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# Study of $\beta^+$ and electron capture decay of $^{76}$Sr in $\gamma$-$\gamma$ coincidence measurements

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The main goal of this work is to establish the nuclear decay scheme of $^{76}$Sr and energy levels of its doubly odd daughter nucleus $^{76}$Rb. The extremely neutron deficient nucleus $^{76}$Sr lying at the $N=Z$ ($=38$) line with half-life of 8.9 s was produced in spallation reactions of 600 MeV protons from the CERN Synchrocyclotron (SC) with a Nb multifoil target in conjunction with a W surface ionization source at the ISOLDE facility. The $\gamma$-spectroscopy measurements have been performed with two Ge detectors which were positioned at about $\pm 30°$ respectively downstream to the $^{76}$Sr beam. The obtained singles and coincidence $\gamma$ spectra were used to determine energies and intensities of $\gamma$ lines assigned to the decay of $^{76}$Sr and to establish some details of the nuclear level configuration of its daughter nucleus $^{76}$Rb up to 1000 keV.

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## I. INTRODUCTION

The study of nuclei around $N=Z$ is one of the major topics in the field of nuclear physics far from stability. However, it is very difficult to achieve sufficiently high production rates of light or especially medium heavy isotopes along $N=Z$ line. There are a few possibilities of producing a beam of such nuclei. One of them is the mass separator facility ISOLDE at CERN where this work was done. We used 600 MeV protons from the CERN synchrocyclotron and ISOLDE facility to produce sources of $^{76}$Sr and to study its decay by $\gamma$ spectroscopy.

It is known that the region $N=Z=40$ contains some of the most deformed nuclei in the nuclear chart [1–3] thus representing the subject of intensive theoretical and experimental studies during the last two decades. The richness of nuclear phenomena occurring in this region, from highly neutron deficient and strongly deformed $^{76,78,80}$Sr to nearly spherical shape $^{84}$Sr, makes the study of these isotopes particularly interesting. The nucleus $^{76}$Sr ($N=Z=38$) is especially attractive due to its strong prolate deformation ($\epsilon_2 \simeq 0.4$) and coherent shell effects for protons and neutrons [1]. Theoretical calculations, which have been carried out in order to predict the deformations of nuclei throughout the periodic table, have had some success in describing the deformed region around $N=Z=40$. In the paper of Nazarewicz *et al.* [4], nuclear high-spin configurations as a function of both proton number and spin with particular reference to the light strontium isotope were studied. The excitation levels for nuclei in this region were produced in calculations based on the nonaxially deformed Woods-Saxon and folded Yukawa potentials.

## II. EXPERIMENTAL SETUP

In order to produce pure sources of the most deficient Sr isotopes, besides the mass separation, an additional chemical separation is necessary. The nucleus $^{76}$Sr was obtained as a spallation product in a 50 g/cm$^2$ thick niobium multifoil target by bombardment with 600 MeV protons of a current of about 3 $\mu$A from the CERN synchrocyclotron. The ion beam of Sr, ionized as SrF$^+$, was produced in the same way as in the experiment of Grawe *et al.* [5], where they demonstrated $^{78}$SrF$^+$ ion transport. Following the mass separation in the ISOLDE-3 on-line mass separator facility [6,7], the beam with an average intensity of $5\times10^2$ atoms/s was transported to the experimental station where two germanium detectors were installed. The $^{76}$Sr nuclei were stopped in a 3 mm thick aluminum cap at the end of the beam pipe. Data were recorded by a 30% efficient Ge(Li) and a 70% efficient HPGe detector positioned symmetrically: at about $\pm 30°$ to the beam line. A 10 mm thick lead plate between the two detectors served to decrease eventual accidental coincidences. Coincidences ($\gamma$-$\gamma$-$\Delta t$) were stored on tapes in a multiparameter mode and later analyzed together with singles spectra by the VAX/VMS computer system.

## III. EXPERIMENTAL RESULTS

We have measured $\gamma$-$\gamma$ coincidence and singles $\gamma$-ray spectra originating from the decay of $^{76}$Sr nucleus up to 1000 keV in order to establish its nuclear decay scheme and to obtain information about the level structure of its daughter nucleus $^{76}$Rb. From the work of Hofmann *et al.* [8], we know the low energy levels of $^{76}$Rb. They established the scheme of the first three excited states of

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this nucleus studying the decay of an isomeric state at 317.0 keV. The mass and level scheme of $^{76}$Rb have been established in experiments of Moltz *et al.* [9] and Epherre *et al.* [10], while nuclear level scheme of the same nucleus has been confirmed in the measurements of Piercey *et al.* [11] and Garcia *et al.* [12]. In the experiment of Ekstrom *et al.* [13], nuclear spins and magnetic moments of neutron deficient rubidium isotopes have been determined, whereas the nuclear ground state spin of $^{76}$Rb ($T_{1/2}=36.8$ s) has been measured earlier [13–15]. A negative parity of the ground state comes from data of beta decay to $^{76}$Kr [9,16].

A decay scheme of $^{76}$Sr based on singles data has been proposed by Grawe *et al.* [5]. In order to be able to establish and support some details of this decay scheme we report here the results of $\gamma$-$\gamma$ coincidence measurements which had not been done so far. Gamma rays of $^{76}$Sr were identified by using both singles and coincidence gamma spectra, whereas the known gamma rays of $^{76}$Rb [9] were used to obtain energy calibration and relative efficiency curve. Results of our measurements are consistent with the proposed scheme for energy level sequence and spins of the ground and first three excited states of $^{76}$Rb with corresponding parities as they are given in the references [5,8,12]. We also assumed that the half-life of $^{76}$Sr is 8.9 s as it was determined in the work of Grawe *et al.* [5]. Our estimated $\beta^+$ and electron capture (EC) branchings are given by neglecting the feeding above the energy level 982.9 keV, while the $Q$ value of 5.7 MeV was deduced from the mass extrapolation [17]. The isomeric transition of 70.4 keV observed by Hofmann *et al.* [8], but not by Grawe *et al.* [5], was not seen.

It is clear that due to high deformability of nuclei in this region, it is difficult to determine accurate values for spins and parities and assign them unambiguously to all relevant energy levels. This is particularly true for nuclei belonging to the 76-isobar chain since they are beyond the regions of most commonly used models. Our experimental results of singles gamma and $\gamma$-$\gamma$ coincidence measurements of the decay of $^{76}$Sr are summarized in Tables I and II. These data suggest that three levels at 476.8, 516.0, and 982.9 keV should have the same spin and parity $1^+$ (Fig. 5). Gated gamma lines and their corresponding coincident $\gamma$ transitions are listed in Table I. Energies and intensities of all identified gamma transitions assigned to the $\beta^+$/EC decay of $^{76}$Sr from both coincidence and singles spectra, with corresponding uncertainties in parentheses, are given in Table II.

TABLE I. Coincident $\gamma$ lines for different gate combinations. Gamma lines in parentheses were found as uncertain gamma lines in coincidence spectra.

| Gated line | Coincident lines |
|---|---|
| 101.4 keV | 145.2, 230.2, 375.4, 414.6, 881.5 |
| 145.2 keV | 101.4, 230.2 |
| 230.2 keV | 101.4, 145.2, (246.6) |
| 375.4 keV | 101.4 |
| 414.6 keV | 101.4 |
| 476.8 keV | (192.5) |

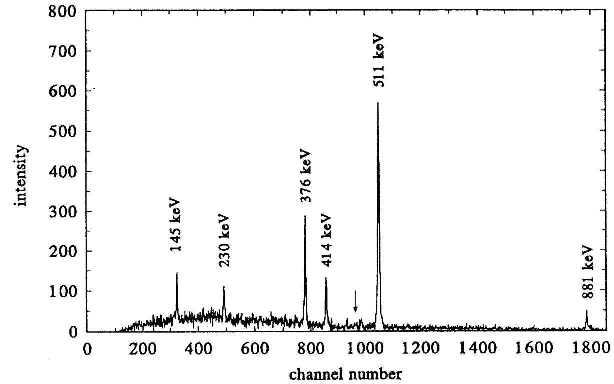


FIG. 1. Coincidence $\gamma$ spectrum with a gate on 101 keV. The arrow denotes the position of a weak 466.9 keV line.

Representative coincidence spectra are shown in Figs. 1–4 while the tentative decay scheme of $^{76}$Sr is given in Fig. 5. Relative intensities are quoted with respect to the strongest line 476.8 keV. Energies of all gamma lines originating from the decay of $^{76}$Sr are determined with an accuracy better than 0.5 keV, while the errors in their spectral intensities are ranging from 10% to 50%.

Gamma lines 506.1 and 516.0 keV (denoted by an asterisk) are sitting at the left and right tail of the strong annihilation line respectively, so that their spectral intensities could not be determined. However, our data are consistent with their assignment to the decay of $^{76}$Sr and with their estimated relative intensities of about 1.0. The transitions 159.8, 317.0, 665.7, and 735.8 keV (labeled by a plus in Table II) fitting in the level scheme well and clearly observed in singles, but not in coincidence spectra, are shown in Fig. 5, together with 506.1 and 516.0 keV, as dashed lines. Gamma lines from singles and coin-

TABLE II. Gamma lines assigned to the decay of $^{76}$Sr. Weak lines 159.8, 317.0, 466.9, 665.7, and 735.8 keV (+) seen only in singles, as well as two lines 506.1 and 516.0 keV (*) affected by the strong annihilation line and for which spectral intensities could not be resolved, are shown as dashed lines in the nuclear level scheme. Errors for energies and relative intensities are given in parentheses.

| $E_\gamma$ (keV) | $I_\gamma$ |
|---|---|
| 101.4(2) | 56.0(140) |
| 145.2(2) | 6.0(20) |
| 159.8(4)$^+$ | 1.2(5) |
| 230.2(2) | 4.7(12) |
| 246.6(3) | 1.5(5) |
| 317.0(3)$^+$ | 1.3(4) |
| 375.4(2) | 27.8(50) |
| 414.6(2) | 12.9(20) |
| 466.9(2)$^+$ | 3.7(9) |
| 476.8(2) | 100.0 |
| 506.1(5)* | |
| 516.0(5)* | |
| 665.7(4)$^+$ | 0.6(3) |
| 735.8(4)$^+$ | 1.1(4) |
| 881.5(2) | 16.7(20) |
| 982.9(2) | 30.0(45) |

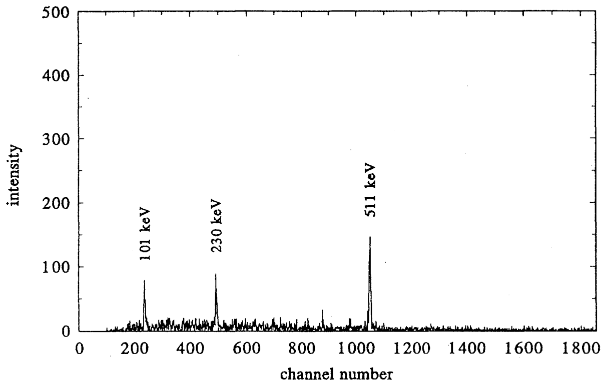


FIG. 2. Coincidence $\gamma$ spectrum with a gate on 145 keV. Two unlabeled weak lines, left to the 511 keV line, are due to 424.0 and 476.8 keV lines belonging to $^{76}$Rb and $^{76}$Sr, respectively.

TABLE III. Energies and corresponding relative intensities of gamma transitions found in both singles and coincident spectra when gate was on the annihilation line, which could not be assigned to the decay of $^{76}$Sr. See also Fig. 4.

| $E_\gamma$ (keV) | $I_\gamma$ |
|---|---|
| 1. 177.3(3) | 3.3(10) |
| 2. 494.4(3) | 6.0(15) |
| 3. 580.6(2) | 7.0(18) |
| 4. 686.4(3) | 1.3(6) |
| 5. 689.6(3) | 3.8(10) |
| 6. 770.0(4) | 1.3(4) |
| 7. 812.9(3) | 3.6(9) |
| 8. 922.2(3) | 4.5(15) |

cidence spectra when the annihilation line was gated (Fig. 4), which could not be placed in our decay scheme of $^{76}$Sr up to 1000 keV, and which do not belong to the decay of $^{76}$Rb either, are shown in Table III.

## IV. DISCUSSION

The nuclear level scheme in Fig. 5 shows strong $\beta^+$ branches only to three energy levels at 982.9, 516.0, and 476.8 keV. All three ($E1$) transitions leading from these energy levels to the ground state are seen in the singles spectra. The calculated log$ft$ values are consistent with an $I^\pi = 1^+$ assignment as suggested in Fig. 5. However, a possible existence of one $0^+$ state above 1 MeV would relax the $\beta^+$/EC feeding of the $1^+$ level at 982.9 keV and make the log$ft$ values more consistent and at the same time allow for the positioning of the coincidence lines which could not be placed into the low energy part of the level scheme. The decay of these three $1^+$ levels into the low lying levels at 246.6 and 101.4 keV is well established through our coincidence data. Virtually all observed coincidences are places in the tentative nuclear level scheme shown in Fig. 5. We assumed that the ground and the first excited state have assignments $1^-$ and $2^-$, respectively, as proposed earlier and strongly suggested by the available data [8,12].

The energy level 1276 keV and an eventual coincidence of 1174 keV with a transition 101.4 keV, as Grawe *et al.* deduced from the singles gamma measurements [5], could not be confirmed since our coincidence measurements were limited to about 1100 keV. Due to the presence of two gamma transitions (1174.1 keV from $^{76}$Rb [9,18] and the background gamma line 1173.2 keV from $^{60}$Co), a gamma transition 1174 keV, in order to be assigned to the decay of $^{76}$Sr, must be confirmed in coincidence measurements.

The dashed transitions leading to and from the isomeric level are very weak and are placed in the nuclear level scheme only on the basis of energy consideration. Their presence is, however, confirmed in both singles spectra and in coincidence with the annihilation line. As a weak $E3$ isomeric transition of 317.0 keV was clearly observed in the singles spectra, there are two reasons we can offer to explain the absence of a strong $E1$ isomeric transition of 70.4 keV: a weak feeding of the isomeric state at 317.0 keV in $\beta$ decay and the fact that most of the strength of 70.4 keV was exhausted by passing through a 3 mm thick Al cap at the end of the beam pipe.

It should be noted that a weak 192.5 keV transition (Table I) found in coincidence with 476.8 keV could not fit into the constructed level scheme. This gamma line is also seen in singles and in coincidence spectrum when the annihilation line is gated (Fig. 4). A weak transition 466.9 keV fitting in the proposed level scheme well is hardly seen in coincidence with 101.4 and 414.6 keV. On the other hand, the gate could not be put on this line due to interference of the 466.0 keV line from the decay of $^{76}$Rb [9,11]. Positioning of this transition into the level scheme may thus also be considered as tentative. The position of this line in the spectrum shown in Fig. 1 is labeled by the arrow. Two unlabeled and hardly observable gamma lines to the left of the annihilation line in the coincident spectrum shown in Fig. 2 belong to two strong transitions 424.0 and 476.8 keV from the decay of $^{76}$Rb [9,11] and $^{76}$Sr, respectively. They were not cleared out by the subtraction of background coincidences. As it can

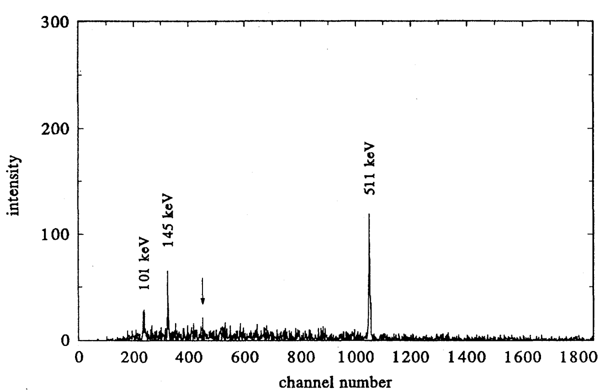


FIG. 3. Coincidence $\gamma$ spectrum with a gate on 230 keV. The arrow indicates the weak 246.6 keV line.

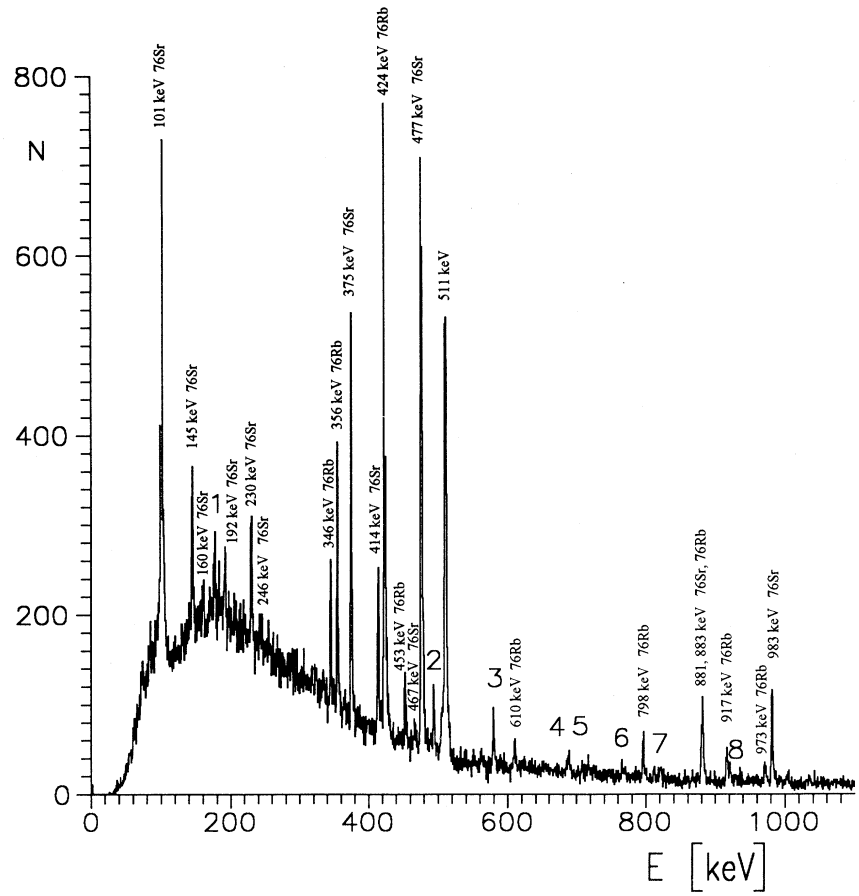


FIG. 4. Coincidence $\gamma$ spectrum with a gate on 511 keV. The dominating lines belong to $^{76}$Sr and $^{76}$Rb. All unidentified lines are denoted with numbers from 1 to 8 in accordance with Table III. The lines 101, 477, and 511 keV are overflown due to expansion of the spectrum. For more precise energies see Tables I–III.

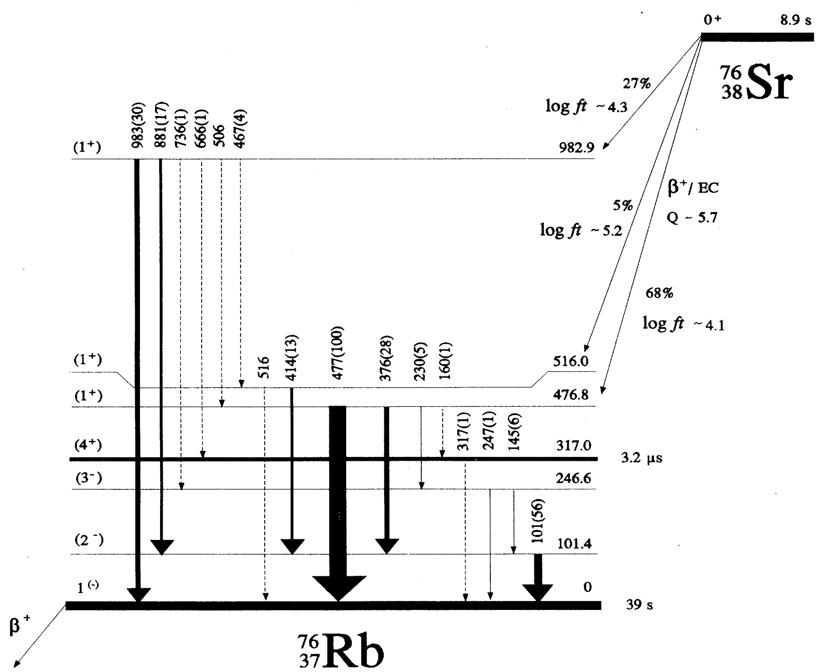


FIG. 5. Proposed energy level and nuclear decay scheme of $^{76}$Sr. More precise energy values of gamma transitions obtained in the experiment are given in Tables I and II.

be noticed, the only weakness of the suggested level scheme could represent two low intensity $M3$ transitions 665.7 and 159.8 keV seen in the singles spectra and fitting energy levels well, in competition with stronger and higher energy $E1$ transitions. They should be considered tentative as well.

The energy level at 246.6 keV is fed through the $1^+$ level of 476.8 keV, as can be seen in Fig. 2, and decays into both the ground and first excited state. Its $3^-$ assignment suggested by Hofmann *et al.* [8] is consistent with a clear sequence of coincident gamma transitions, 230.2, 145.2, and 101.4 keV, but would have certainly had an additional support if we had seen an $E1$ isomeric transition of 70.4 keV. In case that 70.4 keV $(4^+ \rightarrow 3^-)$ cannot be seen, a $2^+$ or $2^-$ assignment for the 246.6 keV level should not be excluded.

Our experimental data suggest that approximately 15% of the missing intensity in the balance between the total intensity feeding the 101.4 keV level and intensity leaving the same level may be attributed to the conversion of an $M1$ transition of 101.4 keV which is consistent with the total conversion coefficient of about 15%.

## V. CONCLUSION

On the basis of $\gamma$-$\gamma$ coincidence and singles $\gamma$-spectra measurements in the decay of $^{76}$Sr, we have partially established the gamma transition sequence and energy level ordering of odd-odd nucleus $^{76}$Rb. The $\beta$-decay strength, typical for Gamow-Teller transitions $0^+$-$1^+$, is divided between three energy levels. Most of the decay strength (68%) goes to 476.8 keV level, while the rest of the decay splits between two levels: 982.9 (27%) and 516.0 keV (5%). The results of our measurements confirm the existence of the first five energy levels up to 516.0 keV and four gamma rays known from the previous work. Their spins and parities are consistent with the values that were suggested earlier. Moreover, our proposed nuclear level scheme strongly suggests the new 982.9 keV level and establishes five new gamma transitions of which four are given with confidence. Seven noncoincident low intensity gamma transitions, seen only in the singles spectra, are placed in the level scheme on the basis of energy consideration.

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