also the captions to the Figs. 4 and 5.)

We estimate the uncertainty due to the imprecise knowledge of the stopping powers to 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 by I. Viedenhöver [6] 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
The results for the transitions $7/2^+ \rightarrow 5/2^+$ in both mirror nuclei show dominantly an E1 character. In the present contribution we report this result for the first time. The exact values for the multiple mixing ratios will be reported in forthcoming publication [17].

As a test we determined some lifetimes in $^{31}$P which are already known and our values are in a very good agreement with the results from earlier measurements [16, 18]. For example we could compare the value of the lifetime of the $3/2^+_1$ state reported in the literature [18] $\tau = 745(35)$ fs with the value derived by us of $\tau = 736(24)$ fs. The agreement is perfect and in our case due to the excellent statistics the error is smaller. The quality of the data is illustrated in Fig. 4.

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 [19]. 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]. Then within the frames of the errors the lifetimes of the analog states in both nuclei are the same.

With significantly better statistics and using much more detectors and a procedure with a gate from above we derived a shorter the lifetime value of 624(24) fs for the $3/2^+_1$ level in $^{31}$S. As it is for the cases of A = 47 [14] and A = 51 [20] 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

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**Figure 4.** Example 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.** Example 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.
smaller errors than previously determined and allow us to distinguish a difference in the B(E1) values of the analog transitions in $^{31}\text{P}$ and $^{31}\text{S}$.

For the $7/2^-$ excited state of $^{31}\text{P}$ we obtained a value which is not different from that reported in the literature [16, 18], but its error is four times smaller. The value derived by us for the $7/2^-$ state of $^{31}\text{S}$ is different from that reported in the Ref. [2]. It is about twice shorter than $1.03(21)$ ps.

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 $^{31}\text{S}$ is about two and a half times larger than the already known B(E1) value characterizing the analog state in $^{31}\text{P}$. The observed significant difference between the B(E1) values is an indication for a symmetry violation component. Such behavior was observed in the mirror couples A = 35 [21] and A = 67 [22] 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 [22]. The presence of a large (induced) isoscalar component could be the reason for the different B(E1) values in the case of $^{31}\text{P}$ and $^{31}\text{S}$ [17]. An extensive discussion on the "isoscalar" term will be presented in the forthcoming paper [23].

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