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THE BREAKDOWN OF ATOMS AT HIGH PRESSURES

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Abstract

Thermodynamic evidence supports the experimental suggestion of a previous paper that at ordinary temperatures sufficiently high pressures are capable of breaking down the quantum structure of atoms, reducing matter to an electrical gas of electrons and protons. We may, therefore look for atomic dissociation under two sorts of conditions: high temperatures and comparatively low pressures, such as we have in the stellar atmospheres, and high pressures and comparatively low temperatures, which we may surmize we have in the interiors of stars, possibly in stars like the sun, and almost certainly in stars of the enormous density of the dark Sirius type. The possibility of two sorts of dissociation, together with the more rapid increase of pressure than density when the diameter of a star is reduced, offers the possibility of a critical condition determining whether a star is of the dark Sirius type or not.

IN THE Physical Review for January 1926 I called attention to a reversal in the behavior of certain properties of potassium (the atom of which has an abnormally loose structure) at high pressures and room temperature, which I suggested might indicate the initiation of an ultimate breakdown of the atom at much higher pressures and an approach to a gas of electrons and protons. Supporting this idea that a breakdown of the atoms is possible at high pressures, there is an argument from a theorem of Schottky's which I presented in the previous paper; furthermore we have the physical feeling that the quantum orbits to which the atom owes its structure ought not to be able to resist an indefinitely great force, and also the fact that there are stars of enormous densities. Nevertheless, the assumption of this sort of atomic disintegration involves certain apparent inconsistencies, for in the atmospheres of the stars we have direct spectroscopic evidence of atomic disintegration, as was first extensively shown by Saha, and simple thermodynamics shows that this decomposition *increases* with rising temperature and *decreases* with rising pressure. Since such decomposition at the high temperatures and greatly reduced pressures of the stellar atmospheres is only partial, it would appear at a first glance that there is no reason to expect any decomposition at all at ordinary temperatures and pressures of tens of thousands of atmospheres. It is the purpose of this note to present additional thermodynamic evidence suggesting that decomposition may nevertheless occur at high pressures and low temperatures, and to resolve the apparent inconsistency.

Let us examine the consequences of assuming that it is possible to apply sufficient pressure to a substance at room temperature to break the atoms down into a perfect gas of electrons and protons. Under such a pressure the thermal expansion must assume the value appropriate to a perfect gas, and the specific heat must also become very much larger than that of a normal solid, because each electron makes its full individual contribution to specific heat. Now thermal expansion and specific heat cannot vary independently, but there is a thermodynamic connection, namely:

$$(\partial C_p/\partial p)_\tau = -\tau(\partial^2 v/\partial \tau^2)_p$$

Hence if C_p is to increase with pressure, $(\partial^2 v/\partial \tau^2)_p$ must be negative, which is the reverse of its usual behavior, because the thermal expansion at constant pressure of normal substances increases with rising temperature instead of decreasing. Now since the thermal expansion of a gas is much higher than that of a normal solid, a higher thermal expansion at low temperatures means a closer approach to the perfect gas condition at low temperatures. This indicates therefore that if a solid is decomposed by high pressure and made to approach the behavior of a gas, the approach to this condition will be most rapid at low temperatures. My experiments on potassium were made at low temperature.

This state of affairs is also consistent with other thermodynamic evidence. In the atmospheres of the stars atomic decomposition decreases with rising pressure; here it increases. Now a homogeneous reaction is driven by pressure in such a direction as to decrease the volume. In the stellar atmospheres, therefore, the volume of the neutral atoms is less that that of the ionized atoms and the detached electrons; this is a consequence of the comparatively low pressures. At high pressures, on the other hand, simple calculation shows that the electrical gas has a smaller volume than that of the undissociated atoms from which it comes. In normal substances under high pressures it appears therefore that the quantum orbits act like skeleton frameworks *distending* the structure; if these frameworks are destroyed, the substance collapses. It was shown in the previous paper that at 300°K the pressure at which the volume of the electrical gas is equal to that of the neutral atoms is of the order of a few 10,000 atmospheres, which is certainly a negligible pressure compared with cosmic possibilities. As temperature increases, the dissociated volume gains relatively to the undissociated volume in consequence of the high thermal expansion of the gas, thus bearing out the evidence above that the approach to gaseous decomposition is closest at low temperature.

In the stellar atmospheres decomposition increases with rising temperature at constant pressure; under our conditions it decreases. This means that in the stellar atmospheres heat must be absorbed by the dissociation, whereas under our conditions heat is given out. The reason for this difference is evident. Under atmospheric conditions the volumes are so large that the electron must be removed to a great distance against the electrostatic forces of the core during decomposition. There is a compensating effect arising from setting free the kinetic energy of the electrons in the quantum orbits, but this is only half the electrostatic effect. Under our conditions however the volume is small, and the electrons on the average are no further away from the core after decomposition than before. The electrical effect vanishes, therefore, leaving the kinetic effect outstanding. Now the kinetic energy of the electrons in the quantum orbits is much higher than the equipartition temperature energy at ordinary temperatures, so that heat must be given out rather than absorbed when an atom decomposes at high pressures. (Has this been considered as a source of stellar energy?) It is also evident, since the kinetic energy of the electrical gas is higher at the higher temperature, that this heat of dissociation decreases with rising temperature, again demanding that decomposition be greater at lower temperatures than high. Further, there is another effect tending to accentuate the reversal of sign of the heat of dissociation at high pressures. After the first few 10,000 atmospheres the internal energy of a solid increases when pressure increases at constant temperature. This increase of internal energy is divided in the ratio of two to one between energy of position and increased kinetic energy of the electrons in their orbits. This latter part is set free during dissociation, so that the heat of dissociation under high pressures is greater by this amount than would be indicated by our argument above applied to normal atoms at atmospheric pressure.

All the lines of evidence converge, therefore, to indicate a pure pressure decomposition of atoms at high pressures, and this decomposition is favored by low temperature. We must then visualize the condition of matter over extreme ranges of pressure and temperature somewhat as follows. The pressure-temperature plane is crossed by a diagonal band rising from low pressures and temperatures to high pressures and temperatures, within which matter exists in the normal form of neutral undissociated atoms as we know them. To one side of this band is the region of high temperature and low pressure in which the atoms are dissociated into a gas of electrons and protons, and it is in this region that we find matter in the stellar atmospheres. On the other side of the band, at high pressures and low temperatures, we also have matter dissociated into an electrical gas. We now have to ask to which of these two regions the apparently perfectly gaseous *interiors* of the stars belong. If to the first, we have decomposition in spite of high pressure, if to the second, in spite of high temperature. It seems almost certain that stars of densities of

50,000, like the dark companion of Sirius, indicate the second region. If the density is of the order of magnitude of unity, and nevertheless the star acts like a perfect gas (as does our sun, according to Eddington), we may suspect the first region, but perhaps even under these conditions the second region is not impossible.

Perhaps the following calculation is worth recording as suggesting possible orders of magnitude. Imagine an atom of atomic number 40, with the negative electricity all concentrated in a uniform spherical shell of radius 1.5×10^{-8} cm. Due to the mutual repulsion of its parts this shell is exposed to a distending pressure of approximately 3×10^{14} dynes/cm^2. The positive nucleus exerts an inward pressure of twice this; the difference, or 3×10^{14} dynes/cm^2, is the effective distending pressure of the quantum structure of the atom preventing collapse. The pressure in the interior of the sun is of the order of ten times higher, so that possibly we may expect pressure dissociation in the sun, although it seems more likely that we have the first sort of dissociation.

As far as I know, no adequate physical difference has been suggested to account for some stars with densities of 1.5 and others with 50,000. In view of the comparatively small range of mass of the stars this seems to demand some explanation. The possibility of two regions of dissociation seems to offer a clue. If the mass of a star is concentrated in spheres of decreasing radius, the pressure rises faster than the density. Thus if the sun were concentrated in a small sphere of density 50,000 times the present density, the pressure would be nearly 2,000,000 times greater (in general pressure varies as (density)$^{4/3}$). This sort of thing suggests instability and critical conditions, with the possibility of some stars in the second state of dissociation. If, however, the sun should turn out to be in the second condition, then we may perhaps recognize the possibility of two different stable states in the second condition, not unlike the two amorphous phases of ordinary matter of van der Waals.

A complete description of the state of affairs involves many complicated considerations. It is evident that the atoms in a star are in varying degrees of dissociation; according to the nature of the atom perhaps some of these are in the first condition, while others may be in the second. We need a detailed mathematical treatment of the comparatively simple problem of the equation of state of matter dissociated into electrons and protons under very high pressures without quantum conditions; this would show how nearly our assumption is realized of perfect gas behavior.

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