Experimental determination of spatial parity violation in a Mössbauer transition in ^{119}Sn

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Experiments were used to determine the asymmetry of photon emission relative to the direction of the nuclear spin, in a Mössbauer transition in ^{119}Sn. One experiment was carried out at temperatures 300–461 K using a source at rest and a resonance detector, whereas the other took place at 300 K and involved careful determination of the Mössbauer spectrum. The quantity $2R$ representing the degree of violation of the spatial parity was found to be $(0.94 \pm 0.08) \cdot 10^{-3}$ in the first experiment and $(0.90 \pm 0.13) \cdot 10^{-3}$ in the second ($2R$ is the doubled ratio of the reduced matrix elements of the E 1 impurity transition and of the M 1 regular transition).

The existence of a weak nucleon-nucleon interaction which violates spatial parity gives rise to spatially odd effects in nuclear processes (for reviews, see Refs. 1–3). Experimental investigations of these effects can help elucidate the role of the weak interaction in these processes and check the quantitative predictions obtained from theoretical models.

In the case of a gamma transition of an excited nucleus to the ground state we can expect P-odd effects of two types because of mixing of multipoles of different parity: circular polarization P_c of radiation from an unpolarized source and asymmetry ΔI of the emission of gamma photons relative to the direction of the nuclear spin (in the latter case a source containing polarized excited nuclei is needed).

In the case of mixing of multipoles of the same order, for example M 1 and E 1, the resultant P-odd effects are, respectively,

$$P_c = -2R, \qquad \Delta I = 3RAp\cos\theta,$$

where $R = Q(E1)/Q(M1)$ is the ratio of the reduced matrix elements for the corresponding multipoles; p is the degree of polarization of the nuclei, defined as the resultant nuclear moment relative to the selected axis; θ is the angle between the photon momentum in the direction of polarization of the nuclei; A is a factor dependent on the spins of the ground j_g and excited j_e states of the nucleus:

$$A = -1/j_e \quad \text{for} \quad j_e = j_g + 1,$$

$$A = -1/(j_e+1) \quad \text{for} \quad j_e = j_g,$$

$$A = j_e/(j_e+1) \quad \text{for} \quad j_e = j_g - 1.$$

The nuclear spins can be polarized by a magnetic field at infralow temperatures, but a degree of polarization amounting to $p \approx 0.2$ (which is sufficient for measurements) can be attained only when the following condition is satisfied for the usual magnetic moments: $H/T = 10^6$–10^7 Oe/K. Even if we use the effective magnetic field of the hyperfine interaction, which reaches a megaoersted in ferromagnets, we need subhelium temperatures for the nuclear polarization. Deep cooling is complicated by the internal heat released by a radioactive sample, which can be 1–10 mW when the activity is 50 mCi. These methodological difficulties account for the fact that the P-odd asymmetry of gamma radiation has been determined by a cryogenic technique only for the ^{180m}Hf nucleus.[4]

We shall use a different method of generation of nuclei in a specific polarized state. It is based on the Zeeman splitting of the excited and ground energy levels of a nucleus in a magnetic field (such a splitting is shown in Fig. 1 for the first two levels of the ^{119}Sn nucleus). Each transition between the Zeeman sublevels corresponds to a specific energy of the emitted gamma photons and specific projections of the nuclear spin in the excited and ground states along the magnetic field direction, which serves as the quantization axis. If photons from one of these transitions are recorded in an energy-selective manner, this makes it possible to separate radiation of that part of an ensemble in which the nuclei have specific spin projections at the moment of emission. In other words, we can use this approach to investigate the emission from "polarized" nuclei without polarizing the whole ensemble.

In the case of dipole radiation the asymmetry ΔI of the gamma photon emission is proportional to R and is manifested mainly in the process of recording circularly polarized radiation corresponding to transitions between the sublevels whose quantum numbers m_e and m_g differ by $\Delta M = m_e - m_g = \pm 1$. A linearly polarized component with $\Delta M = 0$ makes a contribution to ΔI which is proportional to R^2. This is explained by the fact that oscillations of the magnetic and electric dipoles, forming the radiation of these multipolarities, are phase-shifted by $\pi/2$.

The energy resolution of gamma photons necessary in this quasipolarization method can be provided by Mössbauer spectroscopy. A Mössbauer spectrum of the emission from nuclei subjected to a magnetic field represents a set of lines (six lines in the case of ^{119}Sn) corresponding to transitions between the Zeeman sublevels of the nuclear states. One of these lines with $\Delta M = \pm 1$ can be recorded selectively with a resonance detector.

In our experiments the quantization axis was selected conveniently along the effective magnetic field of the hyperfine interaction between the nucleus and its electron environment. A ferromagnetic sample containing emitting nuclei can be magnetized to saturation along the required direction using a relatively weak external field. The hyperfine interaction field is then oriented either parallel or anti-

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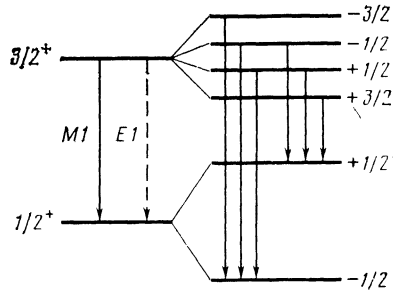

FIG. 1. Zeeman splitting of a Mössbauer transition in the ^{119}Sn nucleus; $\mu(3/2^+) = +0.682$ and $\mu(1/2^+) = -1.046$.

parallel to the external field.

The following experimental setup was then possible. An external magnetic field **H** magnetized a ferromagnetic source containing the emitting nuclei of radioactive ^{119}Sn. With the other parts of the apparatus kept immobile, this source was reversed periodically, altering correspondingly the directions of projections of the spins of those nuclei whose radiation was recorded selectively by a detector. The mutual orientations of the external magnetic field **H**, of the wave vector of the recorded photons **k**, and of the projection of the spin of a nucleus **j** belonging to the quasipolarized subsystem of emitting nuclei are shown in Fig. 2a. We reversed the magnetization and determined the resultant gamma-photon-flux change due to the *P*-odd asymmetry of photon emission relative to the direction of the spin of the emitting nucleus.

The quasipolarized state of the radioactive ^{119}Sn nuclei was attained as follows: an efficient scintillation detector for Mössbauer radiation was developed; a suitable chemical environment of the Mössbauer nuclei created a ferromagnetic source–Mössbauer scintillator resonance pair, which made it possible to record selectively the lowest line in the spectrum when the source and detector were at a fixed position and this could be done without recourse to the traditional (in Mössbauer spectroscopy) Doppler modulation of the gamma photon energy; heating of the source made it possible to tune exactly the investigated emission line of the source so that it was in resonance with the absorption line of the detector.

This method was applied for the first time to a Mössbauer transition in the ^{119}Sn nucleus at 23.8 keV with a width 2.47×10^{-11} keV, providing an opportunity for determining the degree of violation of the *P* parity, i.e., measurements were made of the ratio of the reduced matrix elements of the *E* 1 and *M* 1 multipoles.[5,6]

RADIATION SOURCE AND DETECTOR

A source containing ^{119}Sn Mössbauer nuclei in an excited state should satisfy the following conditions.

1. The source material should be ferromagnetic in the temperature range $\approx$300–500 K convenient for measurements.

2. The positions of the lines in the Mössbauer emission spectrum of the source should make it possible to select an absorber material suitable for resonance detection of one of the lines in the source spectrum.

3. The concentration of the tin nuclei in the source material should be maximal because a strong flux of gamma photons was needed to investigate small *P*-odd effects.

Magnetic structures had been investigated reliably only in the case of binary iron–tin and manganese–tin compounds. Among ferromagnetic representatives of these systems the alloy Mn_2Sn was rejected by us immediately, because its Curie temperature was ≈ -10 °C. The use of this material would require stabilization of subzero temperatures, which would complicate too much the prolonged precision measurements.

Other candidates for a suitable material were the compounds Fe_3Sn and Mn_4Sn, which we considered. The Mössbauer spectra of these compounds had been investigated earlier[7,8] and the Curie temperatures amounting to $\sim$470 and $\sim$150 °C, respectively, were determined. Moreover, the effective (internal) magnetic field H_{int} of the hyperfine inter-

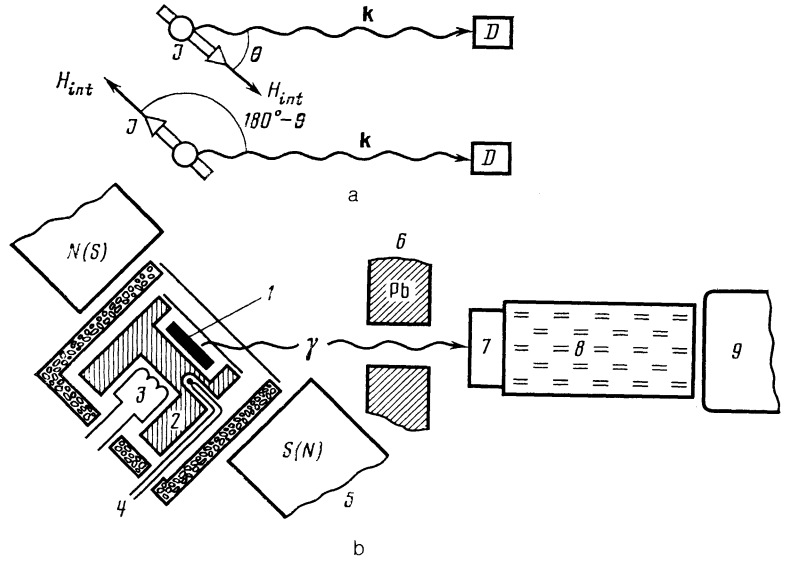

FIG. 2. a) Mutual orientations of the magnetic field **H**, projection of the nuclear spin **J**, and the photon wave vector **k** shown for different directions of the magnetization of the source. b) Experimental setup used to measure the asymmetry of radiation in the fixed geometry: 1) Mn_4Sn source; 2) aluminum can; 3) heater; 4) thermocouple; 5) electromagnet; 6) collimator; 7) resonance scintillator; 8) light guide; 9) photomultiplier.

action at the tin nuclei in these alloys was known to be directed opposite to the magnetization. The complexity of the phase diagrams of these two systems and the need to prepare homogeneous samples made it necessary to develop a technology for preparing these samples and measuring the Mössbauer spectra of the resultant products.

We prepared the alloys Fe_3Sn and Mn_4Sn containing the radioactive isomer ^{119m}Sn. The Mössbauer emission spectra of the samples were investigated in a wide range of temperatures in order to determine the feasibility of resonance detection of a suitable line in the Mössbauer spectrum, since variation of temperature altered the hyperfine interaction field at the tin nuclei and, consequently, shifted the positions of the lines in question.

These two compounds were prepared by melting stoichiometric amounts of the appropriate components (one of which was radioactive ^{119}Sn) in an induction furnace filled with high-purity helium. Measures were taken during melting to prevent sublimation losses of the more volatile component. Planar samples were prepared by casting because the materials were brittle.

An investigation of the Mössbauer spectrum of Fe_3Sn showed that heating of this compound to 120 °C brought the line positions closer to zero velocity, i.e., to a resonance with the detector at rest. However, prolonged precision measurements at elevated temperatures were impossible because of the onset of dissociation of the compound.

A suitable source was the alloy Mn_4Sn for which the Mössbauer spectrum is shown in Fig. 3 (the continuous curves represent the line components of the spectrum corresponding to transitions between the Zeeman sublevels of the tin nucleus). The phase composition of the samples was monitored by recording their Mössbauer spectra at room and nitrogen (78 K) temperatures. The Mn_2Sn phase, which could appear as a result of melting, was paramagnetic at room temperature and should exhibit additional peaks in the region between two humps of the relevant spectrum. At the temperature of liquid nitrogen (78 K) the Mn_2Sn phase was ferromagnetic and the effective magnetic field of the hyperfine interaction at the tin nuclei in this compound reached ≈ 200 kOe, which was five times as high as for the main Mn_4Sn phase, and the admixture of the Mn_2Sn phase would have given rise to an additional more strongly split sextet of lines in the Mössbauer spectrum. The absence of peaks in the inner and outer parts of the spectrum was a demonstration of the required purity of the alloys.

The homogeneity of the alloys was confirmed also by the absence of kinks on the curve representing the temperature dependence of the effective magnetic field of the hyperfine interaction H_{int}. This dependence was similar to the Brillouin function and was obtained by measuring the Zeeman splitting of the source Mössbauer spectra measured at various temperatures; it is shown in Fig. 4 where extrapolation of the curve to the abscissa intercept made it possible to estimate the Curie temperature of the ferromagnetic transition at ~ 435 K.

The quasipolarization method involved selective recording of the radiation due to one of the transitions between the Zeeman sublevels of the emitting nucleus, i.e., separation of one of the lines in the spectrum of the Mn_4Sn source. This was done by a specially constructed resonance scintillation

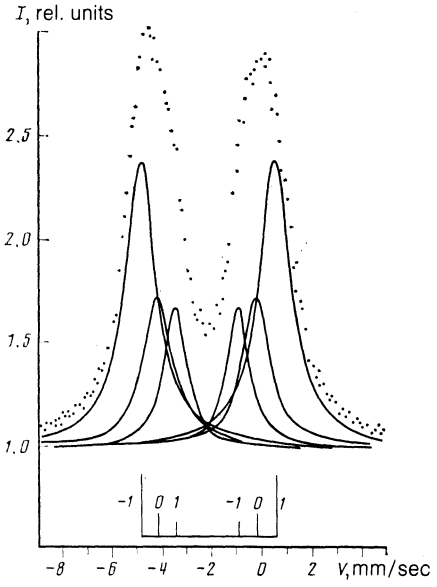

FIG. 3. Mössbauer emission spectrum of the Mn_4Sn source at $T = 300$ K (explanations in text).

detector. The active component of this detector consisted of a substance containing ^{119}Sn and absorbing the Mössbauer radiation and a scintillation polymer. The resonance (Mössbauer) absorption of gamma photons by the tin nuclei was accompanied by the emission of conversion electrons which caused the scintillations.

This detector was relatively insensitive to the background components of the radiation from a Mössbauer source, which included a nonresonance component (i.e., the Mössbauer-transition radiation which experienced recoil in a decay event) and a concomitant x-ray component. This was due to the fact that the Mössbauer absorption cross section was considerably greater than the photoeffect cross section. The high selectivity of the detector made it possible to increase the contribution of the measured part of the resonance radiation I_r to the total detector signal I to about 50%. The emission spectrum of the Mn_4Sn source (Fig. 3) was determined using a resonance scintillation detector in which the absorber had an unsplit Mössbauer line. It is clear from Fig. 3 that the selected resonance pair of a fixed source and detector ($V = 0$) recorded the lines of the right-hand frag-

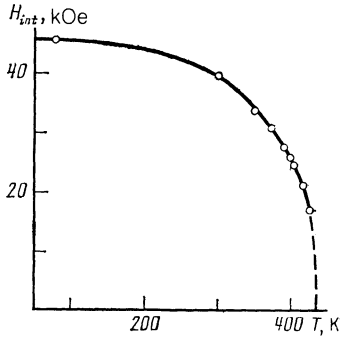

FIG. 4. Temperature dependence of the effective magnetic field of the hyperfine interaction H_{int} of the tin nuclei in Mn_4Sn.

ment of the spectrum corresponding to transitions to the + 1/2 level of the ground state of the ^{119}Sn nucleus.

Exact tuning of the detector to a resonance with the strongest outer line was ensured by heating the source. The effective magnetic field of the hyperfine interaction of the ^{119}Sn nuclei in the Mn_4Sn ferromagnetic matrix decreased as a result of heating and vanished at the Curie temperature (Fig. 4). There was a corresponding reduction in the Zeeman splitting of the nuclear levels and the Mössbauer lines were shifted to the center of gravity of the spectrum and then degenerated into one line as a result of further heating (Fig. 5). A change in the source temperature by 100 °C shifted the lines by an amount of the order of their width. Heating of the source could achieve a resonance with the required line and ensure that the investigated transition dominated the overall detector signal.

The spectra were measured using a magnetized source, which was placed on a vibrator of a Mössbauer spectrometer, and a working resonance detector using the same geometry as in the main experiments. Therefore, the properties of the source-detector resonance pair made it possible, firstly, to dispense with the traditional Mössbauer vibrator technique and to ensure "tuning to resonance" by selection of the chemical shift and variation of temperature, and thus maximize the recording time of the selected Zeeman transition and avoid possible errors due to a change in the experimental geometry in the course of mechanical motion of the source; secondly, the temperature of the source could be used as an independent parameter which did not affect the magnitude of the investigated nuclear effect (but did affect the quantities measured directly); thirdly, it was possible to carry out a "zero" experiment, i.e., to determine the background (apparent) asymmetry of the apparatus by heating the source above the Curie temperature, when the *P*-odd asymmetries of photon emission of all the transitions were mutually compensated.

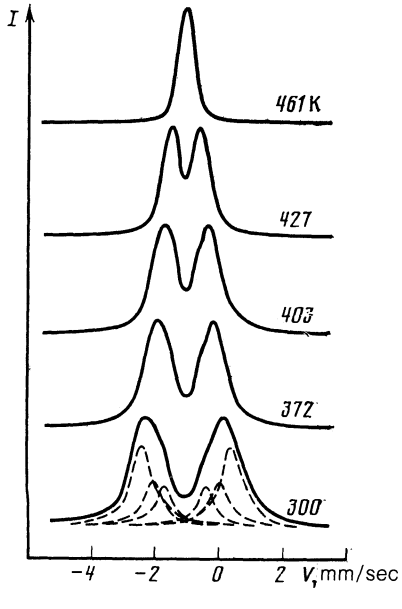

FIG. 5. Changes in the Mössbauer spectrum of Mn_4Sn as a result of heating.

EXPERIMENTAL PROCEDURE

We determined the *P*-odd effects of Mössbauer radiation using the experimental setup shown in Fig. 2b. A source of gamma photons 1 was a sample of Mn_4Sn containing the ^{119}Sn isomer; its dimensions were $12\times6\times0.3$ mm and it was bonded to an aluminum can 2 which equalized the temperature on the surface of the source. The can contained a heating element 3 and it was covered from outside by asbestos heat insulation, whereas the loss of heat by radiation was prevented by a reflecting screen in the form of a metallized Mylar film. The temperature of the source could be varied within the range 300–461 K and monitored with a thermocouple 4.

The source assembly was a rigid but light unit, which was placed on the vibrator of a Mössbauer spectrometer during the preliminary stage of the investigation. In the main experiment this assembly was held rigidly inside the gap of an electromagnet 5. The surface of the source and the field in the electromagnet gap were oriented at an angle of 45° (or 135°) to the average direction to the detector for reasons of convenience. The current in the electromagnet winding was stabilized and every 4 sec its direction was reversed. The field experienced by the emitting tin nuclei was reversed with the same period and, because of the *P*-odd asymmetry of the photon emission, the intensity of the recorded Mössbauer source line varied at the same period.

The gamma radiation was recorded with a resonance Mössbauer scintillator 7 bonded to a quartz light guide 8. The use of this light guide made it possible to place a photomultiplier further away from the electromagnet. A triple magnetic screen was used to protect the photomultiplier from the residual fringing field of the electromagnet. An integral method for recording the radiation was used in our experiments. We determined constant (I) and small alternating (ΔI) components of the anode current in the photomultiplier. The latter component was governed by the investigated *P*-odd effect and by statistical fluctuations of the radiation intensity. The periodic *P*-odd signal was separated from the statistical noise by the method of lock-in storage. The photomultiplier signal was amplified and then subjected to lock-in detection. The sign of the alternating detector signal was reversed in synchronism with the sign of the quantity ΔI, so that if the investigated effect was present, an integrator could accumulate a signal proportional to ΔI and the accumulation time. The lock-in detector was controlled by the same reference voltage as the inverter of the current supplied to the electromagnet 5. An identical control accumulation channel operated in parallel to the main one and the lock-in detector in the channel was governed by a reference voltage which was phase-shifted by $\pi/2$. The output voltage of this channel was determined solely by the noise component of the detector signal.

In addition to the required *P*-odd signal, the photomultiplier output included a synchronous signal from the conversion and β electrons recorded by the scintillator and emitted by the ^{113}Sn nuclei and by the ^{125}Sb impurity. The intensity of the electron flux reaching the scintillator depended on the direction of the magnetic field and varied synchronously with the reversal of this field. This component of the noise was removed by placing a graphite filter 2-mm thick beyond the source; this filter then absorbed almost

all the electrons and hardly changed (by no more than 2%) the fraction of the resonance Mössbauer radiation.

CALCULATION OF THE ASYMMETRY OF GAMMA PHOTON EMISSION FROM POLARIZED NUCLEI IN THE CASE OF *P* PARITY VIOLATION

Violation of the spatial parity in the case of gamma decay of the 23.8 keV excited state of the ^{119}Sn nucleus was manifested by an admixture of the additional $E1$ multipole of opposite parity to the regular $M1$ transition. The ratio R of the reduced matrix elements of these transitions could be determined from the measured radiation asymmetry if we calculated first the angular distribution of the gamma radiation of polarized nuclei for a mixture of these two transitions. Calculations of this kind had been carried out some time ago,[9,10] but for our purpose the treatment could be simpler if we used the relevant theoretical treatment proposed by Frauenfelder *et al.*,[11] which can make clear the results.

The matrix element of the emission, by a nucleus, of an electromagnetic wave of frequency ω in the direction $\hat{\mathbf{k}}$ and with the polarization $\hat{\mathbf{e}}$ ($\hat{\mathbf{e}}\cdot\hat{\mathbf{k}}=0$, where the caret denotes a unit vector) is given by

$$H_{ge}=\langle j_g m_g|\hat{\mathbf{e}}\mathbf{j}\exp(i\hat{\mathbf{k}}\mathbf{r})|j_e m_e\rangle$$

$$=\hat{\mathbf{e}}\langle j_g m_g|\mathbf{j}\exp(i\hat{\mathbf{k}}\mathbf{r})|j_e m_e\rangle=\hat{\mathbf{e}}\mathbf{j}(\hat{\mathbf{k}}),$$

where $\mathbf{j}$ is the current due to the nucleon transitions; j_g, m_g, j_e, and m_e are the moments and their projections along the quantization axis in the ground and excited states; $\mathbf{j}(\hat{\mathbf{k}})$ is a vector function, the actual form of which for the currents of the electric and magnetic types of multipolarity L is given by the expressions[12]

$$\mathbf{J}_E=\left[\frac{\pi\Gamma_E(2L+1)}{\omega(2j_e+1)(L+1)}\right]^{1/2}\mathbf{Y}_{L,L-1,\Delta M}C_{L,\Delta M},$$

$$\mathbf{J}_M=\left[\frac{\pi\Gamma_M}{\omega(2j_e+1)}\right]^{1/2}\mathbf{Y}_{L,L,\Delta M}C_{L,\Delta M},$$

where $C_{L,\Delta M}=C^{j_e m_e}_{L,\Delta M;j_g m_g}$ are Clebsch-Gordan coefficients; Γ_E and Γ_M are the radiative widths of the transitions of the electric and magnetic types, proportional—as is known—to the squares of the corresponding reduced matrix elements; $\mathbf{Y}_{L,L,\Delta M}$ are spherical harmonics.

Following Frauenfelder, we can relate the transition current $\mathbf{j}(\hat{\mathbf{k}})$ and the polarization vector of the radiation $\hat{\mathbf{e}}$:

$$\hat{\mathbf{e}}=[\mathbf{J}^*-\hat{\mathbf{k}}(\hat{\mathbf{k}}\mathbf{J}^*)]/(|\mathbf{J}|^2-|\hat{\mathbf{k}}\mathbf{J}|)^{1/2}.$$

The probability w_γ of the emission of a photon in a solid angle dO can be calculated in the usual way:

$$w_\gamma=\frac{\omega}{\pi}|\hat{\mathbf{e}}\mathbf{J}(\hat{\mathbf{k}})|^2\,dO.$$

We included here a normalization factor for $\hat{\mathbf{e}}$ equal to $(4\pi/\omega)^{1/2}$ which corresponds to finding one photon with specific quantum numbers L and ΔM in a unit volume. Bearing in mind that $|\hat{\mathbf{e}}\mathbf{J}(\hat{\mathbf{k}})]|^2=|[\hat{\mathbf{k}}[\mathbf{J}(\hat{\mathbf{k}})\hat{\mathbf{k}}]]|^2$, we obtain an expression for the angular distribution of the $M1$ multipole radiation with the $E1$ admixture:

$$I=\frac{w_\gamma}{\Gamma_M}=\frac{C^2_{L,\Delta M}}{2j_e+1}|\mathbf{Y}^{(0)}_{1,\Delta M}+R\mathbf{Y}^{(1)}_{1,\Delta M}|^2\,dO, \qquad (1)$$

where $\mathbf{Y}^{(\lambda)}_{1,\Delta M}$ ($\lambda=1$ or 0) are transverse spherical vectors describing the state of photons of electric and magnetic types. Analytic expressions for the components of these vectors along the directions of unit vectors e_φ and e_θ of a spherical coordinate system are given in Table I.

It should be pointed out that the directions of these unit vectors coincide with the triplet of orthogonal unit vectors that can be formed from two physical vectors at our disposal, which are the magnetic field and the photon wave vector:

$$\hat{\mathbf{n}}=\hat{\mathbf{k}},\quad \hat{e}_\varphi=\frac{[\hat{\mathbf{H}}\hat{\mathbf{k}}]}{(|[\hat{\mathbf{H}}\hat{\mathbf{k}}]|)^{1/2}},\quad \hat{e}_\theta=\frac{[\hat{\mathbf{k}}[\hat{\mathbf{H}}\hat{\mathbf{k}}]]}{(|[\hat{\mathbf{k}}[\hat{\mathbf{H}}\hat{\mathbf{k}}]]|)^{1/2}}.$$

Equation (1) and Table I can be used to obtain expressions for the absolute and relative values of the P-odd correction to the radiation which is due to the presence of the "impurity" $E1$ transition and is manifested by the measured gamma radiation asymmetry:

$$\Delta I(\Delta M=\pm1)=\mp\frac{3RC^2_{L,\Delta M}\cos\theta}{2j_e+1},$$

$$\frac{\Delta I}{I}(\Delta M=\pm1)=\mp2R\frac{2\cos\theta}{1+\cos^2\theta}=-2R\xi_c,$$

$$\Delta I(\Delta M=0)=0,\quad \frac{\Delta I}{I}(\Delta M=0)=0.$$

The quantity

$$\xi_c(\Delta M=\pm1)=\Delta M\frac{2\cos\theta}{1+\cos^2\theta}=\Delta M\xi$$

represents the degree of circular polarization of the radiation due to the transitions characterized by $\Delta M=\pm1$. In the linear approximation in respect of the investigated effect the radiation which appears in the $\Delta M=0$ case does not carry information on violation of the spatial parity, as can be seen from the above formulas.

Finally, the relationship between the measured asymmetry of the radiation and the required parameter R representing P-parity violation can be written in the form:

TABLE I. Analytic expressions for components of transverse spherical vectors $\mathbf{Y}^{\lambda}_{1,\Delta M}(4\pi/3)^{1/2}$.

ΔM	$E1$		$M1$	
	e_θ	e_φ	e_θ	e_ψ
0	$-2^{-1/2}\sin\theta$	—	—	$+2^{-1/2}i\sin\theta$
±1	$\mp1/2\cos\theta$	$-1/2\,i$	$+1/2$	$\pm1/2\,i\cos\theta$

$$\Delta I/I = -2R\Delta M|\xi|.$$

All the physical conclusions can be drawn from our experiments on the basis of this one formula. It follows from this formula that the reversal of the magnetization of a sample relative to the direction of the wave vector of the investigated gamma photons should alter the intensities of the Mössbauer lines by small P-odd values proportional to ΔM and to the amplitudes of these lines.

RESULTS OF MEASUREMENT OF THE MÖSSBAUER RADIATION ANISOTROPY

We determined experimentally the small alternating and constant components of the detector signal at the same temperatures at which the Mössbauer spectra of the source were recorded. The results were analyzed in the usual way on the assumption that the distribution law was normal. The correctness of this hypothesis was confirmed by the observation that the resultant value of the average statistical deviation was the same in both recording channels: in the main channel which accumulated the P-odd signal and in the control channel which was phase-shifted by $\pi/2$ (the average signal in the control channel was zero within the limits of the experimental error). Moreover, a similar value of the statistical error was obtained by estimating the absolute number of the recorded gamma photons.

Interpretation of the Mössbauer spectra indicated that the fixed resonance detector recorded simultaneously several lines. The measured alternating detector signal could be converted into the asymmetry of the radiation from a single transition (single line) by allowing for the profile and sign of ΔM for all the lines in the spectrum. Moreover, the detector signal included a component due to the background nonresonance radiation the intensity of which also had to be known before we could calculate the required effect from the experimental results.

In fact, the contribution of the ith line in the spectrum to the change in the signal produced by the fixed detector as a result of reversal of the magnetization of the source was given by the expression

$$\Delta a_i = -4R\Delta M_i a_i |\xi|, \qquad (2)$$

where a_i is the contribution of the ith line to the average detector signal. The average value of $|\xi|$ governed by the experimental geometry was found by numerical integration and amounted to 0.61 ± 0.04.

Summation of Eq. (2) over i, division of both parts of the expression by $\Sigma_i a_i$, and allowance for the fact that the Mössbauer radiation represented only a part of the average detector signal made it possible to transform to measurable quantities. In this way we obtained the expression

$$\Delta I/\rho I = -4R(\Sigma_i \Delta M_i a_i/\Sigma_i a_i)|\xi|, \qquad (3)$$

where $\Delta I = \Sigma_i \Delta\alpha_i$ is the change in the detector signal due to reversal of the magnetization of the source, I is the average detector signal, and $\rho I = I_r = \Sigma_i \alpha_i$ is the fraction of the detector signal corresponding to the resonance Mössbauer radiation. It is clear from Eq. (3) that the required quantity $2R$ could be calculated from the asymmetry $\Delta I(T)$ measured at various temperatures T and from the average detector signal $I(T)$ by determining the normalization factors $\rho(T)$ and $\overline{\Delta M}(T) = \Sigma_i \Delta M_i \alpha_i / \Sigma_i \alpha_i$. The factor $\overline{\Delta M}$ and the relative change in ρ as a result of heating were obtained from an interpretation of the Mössbauer spectra emitted by a magnetized source.

The absolute value of the contribution of the resonance radiation to the detector signal was found after making additional measurements. The part of the signal associated with the concomitant characteristic x-ray radiation was separated using a palladium filter. The contributions made to the detector signal by the resonance and nonresonance components of the radiation of 23.8 keV energy were separated using the method of a calibrated "black" absorber when the source was heated above the Curie temperature. The fraction of the resonance ("recoil-free") photons then fell from 0.26 to 0.12.

The values of the detector signal and its components at various temperatures of the source are plotted in Fig. 6a (the total detector signal at room temperature is taken as unity) and the temperature dependence $\overline{\Delta M}(T)$ is shown in Fig. 6b. Figure 6c gives the values of the P-odd detector signal obtained at several temperatures and reduced to the total signal, and it also gives the values of the average statistical deviation. A comparison of this function with the temperature dependence of the normalization factor $\overline{\Delta M}$ (Fig. 6b) revealed a qualitative agreement between the experimental data and those obtained making assumptions about the structure of the Mössbauer spectrum of the source.

An analysis of the results with the aid of the normalization factors made it possible to find the values of the quantity $2R$ representing the P-parity violation, plotted in Fig. 6d. As expected, this nuclear parameter was independent of the crystal lattice temperature. Averaging of the results with allowance for all types of errors gave a value

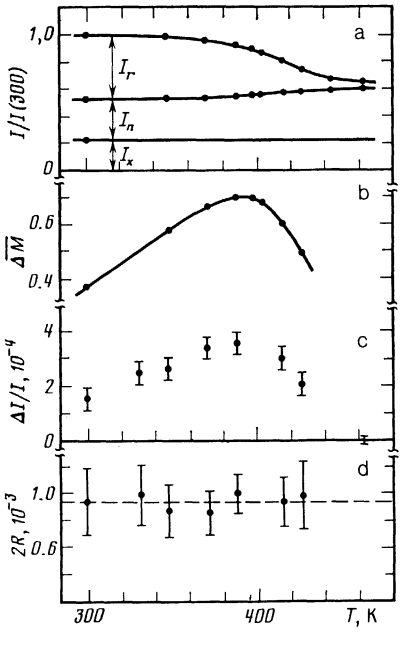

FIG. 6. a) Temperature dependence of the reduced signal $I(T)/I(300)$ from a fixed resonance detector; I_r, I_n, and I_x are the components of the signal due to the resonance, nonresonance, and x-ray radiations. b) Temperature dependence of the normalization factor $\overline{\Delta M}$. c) Experimental temperature dependence of the radiation asymmetry. d) Values of $2R$ obtained from experiments at various temperatures.

$2R = (0.94 \pm 0.08) \times 10^{-3}$ for the degree of violation of spatial parity in the investigated Mössbauer transition in ^{119}Sn.

DIRECT MANIFESTATION OF SPATIAL PARITY VIOLATION IN A MÖSSBAUER SPECTRUM

The high long-term stability of a Mössbauer spectrometer, the relatively high activity of the source, and the use of an efficient resonance scintillator enabled us to detect spatial parity violation in a Mössbauer transition in the ^{119}Sn nucleus by direct measurement of small changes in the Mössbauer emission spectrum of the ferromagnet Mn_4Sn as a result of reversal of its magnetization.

Our experiments involved determination of the Mössbauer emission spectra for the opposite orientations of the magnetization of the source and the subsequent subtraction of these spectra. The measurements were carried out using the traditional Mössbauer method involving recording of a large number of gamma photons. A planar Mn_4Sn sample was attached to the core of a vibrator in such a way that the angle between the normal to its plane and the direction to the detector was 45°.

The data acquisition process was accelerated by measuring the central fragment of the Mössbauer spectrum of Mn_4Sn (in the region of zero velocity of the sample), shown in Fig. 7a. The dashed curves are the three partial lines responsible for this part of the spectrum and the spectral scheme in Fig. 7b shows the corresponding values of ΔM. These lines represent the transitions of the tin nuclei from the states characterized by the $m_e = +3/2, \pm 1/2$ projections of the spin along the direction of magnetization to the state with $m_g = +1/2$. The positions, amplitudes, and widths of these lines were obtained by the usual analysis of the complete Mössbauer spectrum of the source.

Figure 7c shows the results of subtraction of the spectra

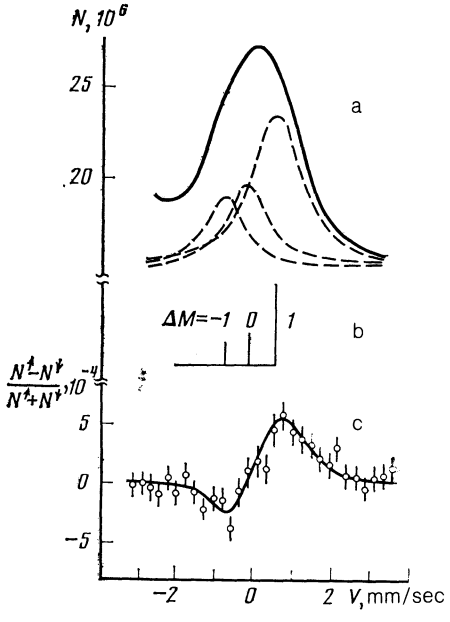

FIG. 7. a) Fragment of the spectrum of Mn_4Sn where the dashed curves represent the individual lines. b) Fragment of a schematic spectrum showing ΔM of the lines. c) Results of subtraction of the spectra measured for opposite directions of the magnetization of the source; $N\uparrow$ and $N\downarrow$ are the numbers of pulses at the maximum of the fragment.

and summation of the content of each of the three neighboring channels. The continuous approximating curve is a superposition of two Lorentzian profiles corresponding to the $-1/2 \rightarrow +1/2$ and $+3/2 \rightarrow +1/2$ transitions for which the P-odd effect has opposite signs. The positions of the lines, the half-widths, and the ratio of the amplitudes were fixed in accordance with the results of a calculation of the complete spectrum. The amplitudes of the lines were found by minimization of the rms deviation of the curve from the experimental points. The value of $2R$ was found to be $(0.90 \pm 0.13) \times 10^{-3}$. Therefore, two largely independent experiments gave values of the measured quantity which agreed within the limits of the experimental error [the first of these values, given above, was $2R = (0.94 \pm 0.08) \times 10^{-3}$.

Our measurements demonstrated the feasibility of solving the inverse problem of separation of unresolved lines in the Mössbauer spectra of ferromagnetic compounds. The "P-odd spectrum" of the Mn_4Sn alloy shown in Fig. 7c had two reliably resolved lines, whereas in the usual spectrum they merged with the line due to the $+1/2 \rightarrow +1/2$ transition to form one wide peak (Fig. 7a). A clear manifestation of the sign of ΔM in the "P-odd spectrum" could be useful for identification of the lines in complex spectra. Finally, the sign of the P-odd change of the lines should make it possible to determine directly the orientation of the effective magnetic field of the hyperfine interaction of the Mössbauer nucleus relative to the magnetization vector of the ferromagnet.

Our investigation demonstrated the usefulness of the Mössbauer effect in quantitative measurements of small violations of spatial parity in gamma-transition nuclei. The results were obtained by two largely independent experimental methods. This should improve the reliability of the data on the properties of the ^{119}Sn nucleus. An additional check of our results could be provided by an experimental determination of the degree of circular polarization $P = 2R$ of the unpolarized ^{119m}Sn source.

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[1]Yu. G. Abov and P. A. Krupchitskiĭ, Usp. Fiz. Nauk **118**, 141 (1976) [Sov. Phys. Usp. **19**, 75 (1976)].
[2]G. V. Danilyan, Usp. Fiz. Nauk **131**, 329 (1980) [Sov. Phys. Usp. **23**, 323 (1980)].
[3]V. P. Alfimenkov, Usp. Fiz. Nauk **144**, 361 (1984) [Sov. Phys. Usp. **27**, 797 (1984)].
[4]K. S. Krane, C. E. Olsen, J. R. Sites, and W. A. Steyert, Phys. Rev. C **4**, 1906 (1971).
[5]A. V. Baluev, L. V. Inzhechik, E. V. Mel'nikov, B. I. Rogozev, A. S. Khlebnikov, V. G. Tsinoev, and V. M. Cherepanov, Pis'ma Zh. Eksp. Teor. Fiz. **43**, 507 (1986) [JETP Lett. **43**, 656 (1986)].
[6]L. V. Inzhechik, E. V. Mel'nikov, B. I. Rogozev, A. S. Khlebnikov, and V. G. Tsinoev, Yad. Fiz. **44**, 1370 (1986) [Sov. J. Nucl. Phys. **44**, 890 (1986)].
[7]L. Meyer-Schutzmeister, R. S. Preston, and S. S. Hanna, Phys. Rev. **122**, 1717 (1961).
[8]C. Djega-Mariadassou, P. Lecocq, G. Trumpy, J. Traff, P. Østergaard, Nuovo Cimento B **46**, 35 (1966).
[9]R. J. Blin-Stoyle, Phys. Rev. **120**, 181 (1960).
[10]G. A. Lobov, Izv. Akad. Nauk SSSR Ser. Fiz. **32**, 886 (1968).
[11]H. Frauenfelder, D. E. Nagle, R. D. Taylor, D. R. F. Cochran, and W. M. Visscher, Phys. Rev. **126**, 1065 (1962).
[12]A. I. Akhiezer and V. B. Berestetskiĭ, Quantum Electrodynamics [in Russian], Nauka, Moscow (1969), Chap. IV. [Transl. of earlier ed., Interscience, 1965].

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