NUCLEAR STRUCTURE INVESTIGATIONS IN MIRROR NUCLEI ^{31}S and ^{31}P

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Abstract

Exited 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- → 5/2+ transitions indicates the presence of a violation of isospin symmetry.

***Key words**: Nuclear spectroscopy, mirror nuclei, germanium detectors angular correlation analysis*

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 deviation 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 ^{31}S and ^{31}P are equal. Using the same reaction as in Ref. 1 the excited states of ^{31}S and ^{31}P were populated 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 branching ratios of the transitions decaying the states of interest, the lifetimes of the two states and the M2/E1 mixing ratios of the transitions. Lifetimes of the analog 7/2- states in ^{31}S and ^{31}P [2] were recently investigated with the Doppler-shift attenuation method (DSAM), the data being analysed using gates from below and making 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.

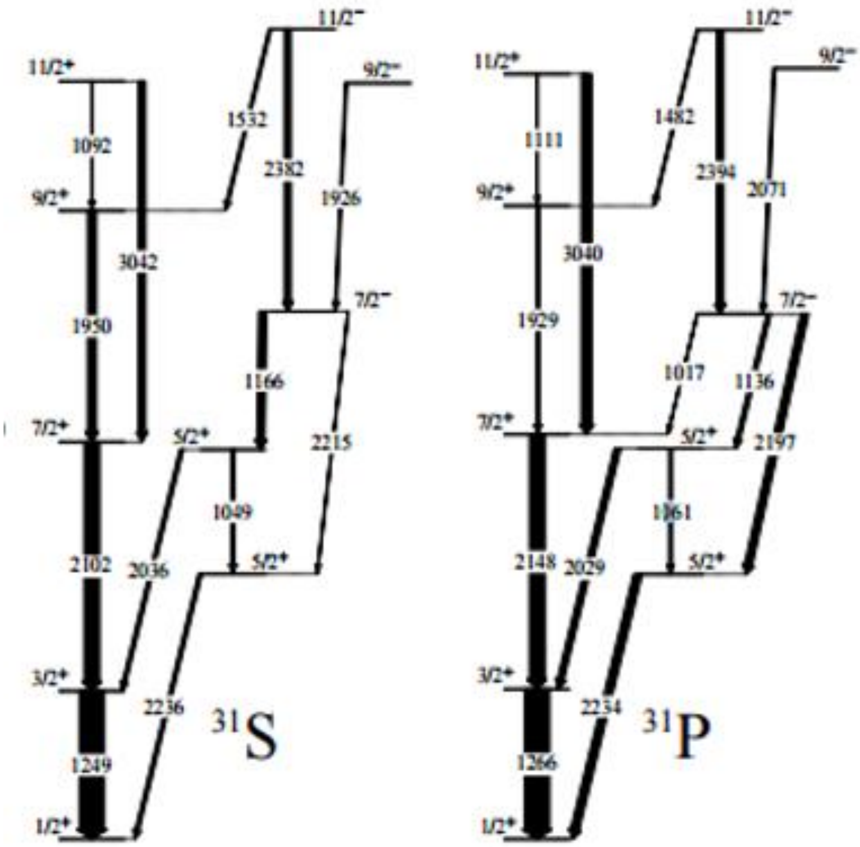

Figure 1. Partial level schemes of mirror couple 31S and 31P from Ref. 1, which shows mainly the yrast cascades of the two nuclei. The different pattern of the decay of the 7/2- states in the mirror couple is clearly seen in the picture.

Experiment and data analysis.

Excited states in ^{31}S and in ^{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 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/cm^2 gold layer on a 1.8 mg/cm^2 ^{12}C foil. In the second step 0.15 mg/cm^2 ^{12}C was 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 gamma 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 ^{152}Eu and ^{56}Co radioactive sources. The data were sorted into coincidence gamma-gamma matrices whereby the detection of protons was required to construct the matrices for ^{31}P.

Angular correlation analyses were performed using the procedure described in the work of Wiedenhoever et al. [5].

We used the code CORLEONE [5]. 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}Mg, ^{28}Si and ^{30}Si. The quality of the experimental data as well as the excellent agreement with the theoretical predictions of CORLEONE is shown in the Ref. 6 for the cases of ^{24}Mg and ^{30}Si.

For a given 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 $7/2_1^-$ 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.

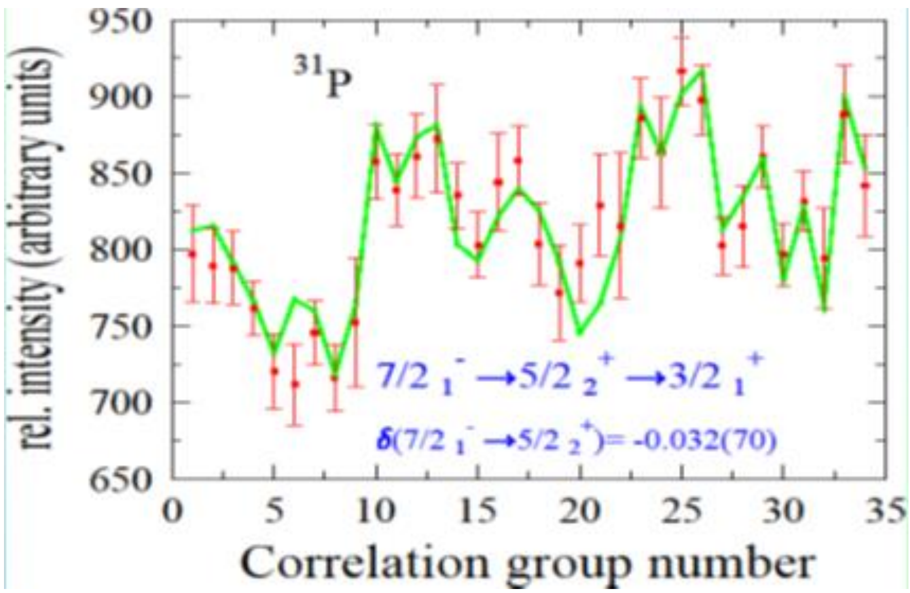

Figure 2. Angular correlation pattern for the cascade involving $7/2_1^-$ → $5/2_2^+$ → $3/2_1^+$ transitions of 31P. The determined multiple mixing ratio M2/E1 delta = -0.032(70) for the transition $7/2_1^-$ → $5/2_2^+$ clearly shows the E1 character of the transition.

Illustrations of the data analysis are shown in Fig 2. The results for the transitions $7/2_1^-$ → $5/2_2^+$ in both mirror nuclei show dominantly an E1 character. The exact values for the multiple mixing ratios are delta = -0.032(70) and delta = -0.071(84) correspondingly for 31P and 31S.

The second step in our analysis was to derive precisely the lifetimes of the states of interest. For this reason a DSAM measurements were utilized.

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 (MS) 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.

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 [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 Schiot [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.

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 lifetimes of the $7/2_1^-$ states in ^{31}P and ^{31}S are presented correspondingly in Figs. 3 and 4. (See also the caption to the Figs. 3 and 4).

We estimate the uncertainty due to the imprecise knowledge of the stopping powers to 10 percent and include it in the final errors of the lifetimes. It should be noted that the derivation of lifetimes in ^{31}P and ^{31}S 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.

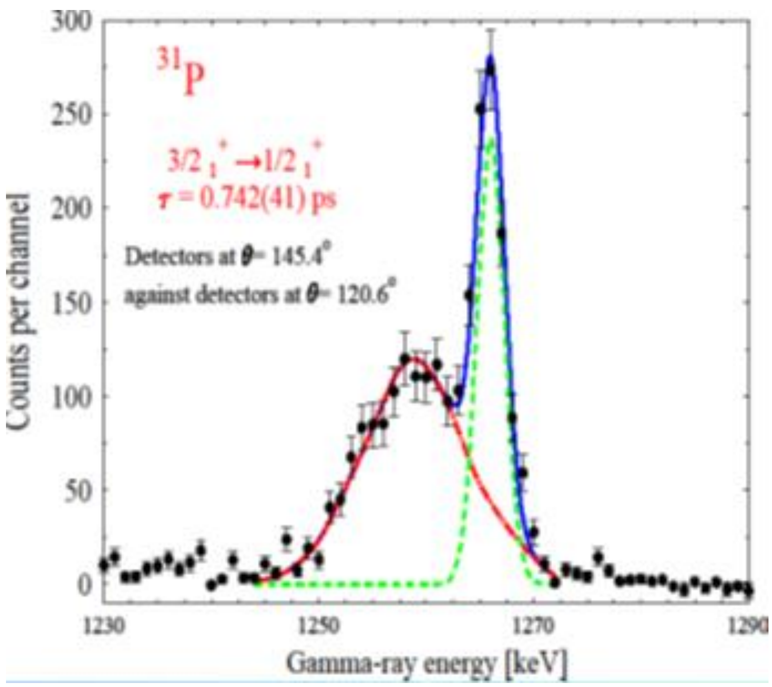

Figure 3 Example of the lineshape analysis of the 1136 keV gamma-ray transition and determination of the lifetime of the $I^{\pi} = 7/2_1^-$ in 31P. The spectrum measured with the detectors of an angle 72.0 deg with respect to the beam axis, the fit (full line) the DSA portion of the fit (dotted line) and the unshifted portion (dashed line) are presented.

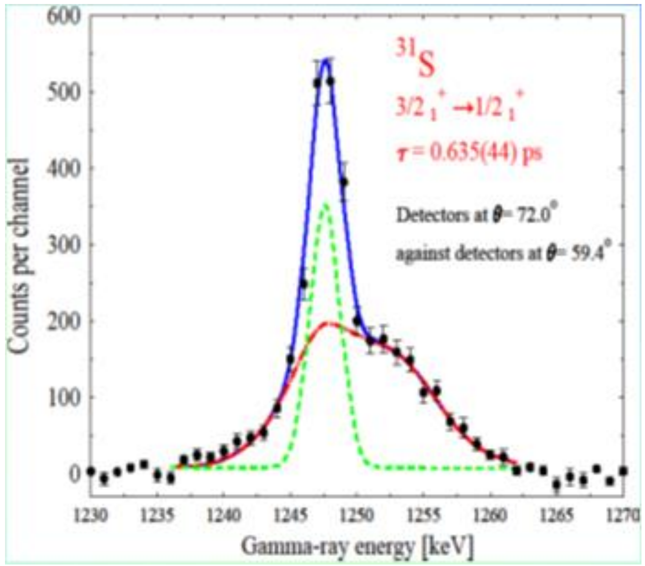

Figure 4 Example of the lineshape analysis of the 1164 keV gamma-ray transition and determination of the lifetime of the $I^{\pi} = 7/2_1^-$ in 31S. The spectrum measured with the detectors of an angle 108.0 deg with respect to the beam axis, the fit (full line) the DSA portion of the fit (dotted line) and the unshifted portion (dashed line) are presented.

Results and discussion.

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]. For example we could compare the value of the lifetime of the $3/2^+$ state reported in the literature [16] τ = 745(35) fs with the value derived by us of τ = 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 Ref. [6]. 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 [17]. 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 [17]. Within the frames of the errors the lifetimes of the $3/2_1^+$ 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 derives a shorter 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 [18] mirror pairs, most of the lifetimes in the nucleus with one proton more in the mirror couples have shorter lifetimes. This is the conclusion also for the lifetime values of $3/2_1^+$ in the A = 31 mirror nuclei.

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 $7/2_1^-$ excited state of ^{31}P we obtained a value which is not different from that reported in the literature, but its error is four times smaller. The value derived by us for the $7/2_1^-$ state of ^{31}S is different from that reported in the Ref. [2] value of 1.03(21) ps. We determined value of 543(35) fs.

Conclusions.

Using precisely determined branching ratios, multipole mixing ratios and lifetimes we could compare corresponding B(E1) values for the analog transitions depopulating the $7/2_1^-$ state of the A=31 mirror couple. The B(E1) value derived by us for the $7/2^-$ state of ^{31}S is 1.11 x 10e-3 +/- 0.8 x 10 E-4 W.u. which is about two and a half times larger than the already known value of 0.42 x 10e-3 +/- 0.2 x 10 E-4 W.u. characterizing the analog state in ^{31}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 [19] and A = 67 [20] 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 [20]. 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 [6].

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