nucleus averages out to a very low value (∿0.3 MHz) of the rapid rotational relaxation of the radical. A natural condition for the appearance of inhomogeneous broadening of the EPR line in a simultaneous observation of a narrow and a broad EDR signal will be the relation $T_{1e}V_h \lesssim 1$, where T_{1e} is the electron spin-lattice relaxation time and V_h is the homogenization rate. Using a value $T_{1e} \sim 10^{-6}$ sec [4] we find that $V_h/2\pi \lesssim 0.1$ MHz. This estimate shows that the width of this signal is apparently governed by the isotropic hyperfine interaction with the protons of the radical itself. The fact that the width of the broad component of Fig. 2 is independent of the concentration indicates that homogenization of the line is connected with a change of the orientation of the spins of the cyclohexane protons surrounding the radical. This change occurs in this case apparently as a result of molecular diffusion, whose coefficients in the plastic region exceed the coefficients of the spin diffusion [10] by several orders of magnitude [5].

We thank M. A. Kozhushner and E. I. Rashba for useful discussions.

[1] P. I. Bekauri, B. G. Berulava, T. I. Sanadze, and E. P. Khakhanashvili, Zh. Eksp. Teor. Fiz. 52, 447 (1967) [Sov. Phys.-JETP 25, 292 (1967)].
[2] N. A. Efremov, M. A. Kozhushner, and V. I. Sokolov, ZhETF Pis. Red. 7, 472 (1968) [JETP Lett. 7, 365 (1968)].
[3] T. I. Sanadze and P. R. Khutsishvili, Zh. Eksp. Teor. Fiz. 56, 454 (1969) [Sov. Phys.-JETP 29, 248 (1969)].
[4] H. Verdun, B. Mecrovici, and F. Volino, J. Chem. Phys. 57, 2414 (1972).
[5] J. G. Aston, transl. in: Fizika i khimiya tverdogo sostoyaniya organicheskikh soedinenii (Physics and Chemistry of the Solid State of Organic Compounds), Mir, 1972, p. 475.
[6] V. B. Stryukov, Dokl. Akad. Nauk SSSR 179, 641 (1968); L. I. Antsiverova, A. V. Lazarev, and V. B. Stryukov, ZhETF Pis. Red. 12, 108 (1970) [JETP Lett. 12, 75 (1970)].
[7] V. B. Stryukov, Stabil'nye radikaly v khimicheskoi fizike (Stable Radical in Chemical Physics), Znanie, 1971.
[8] P. A. Stunzhas, V. A. Benderskii, L. A. Blyumenfel'd, and E. A. Sokolov, Opt. Spektr. 28, 278 (1970); V. A. Benderskii, P. A. Stunzhas, and A. I. Rakoed, Molec. Phys. 24, 449(1971)
[9] E. A. Sokolov and V. A. Benderskii, Prib. Tekh. Eksp. No. 2, 232 (1969).
[10] I. S. Lowe and S. Gade, Phys. Rev. 156, 817 (1967).

INDUCED β-γ CORRELATION OF THE DIRECTIONS FOR ALLOWED β TRANSITIONS

G. A. Denisenko and E. P. Khaimovich
Kazan' Physico-technical Institute, USSR Academy of Sciences
Submitted 28 March 1973
ZhETF Pis. Red. 17, No. 12, 667 - 669 (20 June 1973)

A new type of β-γ direction correlation, which appears only in the presence of definite perturbations, is considered. This effect can be used to determine the characteristics of the excited states of nuclei and to detect acoustic nuclear resonance.

It is known that there are no β-γ direction correlations for allowed β transitions in the case of non-oriented initial states of the nuclei [1]. The reason is that the anisotropy of the γ-quantum angular distribution averaged over the polarizations is due to the even polarization moments that characterize the intermediate state of the nucleus, whereas an allowed β transition produces only odd polarization moments.

We consider in this paper the β-γ direction correlation induced by an external field. Unlike ordinary perturbed angular correlation, when a perturbation from outside the nucleus distorts an already-existing angular dependence, the induced β-γ correlation arises itself only in the presence of definite types of interaction.

The probability of photon emission in a direction $\vec{n}$ is given by [2]

$$W(\mathbf{n}) = \sum_{\ell,\mu} B_\ell(L, I, I_f)\mathcal{P}^{(I)*}_{\ell\mu} D^{(\ell)}_{0\mu}(\mathbf{n}), \tag{1}$$

where B_ℓ are coefficients that depend on the pultipolarity L of the radiation and on the spins I and I_f of the intermediate and final states of the nucleus. $\mathcal{P}^{(I)}_{\ell\mu}$ are even ($\ell = 2k$) polarization moments, and $D^{(\ell)}_{0\mu}$ is a finite-rotation matrix. The preceding allowed β transition yields

$\mathcal{P}^{(I)}_{1\mu} \neq 0$ and $\mathcal{P}^{(I)}_{\ell\mu} = 0$ at $\ell \geq 2$. The external field interacting with the nucleus of spin I leads to a time dependence of the polarization moment in the form

$$\mathcal{P}^{(I)}_{\ell\mu}(t) = \sum_{\ell_1, \mu_1} G^{\mu\mu_1}_{\ell\ell_1}(t)\mathcal{P}^{(I)}_{\ell_1\mu_1}(0), \tag{2}$$

where $\mathcal{P}^{(I)}_{\ell_1\mu_1}(0)$ is the polarization moment resulting from the β transition, and $G^{\mu\mu_1}_{\ell\ell_1}$ is the perturbation factor that takes into account the action of the external field. It follows from (2) and (1) that the induced β-γ direction correlation appears only in perturbations that couple the even and odd polarization moments. Souch a coupling can be ensured by the hyperfine and nuclear quadrupole interactions. Much more interesting, however, is the case when the field outside the nucleus can be varied, controlling by the same token the produced β-γ correlation.

We consider for simplicity a nucleus with I = 1 situated in a crystal field of cubic symmetry and in a constant magnetic field $\vec{H}_0(0, 0, H_0)$. Since there is no quadrupole interaction, and the nuclear Zeeman interaction leads only to $G^{\mu\mu}_{\ell\ell}(t)$, there is no β-γ correlation. Assume that an acoustic wave of frequency ω and wave vector $\vec{k}$ is excited in the crystal. From the equations of motion [3] for the mean values of the quadrupole-moment operator Q_{ij} and the spin operator $\vec{I}$, and from their expressions in terms of the polarization moments, we obtain, in particular

$$\mathcal{P}^{(1)}_{2,\pm 1}(t, \mathbf{r}, \phi_0) = \mathcal{P}^{(1)}_{10}(0)\frac{1}{a}\sqrt{\frac{5}{6}}\left\{\sin\omega_1 a t + 2i\left(\frac{\Delta}{\omega_1}\right)\frac{1}{a}\sin^2\frac{\omega_1 a}{2}t\right\}\times$$
$$\times\exp[\pm i(\omega t - \mathbf{kr} + \phi_0)], \tag{3}$$

where $\omega_1 = (3e/16\hbar)QS\varepsilon_0$, Q is the quadrupole moment of the nucleus, S is the corresponding spin-phonon interaction constant, ε_0 is the deformation amplitude, $h\omega_0$ is the nuclear Zeeman splitting, $a = [1 + (\Delta/\omega_1)^2]^{1/2}$, and $\Delta = \omega_0 - \omega$. Thus, the acoustic oscillations give rise to β-γ direction correlation, and the effect is most appreciable at $\Delta = 0$, i.e., it has a resonant character.

The polarization moments in formula (1) are given by expressions of the type (3), averaged over the coordinates and the initial phase ϕ_0. Such averaging does not destroy the considered effect if the instant at which the acoustic oscillations enter the sample is synchronized with the instant of β-particle registration, i.e., ϕ_0 = const and $L_0|\vec{k}| \ll 1$, where L_0 is the linear dimension of the crystal region occupied by the radioactive nuclei. At $\Delta = 0$, using (3) and (2), we then obtain the following expression for the function of the induced β-γ correlation in normalized form

$$W(\mathbf{n}, \mathbf{p} = \mathbf{z}, t) = 1 + \frac{5}{2\sqrt{3}}A_1(\beta)F_2(LL1I_f)\sin\omega_1 t\sin(\phi_2 - \omega_0 t)\sin 2\theta_2, \tag{4}$$

where θ_2 and ϕ_2 are the angles that determine the direction of γ-quantum emission, $\vec{p} = \vec{p}_\beta/p_\beta$, $\vec{p}_\beta$ is the β-particle momentum and p_β is its magnitude; $A(\beta)$ and $F(\gamma)$ are the usual β and γ parameters [4]. The largest γ-radiation anisotropy is reached if $\omega_0\tau_N \sim 1$ and $\omega_1\tau_N \sim 1$, where τ_N is the lifetime of the nucleus in the intermediate state. For example, for the cascade $0 \to 1 \to 0$ at L = 1, the maximum value δ_{max} of the anisotropy parameter

$$\delta = \left|W\left(\theta_2 = \frac{\pi}{4}\right) - W\left(\theta_2 = \frac{\pi}{2}\right)\right| / W\left(\theta_2 = \frac{\pi}{2}\right)$$

is equal to $0.8p_\beta E^{-1}$, where E is the β-particle energy. Such an asymmetry can be obtained for nuclei with $\tau_N \geq 10^{-5}$ sec at a sound intensity 10^2 W/cm^2 [5], $eQS/h \sim 10^3$ MHz [3], $H_0 \sim 10^2$ Oe, and $L_0 \sim 1$ cm.

Induced β-γ correlation can also be produced by using static pressures that lead to a distortion of the cubic symmetry of the crystal field. This occurs if the splitting ω_Q due to the static deformation satisfies the condition $\omega_Q\tau_N \sim 0.01$. Estimates show that at pressures customarily used in the experiments the range of the lifetimes τ_N can be extended to 10^{-8} sec.

The considered dynamic effect can be used as a sensitive method of detecting acoustic nuclear resonance, while the static effect is suitable for a determination of the quadrupole moments of excited states of nuclei.

[1] A. Z. Dolginov, in: Gamma-luchi (Gamma Rays), AN SSSR, 1961, p. 523.
[2] V. B. Berestetskii, E. M. Lifshitz, and L. P. Pitaevskii, Relyativistskaya kvantovaya teoriya (Relativistic Quantum Theory), Nauka, 1968, Vol. 1.
[3] A. R. Kessel', Akusticheskii yadernyi rezonans (Acoustic Nuclear Resonance), Nauka, 1969.
[4] R. Steffen and H. Frauenfelder, in: Alpha, Beta, and Gamma Spectroscopy (Russ. transl.), Atomizdat, No. 4, 137 (1969).
[5] V. A. Shutilov and G. L. Antokol'skii, Fiz. Tverd. Tela 9, 1231 (1967) [Sov. Phys.-Solid State 9, 958 (1967)].

ENERGY DEPENDENCE OF INCLUSIVE CROSS SECTION OF PARTICLE PRODUCTION IN THE PIONIZATION REGION

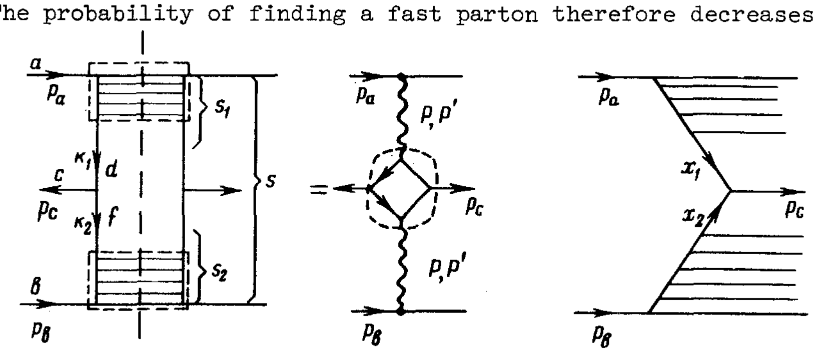
E. M. Levin and M. G. Ryskin
Leningrad Institute of Nuclear Physics, USSR Academy of Sciences

Submitted 28 March 1973
ZhETF Pis. Red. 17, No. 12, 669 - 674 (20 June 1973)

We consider the dependence of the inclusive cross section $f(p_c, s) = E_c d\sigma/d^3p_c$ of the production of pions that are slow in the c.m.s. on the colliding-hadron energy $\sqrt{s}$, and show that the experimentally observed growth of the cross section may be connected with the influence of phase space on the registered particles (Botke's numerical calculations [1] have shown that the influence of phase space extends to very large $s \sim 2000$ GeV^2). The point is that whereas scaling is well satisfied in the fragmentation region, even starting with accelerator energies [2] ($f(p_c, s) = f(x, p_\perp, s) = f(x, p_\perp, \infty)$ at $s > 20$ GeV^2), in the pionization region ($x = p_{\parallel c}/p_{\parallel max} = 0$) the value of $f(p_c, s)$ and the cross section for particle production at 90°, $d\sigma/d\Omega|_{90^\circ cms} = \int f(p_{\parallel c} = 0, p_{\perp c}, s)\, p_\perp^2 dp_\perp/E_c$ increase with increasing s, up to the energies of the ISR colliding beams (thus, at $\sqrt{s} = 30$ GeV, $d\sigma/d\Omega|_{90^\circ}$ is approximately twice as large as at $\sqrt{s} = 6.8$ GeV) [3, 4]. This effect is usually attributed [5] to the contribution of non-vacuum poles (P', ω) with $\alpha(0) = 1/2$ (see Fig. 1a), which fades out very slowly with increasing s, like $s_1^{-1/2} \sim s^{1/4}$. ($s_1 \sim \sqrt{s}$ in the case of 90° particle emission.) But then, to describe the growth of the cross section with energy, the vertex PP' (in a dashed box in Fig. 1a) must be chosen negative. This sign is quite strange if the two-reggeon PP' vertex is expressed in terms of the reggeon residues (as is done in Fig. 1a) and if it is recalled that in all known two-particle reactions the contribution of poles with $\alpha(0) = 1/2$ is positive (or is equal to zero if the channel is exotic [6].

On the other hand, since at accelerator energies ($s \sim 40$ GeV^2) the masses of shower particles with momenta larger than $p_c - \sqrt{s_1}$ and less than $p_c - \sqrt{s_2}$ are quite small ($s_1 \sim s_2 \sim 3$ GeV^2), it is necessary to take phase-space effects into account; these are easiest to explain with the parton model [7].

Particle "c" in Fig. 1b is formed upon collision of two partons. One of the hadrons, "a," carries a fraction x_1 of the momentum ($k_1 = x_1 p_a$), while the second "b" carries x_2. If parton 1 is fast enough ($x_1 \to 1$), then the remaining partons from "a" receive a small fraction of the energy, $\sim 1 - x_1$. The probability of finding a fast parton therefore decreases with increasing



a b c

Fig. 1