A tangle of fractal fibers as a new state of matter

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A system of fractal fibers (a fractal tangle) is formed as a result of evaporation of a weakly ionized atomic vapor from a surface in an external electric field. A fractal tangle has the density of a gas but the behavior of a liquid or solid. The tangle–globule phase transition in this system is similar to the transition in a long polymer fiber with self-intersections. The explosive nature of a fractal tangle is due to its high surface energy, since the system consists of nanometer particles and a significant fraction of the molecules are on the surfaces of the particles. An explosion of a fractal tangle is accompanied by a large number of thermal waves propagating along individual fractal fibers. The result is a large number of hot spots moving inside the system. There is a connection between fractal tangles and ball lightning.

INTRODUCTION

New knowledge in physics can change our ideas about familiar phenomena. For example, the development of lasers and the study of the processes in lasers showed that nonequilibrium conditions are easily created and this led to a large number of disciplines beginning with the word "nonequilibrium" (nonequilibrium plasma, nonequilibrium thermodynamics, nonequilibrium gas dynamics). These disciplines consider systems in which there is a lack of equilibrium between certain degrees of freedom.

The development of fractal ideas in physics may lead to a similar revolution in the physical description of the world. The remarkable books of Mandelbrot[1,2] attracted the attention of physicists to fractal ideas and these ideas led to a number of new directions in physics. Below we will concentrate on one of these directions: the fractal structure of matter.

Experiment shows that besides the homogeneous states of matter (classical liquids and gases) objects with a porous structure are common in physics. The basic elements of these objects are fractal aggregates or fractal clusters (see Refs. 3–17, for example), which are systems of associated particles of nanometer sizes. The fractal properties of these objects are as follows. If we take one of the particles as the center of a sphere whose radius R is much larger than the radius of an individual particle, then the mass m of material inside the sphere depends on radius according to the equation

$$m(R) \sim R^D, \tag{1}$$

where the parameter D is called the fractal dimensionality of the object.

Note that for a continuous solid in three-dimensional space this parameter is equal to 3. For fractal clusters studied experimentally, $D = 1.7$–2.5.

Equation (1) can be used to relate the mass of a cluster to its radius R. Obviously the density of material in a fractal cluster decreases with the radius of the cluster as R^{D-3} and therefore the strength of the cluster decreases with radius. This implies that the size of a fractal cluster is limited.[18] In practice the radius of a fractal cluster consisting of nanometer particles is less than a few microns. Hence a macroscopic object cannot be a fractal cluster, although it can be composed of fractal clusters.

MACROSCOPIC FRACTAL STRUCTURES

A well-known object of this kind is an aerogel,[19,20] which is formed in a solution at supercritical values of the temperature and pressure. The most well-known example is silica-aerogel, which consists of SiO_2 particles (i.e., very porous glass). This example will be used in obtaining numerical estimates. We note that aerogels have fractal properties on a small scale and are homogeneous on a scale much larger than the pore size (practically the entire volume of the system is in the pores).

Another object composed of fractal clusters is a fractal fiber, which was obtained recently in the experiment of Lushnikov, Negin, and Pakhomov[21] using laser irradiation of metallic surfaces (see also Ref. 22). The beginning of this process is the formation of a dense plasma near the surface (the pressure is tens to hundreds of atmospheres and the temperature is several thousand degrees). The plasma disperses into the surrounding space and transforms into fractal fibers (Fig. 1). An external electric field is essential for the formation of fractal fibers. It lines up the induced dipole moments in the fractal clusters and they join together and finally form a fractal fiber. Fractal fibers are the analogs of aerogels, but are anisotropic, since they are formed in an external field (in the experiment of Ref. 21 the diameter of the fibers was 30–40 μm and their length was several centimeters). It is important to note that the fibers form in free space and then attach themselves to electrodes. Also several dozen fractal fibers formed at the same time in the experiment of Ref. 21.

We note that the formation of fractal fibers is universal. It can be shown[23,34] that two requirements must be satisfied in order for fractal fibers to form. First the evaporated material must consist of atoms and ions (and not droplets), and second, the latter stage of the process must occur in an exter-

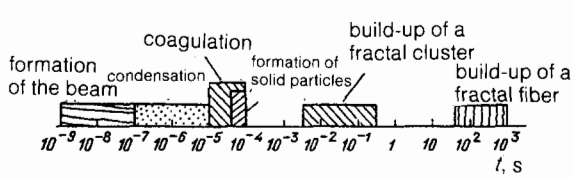

FIG. 1. Time scale of the formation of fractal fibers.

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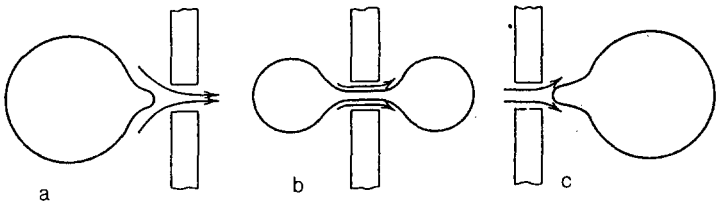

FIG. 2. Passage of an object through a small aperture:[28,29] a–c successive stages of the process.

nal field. In Ref. 21 fractal fibers were formed using surfaces of different materials and different buffer gases. Obviously they can be formed with different methods of treating the surface: laser irradiation, electric breakdown or discharges, interaction of the surface with electron or ion beams, or any other treatment leading to the evaporation of atoms and ions from the surface.

Hence the interaction of energy fluxes with the surface leads to a weakly ionized dense vapor whose evolution in an external electric field can result in the formation of a system of fractal fibers, which is a new state of matter and deserves careful study. Since the formation of this state of matter is universal, it may occur whenever energy fluxes are directed on solid surfaces.

We assume that the fractal fibers formed after treating the surface do not attach to electrodes, but are drawn off into free space; this was the case in Ref. 21. The fibers can intertwine and the resulting tangle of fractal fibers represents a distinctive state of matter, which will be discussed further below. Since the formation of this state is universal, it may occur in various laboratory and natural phenomena. It is possible that it may correspond to certain puzzling natural phenomena.

We consider first the phase states of the material making up a fractal tangle. Two phases are possible, depending on the nature of the interactions between the fibers. In the case of weak interactions between fibers a fractal fiber is not bound to its neighbors but only collides with them. A system of fractal fibers of this kind will tend to break up into separate fibers. In the other limiting case the system of fibers forms a rigid structure analogous to a long polymer fiber with self-intersections.[1)] The formation of a rigid structure in a system of fractal fibers is analogous to a tangle–globule phase transition in a polymer fiber, which has been studied quite extensively.[25–27] This analogy will be used below to obtain numerical estimates.

Therefore a system of bound fractal fibers (a fractal tangle) is a distinctive state of matter and can be formed when a material is subjected to an energy flux in an external electric field. The density of this state corresponds to a gas, but its behavior corresponds to a liquid or a solid. As a demonstration of the liquid properties of this state of matter, we show in Fig. 2 how a rigid fractal tangle passes through a small aperture according to Gaĭdukov's theory.[28,29] Because of its rigid structure, a fractal tangle has surface tension, but it is relatively small because of the small density. A flow of gas near the aperture causes the spherical shape of the fractal tangle to become distorted; a cylindrical jet is pulled away from the surface and in this way all of the material passes through the aperture. Then far from the aperture the spherical shape of the system is restored as a result of surface tension. This is the mechanism used by Gaĭdukov[28,29] to explain how ball lightning passes through an aperture. The laws of gas dynamics were used and the ball lightning was treated as a liquid with a weak surface tension. It can be seen that this result holds for any rarefied system with weak surface tension forces, including fractal tangles. This example shows that a fractal tangle, as a bound rarefied system, can have unusual properties and an understanding of these properties requires a special analysis.

EXPLOSIVE PROPERTIES OF A FRACTAL TANGLE

A fractal fiber is composed of nanometer particles and therefore it has a large internal surface area. The size of the particles in a structure of fractal fibers is determined by how they were formed; in the later stages of the process the growth of the particles is determined by coagulation and growth stops when the temperature of the expanding plasma is comparable to the melting temperature of the material. But the rate of coagulation of the particles decreases sharply with particle radius and so the particle radius depends only weakly on how the particles were formed. Because of the large internal surface, the system has a surface energy, is released when the internal surface area contracts and surface molecules move to the interior of the particles, where they form new chemical bonds (Fig. 3).

The specific internal energy can be quite high. Consider the case of silica-aerogel, whose specific internal surface area is 500–1500 m^2/g (Ref. 19). The corresponding internal energy is 2–5 kJ/g, which is of the order of the specific chemical energy of gunpowder. Hence a system of fractal fibers is an explosive object. This property appears only at sufficiently high temperature, however. If a high temperature is created inside a region on a fractal fiber, a thermal explosion occurs and thermal waves propagate along the fiber and cross over to other fibers at their intersection points. On the thermal wave front the structure melts and breaks up into drops. Coagulation of the drops leads to the release of energy, which goes into evaporating molecules from the surface of

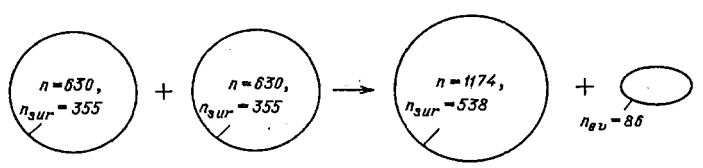

FIG. 3. Coagulation of two SiO_2 drops of specific surface area $S = 740$ m^2/g. Here n is the number of molecules per drop, n_{sur} is the number of molecules on the surface of the drop, and n_{ev} is the number of evaporating molecules, whose later condensation leads to a release of energy.

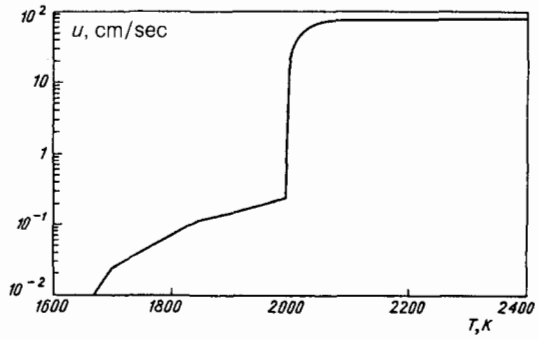

FIG. 4. Propagation velocity of a thermal wave along a SiO_2 fiber as a function of the temperature on the wave front.

the coagulated drops. These molecules travel to a neighboring part of the structure and condense, thereby transporting their energy. A thermal wave of this kind propagates along the fractal fiber. Cooling occurs behind the thermal wave front because of the thermal conductivity of the ambient air or gas.

Using the parameters of silica-aerogel it can be shown that[30] the temperature on the thermal wave front is about 2000 °K, the velocity of the wave is of the order of 10 cm/sec (Fig. 4), and the width of the wave front is of the order of 10 μm. The thermal wave breaks up the fractal fiber and, because of the high temperature, the front can be observed as a moving incandescent point. The number of these points increases with the degree of branching of the waves.

Hence a fractal tangle can have explosive properties. An explosion of the system appears in the form of thermal waves propagating along individual fractal fibers. We note that because heat is drawn off by thermal conduction in the surrounding air, this process is possible when the rate of decrease of the internal energy of the fiber is sufficiently high. The temperature on the front of the thermal wave must exceed the melting temperature of the material, so that the internal surface area of the structure contracts because of coagulation of liquid drops. The specific energy of the structure must therefore exceed a certain threshold value, i.e., there is a threshold value for the specific area of the internal surface of the structure (and hence for the radius of the particles making up the structure) in order for an explosion to be possible.

FRACTAL STRUCTURES AND BALL LIGHTNING

The structure of a fractal tangle considered above also corresponds to ball lightning.[22] Although this is a hypothesis and it can be questioned, more arguments in favor of the fractal structure of ball lightning are appearing as research progresses. Omitting the details, we only note that there are no alternative concepts which can explain the different properties of ball lightning (the way in which its shape evolves, its brightness, the nature of its motion, and so on) to the same degree. We also note that all cases of ball lightning produced in the laboratory with internal energy sources[31–33] involve methods of treating materials that also produce fractal fibers.[21] Information on ball lightning will be used below for additional analysis of the fractal fiber state of matter.

TABLE I. Density of an average ball lightning.

Basis of estimate	value, g/cm³
1. temperature of the incandescent region	$10^{-3,6\pm0,8}$
2. average internal energy	$10^{-4,0\pm0,9}$
3. lift force	$10^{-3,0\pm0,8}$
4. rebound from surface	$10^{-3,7\pm0,3}$
5. constancy of spherical shape	$10^{-4,5\pm1,0}$
6. optical thickness	$10^{-4,0\pm1,0}$
average	$10^{-3,9\pm0,4}$

TABLE II. Surface tension of an average ball lightning.

Basis of estimate	value, J/m²
1. constancy of spherical shape	$10^{-1,7\pm0,5}$
2. passage through an aperture	$10^{-1,0\pm1,5}$
3. electric surface tension	$10^{-1,7\pm0,5}$
average	$10^{-1,5\pm0,5}$

We will use the concept of average ball lightning, i.e., ball lightning with averaged parameters. Some of these parameters are obtained by analyzing the thousands of observations, while others can be calculated using these data. Table I contains estimates for the average density of ball lightning and Table II contains estimates for the surface tension. In row 1 of Table I we use the fact that the temperature of the incandescent region is about 2000 °K. Below this temperature the material of the ball lightning must be heated with the help of different energy-releasing methods. The estimate in row 2 is based on the average observed internal energy. Row 3 uses the fact that the lifting force on ball lightning produced by rising convection currents is equal to its weight and row 4 uses the case observed in Ref. 34, where ball lightning produced on a soldering iron was observed to bounce off the surface of a table. Row 5 uses the constancy of the spherical shape of ball lightning assuming the average value of the surface tension and row 6 is based on the optical thickness of the average ball lightning estimated from observations, assuming its structure corresponds to silica-aerogel. It is evident that all the estimates lie within an order of magnitude and hence the average value can be determined more reliably than any of the separate values. The statistical error indicated for the average does not take into account the errors in each of the estimates.

For the surface tension, row 1 in Table II is based on the same reasoning as row 5 of Table I, but the average value of the density of ball lightning was used. Row 2 is based on the Gaĭdukov theory[28,29] of ball lightning passing through an aperture and row 3 gives the value of the surface tension created by the average electric charge of ball lightning. As in Table I, the error given for the average value does not take into account the errors in the individual estimates.

Based on these values, we analyze the nature of the surface tension in order to obtain an understanding of the system. The usual mechanism of surface tension involves molecules at the surface, which have half the number of chemical bonds as interior molecules. Imagine that an element of the ball lightning is cut by a plane. Then the surface tension is roughly the energy required to split off a unit area of material. We estimate this quantity, assuming that the ball lightning is made up of spheres of radius r_0. The average number density N of these spheres can be found from the relation

$$\bar{\rho} = \frac{4}{3}\pi r_0^3 \rho_0 N, \tag{2}$$

where $\bar{\rho}$ is the average mass density of the ball lightning, and ρ_0 is the average mass density of a particle.

Let ε_0 be the energy required to split off a unit surface area of material, treating the ball lightning as a continuous mass. Then using (2), the surface tension of the ball lightning material for this mechanism is

$$\alpha \le \varepsilon_0 \cdot 2r_0 N \cdot \frac{2}{3}\pi r_0^2/3 = \frac{\varepsilon_0 \bar{\rho}}{\rho_0}, \tag{3}$$

where $2r_0 N$ is the average number of spheres per unit area of the cutting plane whose centers are closer than the distance r_0 from the plane and $2\pi r_0^2/3$ is the average surface area of a cut sphere.

Using silica-aerogel as the material making up the ball lightning and the data of Table I ($\rho_0 = 2$ g/cm^2, $\varepsilon_0 = 7$ J/m^2 (Ref. 46), $\bar{\rho} = 10^{-3.9 \pm 0.4}$ g/cm^3), we have

$$\alpha \le 10^{-3,4 \pm 0,4} \text{ J/m}^2.$$

Comparing this estimate to the data of Table II, we see that this mechanism fails to explain the magnitude of the surface tension.

A mechanism that would lead to a larger surface tension is the penetration of free surface ends of the ball lightning through one another. It is necessary to incorporate the mechanism of restructuring,[35,36] in which weak bonds between elements of the structure are broken and replaced with stronger bonds. The average density near the surface is somewhat higher (but not by orders of magnitude) than inside the ball lightning. Hence a skin is formed on the surface of the ball lightning, which leads to surface tension. External conditions can also lead to a change in shape of the ball lightning,[2)] which is forbidden in the classical mechanism of surface tension.

We estimate the surface tension for this mechanism, using the aerogel model for the skeleton of the ball lightning. The surface tension is of order

$$\alpha \sim \eta N r_0 \xi;$$

where η is the fraction of the surface of a particle participating in the formation of bonds, N is the number density of particles in the structure, r_0 is the particle radius, and ξ is the penetration depth of elements of the structure through one another, which is of the order of the correlation length of the structure, i.e., the distance over which the fractal structure transforms into a homogeneous structure. We use the parameters of typical silica-aerogel with a density corresponding to Table I. We have $r_0 = 1.5$ nm, $D = 2.3$ (Refs. 38–40), and hence $\xi \sim 10$ μm and $N \sim 4 \cdot 10^{15}$ cm^{-3}. Assuming $\eta \sim 0.01$–0.1, we obtain $\alpha \sim 0.02$–0.2 J/m^2, which is not inconsistent with the data in Table II.

PROCESS OF RESTRUCTURING

Therefore restructuring is fundamental in the evolution of a system of fractal fibers. Since restructuring is a process leading to contraction of the structure, a system of fractal fibers is not a stationary state: it contracts and "ages." Evidently restructuring is typical of rarefied fractal structures. Strictly speaking, the model of restructuring of Refs. 35 and 36 applies to fractal aggregates.

As an example of this type, we describe an experimental study of the formation of fractal aggregates of gold in a solution of 7.5 nm particles.[41] A change in the density of the solution can result in a change in the charge on the gold particles and hence can be used to regulate the rate of formation of the fractal aggregate. The cluster-cluster aggregation (CCA) mechanism[42,43] takes place when the rate of the process is high (the time required to form an aggregate in the solution is less than 1 min). In this case small clusters combine into larger ones until fractal aggregates of the maximum size are formed. In this mechanism almost any contact between particles of the clusters leads to their combination and hence a relatively loose structure is formed with a fractal dimensionality of about 1.8.

When the aggregation rate is small (~ 1 day) the RLCA mechanism (cluster-cluster aggregation limited by diffusion)[44,45] takes place. In this case the contact of two particles of the clusters leads to their combination only with a small probability. The result is a denser structure with a fractal dimensionality of about 2.1.

Restructuring of aggregates formed in the CCA mechanism was observed in Ref. 41. These aggregates were formed relatively quickly (over a period of seconds), but they "aged" and transformed into RLCA clusters over an extended period of time (of the order of days). Hence there was a change in structure accompanying its contraction. Experiment shows that this restructuring process is typical of rarefied fractal structures.

PARAMETERS OF FRACTAL TANGLES

We consider some quantitative estimates for a fractal tangle in order to get a picture of a real system of this kind. In order that these estimates be relevant to a real object, we will assume that the parameters of the individual fractal fibers correspond to the experiment of Ref. 21, while the system of fractal fibers is characterized by the parameters of the average ball lightning. The density of an individual fractal fiber is $\rho_f = 0.01$–0.1 g/cm^3 (Ref. 21). Comparing this to the density of the average ball lightning $\bar{\rho} = 10^{-3.9 \pm 0.4}$ g/cm^3 (see Table I), we find that the fibers occupy a fraction $\bar{\rho}/\rho_f = 10^{-2.4 \pm 0.9}$ of the total volume. Hence the system is porous in two different senses. First, the fibers have a porous fractal structure; only about 1% of the volume occupied by a fiber contains actual material. Second, the fibers themselves occupy only a small fraction of the volume of a fractal tangle.

Letting R be the radius of a fiber, we determine the other geometrical parameters of the system. Let dl be the total length of the fibers inside an element of volume dV. Since the mass inside this element of space is equal to $\bar{\rho} dV = \pi R^2 dl \rho_f$, we have

$$\frac{dl}{dV} = \frac{\bar{\rho}}{\pi R^2 \rho_f}. \tag{4}$$

The individual fibers intersect one another and we assume that each fiber has many such intersections. We calculate the average distance between neighboring intersections of the fibers. We draw a line along a fiber and assume that it intersects another fiber of the structure at $x = 0$. Obviously the probability that it will not intersect a fiber at a distance x from this point is equal to $\exp(-x/\lambda)$, where λ is a parameter to be determined. We note that this parameter is analogous to the mean free path of a classical particle scattered by impenetrable walls. It follows from the above equations that

the probability of an intersection at a distance $h \ll \lambda$ from a given point is equal to h/λ. We take an element of area S of a plane perpendicular to the line and construct a volume element formed by this plane with height h. The total length of the fiber inside this volume is $l' = Sh\bar{\rho}/(\pi R^2 \rho_f)$ and its projection onto the plane is equal to $2Rl' \sin\theta$, where θ is the angle between the normal to the plane and the fiber. Averaging over angle, we have for the average projection of the fiber onto the plane

$$\int 2Rl' \sin\theta \mathrm{d}\cos\theta = \frac{\pi Rl'}{2}.$$

The probability of intersection of the line at a distance h from the next intersection is obviously

$$\frac{\pi Rl'}{2S} = \frac{h}{\lambda}.$$

Hence we obtain the average distance between neighboring fiber intersections

$$\lambda = \frac{2Sh}{\pi Rl'} = \frac{2\rho_f R}{\bar{\rho}}. \tag{5}$$

For the parameters of the system considered here ($R = 20$ μm) we have $\lambda = 10^{0.2 \pm 0.9}$ cm.

We consider a thermal explosion of the system, assuming that a randomly created source with high temperature propagates along its own fiber and then multiplies when the fiber intersects with other fibers. In this stage the number of thermal waves and hence the luminosity increases exponentially with time as $\exp(t/\tau)$, where $\tau = \lambda/u$ and u is the propagation velocity of the thermal wave. Putting $u = 30$–60 cm/sec (see Fig. 4), we obtain $\tau = 10^{-1.4 \pm 1.0}$ sec.

The duration of the thermal explosion is determined from the equation $\mathrm{d}l/\mathrm{d}t = -nu$, where l is the total length of the fibers in the system and $n = \exp(t/\tau)$ is the number of simultaneously propagating thermal waves. Assuming a single nucleus at the initial time, we obtain $t_{\exp} = \tau \ln(l/\lambda)$ for the duration of the thermal explosion. Since from (4) the total length of the fibers in the system is proportional to the volume, we find that the lifetime of the system depends on the occupied volume. For the parameters corresponding to average ball lightning we obtain $t_{\exp} = 10^{-0.2 \pm 1.4}$ sec. Note the unsteady nature of the thermal explosion in the system.

TANGLE–GLOBULE PHASE TRANSITION

The system of fractal fibers can be in a bound state and then it will preserve its shape. To analyze this bound state, it is convenient to exploit the analogy with a long self-intersecting polymer fiber. Bonds form at the points of self-intersection of the polymer fiber. A globule–tangle phase transition of the fiber occurs for a certain degree of interaction at the intersection points. In the globule state the system has a rigid skeleton and its shape does not change with time, whereas in the tangle state individual elements of the fiber can move freely with respect to one another.

Obviously the same picture exists in a system of fractal fibers (a fractal tangle) when each of the fibers has multiple intersections with other fibers. Then the theory of the tangle–globule transition in polymers[25-27] can be used to consider the fractal tangle state. The phase transition therefore occurs at a temperature of the order of the Flory temperature T_F determined by the condition $B(T_F) = 0$, where $B(T)$ is the second virial coefficient. We write this relation in the form

$$B(T_F) = \int \exp\left(-\frac{U_{12}}{T_F} - 1\right) \mathrm{d}\mathbf{r}_1 \mathrm{d}\mathbf{r}_2 = 0, \tag{6}$$

where $\mathbf{r}_1$ and $\mathbf{r}_2$ are the coordinates of atoms of the fiber, U_{12} is the interaction potential between atoms of different fibers, and T is the temperature. We estimate the Flory temperature T_F for a clump of fractal fibers. In this case $\mathbf{r}_1$ and $\mathbf{r}_2$ are the coordinates of atoms of fibers, which can form bonds with the atoms of another fiber. We will assume that each fiber of the rigid system is composed of particles and atoms and the high mobility of the particles inside the contact region is taken into account by assuming that bonds are established over the entire contact region. Hence if we project the points of contact of the fibers onto a plane in the contact region, we obtain a nearly continuous region whose size is of the order of the fiber radius. Hence the Flory temperature T_F satisfies the relation

$$R^2\lambda \sim \left(\exp\frac{D}{T_F}\right) R^2 a.$$

The left hand side of this relation corresponds to the region in the virial coefficient where repulsion is strong because of the presence of matter. The right hand side corresponds to the attraction between elements of the fiber, which leads to the formation of bonds. In this equation λ is the distance between the nearest points of contact of the fiber with other fibers, a is the range of the interactions between the molecules, and D is the binding energy per surface molecule.

We estimate the Flory temperature using the parameters of average ball lightning and assuming SiO_2 fractal fibers. We assume a close-packed structure with 12 nearest neighbors to each molecule. Then since $6D = \Delta H = 133 \pm 7$ kcal/mol (Ref. 46), $a = 3 \cdot 10^{-8}$ cm, $\lambda = 10^{0.2 \pm 0.9}$ cm, we obtain

$$T_F = 700 \pm 200 \text{ K}.$$

This estimate shows that a system of bound fractal fibers can form a rigid skeleton, but at a high enough temperature the rigidity of the system is lost and the system transforms into a shapeless mass of fractal fibers.

CONCLUSION

It follows from our analysis of a fractal tangle as a system of fractal fibers that the formation of this object is universal. When a weakly ionized atomic vapor formed by subjecting the surface of a condensed body to an energy flux expands in space, a fractal tangle can be formed if the vapor expands in a strong electric field. This phenomenon occurs for different materials, different gases in which the weakly ionized vapor expands, and different methods of treating the surface: electric, laser, or beam energy.

Typically the density of the object corresponds to a gas but it is a bound state of matter and so it can show the properties of liquids or solids. Because the system consists of nanometer particles, it has a large surface energy, since a significant fraction of its molecules are on the surfaces of particles. This energy is released when the structure contracts as a result of coagulation of the particles. The specific surface energy of these systems can be comparable to the specific chemical energy of gunpowder. In essence, any system composed of nanometer particles, such as aerogels and fractal aggregates, has this property. The distinguishing feature of

this object is that the energy is released as propagating thermal waves along individual fractal fibers.

Also the object is "delicate" in the sense that it is difficult to detect and it breaks up as it ages. In the aging process the particles do not coagulate, as in the contraction of the structure,[47] but rather the numbers of pores decrease. This irreversible process leads to an increase in the average density of the material in space. From the available information, it appears that the typical lifetime of a fractal tangle is of the order of days.

Hence a fractal tangle is a distinctive physical object with unusual properties which requires detailed study. One of the main problems is to develop methods of detecting the objects.

[1)] This was pointed out to the author by V. L. Bychkov.

[2)] We note that according to the collection of observations of Grigorjiev *et al.*,[37] out of 2013 observations of ball lightning its spherical shape was transformed into a ribbon shape in 25 cases and in 15 cases the ribbon shape transformed into a sphere.

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