$$S = \int \left[R_{\mu\mu} + a (R_{\mu\mu} T_{\nu\nu} - R_{\mu\nu} T_{\nu\mu}) + \frac{a^2}{2} \sum_{\rho} (-1)^{\rho} R_{\mu\mu} T_{\nu\nu} T_{\rho\rho} \right.$$

$$\left. + \frac{a^3}{3!} \sum_{\rho} (-1)^{\rho} R_{\mu\mu} T_{\nu\nu} T_{\rho\rho} T_{\sigma\sigma} + m \bar{\phi} \phi \mid W \mid \right] d^4 x , \qquad (9)$$

where

$$R_{\mu\nu} = \frac{1}{2i} (\bar{\phi} \gamma_{\mu} \partial_{\nu} \phi - \partial_{\nu} \bar{\phi} \gamma_{\mu} \phi) \qquad (10)$$

and the tensor T and the determinant $|W|$ are defined in (7).

Weak interactions can be included in the scheme under consideration by introducing gauge fields for the approximate unitary symmetry group of the neutrino and other leptons. The electromagnetic interaction for charged leptons is introduced simultaneously. The weak and electromagnetic interactions are turned on simultaneously by the well-known mechanism of spontaneous breaking of the unitary-group symmetry [3]. In the zero-lepton-mass limit, the unitary symmetry is exact. To obtain the action integral for the leptons in the unitary-symmetry limit, it suffices to regard in (3), (4), and (7) the spinor products as invariant products of unitary multiplets. It is also possible to add to formulas (3), (4), and (7) the terms for leptons with opposite chirality. The unitary groups for states with different chirality need not necessarily coincide in this case.

The gauge fields can be introduced into the so-generalized action integral in a manner covariant with respect to the transformations (3).

The gravitational interaction can be introduced into the scheme in analogous fashion, by introducing gauge fields corresponding to the Poincare group.

We note that if we introduce also gauge fields corresponding to the transformations (3), then, as a consequence of the Higgs effect [4], a massive gauge field with spin 3/2 arises, and the Goldstone particles with spin 1/2 vanish.

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DEPENDENCE OF TWO-PHOTON ABSORPTION COEFFICIENT ON LIGHT POLARIZATION IN CUBIC-SYMMETRY SEMICONDUCTORS

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It is known that investigation of two-photon absorption (TPA) in semiconductors can yield very valuable information concerning the crystal parameters [1 - 4]. Nonetheless, the concrete form of the energy spectrum of the semiconductors was not indicated in the cited references, so that the experimental and theoretical results could not be compared quantitatively.

We have investigated, theoretically and experimentally, two-photon absorption in semiconductors of cubic symmetry for the case of one light beam. It turns out that even in cubic crystals the TPA coefficient can depend on the

polarization and can, in particular, be anisotropic. In addition, we consider the possibility of producing spin orientation [5 - 7] in semiconductors in the cases of TPA.

In the general case, the TPA coefficient $K^{(2)}$ can be represented in the form of an expansion in linearly-independent invariants relative to the symmetry transformation of the crystals, by combinations made up of two vectors $\vec{e}$ and two vectors $\vec{e}^*$, where $\vec{e}$ is the light polarization vector. There are three such invariants in a cubic crystal:

$$|\vec{e}\cdot\vec{e}|, \quad |\vec{e}^* \times \vec{e}^*|, \text{ and } |e_x|^4 + |e_y|^4 + |e_z|^4 \tag{1}$$

where x, y, and z are the principal axes of the crystal.

In the case of a crystal with an isotropic energy spectrum, such as InSb, the expression for $K^{(2)}$ should contain only the spherical invariants:

$$K^{(2)} = K_1 |\, e\, e|^2 + K_2 |[e^* \times e]|^2 . \tag{2}$$

Here K_1 and K_2 have the meaning of the two-photon absorption coefficients for linear and circular polarization of the light, respectively.

Allowance for the third cubic invariant for InSb corresponds to allowance for the corrugation of the valence band, which is negligible in this compound. In semiconductors with more pronounced corrugation, the anisotropic term in $K^{(2)}$ may turn out to be appreciable. In cubic semiconductors with multivalley structure of the energy spectrum, such as lead chalcogenides, the expression for $K^{(2)}$ includes also the third invariant, so that $K^{(2)}$ becomes dependent on the light propagation direction as well as on the direction of the polarization vector.

The concrete calculation was performed for semiconductors with narrow forbidden bands, namely indium antimonide and lead chalcogenides (PbS, PbSe, and PbTe). In these compounds, the structure of the energy spectrum is such that the two-band approximation can be used with sufficient accuracy. The nonparabolicity of the bands was taken into account in the Kane model [8]. Calculation yields for the ratio K_1/K_2 the expression[1)]

$$\frac{K_1}{K_2} = \frac{K_1 v_1 + K_1 v_2}{K_2 v_1 + K_2 v_2} = \frac{20 + \left(16x^2 + \frac{3}{2x^2} + \frac{20}{3}\right)(1+x)^{3/2}\left(\frac{3}{2} - x\right)^2}{30 + \left(\frac{32x^2}{3} + \frac{3}{8x^2}\right)(1+x)^{3/2}\left(\frac{3}{2} - x\right)^2} \tag{3}$$

where the indices v_1 and v_2 correspond to the contributions from the heavy- and light-hole subbands of the valence band of InSb, $x = \varepsilon_g/2\hbar\omega$, ε_g is the width of the forbidden band, and ω is the frequency of the light.

Near the TPA edge, the ratio K_1/K_2 is close to unity, and with increasing frequency it increases to 1.33 as $x \to 1/2$[2)].

[1)] A detailed theory of these materials is now under development by one of the authors.

[2)] In the two-band approximation, the effective mass of the electrons in InSb coincides with the effective mass of the light holes, and the effective mass of the heavy holes is assumed infinite in comparison with that of the light ones. K_1/K_2 is therefore independent of the effective mass.

We performed the calculation in the same approximation for the initial degree of spin orientation for TPA in InSb. This value was found to be 64% at $2\hbar\omega = \varepsilon_g$, and to decrease smoothly with increasing quantum energy in accordance with the formula

$$\rho_0^{(2)} = \frac{17 + \left(\frac{32}{3}x - \frac{2}{x} - \frac{4}{3}\right)(1+x)^{3/2}\left(\frac{3}{2} - x\right)^2}{30 + \left(\frac{32}{3}x^2 + \frac{3}{8x^2}\right)(1+x)^{3/2}\left(\frac{3}{2} - x\right)^2}. \qquad (3a)$$

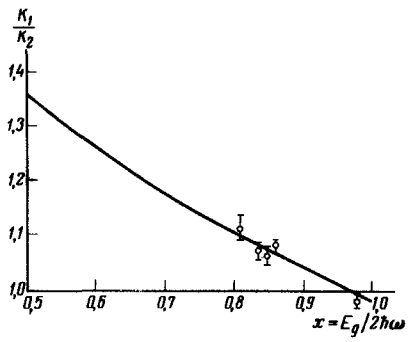
A calculation for the lead chalcogenides shows that the coefficient of the third invariant in the expression for $K^{(2)}$ is proportional to the degree of anisotropy of the valleys. For the compounds PbSe and PbS, the degree of optical orientation of the photoelectrons at the instant of their production is close to 100%.

The experiments to determine the polarization dependences of the TPA coefficient were performed on weakly-doped InSb samples ($p_0 = 10^{14}$ cm^{-3}). The change of the absorption coefficient, due to the change of the polarization of the pumping light, was determined from the change of the excess carrier density Δn. In the experiments on radiative recombination, the pump was a Q-switched CO_2 laser producing a pulse of length $t_p \approx 0.25$ μsec and a maximum power up to 10 kW.

The edge photoluminescence radiation was gathered from the front surface of the sample in a solid angle $\sim 35°$ and was directed to the IR receiver (Ge:Au), the electric signals from which were amplified, synchronously detected, and plotted with an automatic recorder. To exclude the second harmonic from the light reflected from the crystal, the samples were cut in the [100] plane. The observed radiation was unpolarized. We registered the change of the signal level on going from linearly-polarized to circularly polarized pumping at different temperatures and laser-beam intensities.

In the analysis of the results, it is essential to take into account the possible dependence of the lifetime τ on Δn. It can be indicated that if $\Delta n \gg (n_0 + p_0)$ the relative change of the TPA coefficient is connected with the relative change of the luminescence intensity by the relation

$$\frac{\delta K^{(2)}}{K^{(2)}} = \frac{\delta \Delta R}{R} \cdot \frac{1 + 2\kappa - \sqrt{1+2\kappa}}{2\kappa}, \qquad (4)$$



Ratio of TPA coefficients for linear and circular pumping vs. the parameter $x = \varepsilon_g/2\hbar\omega$.

where ΔR is the number of recombination-radiation quanta per unit volume and unit time, $\Delta R = \gamma_r(\Delta n)^2$, γ is the radiative-recombination coefficient, which was measured for InSb in [9], $\kappa = 2\sigma^{(2)}\sqrt{\varepsilon}\gamma_r\tau^2_{nr}j^2/c$, where $\sigma^{(2)}$ is the TPA cross section, ε the dielectric constant, τ_{nr} the time of nonradiative recombination, and j the pump-light intensity.

The figure shows the theoratical dependence of the ratio $(K_1/K_2)(\varepsilon_g/2\hbar\omega)$ and the experimental points obtained using two CO_2 laser spectral lines, 9.5 and 10.6 μ, and also by varying the width ε_g of the forbidden band by varying the sample temperature. To

determine the parameter κ in (4), we also plotted at each temperature curves of $\Delta R(j^2)$, from which we could, knowing the absolute values of ΔR and j, obtain the value of τ_{nr} and then find κ using the values of $\sigma^{(2)}$ given in [10] (neglecting the change of $\sigma^{(2)}$ with changing polarization of the pump). As seen from the figure, there is good agreement between the experimental and the theoretical results.

In the experiments aimed at observing the optical orientation for TPA in InSb, performed at 80°K, a negative result was obtained, due apparently to the smallness of the ratio τ_{sp}/τ (τ_{sp} is the time of spin relaxation) at the indicated temperature. We can therefore only estimate the upper bound of τ_{sp}, by determining τ from the $\Delta R(j^2)$ curve and knowing the sensitivity of the measuring system. We obtained $\tau_{sp} < 10^{-10}$ sec.

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CORRECTION OF μ-MESIC ENERGY LEVELS FOR NUCLEAR POLARIZATION IN THE ADIABATIC APPROXIMATION

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In a number of comparisons of the experimental energies of μ-mesic transitions with the theoretical ones it is necessary to introduce corrections for the polarizability of the nucleus in the muon field [1]. There are as yet no simple and sufficiently reliable methods for calculating such corrections. In nonrelativistic perturbation theory, the correction that must be added to the energy of a μ-mesic atomic level with quantum numbers n, ℓ, and m to account for the polarizability of the nucleus is given by

$$\Delta E^{\mathrm{pol}} = -\sum_{a \neq 0, i} \frac{\langle 0, n\ell m | \Delta V | a, i \rangle \langle a, i | \Delta V | 0, n\ell m \rangle}{E_a - E_0 + \epsilon_i - \epsilon_{n\ell}}, \qquad (1)$$

where the perturbing potential is

$$\Delta V = -\sum_k \frac{e^2}{|\vec{r}_k - \vec{\rho}|} - \langle 0 | -\sum_k \frac{e^2}{|\vec{r}_k - \vec{\rho}|} | 0 \rangle. \qquad (1')$$