MEASUREMENTS OF THE MAGNETIC MOMENTS OF NUCLEAR STATES BY HYPERFINE SHIFT OF CONVERSION LINES

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A procedure for the determination of nuclear magnetic moments by the hyperfine shift of lines of internal conversion electrons (ICEs) has been developed. The range of its application does not depend on the nuclear state lifetime. The technique has been applied to estimate the magnitude of the magnetic moment of the $9/2^+$ 136-keV excitation level in ^{181}Ta.

1. Introduction

The first data concerning nuclear magnetic moments were obtained by studying the hyperfine structure of atomic optical spectra making use of interference spectroscopy. Further progress was closely connected with the creation and development of methods of radio-frequency spectroscopy of atomic beams, which enabled the magnetic moments of practically all stable isotopes to be measured [1]. Unfortunately, those methods turned out of little use for the determination of the magnetic moments of atomic nuclei in excited states. As an alternative, the method of excited angular correlation [2] came into being; however, the measurable lifetime of nuclear states τ is confined there to the range from 10^{-11} to 10^{-5} s. The lower limit is governed by a reachable magnitude of the magnetic field, while the upper one by the resolution of a coincidence circuit.

A lot of other techniques aimed at measuring the magnetic moments of nuclei have been developed, with much more severe restrictions imposed, e.g., the Mössbauer effect or the method of resonance γ-ray scattering. Everybody can get acquainted with a contemporary state of affairs in this domain in monography [3]. The appearance of frequency-tuned lasers brought about a revival of the optical spectroscopy of nuclear moments. A renewed impetus in this direction was given by the discovery of a non-statistical component population of the atomic hyperfine structure at K-capture or internal conversion of γ-rays.

In experiments carried out at the European Organization for Nuclear Research (CERN) and the Petersburg Nuclear Physics Institute (PNPI) in 1977–1978, it was demonstrated that in the case of K-capture [4] or internal conversion [5] – unlike the photoexcitation case – a non-statistical population of components in the hyperfine structure of K-level of the final atom is possible, which is determined by spin selection rules. As a result, the arising X-ray K_α-line turns out shifted with respect to the fluorescence one by an order of the hyperfine splitting magnitude. Such a shift can be measured in a rather simple way by means of crystal-diffraction spectrometers.

Those works stimulated further researches, because there emerged an opportunity to use the effect of hyperfine shift of X-ray lines as a new method for the determination of magnetic moments of excited nuclear states independently of their lifetimes. The idea was implemented in work [6], where the authors managed to determine the unknown earlier magnetic moment of a ^{133}Ba nucleus in the 12.3-keV excited state by measuring a shift of the K_{α_1}-line excited at M4-transition.

The theoretical aspects of the problem have also been studied in detail. In particular, calculations of the magnetic dipole and electric quadrupole hyperfine constants of K- and L_{1-3}-levels have been carried out for all nuclei with the atomic number Z from 10 to 100, and the corresponding data tables have been published

[7–9]. The results of calculations are distinguished by a high accuracy due to the maximal simplicity of the atomic system concerned (an atom with a hole in the K- or L-shell), which is an advantage of this method in comparison with other known methods for the determination of nuclear moments in external fields.

The main obstacle that restricts the application of X-ray crystal-diffraction spectrometers for nuclear moment measurements is a necessity to distinguish the X-ray line that accompanies the nuclear transition under investigation. Therefore, the relevant experiments were carried out only with nuclei, the decay schemes of which are the simplest [4–7, 10, 11]. The application of the coincidence method is complicated in this case owing to a low luminosity of crystal-diffraction devices. The indicated difficulties can be eliminated in a natural way by measuring the energies of conversion lines which undergo the same shifts as the X-ray levels do, but with the opposite sign.

2. Experimental Technique

Making use of the results of work [6], where relations were obtained for the shifts of K_α-lines that accompany conversion transitions of any multipolarity, the expression for a shift of conversion K-lines can be written down as follows:

$$\delta E_K = -\Delta_K \frac{(I_0 - I)(I_0 + I + 1) - L(L+1)}{2L(2I+1)} \times$$

$$\times \frac{1 - Lr/(L+1)}{1+r}, \qquad (1)$$

where I_0 and I are the nuclear spins in the initial and final nuclear states, respectively; L is the transition multipolarity; $r = |M_{\varkappa_2}|^2/|M_{\varkappa_1}|^2$; $|\varkappa_1| < |\varkappa_2|$; $M_\varkappa$ is the partial conversion matrix element; $\varkappa = (l-j)(2j+1)$; $j = |\varkappa| - 1/2$; $l = j \pm 1/2$; l and j are the orbital and total moments of the electron, respectively;

$$\Delta_K = \alpha E_0 \left(\frac{m_e}{m_p}\right) \mu_I \frac{2I+1}{I} \frac{3\alpha Z^3}{3\gamma(2\gamma-1)} (1 - \epsilon_e - \epsilon_m) \qquad (2)$$

is the magnitude of hyperfine splitting for K-level; α is the fine structure constant; Z is the nuclear charge number; $\gamma = \sqrt{1-\alpha^2 Z^2}$; m_e/m_p is the electron-to-proton mass ratio; $E_0 = m_e c^2$ is the electron's rest energy; μ_I is the nuclear magnetic moment in terms of nuclear magnetons; and ε_e and ε_m are corrections for the distributions of charge and magnetization densities over the volume of the nucleus.

It is convenient to express the hyperfine splitting of K-level in terms of the magnetic dipole constant of hyperfine structure a_K,

$$\Delta_K = \frac{2I+1}{2} a_K. \qquad (3)$$

The values of the ratio a_K/g (g is the gyromagnetic ratio, so that the magnetic moment of the nucleus $\mu = \mu_N g I$) are tabulated in works [7–9]. Some elements of the partial conversion matrix were tabulated in work [12]; otherwise, they can be calculated using the computer codes [13].

The minus sign before the expression on the left-hand side of formula (2.) arises because the signs of the energy gains of a conversion electron and an X-ray quantum are different. Similar expressions can also be written down for the shifts of conversion L_1- and L_2-lines.

From expression (2.), it follows that the effect of the hyperfine shift of conversion K-lines manifests itself especially significantly if the value of r differs from unity substantially. If the energies are not too high, such a situation is realized in transitions with M1-multipolarity. In this case, $|M_{\varkappa_1}| \gg |M_{\varkappa_2}|$, so that $r \ll 1$.

It is also evident that the multiplier that makes allowance for the dependence of a conversion line shift on the nuclear spin values in the initial and final states can change its sign, depending on the relationships between initial parameters. The multiplier, which is responsible for the dependence of the shift on partial conversion matrix elements can also change its sign, depending on the transition multipolarity. For instance, at E2-transitions, $|M_{\varkappa_2}| \gg |M_{\varkappa_1}|$, $r \gg 1$, and the multiplier sign changes with respect to that for M1-transition.

The hyperfine shift of conversion lines is very small. Therefore, it is rather difficult to determine it making a simple comparison between the energies of K-lines and γ-quanta. We developed the following measurement procedure for small shifts of conversion lines. We compare the energy difference ΔE_K between K-lines of two close transitions with similar differences for L-lines, ΔE_L, or γ-rays, ΔE_γ. For L-lines, the shift should be about an order of magnitude smaller [7], and it can be neglected (or taken into account approximately). Therefore, the value of the difference $\Delta E_K - \Delta E_L$, as well as that of the difference $\Delta E_K - \Delta E_\gamma$, can be considered to determine the magnitude of the relative shift of K-lines. This approach allows us to get rid of

the majority of systematic errors and to obtain reliable results.

The procedure was verified while studying the hyperfine shift of conversion lines in ^{181}Ta [14–19], and it proved to be good. The fulfilled researches convincingly testified that hyperfine shifts of conversion lines are accessible for measurements already today and on an available equipment, if the technique developed by us is used. This conclusion is also confirmed by the data of work [20], where the energy differences for K- and L-lines of ICEs were measured for 177-keV and 198-keV γ-transitions in ^{169}Tm making use of a prismatic γ-spectrometer, and the corresponding magnitude of hyperfine shift $(E_{L198} - E_{L177}) - (E_{K198} - E_{K177}) = +(0.32 \pm 0.15)$ eV was determined (the relevant theoretical value amounts to 0.21 eV).

Taking into account the achieved measurement accuracy and the expected shift values, which depend on the nuclear magnetic moment μ_I and the nuclear atomic number Z, one can suppose that research conditions are optimal for nuclei with $Z > 70$ and $\mu_I > 2$ nuclear magnetons.

3. Determination of the Magnetic Moment of the $9/2^+$ 136-keV Level in ^{181}Ta

To check this statement, we decided to carry out researches that would allow us to determine the magnetic moment of a nuclear state from the hyperfine shift of conversion lines. As the subject of investigation, the first excited level of the rotational band of the ^{181}Ta ground state was selected. Despite that the ^{181}Ta nucleus is one of the most studied nuclides, experimental data concerning the magnetic moment of its $9/2^+$ 136-keV level are more than twofold different from one another (see Table 1). All those data were obtained by the excited angular correlation method. For this reason, it was interesting to use an essentially different technique to estimate the magnetic moment.

The $9/2^+$ 136-keV level is populated at the β-decay of ^{181}Hf by means of E2-transition with an energy of 346 keV (see Fig. 1).

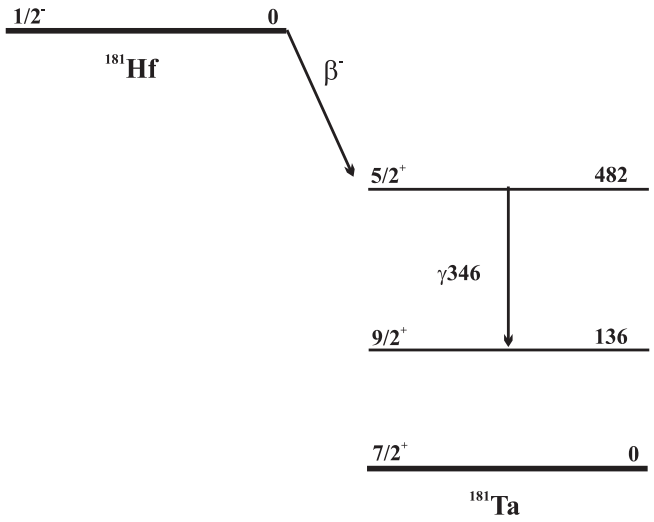

Fig. 1. Fragment of the ^{181}Hf-decay scheme

According to our procedure, it is necessary: 1) to select a close-by-energy γ-transition, which is implemented onto a level with a known magnetic moment; 2) to measure the energy differences between K-lines of those two transitions; 3) to measure the energy differences for L-lines or γ-rays; 4) from the value obtained for either the $\Delta E_K - \Delta E_L$ or $\Delta E_K - \Delta E_\gamma$ difference, to determine the total magnitude of the hyperfine shift of those two conversion lines; 5) to calculate the magnitude of hyperfine shift $\delta E(K346)$ of the conversion line; and 6) using this value, to calculate the magnitude of the magnetic dipole moment of the $9/2^+$ 136-keV level.

The intraband γ-transition with an energy of 343 keV from the first excited level of the rotational band of the ^{175}Lu ground state meets all those requirements. In particular, it is induced at the decay of ^{175}Hf (see Fig. 2), M1-transition is almost pure (the admixture of E2-multipolarity is about 8%), and the magnetic moment of ^{175}Lu is known with a high accuracy (see Table 1).

The radiation source – a mixture of ^{175}Hf ($T_{1/2} =$ 70 days) and ^{181}Hf ($T_{1/2} = 42$ days) – was produced making use of the (n, γ)-reaction, by irradiating hafnium targets with the natural isotope content in a reactor.

T a b l e 1. Magnetic moments of the $9/2^+$ 136-keV level in ^{181}Ta and the ground state of ^{175}Lu (experimental data)

$\mu(9/2^+$ 136-keV ^{181}Ta), nucl. magn.	Source	$\mu(7/2^+$ 0-keV ^{175}Lu), nucl. magn.	Source
1.22 ± 0.18	[21]	2.23799 ± 0.00006	[24, 25]
1.98 ± 0.63	[22]	2.213 ± 0.010	[26]
2.6 ± 0.7	[23]	2.2327 ± 0.0011	[27]
		2.2323 ± 0.0011	[28]

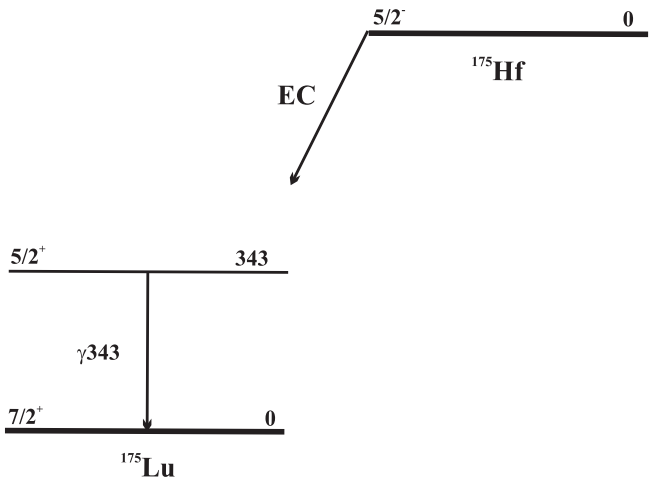

Fig. 2. Fragment of the ^{175}Hf-decay scheme

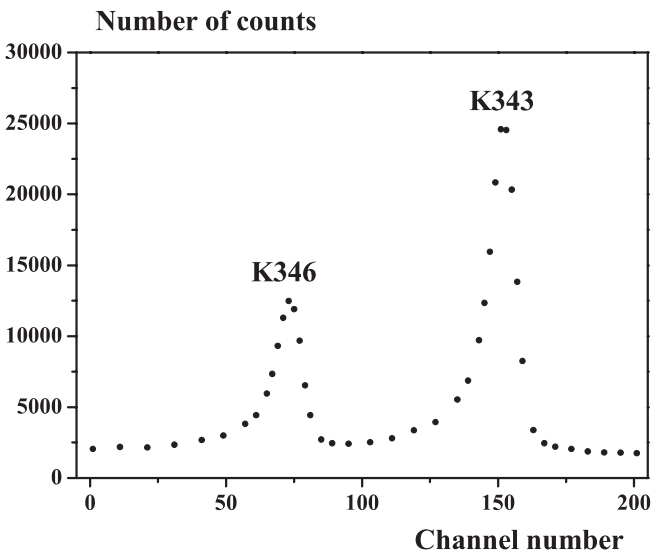

Fig. 3. Fragment of the ICE spectrum for 343-keV and 346-keV γ-transitions at K-shells of ^{175}Lu and ^{181}Ta

The ICE spectra were measured on a magnetic β-spectrometer of the $\pi\sqrt{2}$ type with an iron yoke and the 50-cm-radius equilibrium orbit. The dependence of the pulse count rate (electrons) on the voltage applied between the radiation source and the spectrometer chamber was registered. The magnetic field remained constant at that, being stabilized at three points along the radius by the nuclear magnetic resonance method. The system of stabilization provided the stability of the field in the spectrometer of about 10^{-5} within 24 h. The high voltage supplied to the radiation source was also stabilized with a relative accuracy of 5×10^{-5}.

The registration system of the spectrometer consisted of two Geiger–Müller counters located along electron paths at a distance of 170 mm from each other. The counters were separated away in order to reduce the background produced by the spectrometer, when operating in the coincidence mode. The inner diameter of the first counter was 15 mm, and this counter was oriented vertically; the inner diameter of the second counter was 46 mm, and this counter was oriented horizontally. The own background of counter 1 was 10 counts per minute; in the coincidence mode, this parameter was equal to about 4 counts per hour.

Measurements were grouped in short series, each of them being a multiply repeated scanning of the spectrum in both directions. Single spectra and coincidence ones were accumulated in a memory device to be transferred afterwards to a computer for their processing.

The pulse resolution of the spectrometer was 0.03% at a solid angle of 0.07% of 4π. The spectrometer characteristics allowed the relative intensities of conversion lines to be determined with a 1%-accuracy and the energy difference between lines with an accuracy of no more than 1 eV.

The energy differences between K- and L-lines of ICEs for 343-keV and 346-keV γ-transitions in ^{175}Lu and ^{181}Ta were measured. In Fig. 3, the fragment of the spectrum of ICEs on the K-shell of ^{175}Lu and ^{181}Ta is exhibited. Four measurement series, analogous to those presented in Fig. 3, were fulfilled, as well as 4 measurement series of ICE spectra for L-subshells of ^{175}Lu and ^{181}Ta.

The difference between γ-ray energies was measured with the help of a HPGe-detector 5 cm^3 in volume and with a resolution of 0.9 keV at 344-keV γ-line ^{152}Eu. In Fig. 4, a fragment of the γ-spectrum, which contains 343-keV and 346-keV γ-lines from ^{175}Hf and ^{181}Hf decays, is shown. The figure demonstrates that the lines are located rather close to each other, being – at the same time – well separated in the spectrum, which allows precision data on their energies and intensities to be obtained.

The functional dependence of γ-spectrometer calibration with respect to energy was studied in detail. It was found that deviations from linearity did not exceed 5×10^{-6} in the range 122–344 keV. To minimize probable systematic errors, measurements were carried out in series at various gain factors. Three series of measurements, similar to those shown in Fig. 4, were executed. The obtained values for the difference between the 343-keV and 346-keV γ-ray energies are in good mutual agreement.

The data obtained were treated making use of computer codes [29–31] based on the method, where the "instrumental" curve is inscribed into a certain section of the spectrum. This method allows the energies and the intensities of components to be determined with a high accuracy, even if the line shapes are asymmetric and the lines overlap. The results of measurements are quoted in Table 2. Either the weight or spread error was used as the uncertainty of experimental values, depending on which of them was larger.

The energy differences of the doublets $L_3346 - L_1343$ and $L_3346 - L_2343$ from Table 2 were used to calculate the difference between the energies of 346-keV and 343-keV γ-transitions by the formulas

$$E_\gamma(346) - E_\gamma(343) = E_{L_3}(346) - E_{L_1}(343) +$$

$$+E_{L_3}(Ta) - E_{L_1}(Lu) + \delta E_{L_1}(343), \qquad (4)$$

$$E_\gamma(346) - E_\gamma(343) = E_{L_3}(346) - E_{L_2}(343) +$$

$$+E_{L_3}(Ta) - E_{L_2}(Lu), \qquad (5)$$

where E_{L_1}(Lu), E_{L_2}(Lu), and E_{L_3}(Ta) are the electron binding energies at the corresponding Lu and Ta subshells [32, 33], and $\delta E_{L_1}(343) = 0.109$ eV is the hyperfine shift of the conversion L_1-line. The specific value for the latter quantity was calculated by formulas (2.) to (3) and making use of the magnitude of the magnetic moment of ^{175}Lu in the ground state taken from Table 1.

The values obtained agree well with one another and with the value obtained from γ-spectrum measurements. The weighted average value $E_\gamma(346) - E_\gamma(343) = (2530.6 \pm 0.9)$ eV and the value of $E_K(343) - E_K(346)$ from Table 2 were used to calculate $\delta E_K(346)$ by the formula

$$\delta E_K(346) = \delta E_K(343) + E_K(346) - E_K(343) +$$

$$+E_\gamma(343) - E_\gamma(346) + E_K(Ta) - E_K(Lu), \qquad (6)$$

where $\delta E_K(343) = 0.826$ eV is the hyperfine shift of the conversion K-line calculated by formulas (1)–(3).

T a b l e 2. Energy differences for the K- and L-lines of internal conversion electrons and the γ-lines of 343-keV and 346-keV γ-transitions in ^{175}Lu and ^{181}Ta

Doublet	ΔE, eV	Doublet	ΔE, eV
K343–K346	1573.3 ± 0.5	L_3346–L_2343	3005.2 ± 3.2
L_3346–L_1343	3520.1 ± 1.1	$\gamma346$–$\gamma343$	2530.1 ± 1.5

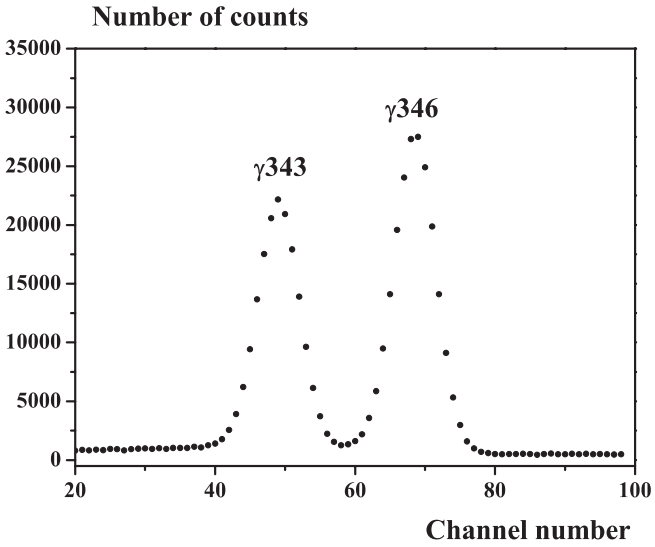

Fig. 4. Fragment of the γ-spectra of ^{181}Hf and ^{175}Hf decays with 343-keV and 346-keV γ-lines

Knowing a hyperfine shift of the K-line of the 346-keV γ-transition, $\delta E_K(346) = -(0.5 \pm 1.1)$ eV, it is easy to calculate the magnetic moment of the $9/2^+$ 136-keV level by the formula

$$\mu_I = -\frac{\delta E_K I}{a_K/g} \frac{4L}{(I_0 - I)(I_0 + I + 1)} \frac{1 + r}{1 - Lr/(L + 1)} \qquad (7)$$

to obtain $\mu(9/2^+\ ^{181}\text{Ta}) = (1.9 \pm 4.2)$ nuclear magnetons.

4. Conclusions

The result obtained qualitatively agrees with the data of other authors; however, the experimental error amplitude is too large. Nevertheless, even such an accuracy is often enough to draw a conclusion about the configuration type of the nuclear state – quasi-neutron or quasi-proton one. Moreover, as was pointed out earlier, this technique allows the magnetic moments of nuclei in excited states to be determined irrespective of their lifetimes, which is its irrefutable advantage.

In principle, nothing prevents anyone from determining the magnetic moments of nuclear states with a high accuracy making use of this technique, because the accuracy of theoretical calculations of hyperfine shifts of conversion lines is very high, and the relative error amounts to a few percent. The main error is induced by the accuracy, with which the energies of γ-quanta and electrons were determined. However,

the corresponding forecast is optimistic. In 1980, nuclear-spectroscopic normals included γ-transitions, the energies of which were determined with a relative error not worse than 10^{-4}, and their total number was 148 [34]. Nowadays, the list of recommended energy standards for nuclear spectroscopy includes about 240 γ-lines which span the energy range from 24 to 4806 keV [35, 36]. This list includes only those γ-lines, the energy of which was determined with a relative error not worse than 10^{-5}. Hence, the accuracy of measurements of γ-transition energies has been improved by an order of magnitude within 20 years. A similar situation is observed for the determination of the energy of ICEs as well. All those circumstances are favorable to a wider application of our technique aimed at the determination of the magnetic moments of nuclear states by analyzing the hyperfine shift of conversion lines.

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ВИЗНАЧЕННЯ МАГНІТНИХ МОМЕНТІВ ЯДЕРНИХ СТАНІВ ЗА НАДТОНКИМ ЗСУВОМ КОНВЕРСІЙНИХ ЛІНІЙ

А.П. Лашко, Т.М. Лашко

Р е з ю м е

Розроблено методику визначення магнітних моментів ядер за надтонким зміщенням ліній електронів внутрішньої конверсії. Область її застосування не залежить від тривалості життя ядерних станів. Методику було використано для оцінки величини магнітного моменту збудженого рівня $9/2^+$ 136 кеВ в ^{181}Ta.