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SPIN STATES OF ATOMS AND MOLECULES IN THE COSMIC MEDIUM

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In various astrophysical systems the states of atoms, molecules, and ions are characterized by their concentrations, velocity distributions, and degrees of ionization and excitation. Until recently, however, no attention was payed to the spin states of these particles. It was assumed that the spins* are chaotically distributed, i.e., that all spin directions are equally probable. To take account of the spins was only to introduce appropriate statistical factors in the expressions for the intensities of spectral lines.[1-5] Under ordinary terrestrial conditions there is a chaotic distribution of spins. In the rarefied cosmic medium, however, the situation is quite different. There is no thermodynamic equilibrium. There are directed fluxes of radiation and of particles. The spin state of particles is as a rule anisotropic, i.e., the spins are oriented.

One distinguishes two types of orientation of particle spins† —alignment and polarization.[6-9] In the case of alignment the spins of the particles are oriented anisotropically, but in such a way that directions along and opposite to a symmetry axis are equivalent, while in the case of polarization these directions are not equivalent, the spins pointing predominantly in one direction.

Orientation of spins arises in two qualitatively different situations: a) static orientation, which becomes established in a system in thermodynamic equilibrium when there is a sufficiently strong external magnetic field, and b) dynamic orientation, which arises in a nonequilibrium system owing to interactions of the particles of the medium with a directed flux of radiation or of fast particles passing through the medium.

*By the spin of a particle we mean its total angular momentum relative to its center of mass.

†Sometimes the term "polarization" is used instead of "orientation," and conversely. [10] It is useful, however, to use the word polarization only for states characterized by a polar vector, and to use the term "orientation" in a wider sense.

Analyses of the physical conditions in various cosmic objects have shown[11-12] that dynamic orientation must be a phenomenon of very wide occurrence, the spins of the particles being as a rule aligned and not polarized. The main mechanism of the alignment of the spins is the resonance scattering of directed unpolarized radiation coming from stars and nebulas.

This phenomenon leads to a number of interesting astrophysical consequences. For example, alignment of particle spins can decidedly alter the transparency of a medium for resonance radiation. This is important, since almost all our information about the cosmic medium (its chemical composition, degrees of ionization and excitation, and so on) is obtained from data on the passage of resonance radiation through the medium in question.

I. STATIC ORIENTATION

In the absence of external fields a medium in thermodynamic equilibrium is isotropic, i.e., all directions are equivalent and the energies of particles do not depend on the orientations of their spins in space. In other words, particle states that correspond to different values of the projection M of the spin I along an axis of quantization are degenerate in energy: $\epsilon_M = \epsilon_{M'}$ for any possible values of M and M′ (I, I − 1, I − 2, . . . , − I). Accordingly, by the well known Boltzmann formula[13]

$$R_{IM'}/R_{IM} = e^{(\epsilon_M-\epsilon_{M'})/kT}, \tag{1}$$

the populations R_{IM} of all the (2I + 1) states corresponding to different orientations of the spin will be equal, so that all possible values of the projection M are equally probable. This means that the spins of the particles are oriented chaotically, i.e., on the average there is no orientation. This is the situation, for example, in dense layers of the atmosphere, where the populations of energy levels of the particles are determined by collisions with the equilibrium gas.

Particle spins in a medium in thermodynamic equilibrium will be oriented if there is a sufficiently strong external field so that the magnetic energy is larger than or comparable with the thermal energy,

$$\mu H \gtrsim kT. \tag{2}$$

In this case, as is well known, an energy level of the particles will be split into $(2I + 1)$ sublevels with different values of M, and according to the Boltzmann formula (1) the populations of these sublevels will be different. The largest population will be that of the sublevel with the lowest energy, corresponding to $M = I$ if the magnetic moment of the particle is positive, $\mu > 0$, or to $M = -I$ if the moment is negative, $\mu < 0$. This means that the spins of the particles are predominantly oriented along the field **H** for $\mu > 0$, or against the field for $\mu < 0$. This is called a static orientation. But the condition (2) which is necessary for a static orientation, is practically never satisfied in any known astrophysical systems. For example, in interstellar gas[14] (on the assumption of local thermodynamic equilibrium) $T \sim 100°K$ and $H \sim 10^{-6}$ Oe, so that $kT \sim 10^{-14}$ erg, but $\mu H \sim 10^{-26}$ erg. Even in magnetic stars[16] with $H \sim 10^3$ Oe and $T \sim 10^4°K$ the quantity $\mu H \sim 10^{-17}$ erg is much smaller than kT $\sim 10^{-12}$ erg. Pulsars are a possible exception, but the observations show that they are nonstationary and doubly nonequilibrium systems. Accordingly, equilibrium static orientation of particle spins does not occur under cosmic conditions.

II. DYNAMIC ORIENTATION

In the absence of thermodynamic equilibrium, as we have already said, a different type of orientation is possible in principle—dynamic orientation, in which the spins of the particles of a medium are oriented as the result of their interaction with a directed flux of radiation or of particles.

The point is that the optical, x-ray, and radio radiation of stars and nebulas, and also directed beams of particles, in passing through the cosmic medium and interacting with it, not only change the momentum distribution of the particles of the medium, but also orient the spins of these particles. While the first of these effects (light pressure and solar wind) have been discussed repeatedly in the astrophysical literature,[1-5] the second effect (the dynamic orientation of atoms and molecules in the cosmic medium) has not been discussed until very recently. Meanwhile the two effects are indissolubly connected, since in a collision both momentum and angular momentum are imparted to a particle. The second process is even more effective, in the sense that an incident flux first orients the particles of the medium and thereafter moves them along in the direction of its propagation.

The primary cause of dynamic orientation of spins is the spin-spin and spin orbit interaction between particles of the medium and particles of an incident flux—photons, protons, electrons, etc., both polarized and unpolarized. But this interaction can lead to orientation only if the angular distribution of the incident particles is anisotropic. In particular, a directed flux of unpolarized light falling on a nonoriented medium and being scattered, leads to alignment of the spins of the particles of the medium even if the scattering is spherically symmetric.

Under cosmic conditions the most effective mechanism of orientation of the spins of atoms, molecules, and ions is the resonance scattering of photons. This is true for the following reasons. First, the cross section for resonance scattering is extremely large, $\sigma_\gamma \sim \pi\lambda^2$. Second, because electromagnetic waves are transverse, the spin of the photon, $s_\gamma = 1\hbar$, unlike those of other particles, is always completely oriented—aligned along (or else opposite to) the direction of propagation of the wave. Third, fluxes of radiation are in many cases anisotropic, whereas the angular distribution of particles is as a rule isotropic.

For optical alignment of particle spins it is necessary that the probability of interaction of the particles with the radiation be larger than or at least comparable with the probability of collision with other particles,

$$W^\gamma \approx N_\gamma \sigma_\gamma c \gtrsim W^c \approx N_p \sigma_p v_p. \tag{3}$$

Besides this it is necessary that the flux of radiation be sufficiently anisotropic:

$$\Omega_\gamma / 4\pi \ll 1. \tag{4}$$

Orientation of spins as the result of optical pumping in laboratory experiments was first obtained by Kastler.[17-20] Under laboratory conditions, however, the oriented particles quickly relax into the isotropic equilibrium state, and the main problem is to suppress the relaxation caused by collisions between the particles themselves or their collisions with the walls.[20-25] Meanwhile there are great regions of cosmic space where there are practically no collisions and all the conditions necessary for optical alignment exist naturally and continually. Nature itself continuously maintains such an orientation. These regions are the upper layers of stellar and planetary atmospheres, the interplanetary medium, comets, interstellar gas clouds close to sources of radiation, the shells of novas and supernovas and of quasars, certain nebulas, and so on. A specific feature of all these objects[14-16] is that they are optically transparent, the radiation fluxes in them are rather large and strongly anisotropic, and the gas density is trifling and the relaxation negligibly small. Under these conditions resonance scattering of the radiation must necessarily lead to alignment of the particle spins. Therefore we can state that dynamic orientation of particle spins, unlike static orientation, is a widely occurring phenomenon in the Universe.

III. THE RESONANCE MECHANISM OF SPIN ALIGNMENT

The degree of alignment of the spins of particles as a result of optical pumping, and the change of the transparency of the medium caused by this alignment, depend on the spins of the particles and on the nature of the orienting radiation. There can be either an increase or a decrease of the transparency of the medium for the resonance radiation. In particular cases complete induced transparency is possible. To illustrate the mechanism of such alignment and change of transparency we shall give a simple and effective example.

Suppose a two-level atom with spin $I_a = 1$ in the

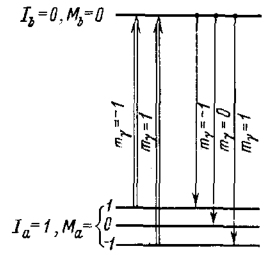

FIG. 1. Diagram illustrating the mechanism of alignment of the spin I_a as the result of resonance scattering of radiation.

ground state and spin $I_b = 0$ in the excited state is in a directed flux of unpolarized radiation Fig. 1). M is the projection of the angular momentum I of the atom along the axis of quantization, which is directed along the incident photon beam. In the case of unpolarized light the beam contains equal numbers of photons with right and left circular polarizations, corresponding to angular momentum projections $m_\gamma = 1$ and $m_\gamma = -1$ along the axis of quantization. There are no photons with the projection $m_\gamma = 0$ because the electromagnetic field is transverse.

According to the law of conservation of the angular momentum component, in the absorption of a resonance photon the atom can go into the excited state with $m_\gamma + M_a = M_b = 0$ only from the sublevels $M_a = \mp 1$, and the transition from the sublevel $M_a = 0$ is forbidden. Therefore the atoms that get into the sublevel $M_a = 0$ cannot thereafter get out of this state unless there is a collision with another atom. On the other hand, in the decay of the excited state there can be transitions into all of the substates M_a, and indeed with equal probabilities, since $I_b = 0$, and all of the properties of a physical system with spin zero are independent of its orientation in space; in particular, the matrix elements that determine the transition probabilities are independent of the projections m_γ and M_a.

Accordingly, in the given case every act of scattering will give an increase of the population of the sublevel $M_a = 0$ and corresponding decreases of the populations of the sublevels $M_a = \pm 1$. Under prolonged action of the beam of resonance photons practically all of the atoms, independently of their original orientations, must go over into the sublevel $M_a = 0$, and the medium will become transparent to the orienting radiation itself.

Complete induced transparency of a medium is of course possible only if there are no collisions between atoms. Moreover, it was assumed above that the orienting radiation is directed in a narrow solid angle along the axis of quantization.

Under laboratory conditions the experiment has been done with metastable atoms He I^m, using the transition $^3S_1 \rightleftarrows {}^3P^0_0$.[25]

It must be emphasized that we are here speaking not about the induced transparency of a medium that arises in very intense radiation fluxes, when the populations of the upper and lower states become equalized, but of induced transparency associated with the orientation of the spins in the lower state, which occurs even when the intensity of the radiation is small.

In the orientation process there is an increase of the ordering of the spins of the particles of the medium; that is, the entropy of the medium decreases. But this does not contradict the second law of thermodynamics, since there is a simultaneous increase of the entropy of the radiation that gets scattered. Before scattering it was concentrated in a narrow solid angle, and after the scattering its angular distribution has become much more nearly isotropic.

IV. THE DESCRIPTION OF ORIENTATION

Unlike static orientation, which is completely determined by the single parameter $\mu H/kT$, dynamic orientation can depend in a complicated way on a number of parameters, and it can have a wide variety of characteristics. The spin state of particles can not only consist of a statistical mixture of states with different value of M, but also can involve coherent superposition of such states.[13] In this case the spin orientation can be described only in terms of a polarization density matrix, and it does not suffice to give the populations of the sublevels with various values of M. In a cosmic medium however, only the longlived multiplet levels of the ground state of an atom or molecule are populated. Their magnetic sublevels do not overlap even in the very small magnetic fields $H \sim 10^{-6}$–10^{-7} which are typical for the interstellar medium; that is,

$$(W^\gamma + W^c)\hbar \ll \mu H \ll kT. \tag{5}$$

Furthermore, the excitation of these sublevels is stochastic in character. The density matrix for such a stationary state of the particles is diagonal in the energy. Owing to the condition (5), however, a density matrix diagonal in the energy will also be diagonal in M in a coordinate system with the axis of quantization in the direction of H. Accordingly, under these conditions the spin state of the particles can be described in terms of the populations R_{IM} of the magnetic sublevels (i.e., the diagonal elements of the polarization density matrix) and the direction of H is practically an axis of symmetry of the system. The stationary values of the populations R_{IM} of the sublevels are determined by the system of balance equations

$$R_{IM} \sum_{I'M'} W_{IM\to I'M'} = \sum_{I'M'} R_{I'M'} W_{I'M'\to IM}, \tag{6}$$

where $W_{IM \to I'M'}$ is the probability of the transition $IM \to I'M'$. In each actual case one must take into account the specific scheme of levels and the transition probabilities owing to all possible causes—collisions, direct and cascade transitions—and also the specific spectrum, angular distribution, and polarization of the orienting radiation. Each concrete case is individual in a double sense. We can, however, carry out a general treatment and bring out the basic relations that enable us to calculate the populations R_{IM} of the magnetic sublevels in various actual conditions. Such a general treatment is possible for the following reasons:

1) The collisions with the equilibrium gas, if they do give appreciable contribution $W^c \lesssim W^\gamma$, will only lead to a decrease of the degree of orientation produced by the optical pumping, but will not change the character of this orientation. But in the most interesting astrophysical cases $W^c \ll W^\gamma$ and collisions can be neglected altogether.

2) Only dipole transitions are of importance for optical pumping. Therefore there are only three types

of resonance levels, namely levels with spins $I_b = I_a - 1$, $I_b = I_a$, and $I_b = I_a + 1$, where I_a is the spin of the ground state.

3) If there are several resonance levels with the same spin value I_b, then optical pumping through these levels leads to exactly the same resultant populations $R_{I_aM_a}$ as pumping through a single level with the spin I_a.

4) The probabilities $W^{\gamma}_{IM\to I'M'}$, and consequently also the populations R_{IM} of the magnetic sublevels, do not depend on the details of the angular distribution and polarization of the radiation; if the conditions (5) are satisfied they are completely determined by just three parameters ρ_m. These parameters are the diagonal elements of the density matrix of the resonance radiation in the representation characterized by definite values of the projection of the angular momentum of the photon on the axis of quantization, $m_\gamma = 1, 0, -1$. The parameters ρ_m are normalized so that they represent the (dimensionless) numbers of photons in the corresponding cells of phase space. Furthermore the probabilities of direct dipole transitions of electric or magnetic type are given by the relations[26]

$$\begin{aligned} W^{\gamma}_{IM\to I'M'} &= \gamma_0 \left(C^{I'M'}_{IM\,1m}\right)^2 \rho_m, \\ W^{\gamma}_{I'M'\to IM} &= \gamma_0 \left(C^{I'M'}_{IM\,1m}\right)^2 (1+\rho_m), \qquad \varepsilon_{I'M'} > \varepsilon_{IM}, \end{aligned} \tag{7}$$

where γ_0 is the total probability of spontaneous transition and the $C^{I'M'}_{IM1m}$ are Clebsch-Gordan coefficients. It is important to emphasize that decidedly different angular and polarization states can correspond to the same values of the ρ_m.

In the case of isotropic unpolarized radiation

$$\rho_1(\nu) = \rho_0(\nu) = \rho_{-1}(\nu) = J_\nu \lambda^2/2h\nu, \tag{8}$$

where J_ν is the intensity of the radiation (erg cm^{-2} sec^{-1} Hz^{-1} sr^{-1}).

In the case of a directed flux of polarized radiation

$$\begin{aligned} \rho_{\pm 1}(\nu) &= (3/2)(\Omega_\gamma/4\pi)(\lambda^2 J_\nu(\theta)/h\nu) \\ &\quad \times \{1 \pm \eta\cos\theta - (\sin^2\theta/2)[1-(-1)^\Delta \xi\cos 2\alpha]\}, \\ \rho_0(\nu) &= (3/2)(\Omega_\gamma/4\pi)(\lambda^2 J_\nu(\theta)/h\nu)\sin^2\theta\,[1-(-1)^\Delta \xi\cos 2\alpha], \end{aligned} \tag{9}$$

where η and ξ are the degrees of circular and linear polarization, θ is the angle between the direction of the beam and the direction of **H**, α is the position angle characterizing the linear polarization, $\Delta = 1$ for electric dipole transitions, and $\Delta = 0$ for magnetic dipole transitions.

V. THE POPULATIONS OF THE MAGNETIC SUBLEVELS

The most important case for astrophysics is the alignment of spins by directed unpolarized radiation of small intensity ($\rho_m \ll 1$). To graphically illustrate the dependence of the optical resonance polarization on the directions of the pumping and on the spin characteristics of the atom, Fig. 2 shows the stationary values of the populations R_{IM} of the magnetic sublevels for a two-level system with the respective spins I_a and I_b in the ground and excited states. Owing to the features of optical pumping listed in the preceding section, the results of the calculations for a two-level system can be used to calculate the spin alignment of actual many-level systems for an arbitrary angular distribution of the orienting radiation.[12]

The values of R_{IM} for various I_a and I_b are shown in polar coordinates as functions of θ, the angle between the directions of the orienting beam and of the field **H**. A circle shows the equilibrium populations $R_{I_aM_a}$ for any M_a, which become established in an isotropic medium in the absence of directed fluxes of radiation and particles. All of the graphs are to the same scale. Comparisons between them show graphically how the nature and degree of the orientation change with in-

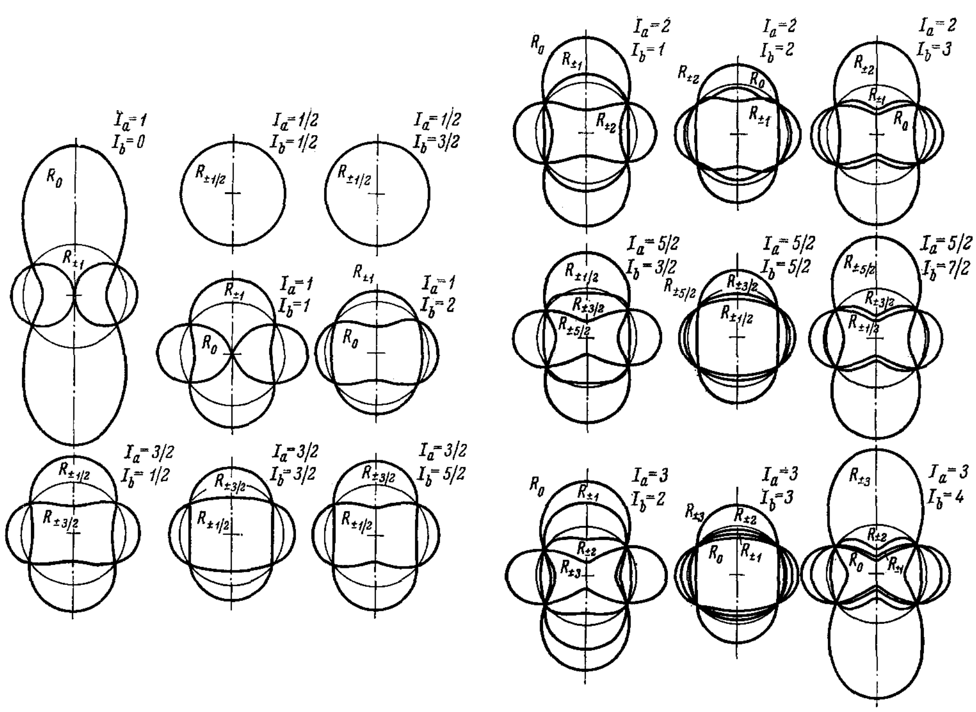

FIG. 2. The populations R_{M_a} of the magnetic sublevels of a state with spin I_a, as established by optical pumping through a level with spin I_b under the action of directed unpolarized radiation.

crease of the value of I_a with various relations between I_a and I_b.

As can be seen from Fig. 2, for $I_a \geq 1$ the populations $R_{I_aM_a}$ with different values of M_a are not the same for any direction of the orienting beam, except at $\theta = 54°44'8''$ and $\theta = 125°15'52''$, where $\sin^2\theta = \frac{2}{3}$ and $\rho_1 = \rho_0 = \rho_{-1}$. Alignment of spins $I_a = 0$ and $I_a = \frac{1}{2}$ is impossible.

If the orienting radiation is predominantly directed along the magnetic field ($\theta < 55°$ or $\theta > 125°$) then in the cases $I_b = I_a$ and $I_b = I_a + 1$ the sublevels with the maximum value $|M_a| = I_a$ are most heavily populated. If, on the other hand, the orienting radiation is directed mainly transverse to the field H ($55° < \theta < 125°$), the most heavily populated sublevels are those with the smallest value of $|M_a|$ (0 or $\frac{1}{2}$).

The situation is exactly the opposite in the case $I_b = I_a - 1$. In particular, in the case of pumping along the magnetic field ($\theta = 0°$ or $\theta = 180°$) for $I_a = 1$ and $I_b = 0$ all of the atoms are concentrated in the level $M_a = 0$, whereas for $I_a = 1$ and $I_b = 1$ all of the atoms are concentrated in the levels with $|M_a| = 1$.

We must also point out the very high degree of orientation in the case $I_a \gg 1$ and $I_b = I_a + 1$ for $\theta \approx 0°$ and $\theta \approx 180°$, when the atoms are predominantly concentrated in the sublevels $|M_a| = I_a$.

Figure 2 also allows us to determine values of $R_{I_aM_a}$ in the more general case when the angular distribution and degree of linear polarization of the radiation are arbitrary, since then $\rho_1 = \rho_{-1}$ and the entire situation is determined by only a single parameter, the ratio ρ_0/ρ_1, to which there corresponds a definite effective value of the pumping angle θ,

$$\sin^2\theta = 2\rho_0/(2\rho_1 + \rho_0). \tag{10}$$

As already noted, the values of R_{IM} represented graphically in Fig. 2 enable us, without solving the balance equation, to estimate the populations $R_{I_aM_a}$ of the magnetic sublevels of the ground state of a many-level system subjected to optical pumping with radiation with an arbitrary spectrum. In cases in which the predominating effect is that of resonance levels with the same value of I_b, the resulting populations $R_{I_aM_a}$ will be the same as for a single resonance level I_b, independently of the number of levels through which the pumping goes. In the general case it is necessary to know the relative contributions of all the resonance levels with $I_b = I_a - 1$, with $I_b = I_a$, and with $I_b = I_a + 1$.

In this way, for example, we can determine the nature of the alignment of the spin $I_a = \frac{3}{2}$ of the 0 II ion in a flux of hard ultraviolet radiation with a continuous spectrum. The only allowed transitions from the ground state $(1s^2 2s^2 2p^3)^4S^0_{3/2}$ are those to the states $(1s^2 2s^1 2p^4)^4P$, $(1s^2 2s^2 2p^2 ns)^4P$, and $(1s^2 2s^2 2p^2 nd)^4P$.[27] Each of these resonance states is a triplet—a group of closely spaced levels with spins $I_b = \frac{1}{2}$, $I_b = \frac{3}{2}$, and $I_b = \frac{5}{2}$—and the ratios of the contributions of these sublevels are 2 : 4 : 6. The corresponding estimate made from Fig. 2 agrees well with the exact value

$$R_{M_a=3/2}/R_{M_a=1/2} = (2.6 + \cos^2\theta)/(2 + 1.4\sin^2\theta). \tag{11}$$

The results we have given also allow us to estimate the spin alignment of atoms and molecules that arises owing to their interaction with a directed beam of fast electrons or protons, since the field of a fast charged particle is to a large extent equivalent to the field of a transverse electromagnetic wave.[26]

VI. SPECIAL FEATURES OF THE ALIGNMENT OF ATOMS AND MOLECULES WITH HYPERFINE STRUCTURE

The situation is somewhat more complicated in the case when there is hyperfine splitting of the levels, owing, for example, to the interaction of the angular momentum I^{el} of the electronic structure with the angular momentum I^{nuc} of the nucleus, or to Λ-type doubling in molecules. The ground state of the particles is no longer a single level, but is a whole group of closely spaced levels with different values of the total spin $F = I^{el} + I^{nuc}$, and all of these levels are populated, since the probabilities of radiative transitions between them are very small. The interaction with a directed flux of radiation (optical pumping) changes the relative populations of the magnetic sublevels, and also causes a transfer from one level to another. Therefore to describe the spin state of the particles in a given case it is necessary to indicate the populations of the magnetic sublevels of all the levels of the hyperfine structure of the ground state.

As examples, we show in Figs. 3 and 4 the populations R_{FM} of the magnetic sublevels of the hyperfine multiplet for the ground states of hydrogen atoms, H I, $F_a = 0$ and 1, and of Na I atoms, $F_a = 1$ and 2. In the absence of the hyperfine interaction, i.e., for $I^{nuc} = 0$, alignment of the spins of these atoms is altogether impossible, since in the ground state the spin of the electronic structure is $I^{el}_a = \frac{1}{2}$. The only resonance transitions from a ground state $^2S_{1/2}$ are to states $^2P_{1/2}$ and $^2P_{3/2}$. In such transitions there is no change of the spin state of the nucleus, since for practical purposes electromagnetic radiation interacts only with electrons. Because of this optical pumping through the state $^2P_{1/2}$ ($I^{el}_a = \frac{1}{2} \rightarrow I^{el}_b = \frac{1}{2}$) does not give any alignment of the spins F_a, and pumping through the state $^2P_{3/2}$ leads to alignment only if the hyperfine structure components of the resonance state $^2P_{3/2}$ are split apart, i.e., when owing to the spin-spin interaction ($I^{el} \cdot I^{nuc}$) the spin state of the nucleus can change during the lifetime of the atom in the excited state. Therefore the degree of alignment of the spins F_a will depend essentially on the size of the hyperfine splitting in the excited state $^2P_{3/2}$. In the case of Na I the components $F_b = 3, 2, 1, 0$ are almost completely split, and therefore the degree of alignment of the spins $F_a = 1$ and $F_a = 2$ is high; for $F_a = 2$ the ratio $(R_{M=2}2 - R - R_{M-0})/R_{M-0}$ amounts to 66 percent.[21,24,30] For the H I atom, on the other hand, the components $F_b = 1$ and 2 of $^2P_{3/2}$ have an overlap of almost 95 percent, and the interference term that cancels the effect is large. Therefore the degree of alignment of $F_a = 1$ is lower; the ratio $(R_{M=1} - R_{M=0})/R_{M=0}$ is only 2.6 percent.

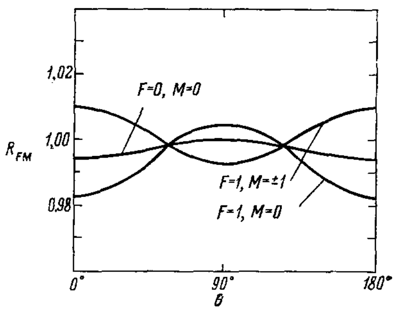

FIG. 3. The populations R_{FM} of the magnetic sublevels of the ground state of hydrogen atoms, $2S_{1/2}$, F = 0 and F = 1, which are established as the result of pumping by directed unpolarized ultraviolet radiation. θ is the angle between the direction of the field **H** and that of the beam of radiation.

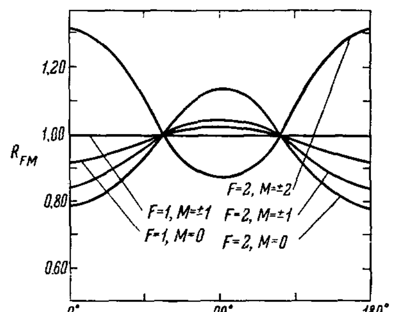

FIG. 4. The populations R_{FM} of the magnetic sublevels of the ground state of NaI atoms, F = 1 and F = 2, which are established as the result of optical pumping by directed unpolarized radiation. θ is the angle between the direction of the field $\mathbf{H}_0$ and that of the beam of radiation.

But even this amount of alignment can have a very important effect on the transmission of the radio radiation at $\lambda = 21$ cm corresponding to the resonance transition between the levels $F_a = 1$ and $F_a = 0$ of the hyperfine structure of the ground state of H I, since in the equilibrium state with no pumping the populations of these levels of H I are almost equal and the medium is practically transparent for the radiation at $\lambda = 21$ cm.

Finally, we note that an especially strong orientation effect under cosmic conditions must occur in those astrophysical systems in which there is maser amplification of radio radiation, for example in cosmic sources of radio radiation from OH,[31 32] H_2O,[33-35] etc. The propagation in the medium of an intense, directed, polarized, and highly monochromatic radiation corresponding to the resonance transition between hyperfine-structure levels of the ground state must itself lead to orientation of the particle spins in both resonance levels, the lower and the upper; if there is a high degree of circular polarization of the radio radiation the result will be that the particle spins will be polarized, not aligned.

VII. PROPERTIES OF AN ORIENTED MEDIUM

The optical properties (refraction and absorption) of a medium containing particles with polarized or aligned spins are strongly dependent on the direction of observation and the polarization of the incoming radiation. In such an oriented medium there can be propagation in a given direction of two independent waves with orthogonal polarizations κ_+ and κ_-, and with different speeds and different rates of damping (or increase) K_+ and K_-. The difference between K_+ and K_- has the result that orignally unpolarized radiation passing through an oriented medium acquires the polarization κ_+ or κ_-, depending on whether $K_+ < K_-$ or $K_- < K_+$. In this case [condition (5)] the dependence of the optical properties of the oriented medium on the populations R_{IM} of the magnetic sublevels is determined by only the average values of M and M^2,

$$\langle M\rangle = \sum_M MR_{IM}, \qquad \langle M^2\rangle = \sum_M M^2 R_{IM}.$$

In the absence of polarization and alignment

$$\langle M\rangle_0 = 0, \qquad \langle M^2\rangle_0 = I(I+1)/3.$$

In the case of polarization $\langle M\rangle \neq 0$, and in the case of alignment $\langle M\rangle = 0$ but $\langle M^2\rangle \neq \langle M^2\rangle_0$; for $\langle M^2\rangle > \langle M^2\rangle_0$ the spins are aligned predominantly along the field **H**, and for $\langle M^2\rangle < \langle M^2\rangle_0$ they are predominantly transverse to the field **H**.

The characteristic polarizations κ_+ and κ_- depend on the angle ϑ between the direction of propagation of the radiation and the direction of **H**. They are given by the following expression $[\kappa_+ = \kappa_- - (\pi/2)]$[36]:

$$\operatorname{ctg} 2\varkappa_\pm = \frac{2}{3} A \frac{\langle M_a\rangle + (-1)^{I_b - I_a}\langle M_b\rangle e^{-\varepsilon_{ba}/kT}}{(2I_a+1)(\langle M_a^2\rangle - \langle M_a^2\rangle_0) - (2I_b+1)(\langle M_b^2\rangle - \langle M_b^2\rangle_0)e^{-\varepsilon_{ba}/kT}} \frac{\cos\vartheta}{\sin^2\vartheta}, \tag{12}$$

where $A = [-\delta_{I_b, I_a - 1}(2I_a - 1) + \delta_{I_b, I_a} + \delta_{I_b, I_a+1}(2I_a + 3)](2I_a + 1)$; $\cos 2\kappa = (J_+ - J_-)/(J_+ + J_-)$ and $\sin 2\kappa = (J_\parallel - J_\perp)/(J_\parallel + J_\perp)$ are the degrees of circular and of linear polarization. The quantity $e^{-\epsilon_{ba}/kT}$ characterizes the ratio of the mean populations of the upper and lower levels.

In the case of a dipole resonance transition the coefficients of absorption (or amplification) of the radiation with the polarizations κ_+ and κ_- are given by the following relation*:

$$\begin{aligned} K_\pm/K_0 = {} & (1 - e^{-\varepsilon_{ba}/kT}) + (3/2)B\{[\langle M_a\rangle + (-1)^{I_b - I_a}\langle M_b\rangle e^{-\varepsilon_{ba}/kT}] \\ & \times \cos\vartheta\cos 2\varkappa_\pm + A^{-1}[(2I_a+1)(\langle M_a^2\rangle - \langle M_a^2\rangle_0) \\ & - (2I_b+1)(\langle M_b^2\rangle - \langle M_b^2\rangle_0)e^{-\varepsilon_{ba}/kT}]\{1 - 3\sin^2\vartheta\sin^2[\varkappa_\pm - (\pi/4)]\}. \end{aligned} \tag{13}$$

where $B^{-1} = -I_a\delta_{I_b, I_a-1} - I_a(I_a + 1)\delta_{I_b, I_a} + (I_a + 1)\delta_{I_b, I_a+1}$; K_0 is the absorption coefficient in the case of chaotically oriented spins and zero population of the upper level. The first term in (13) characterizes the transmission of the radiation in the absence of orientation and alignment. The second and third terms are respectively due to the polarization and the alignment of the spins.

In the case of an "aligned" medium, which is most important for astrophysical applications, the characteristic polarizations $\kappa_+ = \pi/4$ and $\kappa_- = \pi/4$ (sic) are linear polarizations; the transparence of the medium for optical radiation ($e^{-\epsilon_{ba}/kT} \ll 1$) is different for the polarizations parallel and perpendicular to the

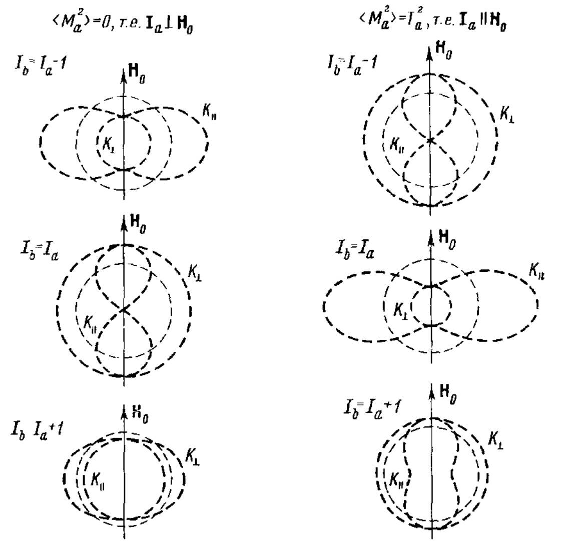

FIG. 5. Angular dependence of the coefficient of absorption (K < 0) of resonance radiation $I_a \rightarrow I_b$ by particles with aligned spins I_a for $R_{I_a} \gg R_{I_b}$. $K_\perp$ and $K_\perp$ correspond to two perpendicular linear polarizations. The thin-line dashed circles show the value of $K_\perp = K_\parallel$ in the absence of orientation.

*If the condition (5) is not satisfied, there is an additional contribution to the transition probability from the terms of the density matrix which are not diagonal in M. As noted earlier (Sec. IV), however, the condition (5) is fulfilled in the cosmic medium.

magnetic field **H**, and is given by the following relations (Fig. 5):

$$K_\parallel/K_0 = 1 + c\,(\langle M_a^2\rangle - \langle M_a^2\rangle_0)\,(1 - 3\sin^2\vartheta),$$
$$K_\perp/K_0 = 1 + c\,(\langle M_a^2\rangle - \langle M_a^2\rangle_0), \tag{14}$$

where $c \equiv (3B/2A)(2I_a + 1)$. The difference between the values of $K_\parallel$ and $K_\perp$ must lead to a linear polarization of the transmitted radiation, with the direction of the polarization vector related to that of the magnetic field.

Accordingly, spin alignment can have various large effects on the transparency of a medium for resonance radiation. The optical thickness of the medium is decreased for some lines and increased for others, so that spin alignment leads to anomalous intensity ratios of the lines in a multiplet.

Moreover, when there is hyperfine splitting the spin orientation of the particles of a medium can itself have the result that in its passage through the medium the radio radiation corresponding to a transition between hyperfine-structure levels of the ground state will be amplified instead of attenuated (Fig. 6). The point is that according to (13) with spin orientation individual magnetic sublevels of the upper level may have a population inversion as compared with the corresponding lower sublevels, even if the average population of the upper level is less than that of the lower level ($e^{-\epsilon_{ba}/kT} \lesssim 1$). Accordingly, as the result of orientation there is a possibility of coherent amplification of resonance radio radiation passing through a medium. This sort of situation for H I and OH has been treated in[37,38,39].

VIII. POSSIBLE ASTROPHYSICAL METHODS MAKING USE OF THE PHENOMENON OF COSMIC SPIN ORIENTATION

Accordingly, spin orientation of the particles of a medium can decidedly alter its optical properties for resonance radiation. Therefore in the analysis of the spectra of various astrophysical objects it is necessary to take the possibility of orientation into account. In astrophysics the number of atoms of a given type, or more exactly the total number along the line of sight, $\int N dl$, is usually determined by constructing the so-called growth curve, which gives the dependence of the equivalent width w_λ of an absorption line on the corresponding optical thickness τ, for various lines. In the construction of this curve one must allow for the effect of alignment, especially for those atoms that correspond to lines with $\tau \lesssim 1$. Alignment of the particle spins I_a leads, in particular, to a change of the relative intensities of lines corresponding to optical transitions between a given level I_a and different levels I_b. Such an anomaly in the relative intensities manifests itself in a large spread of the points which should fall on the growth curve; such a spread can usually not be eliminated by a simple variation of parameters. The spread can be eliminated, however, by introducing into the values of the optical thickness τ corrections for the spin alignment, in accordance with Eq. (14). We emphasize that these corrections, although they are indeed determined by a single parameter, are different for different I_b, not only in magnitude, but also in sign. Accordingly, the construction of a growth curve with allowances for alignment allows us not only to determine the total number of atoms in the level I_a, $\int N\,dl$, but also to estimate the effective value of the quantity $\langle M_a^2 \rangle$, which characterizes the degree of alignment of the spin I_a. The correctness of this interpretation can be confirmed by the fact that the choice of a single additional parameter allows the elimination of the spread of a large number of points on the growth curve. Values of $\int N\,dl$ found with allowances for spin orientation are in general different from values obtained by the usual method. In other words, the effect in question can give corrections to the values of the partial densities of atoms, molecules, and ions; that is, generally speaking it can change the data on chemical composition, degree of ionization, and excitation.

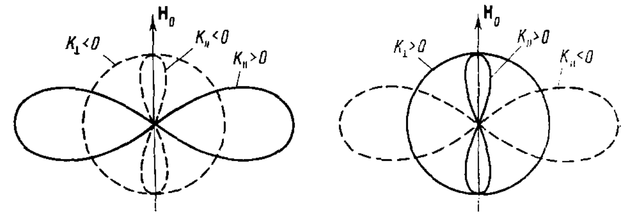

FIG. 6. Angular dependence of the coefficient of absorption (K < 0) or amplification (K > 0) of resonance radiation $I_a \rightarrow I_b$ by particles with aligned spins for $\langle R_{I_a M_a}\rangle \sim \langle R_{I_b M_b}\rangle$. $K_\perp$ and $K_\parallel$ correspond to two perpendicular linear polarizations. The solid line is for amplification, K > 0, and the dashed line for absorption, K < 0.

Moreover, inclusion of this effect can give qualitatively new information regarding the anisotropy of the physical conditions in objects under investigation, primarily about the anisotropy of the radiation field. This can be extremely important. For example, in a number of cases it is not known in advance where spectral absorption lines are produced—in the immediate neighborhood of the source of continuous radiation, in its envelope, or far from the source, in a gas cloud which is accidentally in the line of sight. In the former case the particles are in a flux of intense directed radiation and the degree of spin alignment is high; therefore by determining the effective value of $\langle M^2 \rangle$ we can estimate the distance from the source of the orienting radiation to the absorbing region.

Finally, the fact that the populations R_{IM} of the magnetic sublevels, which are established as the result of optical pumping, depend on the direction of the magnetic field H enables us to use this phenomenon to determine the direction of H in the region of space in question. As we see from (14), an analysis of the spectrum with spin orientation effects included allows us to determine not only the effective value of $\langle M^2 \rangle$ but also the effective value of the angle ϑ between the direction of the magnetic field H and the direction of observation. To calculate the total optical thickness of a medium we must integrate the attenuation (or amplification) coefficient along the line of sight, $\tau = \int K\,dl$. In doing so we must allow for the fact that the direction of the magnetic field H, i.e., the angle ϑ, like the parameter $\langle M^2 \rangle$, depends on the coordinate l. The direction of H in the region in question can vary. As a rule, however, there is a regularly behaving component of H. There is a large-scale magnetic field regular on the average even in such regions as the interplanetary medium,[40] the interstellar medium in the Galaxy,[41] and so on.

We shall give a concrete illustration of the method of determining H.[30] The doublet of lines D_1 ($\lambda = 5896$) and D_2 ($\lambda = 5890$) in the spectrum of comets arises owing to single scattering of solar radiation by Na I atoms in the atmosphere of the comet. The ratio of the intensities of D_1 and D_2 naturally depends on the angle of scattering, i.e., it is determined by the differential cross sections for scattering of the radiation. As for the D_1 line, it is unpolarized and the plot of its angular distribution is spherically symmetric and does not depend on either the direction of H or on the populations $R_{F_aM_a}$ of the magnetic sublevels. The situation is different for D_2, which is partially linearly polarized; its degree of polarization and angular distribution are decidedly anisotropic and depend on the populations $R_{F_aM_a}$ of the magnetic sublevels of the hyperfine structure, $F_a = 1, 2$, of the ground state of Na I. The spins of the Na I atoms in the atmosphere of the comet are oriented owing to the scattering of the solar radiation itself. In Fig. 4 we gave the dependence of the populations of the magnetic sublevels $F_a = 1$ and $F_a = 2$ of the ground state of Na I on the angle θ between the direction of H and the direction of the pumping, i.e., in this case the direction toward the Sun. The values of R_{FM} uniquely determine the angular distribution of the scattered radiation. Therefore by measuring the intensities of the D_1 and D_2 lines and the degree of polarization of the D_2 line one can determine two angles characterizing the effective direction of H in the region of interplanetary space where the head of the comet is located at the given time. We emphasize that this method can be applied also in the case of small fields for which other optical methods are of no use.

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