related with the cross section of the corresponding photoprocesses. In particular, a study of the reaction (2) yields an estimate of the cross section of the reaction

$$\gamma + \pi^- \to \pi^- + \pi^0. \qquad (3)$$

If w is the total energy of the two pions produced in reaction (2) in their c.m.s., and m is the pion mass, then, as shown earlier[1], we have for the xenon nucleus and our energy $\bar{\sigma}_p \cong \sigma_c/7.5$, where $\bar{\sigma}_p$ is the average value of the cross section of the reaction (3) in the interval $4m^2 \leq w^2 \leq 21m^2$. Then using the measured value of σ_c we find that $\bar{\sigma}_p = 0.35 \pm 0.12$ mb.

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PARAMAGNETIC COUNTER OF ELEMENTARY PARTICLES

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THE methods of quantum electronics and optics of coherent sources of light make it possible to control various degrees of freedom of solids and liquids which, interacting with weak external perturbations, display a high selectivity and give strong response signals. A sufficient lowering of the temperature of the substance of such a quantum device leads to a strong reduction in the noise and provides the unusual sensitivity of the arrangement. A special place is occupied by devices (quantum counters)[1] containing unexcited molecules, and, consequently, having no noise background from spontaneous emission. Hence, together with an unlimited lowering of the temperature, the sensitivity of such a device increases without limit.

The possibility of detecting individual photons and phonons by a quantum counter has already been discussed in the literature.[2,3] In the present work, we investigate the prospects of using paramagnetic crystals to study the magnetic properties of elementary particles and to detect their presence by means of their magnetic interaction with the counter. As an example, we estimate the efficiency and sensitivity of a paramagnetic neutron counter (PNC).

The main scheme of the PNC is as follows. A crystal containing magnetic ions is placed in the path of a neutron flux. The energy spectrum of the magnetic ions has the levels $E_1 < E_2 < E_3$, where E_1 corresponds to the ground-state level. The crystal is cooled to a temperature $T \ll (E_2 - E_1)/k$ at which the levels E_2 and E_3 are unpopulated. The magnetic scattering of the neutrons on the ions produces the transitions $E_1 \to E_2$, which are detected by the excitation produced by the light from the transitions $E_2 \to E_3$, and the phototube counts of spontaneous-emission transitions $E_3 \to E_{2,1}$.

Under stationary operation, the efficiency of the PNC is determined by the ratio of the number of $E_1 \to E_2$ transitions produced by neutrons to the number of neutrons passing through the counter:

$$B = Nl\sigma_{12} \sim (10^{-2} - 10^{-4})\, l, \qquad (1)$$

where l is the length of the crystal along the direction of the neutron flux, σ_{12} is the cross section for the scattering of a neutron on the magnetic system with a transition of the magnetic particle $E_1 \to E_2$, and $N \sim 10^{22}$ is the number of magnetic particles in a unit volume. If the phototube records individual photons, then the limit of sensitivity of the PNC is determined by the value of I_{min} of the neutron flux giving rise to the $E_1 \to E_2$ transitions with a probability $W_{12\,min}$ comparable in magnitude with the probability v_{12} of a $E_1 \to E_2$ relaxation transition. The value of $W_{12\,min}$ should also be compared with the transition probabilities q_{12} and q_{13} under the action of the light pumping. Here, the probability of light pumping q_{23} should exceed the probability v_{21} of the relaxation transition. We thus have

$$W_{12\,min} = \sigma_{12} I_{min} \sim v_{12},\ q_{12},\ q_{13}, \qquad q_{23} > v_{21}. \qquad (2)$$

In paramagnetic crystals, the relaxation transitions $E_1 \to E_2$ are due to cross relaxation[4] and the spin-phonon interaction.[3] The first mechanism is described by the formula

$$v \sim \exp\left\{-\frac{\hbar\omega_{12}}{kT} - \frac{\omega_{12}^2}{\langle\Delta\omega^2\rangle}\right\}, \qquad (3)$$

and is not very effective for spectral lines with a small relative width $\langle\Delta\omega^2\rangle^{1/2}$ of the energy split-

ting $E_2 - E_1$ and is rapidly weakened as the temperature is lowered. Allowance for the spin-phonon interaction leads to the relation

$$I_{min} \sim \frac{v_{12}}{\sigma_{12}} = \frac{\omega_{12}^3 G^2 |Q_{12}|^2}{\pi\hbar\rho w^5 \sigma_{12}} \left[\exp\frac{\hbar\omega_{12}}{kT} - 1\right]^{-1}, \quad (4)$$

where ρ is the crystal density, w is the velocity of sound in the crystal, G is the spin-phonon coupling constant, and $|Q_{12}|$ is the matrix element of the spin part of the spin-phonon interaction operator. Let $\hbar\omega_{12}/k = 1°K$; then, for $v_{12} \sim 1$ sec^{-1}, $Al = 10$ cm^3, $\sigma = 10^{-24}$ cm^2, and $T < 1°K$, we have

$$I_{min} \sim 10^{24} e^{-1/T} \ (\text{cm}^2\text{-sec})^{-1} \quad (5)$$

(with T in degrees). Let a flux of elementary particles I (cm^{-2}-sec^{-1}) fall on the counter. Then the minimum value of the scattering cross section detectable by the counter is

$$\sigma_{min} \sim e^{-1/T}/I \ \text{cm}^2 \quad (6)$$

Taking into account the noise due to forbidden transitions induced by the light pumping, we arrive at the following results:

$$q_{12} \sim F_{13}F_{32}/\tau\varphi^2, \quad \varphi = (\nu_{23} - \nu_{12})/\Delta\nu_{12}, \quad \Delta\nu = 1/2\pi\tau,$$
$$F_{13} = |\langle 1|\mu|3\rangle E/2\hbar\Delta\nu_{13}|^2,$$
$$E^2 \sim 8M\Delta\nu_{23}\hbar^2/|\langle 2|\mu|3\rangle|^2, \quad M = G^2|Q_{12}|^2\omega_{12}^3/2\pi\hbar q w^5, \quad (7)$$

where $\Delta\nu$ is the width of the line in frequency units, $\langle 2|\mu|3\rangle$ is the matrix element of the electric or magnetic dipole moment. In the derivation of (7), we employed formula (7) from [5] for the probability of a two-quantum transition; M describes the background from the zero oscillations of the crystal lattice in the process of spin-lattice paramagnetic relaxation.

To obtain a numerical estimate of the counter sensitivity, we used the experimental data for Cr^{3+} in Al_2O_3.[6,7] From (5) and (6), we obtain

$$I_{min} \sim q_{12}/\sigma_{12} \sim 10^{-18} \ (\text{cm}^2\text{-sec})^{-1} \quad q_{12} \sim 10^{-42} \ \text{sec}^{-1} \quad (8)$$

$$\sigma_{min} \sim q_{12}/I_{min} \sim 10^{-42} \ I^{-1} \ \text{cm}^2 \quad (9)$$

Conditions (8) and (9) are much stricter than (5) and (6). However, we can improve the numerical estimates obtained from them by forbidding the transition $E_1 \rightarrow E_3$, by using the unusual dependence of q_{12} on the amplitude of the light pumping, and by the application of methods of separating the signal from the background noise.

In substances in which the cross section for magnetic scattering is comparable with the cross section σ_n for scattering due to other interactions between neutrons and the nuclei of the paramagnetic crystal, other additional sources of noise appear. In practice, it is sufficient to consider σ_n for (n,γ) reactions.[8] The probability of transitions $E_1 \rightarrow E_2, E_3$ due to the recoil nucleus of the paramagnetic with the emission of a γ quantum is negligible ($\sigma_\gamma \sim 10^{-29}$ cm^2[9]) and this noise does not have to be considered. The radiation spectrum from the crystal due to the action of the γ quanta does not coincide with a fixed narrow fluorescence line $E_3 \rightarrow E_1, E_2$ and is considerably broader than it. This source of noise can also be removed through the replacement of the paramagnetic ion by a related nonmagnetic ion and subtraction of the spectrum.

To eliminate the noise we can also use the dependence of σ_{12} on the angle between the neutron flux and the crystal axes.[10]

As a working substance for a counter operating at helium temperatures, we can use a CeF_3 crystal in which for Ce^{3+} we have $E_2 - E_1 \sim 150$ cm^{-1}, $E_3 - E_2 \sim 2100$ cm^{-1}[11], $\sigma_{12} \sim 0.6$ b[12], $\sigma_n(Ce^{140}) = 0.62$ b, and $\sigma_n(F^{19}) < 10$ mb[8].

From our calculations, it follows that in the region of very low temperatures 0.1—0.001°K, we can produce quantum counters on the basis of paramagnetic spin systems whose sensitivity greatly surpasses all existing devices of this type. In particular, such devices could be used for the detection of uncharged particles (for example, the neutrino) by the observation of their magnetic scattering on the spin system.

According to the four-component neutrino theory,[13] the cross section for magnetic scattering of the neutrino is $\sigma_\nu \sim (\mu_\nu/\mu_n)^2\sigma_{12} \sim 10^{-38}$ cm^2, where μ_ν is the magnetic moment of the neutrino. In the case of a neutrino flux in a reactor $I \sim 10^{13}$ (cm^2 sec)$^{-1}$, three photons per second reach the phototube of a counter containing 10^{24} paramagnetic ions. According to (6) and (9), this signal can be observed on the background of noise.

If the kinetic energy of the neutrino is sufficiently large to excite the direct transition $E_1 \rightarrow E_3$, then the need for light pumping vanishes and the noise signal (9) is eliminated. In this case the photomultiplier will record fluorescence produced by the neutrino flux.

We note that the $E_1 \rightarrow E_2$ transitions can be produced by nonmagnetic interactions between ions and elementary particles, for example, effects associated with the recoil nucleus of the ion and interactions with the f- or d-electron shell.

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ON THE DIFFERENCE IN PEAK HEIGHTS FROM QUADRUPOLE SPLITTING OF MÖSSBAUER SPECTRA

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IN a number of our experiments with organic tin compounds[1,2] we found a quite large difference in the peak heights from doublet splitting of Mössbauer spectra. An example is the spectrum of polycrystalline triphenylchlorstannane, $Sn(C_6H_5)_3Cl$, shown in the figure. A similar asymmetry was seen with SnO[3] and various compounds of iron.[4-6] Two proposals were made for explaining the difference in peak height from doublet splitting: 1) the doublet splitting is caused by the presence of two chemical forms of the substance, i.e., we are dealing with a superposition of two unsplit single lines with different values of the chemical (isomer) shift;[1,5,6] 2) the doublet results from quadrupole splitting—the difference in the peaks results from anisotropy of orientation of the crystals relative to the direction of motion of the γ quanta. A detailed analysis of these two assumptions and a critique of them for specific cases was given in [7].

In [2] (and in more detail, by Karyagin[8]) a third possibility for explaining the asymmetry of the doublet splitting of Mössbauer spectra was proposed, which for most cases seems to be the correct one. As is shown in these papers, the quadrupole splitting of the Mössbauer spectra from isotropic polycrystalline samples should as a rule give different peak heights, while the peaks will be equal in height only for the special case of an isotropic Mössbauer effect. Thus the asymmetry of the Mössbauer doublets does not require the presence of two chemical forms or anisotropy of the sample; it occurs even for an isotropic polycrystalline sample, as a direct consequence of the anisotropy of the Mössbauer effect for single crystals, which was treated theoretically by Kagan[9] and found in various experiments.[10,11]

In fact, for a single crystal with its axially symmetric electric field directed at an angle ϑ relative to the direction of the γ quanta, the ratio of the probabilities I for M1 absorption of a quantum by a nucleus with spin $1/2$, with transition to the $\pm 3/2$ sublevels (I_π) and $\pm 1/2$ (I_σ) of the excited nucleus can be shown[12] to be:

$$\frac{I_\pi(\vartheta)}{I_\sigma(\vartheta)} = \frac{2\sqrt{5}\,\bar{P}_0(\cos\vartheta) + \bar{P}_2(\cos\vartheta)}{2\sqrt{5}\,\bar{P}_0(\cos\vartheta) - \bar{P}_2(\cos\vartheta)} = \frac{1+\cos^2\vartheta}{5/3-\cos^2\vartheta}, \qquad (1)$$

where $\bar{P}_0$ and $\bar{P}_2$ are normalized Legendre polynomials. In polycrystalline isotropic samples we get

$$\frac{i_\pi}{i_\sigma} = \frac{\int_0^\pi I_\pi(\vartheta)\sin\vartheta d\vartheta}{\int_0^\pi I_\sigma(\vartheta)\sin\vartheta d\vartheta} = 1, \qquad (2)$$

i.e., the two quadrupole peaks have equal heights. But if the Mössbauer effect is anisotropic for the single crystal and is characterized by a probability $f'(\vartheta)$, then

$$\frac{i_\pi}{i_\sigma} = \frac{\int_0^\pi I_\pi(\vartheta) f'(\vartheta)\sin\vartheta\, d\vartheta}{\int_0^\pi I_\sigma(\vartheta) f'(\vartheta)\sin\vartheta\, d\vartheta} = F[f'(\vartheta)] \neq 1, \qquad (3)$$

i.e., the two peaks differ in height, and from obser-