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Short Note

The β-delayed one- and two-proton emission of ^{27}S

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Abstract. In an experiment performed at the GANIL LISE3 facility, radioactive ^{27}S isotopes have been produced by projectile fragmentation of a 95 AMeV ^{36}Ar primary beam. After selection by means of the LISE3 separator, the isotope of interest was implanted in a silicon-detector telescope where its half-life ($T_{1/2} = 15.5(15)$ ms) and its main decay branches were measured.

PACS. 21.10.-k Properties of nuclei; nuclear energy levels – 23.40.-s Beta decay; double beta decay; electron and muon capture – 23.50.+z Decay by proton emission

Neutron-deficient nuclei very far from the valley of stability are characterized by large Q_β-values and therefore a large number of daughter states can be reached by β^+ emission. In particular, the isobaric analog state (IAS) can be fed by superallowed β-decay in nuclei with $T_Z \leq 0$. In these daughter nuclei, the particle separation energy becomes so low that the IAS might decay by β-delayed multi-particle emission. For example, in the $T_Z = -5/2$ nuclei (^{23}Si, ^{27}S, ^{31}Ar, ^{35}Ca, ^{39}Ti and ^{43}Cr) the β-delayed two-proton emission has been found as a rather strong decay mode.

Intermediate-energy beams available at GANIL offer the possibility to produce very proton-rich nuclei in sufficient amounts to perform decay spectroscopy measurements after implantation. The present work reports on a new study of the decay modes of ^{27}S.

Provided by the GANIL facility, a 2 μA ^{36}Ar^{18+} beam at 95 AMeV bombarded a 357 mg/cm^2 thick carbon target in the SISSI device. After fragmentation, isotopes of interest were selected by the Alpha and LISE3 spectrometers [1] (beryllium degrader of 1062 μm) which allows to get relatively pure secondary beams. However, for very exotic nuclei with low production rates, the contaminants may be as strong as the selected isotopes or even stronger. At the final focus of LISE3, transmitted fragments are stopped in a silicon-detector telescope represented schematically in fig. 1. The germanium clover detector allowed to measure γ-rays in coincidence with β-particles and/or protons. This setup has yielded a γ efficiency of 1.5% at 1.3 MeV. For β or $\beta\gamma$ events, the trigger efficiency depends on the efficiency to detect β-particles which was about 40%, whereas for β-delayed one-proton or two-proton emission the efficiency was close to 100%. The isotopes have been identified on a ΔE-TOF matrix, the energy loss ΔE being measured by means of the silicon detectors and TOF being the time of flight between the production target and the detectors. The TOF has been started in the usual way by the silicon detector E1 and stopped by the cyclotron radiofrequency.

The production rate for ^{27}S was about 1.1 isotopes per second with contaminations from ^{26}P (10%), ^{25}Si (45%), ^{24}Al (150%), and ^{23}Mg (150%). The setting on ^{27}S lasted about 2.5 hours and allowed to accumulate about 10000 ^{27}S.

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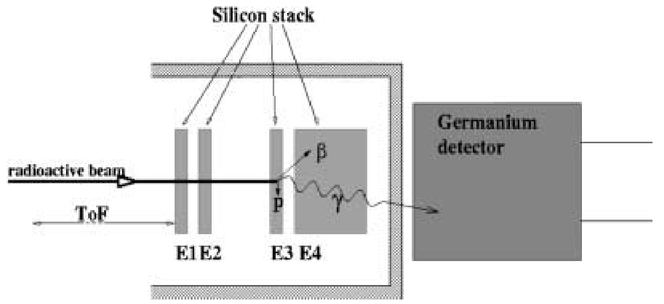

Fig. 1. Schematic view of the silicon telescope and the germanium clover detector. The silicon detector thicknesses are 500 μm, 500 μm, 500 μm, and 6 mm (from left to right) respectively.

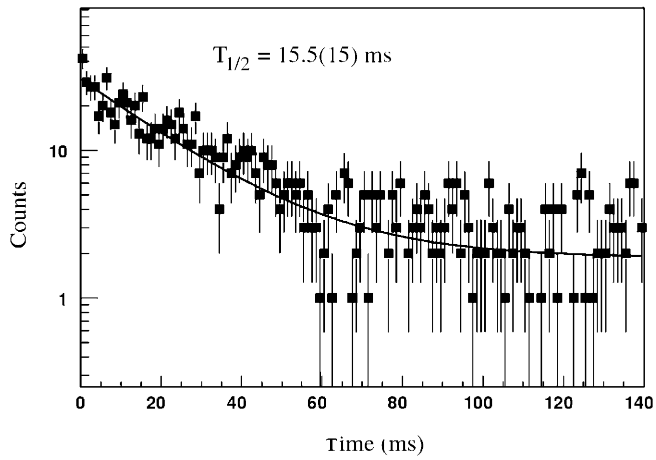

Fig. 2. Beta-decay half-life of ^{27}S as determined from the time difference between a ^{27}S implantation in the silicon telescope and its β decay (only the events of energy above 1 MeV have been taken into account). The solid line is a fit with a one-component + background curve.

In order to determine the half-life of ^{27}S, we have used the time difference between the implantation of an unambigously identified ^{27}S nucleus and the detection of light-particle emission (*i.e.* β-particles or protons). Without any beam pulsing, the correlation of implantation and radioactivity is possible if the implantation rate is smaller than the decay constant (= 1/lifetime). In our case, the total rate was about five implantations per second for a decay constant of 65/s. Figure 2 shows the time distribution of ^{27}S decay events. The curve is fitted by a one-component decay curve and a constant background. The constant background takes into account uncorrelated events due to implants other than ^{27}S (mainly ^{25}Si, ^{26}P). The half-life is determined to be $T_{1/2} = 15.5(15)$ ms. The half-lives determined by gating on different peaks in the energy spectrum agree with the average value as given above. The weighted mean value for the four identified one- and two-proton groups yields a value of 17^{+5}_{-4} ms. The above value compares well with but is more precise than a previous work which yielded a value of $T_{1/2} = (21 \pm 4)$ ms [2]. Shell model calculations [3] performed using the USD interaction [4] yield a half-life for ^{27}S of 12.2 ms, a value which is in reasonable agreement with our measurement.

To study their decay, ^{27}S nuclei have been stopped in the E3 silicon detector. This detector has been calibrated in a separate setting of LISE3 using the well-known protons from the decay of ^{25}Si [5]. Above 5.7 MeV, a linear extrapolation was used. The detector E4 was calibrated only by means of high-energy proton groups where the protons either escape from E3 (angles close to the beam axis) or are completely stopped in the E3 detector (full energy signal, angles perpendicular to beam axis). With the help of two-dimensional spectra E3 *versus* E4, E4 can be calibrated in the interesting region. However, this procedure suffers from energy loss in the dead layers of both detectors and yields thus high error bars. Figure 3 presents the charged-particle spectrum from the decay of ^{27}S. Labels $1p_n$ and $2p_n$ correspond to one- and two-proton emission, respectively.

From decay-energy considerations, the peak labeled "$2p_0$" at (6270 ± 50) keV is attributed to the decay by two-proton emission of the IAS in ^{27}P to the ground state of ^{25}Al. This decay has already been observed by Borrel *et al.* [2] who found a decay energy of 6410(45) keV. The average value of both measurements is 6340(35) keV. With the known mass excess of ^{25}Al of $\Delta m = -8915.7(7)$ keV, we determine the mass excess of the IAS to be $\Delta m = 12002(35)$ keV. The mass excess of the ^{27}P ground state is measured to be $\Delta m = -750(40)$ keV, which yields an excitation energy of $E^* = 12752(50)$ keV for the IAS.

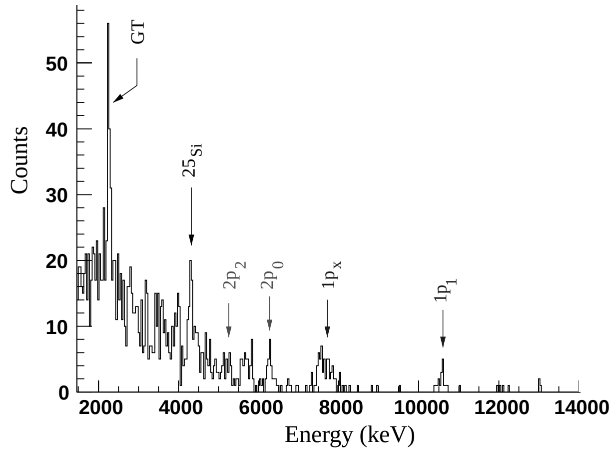

Fig. 3. Charged-particle spectrum of the decay of ^{27}S nuclei implanted in the E3 silicon detector. Proton groups above about 7 MeV have to be reconstructed by summing the energy signals from detectors E3 and E4.

The peak "$2p_2$" exhibits the same time distribution as "$2p_0$", compatible with the measured half-life of ^{27}S. Moreover, the energy difference with "$2p_0$" allows us to tentatively attribute this line to the transition from the IAS to the first $3/2^+$ state in ^{25}Al. Due to the limited statistics, no coincident γ-ray could be observed. The peak at 5.7–5.8 MeV is most probably a mixture of protons from ^{25}Si ($E_{\mathrm{CM}} = 5.8$ MeV) and ^{27}S. The ^{27}S contribution is most likely a one-proton emission from a Gamow-Teller fed state, as the feeding of the first excited state in ^{25}Al by two-proton emission from the IAS, which would fit in terms of the energy expected, is hindered due to angular-momentum conservation.

The proton lines labeled "1p$_n$" are assigned to the emission of one proton from the IAS to excited states in ^{26}Si for two main reasons: first, they exhibit the same time distributions as the "2p$_n$" lines and second, their energies are higher than that of the "2p$_0$" line. However, due to the thickness of the E3 silicon detector (500 μm), protons with energies higher than $\sim$ 6 MeV have a high probability to escape the E3 detector. Therefore, these proton groups have to be rebuilt by summing the E3 and E4 energy signals. As mentioned above, due to dead layers, this method yields large error bars on the energy values ($\sim$ 400 keV).

The "1p$_1$" line at (10560 ± 400) keV can be attributed to the one-proton emission of the IAS to the first excited 2^+ state at 1795 keV in ^{26}Si. Based on ground-state mass excess values [6] and the excitation energy of the IAS as determined above, the energy for this peak is expected to be (10063 ± 35) keV, which is in fair agreement with the measured value.

The events labeled "1p$_x$" which give a large peak around 7.8 MeV could correspond to a one-proton emission from the IAS to excited states in ^{26}Si or to Gamow-Teller fed transitions involving levels below the IAS in ^{27}P. However, due to the low counting rate, no proton-γ coincidences could be observed. Although we have no firm proof that this peak originates from a decay of the IAS, this assumptions seems to be reasonable, as shell model calculations [3] predict no Gamow-Teller fed level above 8 MeV with a branching ratio of more than 0.5% which would be necessary to explain this peak by other means than the IAS.

In fig. 3, one can notice an intense peak at (2260 ± 40) keV ("GT"). It corresponds probably to the emission from a low-lying state in ^{27}P strongly fed via Gamow-Teller β-decay. It decays with a 15 ms half-life. As only the first three excited states in ^{27}P are presently known [7], it is not possible to attribute this line to the transition between two well-defined levels. However, when considering the mirror nucleus of ^{27}P, ^{27}Mg, one expects a similar $(3/2^+, 7/2^+)$ level at around 3100 keV in ^{27}P (predicted at 3390 keV in [3]). Therefore, the proton group at 2260 keV could de-excite such a level to the ground state of ^{26}Si.

The proton group labeled "^{25}Si" at (4280 ± 40) keV is assigned to a contamination by ^{25}Si ($T_{1/2} = 218$ ms). It corresponds to the most intense proton transition of this nucleus and its flat time distribution corroborates this assignment. Table 1 summarizes our results and fig. 4 shows a partial decay scheme for ^{27}S.

The $A = 27$, $T = 5/2$ sextet is not sufficiently known to allow to determine the coefficients of the isobaric multiplet mass equation. However, Coulomb displacement energy systematics represent an alternative method to determine the ^{27}S ground-state mass. Using the following parametrisation of Coulomb displacement energies [8],

$$\Delta E_{\mathrm{C}} = 1440.8(\tilde{Z}/A^{1/3}) - 1026.3\,(\mathrm{keV}) \qquad (1)$$

where ΔE_{C} is the Coulomb energy difference between two neighbouring nuclei, A the common mass number and $\tilde{Z}$ the mean atomic number, one obtains $\Delta E_{\mathrm{C}} = 6418$ keV for $\tilde{Z} = 15.5$ and $A = 27$. This formula has an average uncertainty of 90 keV [8]. The energy difference between the ground state of ^{27}S and the IAS in ^{27}P is equal to

Table 1. β-delayed one- and two-proton groups as identified in fig. 3. The first column gives the experimentally observed energies and the second column corresponds to the peak labels in fig. 3. The last columns give the number of counts in the different one- or two-proton groups and their branching ratios.

E_{p} (keV)	Label	Intensity	BR (%)
2260 (40)	GT	140 (25)	1.9 (4)
4280 (40)	^{25}Si	78 (18)	-
5315 (60)	2p$_2$	20 (7)	0.4 (2)
6270 (50)	2p$_0$	32 (13)	0.7 (3)
7800 (400)	1p$_x$	65 (20)	1.4 (5)
10560 (400)	1p$_1$	16 (5)	0.9 (4)

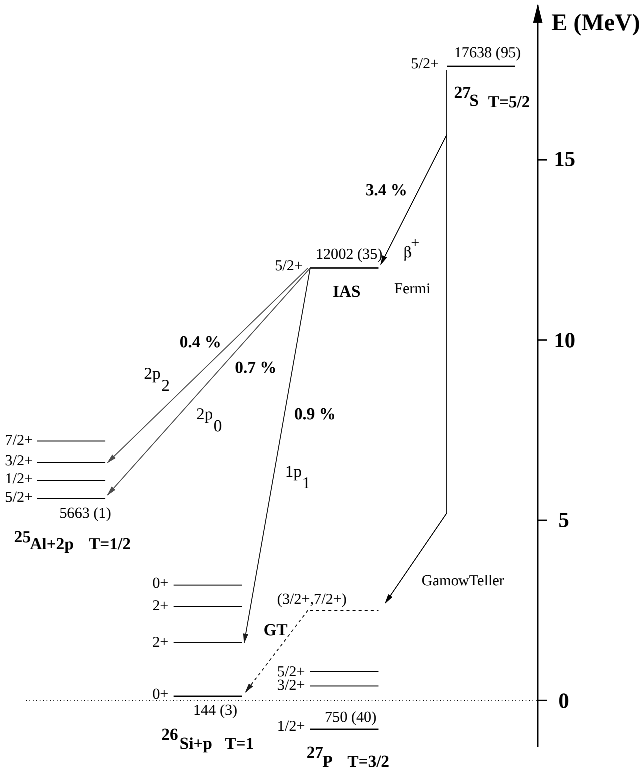

Fig. 4. Proposed partial decay scheme of ^{27}S. The levels in ^{25}Al and ^{26}Si are from [5]. The energy plotted on the y-axis is the mass excess of the different levels.

$\Delta E_C - \Delta_{nH}$, with Δ_{nH} being the mass difference between the neutron and the hydrogen atom. The $\Delta E_C - \Delta_{nH}$-value of (5636 ± 90) keV, together with the mass for the IAS in ^{27}P (12002 ± 35) keV, leads to a mass excess of the ^{27}S ground state of (17638 ± 95) keV. This value compares very well with the mass extrapolation of Audi and Wapstra [6] of $\Delta m = (17510 \pm 200)$ keV.

The sum of branching ratios for the identified β-delayed two-proton decays via the IAS is (1.1 ± 0.5) % and the β-delayed one-proton emission from the IAS has an observed branching ratio of (2.3 ± 0.9)% yielding a lower limit on the feeding of the IAS of (3.4 ± 1.4)%. This branching ratio limit may be compared to a model-independent value of (3.0 ± 0.5)%. The model-independent value is determined under the assumption of a pure Fermi decay by using the Q_β-value for the superallowed β^+ decay of (5636 ± 90) keV, the experimental half-life as measured in the present work, and log f-values from [9].

In summary, we measured decay properties of the proton-rich nucleus ^{27}S, the main results being a precise value for the half-life and a mass excess value for ^{27}S determined via Coulomb displacement systematics which is in excellent agreement with the mass extrapolation of Audi *et al.*

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