Precise mass measurement of the ^{32}S member of the (A=32,T=2) quintet of analogue states

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Abstract. This contribution presents a precise measurement of the excitation energy of the lowest (0^+,T=2) state in ^{32}S. Combined with the mass excesses of the ^{32}S ground state and of the four other members of the (A=32,T=2) quintet of analogue states, it allows to test the validity of the Isobaric Multiplet Mass Equation to the third order in T_z, which renders it highly sensitive to the mechanisms inducing isospin mixing in the involved sd-shell nuclei. The (0^+,T=2) isobaric analogue state in ^{32}S was resonantly populated in the ^{31}P(p,γ) reaction at ∼3.3 MeV incident energy. The measurement procedure, involving high-purity germanium detectors, is described and the preliminary result obtained with a digital data acquisition system is presented.

1. Introduction

The Isobaric Multiplet Mass Equation (IMME) was proposed by E.P. Wigner in 1957 [1] in the framework of the isospin formalism introduced by W. Heisenberg in 1932 [2]. Treating the charge-dependent components of the nuclear Hamiltonian (dominated by the Coulomb interaction) in first-order perturbation theory, E.P. Wigner established a simple relationship (in black in Eq.1) between the masses of the isobaric analogue states belonging to a given isospin T multiplet:

$$E(T,T_z) = a + b\,T_z + c\,T_z^2 + d\,T_z^3 + e\,T_z^4 + \cdots \tag{1}$$

where T_z = (N-Z)/2 is the isospin projection along the z-axis. The cubic and higher-order terms of the expansion (in red in Eq.1) are usually neglected as their absolute values are typically lower than 10 keV, while the first three terms of the equation are larger than 140 keV [3].

The simplistic quadratic form of the IMME appears to be valid in most of the studied cases [3], which makes it a very powerful tool to predict with a precision of the order of 100 keV the masses of exotic nuclei that are difficult to access experimentally. The many applications of the IMME cover the fields of, e.g., astrophysics [4, 5], exotic radioactive decay modes [6], nuclear structure [7] and the modeling of nuclear interactions [8, 9]. On the other hand, the rare failure of the IMME evidences charge-dependent components of the nuclear forces, besides the Coulomb interaction, which can produce sizeable isospin mixing effects. Nowadays, 8 quintets of isobaric analogue states are known [3]. The (A=32,T=2) quintet, together with the (A=8,T=2) one, requires the inclusion of a cubic term in the IMME to restore its validity [10]. This anomaly

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triggered a number of studies pointing the mixing between the (0^+,T=2) state and (0^+,T=1) states in ^{32}Cl, ^{32}S and ^{32}P and between the (0^+,T=2) state and (0^+,T=0) states in ^{32}S [11, 12]. In the (A=32,T=2) multiplet, the $^{32}\mathrm{S}^{IAS}$ isobaric analogue state at $\sim$12 MeV excitation energy plays a peculiar role: because of its $T_z = 0$ value, its mass excess should be exactly equal to the first coefficient of the IMME. It provides therefore a strong constraint to the fit of the next leading terms. This is clearly shown by the reduced χ^2 value (χ^2/ndf) of the quadratic fit of the IMME. Indeed, the χ^2/ndf value of $\sim$32 decreases to $\sim$14 when reducing the mass excess of the $^{32}\mathrm{S}^{IAS}$ state by $5\,\sigma$. On the contrary, it increases up to $\sim$64 when the $^{32}\mathrm{S}^{IAS}$ mass excess is increased by $5\,\sigma$. The $1\,\sigma$ uncertainty on the currently adopted value is very small, of the order of 0.3 keV [3]. Owing to the high excitation energy of the state, an independent high-precision measurement of its value is therefore relevant and motivated the present work.

2. Experiment

The excitation energy of the (0^+,T=2) $^{32}\mathrm{S}^{IAS}$ state was determined following the procedure described in [10]. The latter work led to the most precise value known to date and is therefore used in the most recent compilation [3]. In our work, the state was resonantly populated in the ^{31}P(p,γ) reaction at the AIFIRA platform of the LP2iB laboratory, France [13], with a 2 to 4 μA, $\sim$3.3 MeV proton beam impinging on a 150 μg/cm^2 $\mathrm{Ni_2P}$ target supported by a 250 mg/cm^2 Ta foil. The excitation energy of the $^{32}\mathrm{S}^{IAS}$ state was derived from the measurement of the prompt high-energy γ-rays emitted in its decay, with three 40% high-purity germanium (HPGe) detectors. They were placed at a distance of 15 cm from the target, the latter being fixed to the end of the beam line. As shown in Fig.1, the HPGe detectors, were oriented at -90°, 0° and +90° with respect to the incoming-beam direction. The alignment of the detectors with respect to the beam axis was regularly checked with a laser system (not visible in the picture).

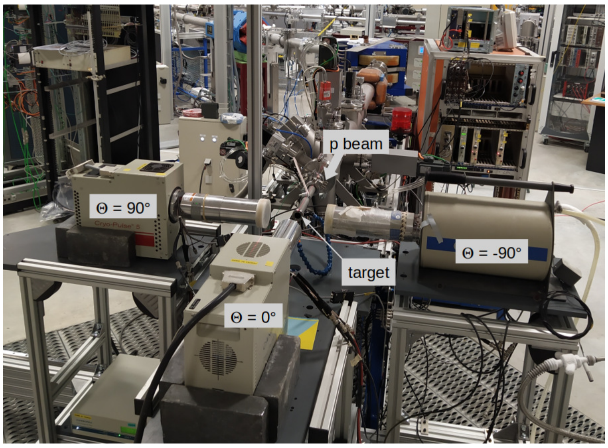

Figure 1. (Color online) Photo of the experimental setup constituted by three HPGe detectors surrounding the target.

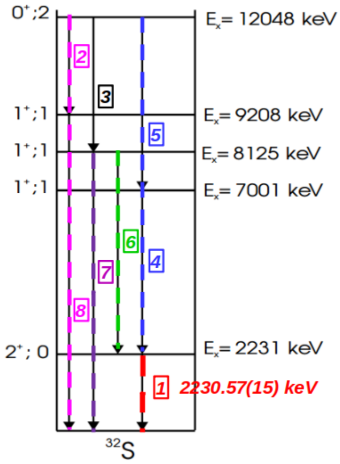

Figure 2. (Color online) Decay scheme of the $^{32}\mathrm{S}^{IAS}$ state, adapted from [10]. The γ transitions are labelled by increasing energy values (with $E_{\gamma 1}$ from [14]).

2.1. *Procedure*

As shown in Fig.2, the excitation energy of the $^{32}\mathrm{S}^{IAS}$ state can be deduced from the measurement of several cascading γ-rays with energies ranging from 2.2 (transition #1) to 9.2 MeV (#8). Four different decay paths, involving the transition sequences 1-4-5, 1-6-3, 7-3 and 8-2 lead to four independent evaluations of the energy of the state. The final result is obtained as the weighted average of the four values. In this work, two fully independent analog and digital (FASTER [15]) front-end electronics and data acquisition systems (DAQs) were used.

This allowed us to check the stability of the detector-response functions over the 10 days of data taking and to choose the most precise and reliable electronic chain.
Owing to the large energy range of interest, and to the high desired precision, the energy measurement of the individual γ-ray lines was performed following a dedicated procedure:

- the stability of the detector-response functions and the associated electronic systems was monitored online using a low-activity ^{56}Co calibration source placed in close vicinity of the irradiated target;
- on-line calibration runs, using well-known γ-rays from the ^{27}Al(p,γ), ^{23}Na(p,γ) and ^{35}Cl(n$_{th}$,γ) reactions, were regularly performed in between ^{31}P(p,γ) measurements;
- the temperature of the experimental room was monitored to possibly correct for systematic day-and-night effects on the data.

Fig.3 shows the superposition of γ-ray energy spectra obtained with the -90° HPGe detector for some selected runs and the digital DAQ. The γ-ray lines from the ^{32}S^{IAS} state are identified (labels 3 to 8). As can be seen in the figure, they are surrounded by high-intensity calibration lines, allowing one to precisely determine their energy (calibration over an appropriate energy range) and to monitor the stability of the detector-response functions from one run to another.

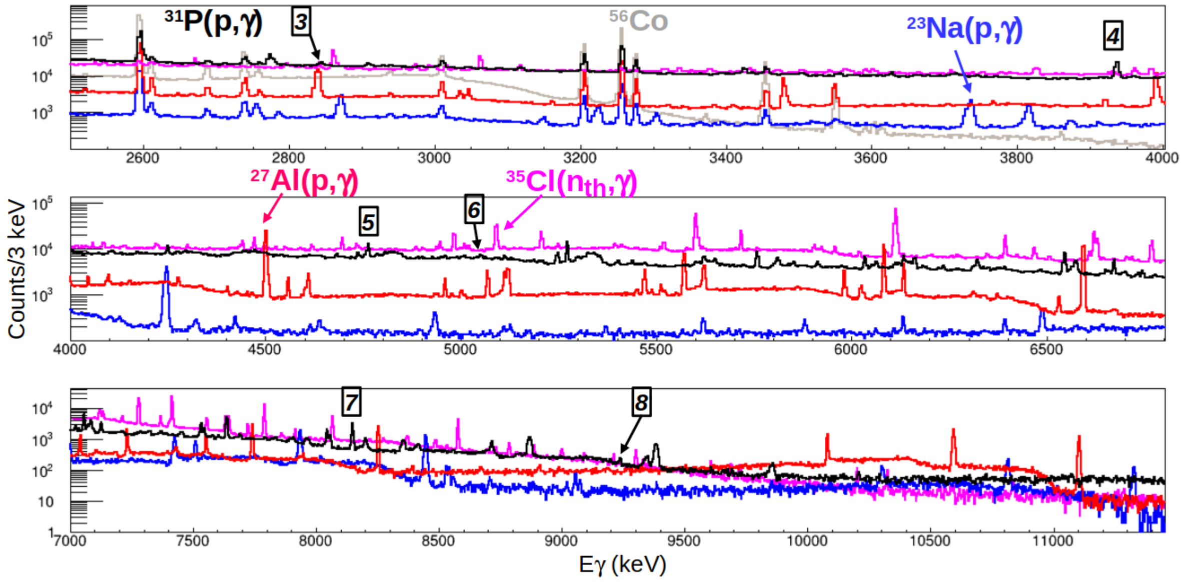

Figure 3. (Color online) Selection of γ-ray spectra obtained with the θ=-90° HPGe detector and the digital DAQ. Labels 3 to 8 refer ot the γ-ray lines from the ^{32}S^{IAS} state. The coloured spectra were obtained in (p,γ) and (n$_{th}$,γ) calibration runs.

The calibration lines, as well as the γ-ray lines from the ^{32}S^{IAS} state, were fitted following the procedure described in [16]: the fit function is the sum of a Gaussian, a shifted asymmetric-Gaussian on the lower energy side and either a second-degree polynomial or a smoothed step function to account for the background. The stability of the fit results over the entire duration of the experiment was checked: the centroids were found to be consistent with each other within ±0.2 keV at 2.2 MeV (transition #1) to ±2 keV at 9.2 MeV (transition #8) for the three detectors and the two DAQ data sets.

2.2. *Preliminary results*

The preliminary values of the ^{32}S^{IAS} state energies obtained with the three HPGe detectors and the digital DAQ are compared in Table 1 to those given in [10]. For each detector, the values derived from the four decay paths are consistent with each other. They lead to three independent weighted average values that are also consistent with each other within 1σ. It is worth noting that the 0°-detector data were corrected for the Doppler shift induced by the recoil of the nuclei produced in the (p,γ) reactions, which contributes up to $\sim$10 keV for the highest energy peaks. However, the weighted-average values systematically exceed by 2 keV the reference one from [10]. The preliminary value obtained in this work as the weighted average of the mean values from the three detectors is E(^{32}S^{IAS}) = 12050.34(27) keV, while the reference value is 12047.96(28) keV[10]. When combined with the mass excess of ^{32}S given in [3], the mass excess of the ^{32}S^{IAS} member of the (A=32,T=2) multiplet is -13965.19(27)keV. A quadratic fit to the IMME with the preliminary value obtained in this work gives a χ^2 of 198 for 2 degrees of freedom, nearly three times larger than the current one. Furthermore, a cubic fit does not restore the validity of the IMME. The failure of both the quadratic and cubic fits to the IMME for the (A=32,T=2) multiplet is unlikely and calls for further tests of the calibration procedure and a consistency check of the data sets taken with the two independent DAQs.

Table 1. Comparison of the ^{32}S^{IAS} state energies obtained with the three HPGe detectors and the digital DAQ to those given in [10].

Decay sequence	[10]	This work θ=-90°	 θ=0°	 θ=+90°
1-4-5	12047.96(53)	12050.30(76)	12049.26(104)	12050.00(91)
1-6-3	12048.10(35)	12050.10(104)	12050.60(80)	12050.64(94)
7-3	12047.86(28)	12049.95(83)	12050.37(72)	12050.86(84)
8-2	12048.01(72)	12049.82(200)	12052.25(163)	12050.92(167)
Average	12047.96(28)	12050.11(48)	12050.38(45)	12050.55(49)

Conclusion

The (0$^+$,T=2) isobaric analogue state in ^{32}S was resonantly populated in ^{31}P(p,γ) reactions. Three HPGe detectors were used to determine its excitation energy from the measurement of the prompt high-energy γ-rays emitted in its decay. A precision of $\sim$0.3 keV, comparable to the most precise value reported in the literature, was achieved thanks to an online monitoring and dedicated (p,γ) and (n$_{th}$,γ) calibration reactions. The preliminary value, significantly larger than the adopted one, requires a more careful check of the calibration procedure and a comparison to the value given by the independent analog electronics during the same experiment.

Acknowledgments

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