

## Study of the neutron rich sulfure isotope $^{43}\text{S}$ through intermediate energy Coulomb excitation

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**Abstract.** The reduced transition probability  $B(E2: 3/2^- \rightarrow 7/2^-_2)$  has been measured in  $^{43}\text{S}$  using Coulomb excitation at intermediate energy. The nucleus of interest was produced by fragmentation of a  $^{48}\text{Ca}$  beam at GANIL. The reaction products were separated in the LISE spectrometer. After Coulomb-excitation of  $^{43}\text{S}$  in a  $^{208}\text{Pb}$  target, the  $\gamma$  rays emitted in-flight were detected by 64  $\text{BaF}_2$  detectors of the Château de Cristal array. The preliminary value deduced for the reduced transition probability  $B(E2: 3/2^- \rightarrow 7/2^-_2)$  is in agreement with the predictions of the shell model calculations and supports a prolate-spherical shape coexistence in the  $^{43}\text{S}$  nucleus.

### 1. Motivation

The structure of atomic nuclei near the line of beta stability can be understood in terms of the shell model assuming a modified harmonic oscillator nuclear potential with a spin-orbit interaction. One of the greatest successes of this model was the reproduction of the magic numbers at 2, 8, 20, 28, 50, 82 and 126 observed in the stable nuclei. Nuclei with magic numbers have a closed shell configuration, and are characterized by a large  $2^+_1$  excitation energy and low  $B(E2: 2^+_1 \rightarrow 0^+_1)$  reduced transition probability. The universality of the properties of nuclei with neutron magic has been questioned in the last decades as a result of the new experimental observations provided by the radioactive beam facilities.

At  $N=28$ , there is a large drop of the excitation energy of the first  $2^+$  state from  $^{48}\text{Ca}$  to  $^{42}\text{Si}$  (from 3832 keV to 770 keV) revealing a strong change in their structure, which has been ascribed to a reduction of the  $N=28$  shell gap combined with the degeneracy of the proton  $s_{1/2}$  and  $d_{3/2}$  orbitals. In order to prove the reduction of the shell gap, it is necessary to understand the evolution of the single particle energy levels involved in this region of the nuclear chart and to determine where the deformed intruder configurations obeying deformation become the ground state of the  $N = 28$  isotones.

Recent results on the structure of the  $N=28$  sulfur isotone  $^{44}\text{S}$  [1, 2, 3] were interpreted as indications of shape coexistence at low excitation energy in this nucleus. Different theoretical approaches provide different interpretations for the type of shape coexistence: prolate - spherical shape coexistence is predicted in the shell model approach, while mean-field calculations consider a wide configuration mixing [4].

Spectroscopic information on the  $N=27$  nucleus  $^{43}\text{S}$  is of special interest, as it can be used to deduce information on the shape of the nucleus in different neutron configurations and on the predicted competition between spherical and deformed configurations.

First experimental results regarding the structure of  $^{43}\text{S}$  were obtained by Ibbotson et al. [5] in a Coulomb excitation experiment, which revealed the presence of a level at around 940 keV excitation energy. From the excitation cross section Ibbotson deduced  $175(69) \text{ e}^2\text{fm}^4$  for the reduced transition probability of this transition. In addition, an isomeric state at 319 keV [6] with a lifetime of 475(48) ns and a reduced transition probability to the g.s. of  $352 \text{ e}^2\text{fm}^4$  was extracted. This value suggest an E2 transition type between the isomeric state and the ground state. Magnetic moment measurements by Gaudefroy et al. [7] confirmed a spin and parity of  $7/2^-$  for the isomeric state and a spin and parity of  $3/2^-$  was assigned to the ground state. Within the shell model framework, these spectroscopic data are interpreted as the result of the progressive reduction of the  $N = 28$  shell gap and the increase of correlation energy going from stability toward exotic nuclei.

The present experiment aimed to re-measure the reduced transition probability  $B(E2: 3/2^- \rightarrow 7/2^-_2)$ . This observable provides direct information on the deformation of the states. Additionally, we expected to populate higher spin states which will give access to additional information regarding the structure of  $^{43}\text{S}$ .

## 2. Experimental set-up.

A schematic picture of the experimental set-up is shown in Figure 1. The nuclei of interest were produced by fragmentation of a  $^{48}\text{Ca}^{19+}$  primary beam of 60 MeV/u energy with an average intensity of  $\sim 4 \mu\text{A}$  impinging on a  $145 \mu\text{m}$  Be target. The produced fragments were separated by means of the  $B\rho-\Delta E-B\rho$  method [8] in the LISE3 spectrometer, and their energies were determined in terms of their magnetic rigidity values. At the final focal plane of the spectrometer two position sensitive detectors were placed in order to reconstruct the trajectories of the incoming ions [9]. These detectors were also used for the Time-of-Flight (TOF) measurement with respect to the cyclotron radio-frequency. Afterwards, the selected and identified nuclei were excited in the Coulomb field of a lead target of  $200 \text{ mg.cm}^{-2}$  thickness.

After passing the lead target, the nuclei that suffered Coulomb excitation were scattered into a  $500 \mu\text{m}$  thick round shape Double Sided Silicon Strip Detector (DSSSD) [10], which had a central hole of 3 cm diameter. It consisted of four quadrants with 16 annular strips of 1.9 mm width and 2 mm pitch on the front side and 8 radial strips at  $3.4^\circ$  pitch on the back side. The inter-strip distance was  $100 \mu\text{m}$ . This detector was mounted at a distance of 41.2 cm from the secondary target. In this way the DSSSD covered angles from  $1.5$  to  $6.5^\circ$  in the laboratory frame. This angular covering ensures that nuclei up to the grazing angle of the reaction are detected. The scattered ions were identified in an event-by-event basis by the combined measurement of  $\Delta E$  and the TOF in the DSSSD (Figure 2). The DSSSD was followed by a residual energy detector, which consisted of four non-segmented silicon quadrants of  $1500 \mu\text{m}$  thickness, which ensured that all particles that emerge from the DSSSD were stopped in its active area.

The nuclei that suffered Coulomb excitation, de-excited in flight by emission of  $\gamma$ -rays. 65 hexagonal BaF<sub>2</sub> crystals of the Château de Cristal were placed in a close geometry surrounding the secondary target. The  $\gamma$ -ray efficiency was determined to be 31% at 1274 keV, allowing for performing a coincidence measurement of the prompt  $\gamma$ -radiation and the ion identified in the DSSSD. The energy resolution was 11% and a time resolution of  $\sim 1$  ns was obtained.

Nuclei that passed through the central hole of the DSSSD-PAD telescope were identified in an ionization chamber through the measurement of their energy loss, and came to rest in a plastic scintillator mounted at 0 degrees downstream. Two HP Ge detectors were placed surrounding the implantation setup in order to detect the delayed gamma transitions corresponding to the decay of the isomeric states populated in the fragmentation reaction at the entrance of the spectrometer and survived the flight path through LISE.

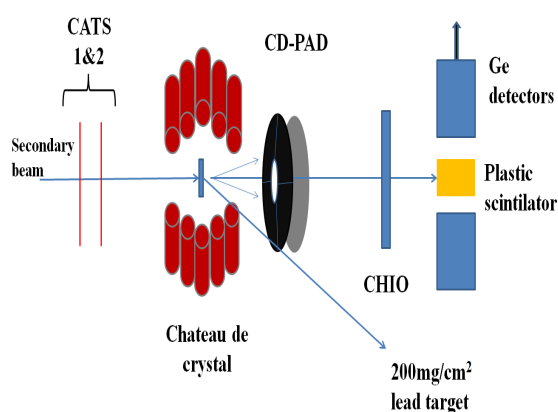


Figure 1: Schematic picture of the experimental Set-up

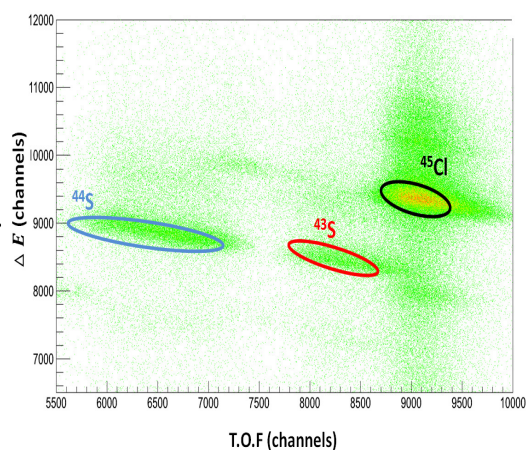


Figure 2:  $\Delta E$  in one quadrant of the DSSSD vs. TOF identification plot

### 3. Preliminary results

The first nucleus investigated was the <sup>44</sup>Ca due to the high probability of its production and its good selection by the LISE spectrometer. In addition, the reduced transition probability  $B(E_2:0^+_1 \rightarrow 2^+_1)$  is well known in this nucleus [11], thus it can be used for normalization in the relative determination of other  $B(E_2)$  values. Moreover, the transition of 1157 keV from <sup>44</sup>Ca was also used to determine the effective angle of each of the Château de Cristal detectors, necessary to have an accurate Doppler correction. In Figure 3, the singles spectrum obtained without (a) and with (b) Doppler correction for a <sup>44</sup>Ca beam is shown. These spectra have been obtained by gating on the <sup>44</sup>Ca ions identified in the DSSSD detectors and requiring that the time difference between detected ion and the  $\gamma$ -ray emission is maximum 5 ns. In addition, only events with  $\gamma$ -ray multiplicity one were taken into account.

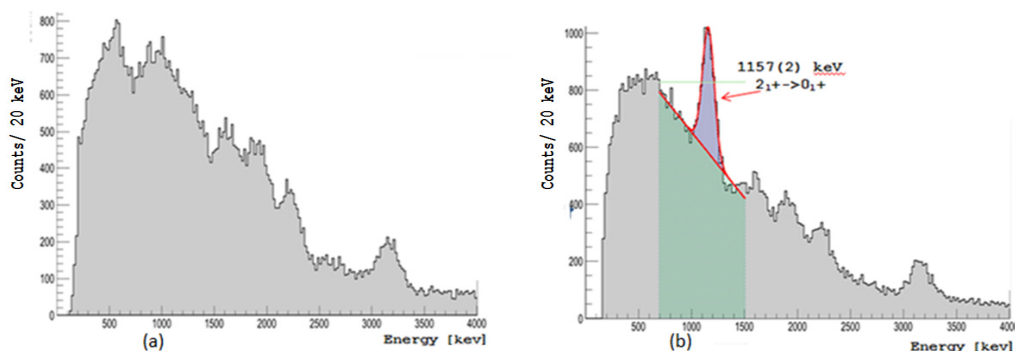


Figure 3: <sup>44</sup>Ca spectrum from the whole Chateau de Crystal.  
 (a) without Doppler correction, (b) Doppler corrected spectrum

Similarly to the  $^{44}\text{Ca}$  spectrum, the spectrum associated with the Coulomb excitation of  $^{43}\text{S}$  was also extracted and is presented in Fig. 4. Two  $\gamma$ -rays resulting from  $7/2_1^- \rightarrow 3/2^-$  and  $7/2_2^- \rightarrow 3/2^-$  transitions with the energies of 319 keV and 920 keV can be clearly seen.

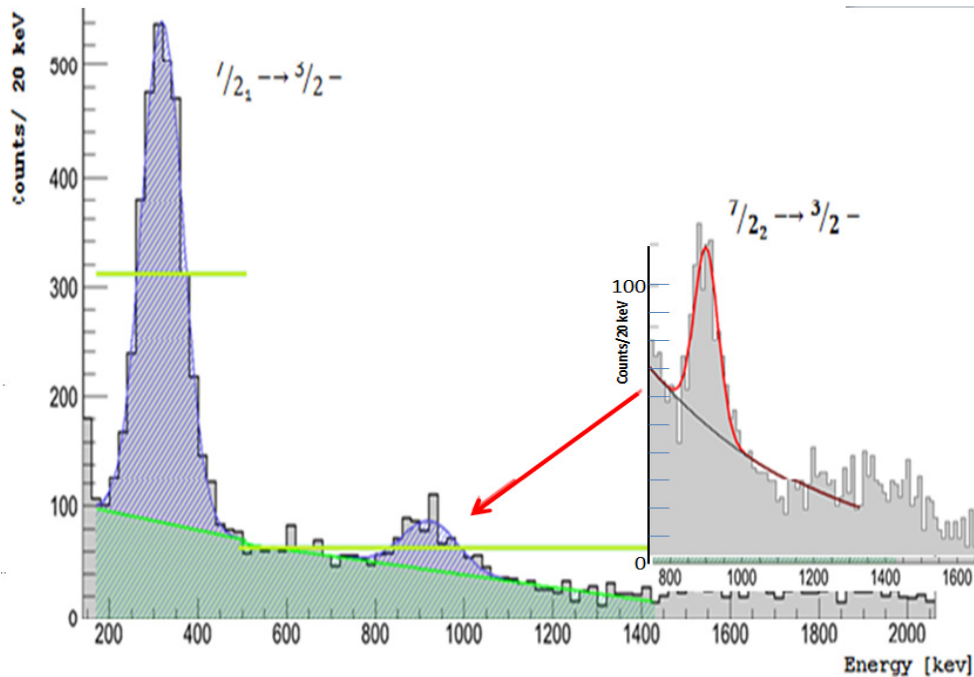


Figure 4: Coulomb excitation singles spectrum of  $^{43}\text{S}$

The number of counts in the 926 keV peak were determined by fitting a Gaussian plus an exponential background function the single spectra. Using the known reduced transition probability  $B(E2:0_1^+ \rightarrow 2_1^+)$  from  $^{44}\text{Ca}$ , a preliminary value of  $257(27) e^2\text{fm}^4$  was obtained for the reduced transition probability  $B(E2:7/2_2^- \rightarrow 3/2^-)$  in  $^{43}\text{S}$ .

Following work will consist of implementation of the adback algorithm between the  $\text{BaF}_2$  detectors, which will reduce the background in the  $\gamma$ -ray spectrum and increasing the statistics for the transitions of interest. Therefore, a more accurate value of the  $B(E2)$  reduced transition probability will be extracted.

The large yield of the 319 keV transition in the prompt  $\gamma$ -ray spectrum is under study in order to establish if its decay is compatible with previous measurements.

#### 4. Conclusions

The preliminary value for the transition probability  $B(E2: 3/2^- \rightarrow 7/2_2^-)$  of  $257(27) e^2\text{fm}^4$  has been deduced. This value is larger than the previous one obtained by Ibbotson et al. [5] and further support the presence of deformation in  $^{43}\text{S}$ . Further work will focus on the implementation of the adback routine to reduce the uncertainties of the  $B(E2)$  values and on a detailed analysis of the origin of the observed prompt 319 keV transition.

## 5. Acknowledgments

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