THE DECAY OF ^{191}Pt

A.P. Lashko*

Institute for Nuclear Research, National Academy of Sciences of Ukraine, 03680, Kiev, Ukraine

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The energy difference for $\gamma 268$ and $\gamma 295$ lines was measured with gamma-spectrometer. The $\gamma 268\,keV$ transition is excited in the ^{191}Pt decay, while another transition, the energy of which is known up to a high precision, accompanies the ^{192}Ir decay. A measured energy value of the $3/2^- \to 7/2^-$ transitions ($268\,keV$), along with the data from our previous work, allowed us to perform a high-precision calculation of energy levels in ^{191}Ir and energies of γ-rays deexciting these levels..

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1. INTRODUCTION

Decay of the $^{191}Pt\,(I^\pi = 3/2^-,\, T_{1/2} = 2.8\,days)$ occurs by the electron capture to 16 levels of the ^{191}Ir, excluding the $11/2^-$ isomeric state. In the process 50 γ-transitions in the energy range 42 to $935\,keV$ are excited. According to the recent review [1], energies of these transitions are measured, at best, to within several tens of electron-volts. The data on energies of excited states of atomic nuclei known with an accuracy of several electron-volts and higher become increasingly required today. The evolution of technique of high-precision measurement of γ-ray energy based on the semiconductor spectrometers, along with the essential extension of nuclear-spectroscopic standards mesh, have provided great scope for all-inclusive measurements of energies of excited nuclear states populated in the decay of sources with more or less noticeable life-time. Isotope ^{191}Pt appeared to be an appropriate object for such purpose. Our long-standing researches [2-5] allowed high-precision determination of the energies of 9 levels of the ^{191}Ir and the energies of 36 γ-quanta accompanying the decay of ^{191}Pt. Until recently, energies of $7/2^-$ level ($390\,keV$) and $11/2^-$ level ($171\,keV$) can not be determined with such an accuracy. We failed to measure energies of any transitions that might relate these levels with others. To this end, either the energy of the very weak ($6.4 \times 10^{-5}\%$) $41\,keV$ γ-transition or the energies of the $268.0 + 268.8\,keV$ doublet should be measured. This problem was finally resolved in the present paper.

2. EXPERIMENTAL TECHNIQUE

The number of levels exciting in the radioactive decay of mother nucleus is generally less than the number of γ-rays deexciting these levels. It is not necessary for all γ-rays to be measured, in order to get information about their energies. The reference nuclear transition method can be used instead. Application of this method allows one to essentially reduce laboriousness of the experiments.

Procedure of determination of energies of excited nuclear states and γ-rays deexciting these states by the reference nuclear transition method reduces to the following basis stages:

1) the most appropriate for measurement single intense γ-lines are chosen as reference lines;

2) the set of references is selected from the list of recommended energy standards for nuclear spectroscopy. In order to minimize the errors arising from an ambiguity of calibration curve, it is necessary to select such references that would be close to the measured γ-line while still being easily resolved in the spectrum;

3) the mixed radioactive source of required composition is prepared with desired ratios of specific activities of radionuclides entering into the source. For statistical error (uncertainty in determination of distance between lines) to be minimized, the reference and measured line should have close intensities;

4) to minimize possible systematic errors, measurements are performed by series on different detectors, at various geometries, different amplification coefficients and different quantization levels of the input signal on amplitude-digital converters;

5) energies of reference transitions are determined;

6) to calculate energies of levels, a set of linear equations is derived and then it is solved with the least-squares procedure;

7) energies of all γ-quanta accompanying the decay of mother nucleus are calculated on basis of the obtained data.

The technique of such measurements and the problems concerning preparation of a mixed radioactive source of optimal composition were reported in detail in [6-7].

*Corresponding author E-mail address: lashkoa@kinr.kiev.ua

The energy difference for $\gamma 267$ and $\gamma 295$ lines was measured with gamma-spectrometer, which comprises two horizontal detectors made from high-purity germanium (coaxial $GEM-40195$ with $1.73\,keV$ resolution for $\gamma 1332$-line of ^{60}Co and planar $GLP-36360/13$ with $580\,eV$ resolution for $\gamma 122$-line of ^{57}Co) and multichannel ORTEC buffer 919 SPECTRUM MASTER. The $\gamma 267\,keV$ transition is excited in the ^{191}Pt decay, while another transition, the energy of which is known up to a high precision, accompanies the ^{192}Ir decay. To prepare a mixed radioactive source of required composition, the ^{191}Pt was obtained in (n,γ) reaction under irradiation of enriched platinum (^{190}Pt isotope content is $0,8\%$) with research reactor WWR-M. The ^{192}Ir ($T_{1/2}=74\,days$) was also produced in (n,γ) reaction under irradiation of enriched iridium (^{191}Ir isotope content is 94%) by slow neutrons.

The functional dependence of the energy calibration of the γ-spectrometer was investigated in detail. It was established that the deviation from linearity does not exceed 3×10^{-5} for the energy range from 84 to $604\,keV$. To minimize possible systematic errors, we performed a series of measurements using sources with different ratios of specific activities of 191Pt, ^{182}Ta, and ^{192}Ir, at different gains and channel widths of an amplitude digital converter (4096 and 8192 quantization levels of the input signal). 18 series of measurements were performed in all. The spectra were also analyzed with respect to the half-decay period to exclude possible impurities of other radionuclides. To the same end, we determined with high accuracy the relative intensities of the γ-lines accompanying decay of ^{191}Pt. The results of these measurements are shown in Table 1. Good agreement with the data of other researchers is observed, which confirms the absence of "foreign" γ-lines in the spectral regions of interest.

Table 1. *Intensities I of the γ-lines from the decay of ^{191}Pt for the energy range above $150\,keV$ in the relative units*

Energy, keV	I, Our data	I, Compilation [8]	Energy, keV	I, Our data	I, Compilation [8]
172.2	39.8 ± 1.2	44 ± 2	479.9	0.71 ± 0.05	0.71 ± 0.07
179.0	11.2 ± 0.3	12.7 ± 0.6	494.7	0.77 ± 0.03	0.75 ± 0.07
187.7	4.69 ± 0.14	5.2 ± 0.3	538.9	180 ± 4	171 ± 9
219.7	10.1 ± 0.3	10.3 ± 0.5	541.7	5.00 ± 0.15	4.6 ± 0.5
221.8	1.80 ± 0.06	1.45 ± 0.15	568.9	0.69 ± 0.04	0.66 ± 0.05
223.7	1.54 ± 0.05	1.40 ± 0.15	576.4	1.56 ± 0.06	1.47 ± 0.11
268.0	9.2 ± 0.4	9.7 ± 1.0	583.6	1.02 ± 0.05	0.95 ± 0.07
268.8	19.8 ± 0.9	20.6 ± 2.0	618.4	0.17 ± 0.04	0.11 ± 0.04
351.2	41.8 ± 1.0	42 ± 2	624.1	19.1 ± 0.6	17.6 ± 0.9
359.9	74.2 ± 1.8	75 ± 4	633.1	0.40 ± 0.07	0.30 ± 0.03
396.6	0.21 ± 0.05	0.13 ± 0.04	658.9	0.20 ± 0.04	0.19 ± 0.02
409.5	100	100 ± 5	680.2	0.096 ± 0.009	0.086 ± 0.017
445.1	0.76 ± 0.05	0.68 ± 0.07	762.6	0.169 ± 0.011	0.15 ± 0.02
456.5	42.3 ± 1.0	42 ± 2	806.4	0.068 ± 0.020	0.047 ± 0.009
458.6	0.78 ± 0.08	0.54 ± 0.10	935.3	0.143 ± 0.009	0.15 ± 0.02

3. RESULTS AND DISCUSSION

The g-spectra were treated using the programs developed by us [9–11] based on the method of fitting the "instrumental" peak into the spectrum region of interest. This method allows a high-precision measurement of energies and intensities of the components in the case of lines of asymmetric shape and overlapping lines. This technique implies measuring a single gamma peak from the obtained spectrum (or, if such a peak is absent, specially measured single gamma peak with the shape similar to that of the line in the studied region of spectrum) with high statistical accuracy. After subtraction of the background, it is described by the multiple cubic-spline interpolation, and it is used as "instrumental", i.e. defines the experimental peak shape for the subsequent analysis by the least-squares method. The experiment was a considerable challenge due to the fact that the $\gamma 267$ line is not completely resolved in the spectrum with the $\gamma 268$ line (see Fig.1).

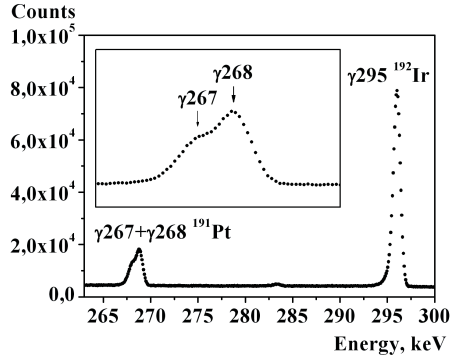

Fig.1. *Part of the γ-spectrum in the energy region 260...300 keV from the decay of ^{191}Pt, measured with the HPGe-detector $GLP-36360/13$*

Special care must be used to control an accuracy of component decomposition of the $\gamma 267 + \gamma 268$ doublet. Intensities of these two γ-lines are known to within 5%. Control over the change in component intensities still did not ensure correctness of determination of γ-line energies with an accuracy of several electron-volts. We made use of the fact that the $\gamma 268$ energy was previously determined with a precision of $1.7\,eV$ as the energy difference of the $5/2^+$ $351\,keV$ and $1/2^+$ $82\,keV$ levels, between which this transition occurs [5]. Simultaneously with the component decomposition of the doublet the energy difference for $\gamma 267$, $\gamma 268\,keV$ lines of ^{191}Pt and $\gamma 295\,keV$ line of ^{192}Ir was determined. Requirement for the deviation of the $\gamma 268$ energy from measured value not to exceed 3σ served as a criterion of accuracy of γ-spectrum fitting procedure. First, the energy difference for $\gamma 267$ line of ^{191}Pt and $\gamma 295$ line of ^{192}Ir were determined as a weighted mean from the results of all measurements and then the transition energies were found. The measurement results are in good agreement with each other. Taking into account that the energy of the recoil nucleus for $\gamma 267$ of ^{191}Pt is $0.20\,eV$, we obtained the value $267952.8 \pm 1.8\,eV$ for the transition energy. In the same way we previously determined the energies of 19 transitions from the decay of ^{191}Pt [3-5]. Their location in the ^{191}Pt decay scheme is shown in Fig.2.

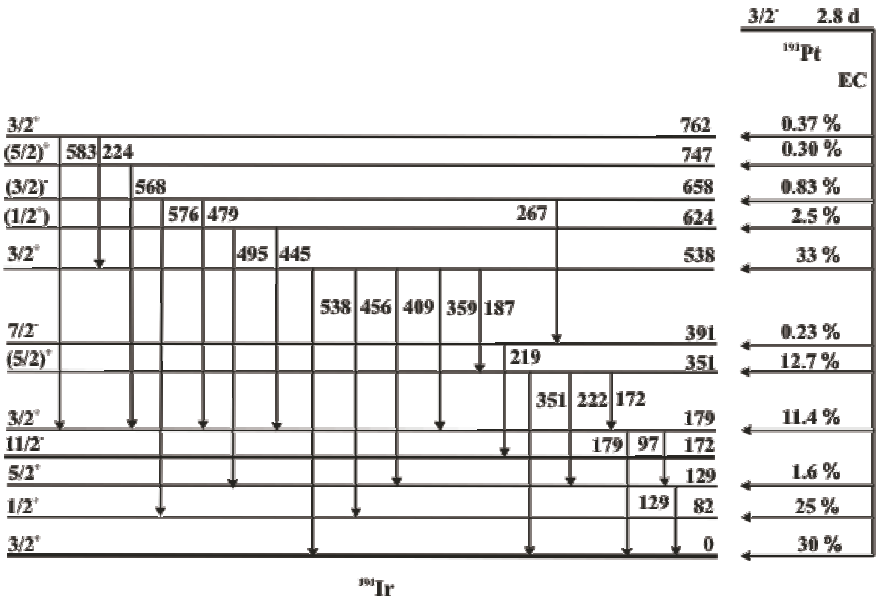

Fig.2. *Fragment of the schematic diagram of* ^{191}Pt *decay*

Using the data on the transition energies and the Ritz rule for cascade transitions ($E_1 + E_2 = E_3$, where E_3 is the energy of the closing direct transition between the boundary levels), we formulated the system of linear approximate equations of different weight to calculate the level energies:

$$\begin{aligned} a_1x + b_1y + ... + m_1\nu &= t_1 \pm \Delta t_1\,, \\ a_2x + b_2y + ... + m_2\nu &= t_2 \pm \Delta t_2\,, \\ ..... &= ..... \\ a_Nx + b_Ny + ... + m_N\nu &= t_N \pm \Delta t_N\,, \end{aligned} \qquad (1)$$

where a, b,..., m are specified numbers (generally they are equal to ± 1 or zero), t and Δt are the transition energies and their errors; x, y, ..., ν are unknown level energies. Since N is larger than the number of unknowns, the system was solved by the least-squares method [12]; i.e., we determined such values of unknowns at which the sum

$$\sum_{i=1}^{N} p_i(t_i - a_ix - b_iy - ... - m_i\nu)^2\,, \qquad (2)$$

($p_i = (\Delta t_i)^{-2}$; $i = 1, 2, ..., N$) was minimum. The errors of all parameters can be obtained using the parabolic dependence $\chi^2 = \chi^2(\alpha_i)$, where $\alpha_i(x, y, ..., \nu)$ is the parameter studied. In this case, all other parameters are fixed and correspond to optimal values. The standard errors $\Delta\alpha$ are determined using the relation:

$$\chi^2(\alpha_i^{opt} \pm \Delta\alpha_i) = \chi^2_{min} + 1\,, \qquad (3)$$

where α_i^{opt} is the optimal value of the parameter ai, which minimizes χ^2. After determination of the energies of nuclear excited states, it was quite easy to calculate the γ-transition energies between these states. The results of the calculations, along with the weighted mean values from compilation [1], are shown in Table 2. We determined the energies of 11 levels of ^{191}Ir and the energies of 39 γ-quanta accompanying decay of ^{191}Pt with an accuracy exceeding the known values by an order of magnitude. Most of them completely correspond to the requirements imposed on the fourth-order energy normals.

Table 2. *Energies of the ^{191}Ir levels and γ-ray photons excited in ^{191}Pt decay: present work and compilation [1]*

Energy levels, eV	γ-rays energy, eV	Energy levels, eV [1]	γ-rays energy, eV [1]
82427.0 ± 0.9	82427.0 ± 0.9	82405 ± 7	82398 ± 7
129431.9 ± 1.0	47004.9 ± 1.4	129396 ± 7	–
	129431.9 ± 1.0		129400 ± 7
171296 ± 6	41864 ± 6	171320 ± 30	41930 ± 30
178977.3 ± 0.9	49545.4 ± 1.4	178934 ± 10	49590 ± 30
	96550.3 ± 1.3		965517 ± 9
	178977.2 ± 0.9		178960 ± 30
351187.5 ± 1.4	172210.1 ± 1.7	351139 ± 16	172190 ± 20
	221755.5 ± 1.7		221740 ± 80
	268760.3 ± 1.7		268710 ± 80
	351187.1 ± 1.4		351170 ± 30
390968 ± 4	219672 ± 5	390970 ± 50	219650 ± 50
538904.2 ± 0.9	187716.6 ± 1.7	538839 ± 15	187690 ± 40
	359926.5 ± 1.3		359880 ± 30
	409471.8 ± 1.4		409440 ± 20
	456476.6 ± 1.3		456470 ± 50
	538903.4 ± 0.9		538870 ± 50
624098 ± 5	85194 ± 5	624060 ± 40	85150 ± 80
	445120 ± 5		445130 ± 80
	494666 ± 5		494690 ± 70
	541671 ± 5		541640 ± 100
	624097 ± 5		624060 ± 60
658920.5 ± 3.2	267952.8 ± 1.8	658870 ± 50	267920 ± 80
	307732.7 ± 3.5		308000 ± 1000
	479942.5 ± 3.3		479950 ± 70
	576492.6 ± 3.3		576460 ± 80
	658919.3 ± 3.2		658750 ± 150
747833 ± 6	208929 ± 6	747780 ± 70	208960 ± 150
	396645 ± 6		396700 ± 200
	568855 ± 6		568810 ± 80
	618400 ± 6		618700 ± 400
	747833 ± 6		748000 ± 200
762580.3 ± 2.9	138482 ± 6	762520 ± 50	138200 ± 200
	223676.0 ± 3.0		223670 ± 80
	411392.3 ± 3.2		411000 ± 1000
	583602.0 ± 3.0		583610 ± 80
	633147.3 ± 3.1		633180 ± 100
	680152.0 ± 3.0		680000 ± 200
	762578.7 ± 2.9		762600 ± 150

4. CONCLUSION

At present, the list of the recommended energy standards for nuclear spectroscopy includes about 240 γ-rays covering the energy range from 24 up to 4806 keV [13, 14]. For all of them the relative error in energy definition does not exceed 10^{-5}.

The reference line should be close to the measured γ-line for precision determination of transition energies. This allows minimization of the errors arising due to an ambiguity of calibration curve of the spectrometer. Therefore, in deciding on reference γ-lines, the presence of convenient nuclear-spectroscopic standards in a given part of spectrum is of no small importance.

^{191}Pt isotope is sufficiently produced in the slow-neutron reaction (n, γ) (activation cross-section is about 800 $barns$ [15]). Only the need for using platinum enriched by ^{190}Pt isotope is a problem, because content of this isotope in natural isotopic mixture does not exceed $0,013\,\%$. However, the large number of sufficiently intense γ-lines, which can be used as references in energy range from 50 to 760 keV, makes up for this inconvenience.

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РАСПАД ^{191}Pt

А.П. Лашко

На γ-спектрометре измерена разность энергий линий γ268 и γ295 кэВ. Переход γ268 кэВ возбуждается при распаде ^{191}Pt, а второй, энергия которого известна с высокой точностью, сопровождает распад ^{192}Ir. Измеренное значение энергии перехода $3/2^- \rightarrow 7/2^-$ 268 кэВ позволило, совместно с данными нашей предыдущей работы, рассчитать с высокой точностью энергии уровней ^{191}Ir и энергии разряжающих их γ-лучей.

РОЗПАД ^{191}Pt

А.П. Лашко

На гамма-спектрометрі поміряли різницю енергій ліній γ268 та γ295 кеВ. Перехід γ268 кеВ збуджується при розпаді ^{191}Pt, а другий, енергія якого відома з високою точністю, супроводжує розпад ^{192}Ir. Отримане значення енергії переходу $3/2^- \rightarrow 7/2^-$ 268 кеВ дозволило, разом з даними нашої попередньої роботи, розрахувати з високою точністю енергії рівнів ^{191}Ir та енергії розряджаючих їх γ-променів.