PHYSICAL REVIEW C **94**, 044316 (2016)

Lifetime measurement of the first excited state in ^{37}S

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(Received 27 June 2016; revised manuscript received 14 September 2016; published 19 October 2016)

Lifetime of the $3/2^-$ first excited state in ^{37}S populated by the β^- decay of ^{37}P has been measured using β-γ delayed coincidence technique. The $B(E2; 7/2^- \rightarrow 3/2^-)$ value in ^{37}S deduced from the lifetime comes close to the $B(E2; 0^+ \rightarrow 2_1^+)$ value in weakly deformed ^{38}S but deviates significantly from that in spherical ^{36}S. This manifests that ^{37}S is a weakly deformed rather than spherical nucleus.

DOI: 10.1103/PhysRevC.94.044316

I. INTRODUCTION

One of the primary issues in nuclear physics focuses on the interplay between single-particle and collective degrees of freedom, which is a manifestation of the many-body nature of the atomic nucleus [1,2]. Odd-A nuclei outside the semimagic core offer an excellent testing ground to investigate the competition between single-particle and core collective excitations. In this work, our attention is paid to the $N = 21$ isotones.

We have noticed that the energy of the $3/2^-$ first excited state along the $N = 21$ isotones undergoes a variation (see Fig. 1). It reaches a minimum value of 646 keV in ^{37}S. The $3/2^-$ state involves either the odd neutron excitation across the $N = 28$ shell gap or the break-up of the inert ^{36}S core. Since both the $f_{7/2} \rightarrow p_{3/2}$ excitation and the core breaking require considerable costs in energy, the minimum is beyond general expectation. The abnormality can be explained in two essentially different ways.

On the one hand, this phenomenon can result from the collapse of $N = 28$ shell gap between $f_{7/2}$ and $p_{3/2}$ single-particle orbitals [4]. The proton-neutron interactions between $\pi(d_{3/2}, s_{1/2})$ and $\nu(p_{3/2}, f_{7/2})$ orbitals account for reducing the size of the $N = 28$ gap. The interaction strength can be derived from the energy changes of the first excited states from ^{41}Ca to ^{35}Si. The reduction of $N = 28$ closure δG caused by the removal of one pair of protons from the $d_{3/2}$ orbital can be written in the first order as $\delta G = 2(V^{pn}_{d_{3/2}p_{3/2}} - V^{pn}_{d_{3/2}f_{7/2}})$, which amounts to 649 keV extracted from the differential energy change of the $3/2^-$ states from ^{41}Ca to ^{37}S [4]. Similarly, the two protons added to the $s_{1/2}$ orbital between ^{35}Si and ^{37}S induce a shell gap reduction $\delta G = 2(V^{pn}_{s_{1/2}p_{3/2}} - V^{pn}_{s_{1/2}f_{7/2}}) =$ 264 keV [4].

On the other hand, the $3/2^-$ state in ^{37}S can be formed by coupling the odd neutron at $f_{7/2}$ Fermi level to the 2_1^+ core. Therefore, the $3/2^-$ level energy is associated with the 2_1^+ excitation in the core. If the core is deformed and the 2_1^+ excitation is low in energy, one expects a $3/2^-$ low-energy state. Actually, two $\nu f_{7/2}$ particle-two hole intruder configuration may result in the low-energy 2_1^+, like the case in the semi-magic nucleus ^{32}Mg [5–7]. Taking the energies of $(\nu f^3_{7/2})_{7/2^-}$ and $(\nu f^3_{7/2})_{3/2^-}$ states in ^{43}Ca into account, one expects that the energy difference between $3/2^-$ and $7/2^-$ intruder states with three $f_{7/2}$ neutrons in ^{37}S can be about 593 keV [3].

To shed light on which mechanism is more likely to be responsible for lowering the $3/2^-$ state in ^{37}S, we have to know the reduced electric quadrupole transition probability, $B(E2)$ value, from the ground state $(7/2^-)$ to the first excited state $(3/2^-)$, which directly reflects the degrees of single-particle and collective excitations. For ^{37}S, its low-excitation level structure was studied by β^- decay of ^{37}P [8] and (d,p) transfer reaction of ^{36}S [9–11], and its shell-model description was presented in Ref. [12]. Recently, the particle-core coupling in ^{37}S was investigated using binary grazing reactions produced by the interaction of ^{36}S beam with ^{208}Pb target [13]. However, the $B(E2; 7/2^- \rightarrow 3/2^-)$ value has not been reported so far. The aim of the present work is to extract the $B(E2; 7/2^- \rightarrow 3/2^-)$ value by measuring the lifetime of $3/2^-$ state in ^{37}S.

II. EXPERIMENT

The experiment was carried out at the Radioactive Ion Beam Line at the Heavy Ion Research Facility in Lanzhou (HIRFL-RIBLL1) [14]. The ^{40}Ar primary beam at $70A$ MeV was supplied to bombard a ^{9}Be target with a thickness of 987μm. The secondary beam of ^{37}P at $39A$ MeV and with an intensity of about 900 pps and a purity of about 80% was separated and purified by RIBLL1. The low excited states of ^{37}S were populated by the β^- decay of ^{37}P.

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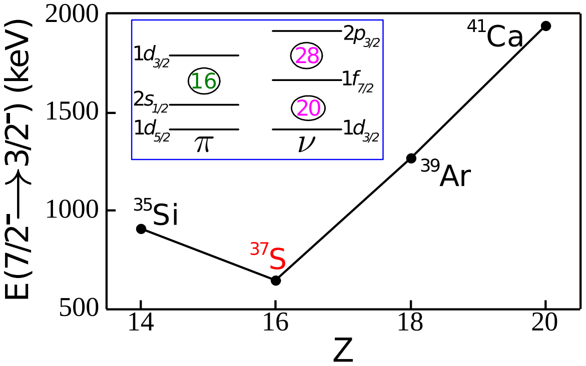

FIG. 1. Schematic representation of the energies of the first excited states in the $N = 21$ isotones [3]. The insert indicates the relevant single-particle orbitals of proton and neutron.

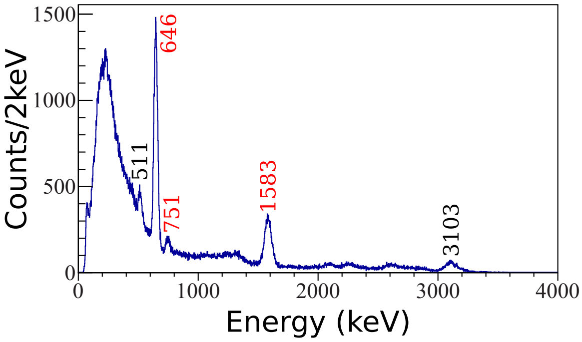

FIG. 2. Total projected spectrum of γ rays measured by $\mathrm{LaBr_3}$ detectors. The full energy peaks of de-excited γ rays of ^{37}S is marked by red numbers. The 3103-keV γ ray comes from ^{37}Cl following the β^- decay of ^{37}S.

The detection system was introduced as follows. The single silicon detector (SSD) with a thickness of 1 mm and 50×50 mm^2 active area was used as a deposition of the secondary beam. The β particles were detected by a 50 mm diam. × 3 mm EJ212 plastic scintillator (PS) coupled to the Hamamatsu R2083 photomultiplier tube (PMT), at a distance of about 5 mm from the SSD. The energy calibration of PS detector using ^{207}Bi standard β source showed that the thickness can assure an absorption about 700 keV from β rays passing through the PS. The resulting signal was sufficient to provide excellent timing and to maintain a detector response independent of β-ray energy for $E_\beta \geqslant 1.5$ MeV [15]. The γ rays were detected by two fast timing 50 mm diam. × 75 mm $\mathrm{LaBr_3}$:Ce scintillators (hereinafter referred to as $\mathrm{LaBr_3}$) coupled to the Hamamatsu R9779 PMTs, positioned at 90° to the beam axis. The energy resolutions of $\mathrm{LaBr_3}$ detectors were about 30 keV at full width at half-maximum (FWHM) for the 662-keV γ ray of ^{137}Cs. A typical β-γ timing resolution was about 200 ps FWHM at 1332 keV of a ^{60}Co source, while a typical γ-γ timing resolution was about 280 ps FWHM at 1173 keV and 1332 keV of the ^{60}Co source. Two HPGe detectors, with energy resolutions of about 2.3 keV at FWHM for the 1332.5-keV γ ray, were used to identify the characteristic γ rays and deduce the γ-ray coincidence relations.

Events has been collected when PS detector was fired. Approximately 7.4×10^9 β-γ coincidence events were recorded. The lifetime of $3/2^-$ state in ^{37}S was measured by β-γ fast timing coincidence technique [15,16].

III. EXPERIMENTAL RESULTS

The gating energy window for β particles was centered at about 800 keV with $\Delta E/E \simeq 60\%$ [15]. All γ rays coincident with β particles reported in the Ref. [8] have been observed in our experiment. Moreover, from the γ-γ coincidence relations and relative intensities, we found that there is an evident coincidence for 1583-keV γ ray with 646-keV one rather than 751-keV one, which confirms the level scheme of ^{37}S proposed by Warburton and Becker [12].

The total spectrum of γ-ray energy detected by $\mathrm{LaBr_3}$ detectors is presented in Fig. 2. All the γ rays of interest, i.e., 646, 751, and 1583 keV, can be seen clearly in the spectrum. The time spectra by gating on β ray with the 1583-, 751-, and 646-keV γ rays are illustrated in Fig. 3. By comparing delayed and prompt time spectra, one can clearly see that there is a long lifetime for the 646-keV ($3/2^-$) level (see bottom panels of Fig. 3). Meanwhile, the β and 751-keV or 1583-keV γ time spectra indicate no existence clue of measurable lifetimes for the corresponding levels above the $3/2^-$ state in energy. Therefore, the indirect feedings from higher levels do not introduce significant errors for lifetime determination of 646-keV level. The lifetime is extracted by fitting the whole time spectrum using the convolution method expressed as [17]

$$F(t) = N_0 \int_{t_0}^{+\infty} \frac{1}{\sqrt{2\pi}\sigma} e^{-(t-t')/2\sigma^2} \frac{1}{\tau} e^{-(t'-t_0)/\tau}\, dt'$$
$$= \frac{N_0}{2\tau} e^{-\frac{t-t_0}{\tau}} e^{\frac{\sigma^2}{2\tau^2}} \left[1 - \mathrm{erf}\left(\frac{\sigma}{\sqrt{2}\tau} - \frac{t-t_0}{\sqrt{2}\sigma}\right)\right]. \quad (1)$$

This expression is the convolution of Gaussian prompt function and exponential decay function, where N_0 is the normalization

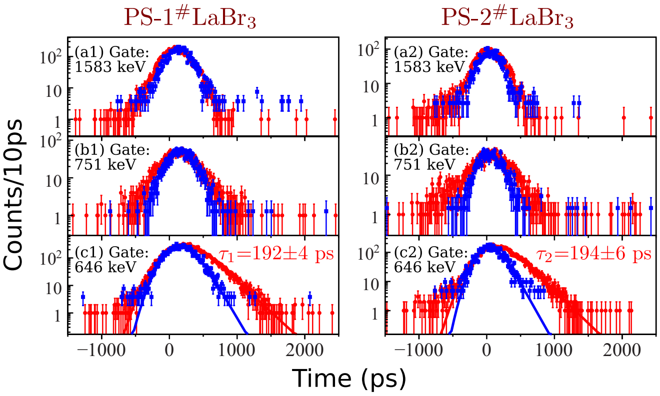

FIG. 3. The delayed time spectra (red markers and lines) of coincident β and (a) 1583-, (b) 751-, and (c) 646-keV γ rays; the β-γ prompt time spectra (blue markers and lines) from ^{60}Co source providing a reference standard.

constant, σ is the width of Gaussian prompt distribution, t_0 is the centroid of Gaussian function, $\mathrm{erf}(\cdots)$ is the error function, and the lifetime is referred to as τ. It is worth mentioning that the convolution method is useful for the longer-lifetime state with the low limit 105 ps, which results from fitting the prompt spectra, for our experimental setups [15]. The fitting results of two delayed time spectra shown in bottom panels of Fig. 3 are consistent with each other. The lifetime of the 646-keV level in ^{37}S is obtained as the weighted average of the two results: $\tau = 193(4)$ ps.

The $B(E2; 7/2^- \to 3/2^-)$ value in unit of $e^2\mathrm{fm}^4$ is calculated by the formula

$$B(E2)\uparrow = \frac{8.162\times 10^{17}}{(1+\alpha_T)(E_\gamma)^5\tau}\frac{2J_f+1}{2J_i+1}, \qquad (2)$$

where τ, E_γ, α_T, J_f, and J_i are the mean lifetime in ps, the γ-ray energy in keV, the total conversion coefficient taken from BrIcc [18], angular momenta of final and initial levels, respectively. The $B(E2)$ value in W.u. (Weisskopf units), is also introduced to extract the information of collective quadrupole motion relative to single-particle model. $B(E2)$ in W.u. is the ratio of $B(E2)\uparrow$ value in $e^2\mathrm{fm}^4$ to the Weisskopf $B(E2)\uparrow$ value given by

$$B(E2)\uparrow_{(S.P.)} = 5.94\times 10^{-2}A^{4/3}\frac{2J_f+1}{2J_i+1}e^2\mathrm{fm}^4, \qquad (3)$$

where A denotes the mass number. According to Eqs. (2) and (3), the reduced electric quadrupole transition probability in ^{37}S is $B(E2; 7/2^- \to 3/2^-) = 18.78(40)\ e^2\mathrm{fm}^4 = 5.13(11)$ W.u..

IV. DISCUSSION

Taking into account the spherical shape of ^{36}S [19] and weakly deformed shape of ^{38}S [20], one expects that ^{37}S should be located in between. In fact, the $B(E2; 7/2^- \to 3/2^-)$ value in ^{37}S differs greatly from the $B(E2; 0^+ \to 2_1^+)$ value of $2.51(^{+25}_{-15})$ W.u. in ^{36}S [21] and approaches that of 6.19(79) W.u. in ^{38}S [21]. It means that ^{37}S is deformed to some extent. Therefore, except for single-particle excitation, collective excitation is indispensable for ^{37}S. The question mentioned in Sec. I naturally comes out: which excitation mode is dominated for the $7/2^-$ and $3/2^-$ states?

To answer this question, we resort to some simple calculations as follows. In the two-configuration way, the wave functions of $7/2^-$ and $3/2^-$ states can be written as

$$\begin{aligned}|7/2^-\rangle &= \sqrt{\alpha}|7/2^-\rangle_s + \sqrt{1-\alpha}|7/2^-\rangle_i,\\ |3/2^-\rangle &= \sqrt{\alpha}|3/2^-\rangle_s + \sqrt{1-\alpha}|3/2^-\rangle_i,\end{aligned} \qquad (4)$$

where α and $1-\alpha$ denote the mixing amplitudes of single-particle and collective intruder configurations signed with the subscripts s and i, respectively. For the reason of simplicity, we assume the same form of wave functions for $7/2^-$ and $3/2^-$ states. We adopt the approximation used in Refs. [22,23] to obtain the mixing parameter from the reduced electric quadrupole transition probability:

$$B(E2) = [\alpha\sqrt{B_s(E2)} + (1-\alpha)\sqrt{B_i(E2)}]^2, \qquad (5)$$

where the reduced probabilities $B_s(E2)$ and $B_i(E2)$ of single-particle and collective transitions can be extracted from the neighboring nuclei.

Fortunately, we can get the smaller $B(E2; 7/2^- \to 3/2^-) = 2.62(70)$ W.u. in ^{35}Si than that in ^{37}S as the single-particle transition approximation [24]. As for collective transition probability, the $B(E2; 7/2^- \to 3/2^-) = 11.7(9)$ W.u. in ^{31}Mg is, to the extent of our knowledge, the only known value of the transition between the $7/2^-$ and $3/2^-$ intruder states in the nearby nuclei of ^{37}S in experiment [3,25,26]. Finally, from Eq. (5), we deduce that the percentage of single-particle component is $\alpha \simeq 64\%$ and that of collective intruder-state component is $1-\alpha \simeq 36\%$.

The deduced constitution can be examined by the previous results of (d,p) reactions and shell-model calculations. It is well known that (d,p) reactions may gain an insight into the distribution of the single-particle strength, i.e., spectroscopic factor (SF). The $^{36}\mathrm{S}(d,p)^{37}\mathrm{S}$ reaction showed that the $7/2^-$ ground state was populated in $f_{7/2}$ neutron transfer with an average amplitude 0.73 [9–11]. Similarly, 55% of the $p_{3/2}$ single-neutron strength was located in the $3/2^-$ first excited state at 646 keV, while the $3/2^-$ state at 3262 keV carried about 10% of the sum-rule limit [9–11,13]. The single-particle components are consistent with our results. The residual parts, after subtracting the contributions from $f_{7/2}$ and $p_{3/2}$, can be assumed as coming from the intruder states. The average strength of the intruder states obtained by the approximation $\sqrt{(1-0.73)(1-0.55)} = 35\%$ provides a support for our conclusion. In addition, shell-model calculations can give the wave functions of energy levels. The $7/2^-$ and $3/2^-$ states were found to be $\pi(d_{5/2})^6(s_{1/2})^2 \bigotimes \nu(f_{7/2})$ and $\pi(d_{5/2})^6(s_{1/2})^2 \bigotimes \nu(p_{3/2})$ with the amplitudes of 70% and 63%, respectively [13], which are also in good agreement with our conclusions. However, the residual parts of the wave functions were not intruder components any more [13]. The reason is obvious since the valence protons and neutrons were confined in the sd and pf shells and certainly unable to give the intruder states. The suggested $3/2^-$ and $7/2^-$ intruder states lay at 1992 and 2023 keV [12,13]. If they are true, the intruder states are considerably low in energy and may strongly mix with the normal states. Therefore, it is not surprising that the first $7/2^-$ and $3/2^-$ states contain a certain degree of intruder components.

Now let us examine the systematics of level structures along the $N = 21$ isotones. The very close $B(E2; 7/2^- \to 3/2^-)$ and SF values in ^{41}Ca and ^{37}S reflect that the $7/2^-$ and $3/2^-$ states have a similar intrinsic structure in both nuclei [3,27]. Likewise, the $7/2^-$ and $3/2^-$ levels in ^{41}Ca were described as the mixtures of single-particle and deformed states [28–30]. However, ^{35}Si does not obey this systematics. The discrepancy is embodied in the resultant small $B(E2; 7/2^- \to 3/2^-)$ value from the large intruder-state strength for ^{35}Si if taking into account the small SF values [11,24]. An explanation of this abnormality is that the transition between the $7/2^-$ and $3/2^-$ intruder components is partly forbidden.

V. SUMMARY

The lifetime of the $3/2^-$ state in ^{37}S from the β decay of ^{37}P has been determined by the β-γ delayed coincidence technique for the first time. The $B(E2; 7/2^- \rightarrow 3/2^-)$ value of ^{37}S is derived as 5.13(11) W.u. from the lifetime of 193(4) ps. It is found that the $B(E2; 7/2^- \rightarrow 3/2^-)$ value of ^{37}S is close to the $B(E2; 0^+ \rightarrow 2_1^+)$ of ^{38}S with small deformation but is far from that of ^{36}S with spherical shape. From the calculations with the $B(E2)$ values, we argue that the $7/2^- \rightarrow 3/2^-$ excitation can be described as the mixture of a major single-particle and a certain amount of ^{36}S core's intruder collective excitations. The ^{37}S is proved as a weakly deformed nucleus. Of course, the small energy of the $3/2^-$ level in ^{37}S compared with those in ^{35}Si, ^{39}Ar, and ^{41}Ca is attributed to these two excitation modes.

ACKNOWLEDGMENTS

The authors are grateful to the staff in HIRFL-RIBLL1 for their technical and operation support during the experiment. This work was supported by the National Basic Research Development Program of China (Grant No. 2013CB834403) and the National Natural Science Foundation of China (Grants No. 11305220, No. 11179016, and No. 11205207).

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