The Inertia of Energy

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THE INERTIA OF ENERGY[1]

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RELATIVITY may stay or go; the quantum theory may quarrel with the undulatory theory until there is no more left of either of them than of the traditional Kilkenny cats; and the unscientific may scoff: "What are the latest conclusions of science? I have not seen the morning papers." Yet I think we may safely say that the twentieth century, young as it is, has made at least one permanent contribution of the first magnitude to physical science—the doctrine of the inertia of energy.

To call any concept of physics permanent in these iconoclastic days is perhaps unsafe; yet the case for the inertia of energy is a strong one. Radical though it may be, and subversive of established ideas, it comes nevertheless of an old and respected family. Because Einstein's name is connected with it, it is perhaps rather generally supposed that this doctrine is in some abstruse way a corollary of the theory of relativity and consequently to be regarded with suspicion by the conservative. Not so; nothing has a better right to the name classical. It traces its descent in direct line from Maxwell and Newton; its pedigree is unimpeachable; its arms display no bar sinister. If the theory of relativity also leads to this doctrine, so much the better for relativity; it gains strength rather than imparts it.

The eighteenth century, like all its predecessors, was materialistic in its attitude toward natural phenomena. The modern concept of energy was not recognized; forces of all kinds were regarded as properties of matter, just as gravitational force was regarded until Einstein declared it to be not a material property at all, but

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a space property. By the introduction of the concept of energy and its elevation to a rank coequal with matter the nineteenth century made a notable departure from this traditional materialism. At the close of the century the two concepts, matter and energy, divided the province of physical science equally between them.

This joint sovereignty presented to the philosophic onlooker several curious features. In the first place, it was a coalition uniting views as extreme as any in the history of human government, for matter is certainly ''material,'' and energy nothing if not immaterial. Moreover, matter had an established position with a pedigree of centuries behind it; it had been recognized ''always, everywhere and by all,'' while energy, when it first came into notice, had even been introduced as a state or condition of matter. Its enthronement as joint sovereign had come about by virtue of its executive ability, the power it had shown of correlating phenomena and reducing the hitherto independent and intractable to law and order. Similar ability was shown by Mexico's benevolent despot, President Diaz, when he enlisted the roving bandits as members of the rural police force. The conservative citizens of the domain of physics, while acknowledging the equal sovereignty of energy, always retained in their hearts a special feeling of respect for matter as the ultimate reality, the substance of things, whose existence permitted energy to be, and without which energy would be but an empty name.

This state of mind was rudely disturbed when Einstein announced that henceforth the tail was to wag the dog; that matter must be regarded merely as another aspect of that protean concept, energy; that there was a definite numerical equivalent relation between them. Just as 4.2×10^7 ergs of energy equal one calory of heat, so one gram of matter may disappear as such, giving rise to 9×10^{20} ergs of energy.

But how can matter disappear? What then becomes of the law of conservation of matter, established over a century ago by Lavoisier, and long regarded as a great and permanent contribution to science? And how can energy appear without a corresponding disappearance of energy elsewhere? What of the law of conservation of energy, which has, since its foundation, enjoyed an esteem equal to that accorded the law of conservation of matter?

The doctrine of inertia of energy declares unflinchingly that both laws are wrong; that matter may actually disappear as such and energy in equivalent quantity appear in its stead. In place of the two former laws we have one broader principle—the conservation of matter-energy.

But under what circumstances does matter disappear, and why has this strange fact never been shown by the many careful and ingenious experiments on gravitation carried out during the nineteenth century? The explanation lies in the very large coefficient in the relation between matter and energy, 9×10^{20}. Experiment is well-nigh hopeless before the twentieth power of ten. The coefficient for the mechanical equivalent of heat contains only the seventh power of ten, and this permits an experimental verification of the principle. This fact undoubtedly assisted the physicists of the mid-Victorian period in familiarizing themselves with the idea that work and heat were interconvertible—a concept as strange to the physicists of those days as the equivalence of matter and energy is to us of to-day. It is said that Poggendorff refused to publish Mayer's paper on the mechanical equivalent of heat. "Why," said he to the author, "if this be true, water could be warmed by shaking it!" To this Mayer for some time could find no reply. The answer came only when it was shown experimentally that such was indeed the case. There is no denying the difficulty of a concept as revolutionary as the annihilation of matter and the creation of energy; and unfortunately we can not verify the theoretical principle by experiment. This theory asserts that when a hot body cools off, emitting heat and light, it must lose a little of its mass. For example, a gram of water at 100° will have when cooled to zero a mass less than one gram by the mass-equivalent of the energy that has been radiated away. To calculate this we divide the 100 calories, or rather 4.2×10^9 ergs, by 9×10^{20}, obtaining about 5×10^{-12} gram. Now even when dealing with masses of the order of a kilogram it is not possible at present to detect a difference less than one part in a billion (10^9).

The most vigorous chemical reaction known is that of the union of oxygen and hydrogen. In the formation of 18 grams of water about 69,000 calories or 3×10^{12} ergs of energy are liberated. This, on division by 9×10^{20}, gives us for the decrease in mass 3×10^{-9} gram, about one part in six billion.

In the case of energy liberated by radioactive bodies experiment is, at first sight, not quite so hopeless. One gram of radium in transforming into radium D (the first considerable stop-over in the series) would liberate about 130 calories per hour. This transformation is very slow, the average life of a radium atom being 2,600 years, or about 2×10^7 hours. Hence the total energy liberated in the transformation of one gram of radium into radium D (and helium) will be about $130 \times 2 \times 10^7 \times 4.2 \times 10^7 = 1.1 \times 10^{17}$ ergs. Dividing by 9×10^{20} we obtain 1.2×10^{-4} gram, or about one part in 10,000.

But such an experiment is impracticable. Starting with a gram of radium, the total amount transformed in one year would be 0.4 mg, and the actual loss in weight (of radium and helium together) only 5×10^{-8} gram. And to ensure that there is no error introduced by leakage (helium in the form of alpha rays) the containing case of lead would have to be constructed with preposterously thick walls, reducing the proportional change of weight far below the detectable limit.

Passing to the astronomer's laboratory we obtain quantities which seem large enough indeed to measure. The total energy radiated by our sun per second is enormous. Converted into its mass equivalent it gives the rather surprising figure of 4 million tons per second. This is not so easy to detect as might appear, for so super-enormous is the sun's mass that he is good for this rate of expenditure for something like 10 million million years.

So it appears that our sun and all the other stars in the heavens are slowly dissolving into light. Strange and novel as this idea may appear, it is no new thing, for a strikingly similar doctrine was taught in the eighteenth century, based upon the then current materialistic corpuscular theory of light. The following quotation from Nicholson's ''Natural Philosophy'' (London: 1786) illustrates this point and incidentally shows to what heights of speculation men dared to go in those days.

> If the comets be habitable, they must be possessed by creatures very different from any we have been used to behold and consider. There may, however, be other uses for which it is conceivable that they may have been formed. The matter which composes their tails must fall in process of time to the sun or the nearest planet that may pass through it, where it may supply defects and answer purposes which our total ignorance of its properties scarcely allows us even to conjecture. In the sun it may serve to recruit the waste of matter that luminary may suffer by the constant emission of particles of light.

Perhaps the only distinction to be drawn between eighteenth and twentieth century ideas regarding the decay of the sun's mass is that the eighteenth century idea was thoroughly materialistic, while that of the twentieth century is just the opposite.

It is at once evident that the eighteenth century idea in this matter is properly to be described as Newtonian, for that great philosopher was one of the principal supporters of the corpuscular theory of light; but in what way are we justified in saying that the modern doctrine of the equivalence of matter and energy can be traced back to Newton and to Maxwell?

The principle of the inertia of energy was first announced by Einstein in 1905[2] as a consequence of the special theory of rela-

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[2] *Annalen der Physik,* Vol. 18, p. 639, 1905.

tivity. Very soon after[3] he showed that this principle could be deduced from a strictly classical basis. Consider a hollow cylinder with closed ends, containing a movable plug or piston. Suppose at first that this piston is in contact with the left end of the cylinder with a trace of some explosive between them. If this explosive be set off the piston will be driven to the right and the cylinder, by the reaction, to the left. This relative motion will continue until the piston strikes the right end of the cylinder.

To an outside observer, unaware of the presence of the piston within, it would appear that the cylinder, without the application of any outside force, shifted its center of mass (or inertia) slightly to the left, in defiance of classical mechanics. If he was convinced of the correctness of the usually received mechanical principles, he might be led to infer that a concealed mass on the inside of the cylinder had shifted its center of inertia to the right to an extent sufficient to equalize the motion of the cylinder, and the hidden mechanism of the trick would stand revealed to the eye of reason.

Einstein considers a similar cylinder without any piston, but with the left end a little warmer than the right. If a pulse of radiant energy leaves the left end and travels through the cylinder to the right end we have a state of affairs analogous to that of the moving piston. As shown by Maxwell, on strictly classical grounds, radiant energy possesses momentum and will exert a pressure upon a surface against which it strikes; and by Newton's third law of motion, it must exert an equal and opposite pressure upon the surface which it leaves. The effect of this moving piston of radiant energy will be therefore to shift the center of mass (inertia) of the cylinder to the left by an amount too small indeed to be experimentally verified, but which an acceptance of classical theory requires us to recognize. By the cooling of the left end of the cylinder and the warming of the right end a certain amount of energy has been transferred from one end to the other; and to preserve the classical doctrine of the unchangeable center of inertia of a conservative system we must assume the simultaneous transfer of a small inertia from one end to the other. Maxwell showed that radiant energy possessed momentum; to this Einstein added the possession of inertia. In order to preserve unchanged the laws of classical mechanics the inertia equivalent of the energy-piston must be 9×10^{20} ergs per gram. This coefficient is the square of the speed of travel of radiant energy and gets into the formula because the speed of travel of the energy-piston is a factor in determining the shift of the cylinder. Were this speed infinite the cylinder

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[3] *Annalen der Physik,* Vol. 20, p. 627, 1906.

would not have time to move at all before the impact on its far end stopped its motion; and the more slowly the energy travels the greater its inertia equivalent. The parallel to the material piston holds throughout.

Mass may be measured either by its inertia or its weight; in fact, inertia and weight (or gravitation) have always been regarded as the only two properties of matter sufficiently characteristic to serve as a basis for its definition: matter is that which possesses inertia and exhibits gravitation. It was the failure to show any ability to gravitate which brought the abandonment of Kelvin's ether-vortex atoms; inertia they had in plenty. Does energy possess weight as well as inertia?

We have seen that in the case of radioactive bodies there is a loss of energy which, in several thousand years, should cause a measurable change in inertia. There is no doubt that radioactive products of the necessary age lie ready to hand in the form of uranium and lead, the beginning and end of a chain of transformations which has required many thousand years for completion. So slowly does uranium break down that a portion of it may travel the long way to lead, while another portion still remains as uranium. If during these transformations the escaping energy carried off inertia without weight we might expect that uranium and lead would have equal weights but different inertias, and in consequence would not exhibit the same acceleration under the action of gravity. But this question of the proportionality of weight and inertia, or the variability of gravitation with the nature of the substance, has been subjected to very searching experimental tests, the most delicate of which are those carried out by Eötvös with his torsion balance.[4]

For most substances this investigator found that inertia and weight were proportional to an accuracy of one part in 200 million; for radium compounds, where only comparatively small quantities were available, the precision reached was about two parts in a million.

We may therefore safely conclude that energy possesses both of the characteristic attributes of matter, and that matter may be converted into energy with a definite numerical equivalent relation.

It is a poor rule that does not work both ways. If the union of oxygen and hydrogen to form water results in a slight diminution in the mass of the reacting substances, how will it be in the case of electrolysis of water? Will the resulting oxy-hydrogen gas weigh a trifle more than the water?

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[4] *Annalen der Physik,* Vol. 68, pp. 11–66, 1922.

Yes, we must admit this to be the case, though the magnitude of the change is too small for us to pick up experimentally. The increase in mass must measure the energy applied to dissociate the compound. This leads us to view in a new light our concept of potential energy, which ceases to be an imponderable, and becomes a definite weighable quantity.

The idea of matter turning into energy is of such a transcendental character as to cause dismay and confusion to those of us who learned our elementary physics before the discovery of X-rays. Can we form any mental picture which will be helpful?

I think that this is possible. Einstein's theory of gravitation supplies us with a mental picture of matter which lends itself excellently to illustrating the conversion of matter into energy.

Einstein's theory of gravitation stands apart from all other attempts to explain this mystifying phenomenon in that he begins by denying that there is any force of attraction between two gravitating bodies. His strategy is excellent; having denied the existence of such a force he does not have to set up machinery to account for it. He replaces action at a distance by action in contact, of a transcendental nature, perhaps, but one of which a fair analogy can be given. It is like the deflection of a moving object by a surface of constraint.

Imagine a level surface of still water of indefinite extent; this surface will be two-dimensional, having length and breadth, but no thickness. The surface being perfectly flat, the geometry of figures traced upon it will be Euclidean, that is to say, the sum of the angles of a triangle will be exactly 180°, and through a given point only one parallel can be drawn to a given straight line. But suppose the surface, instead of being flat, is spherical, like the surface of the ocean viewed on the large scale; the geometry of figures traced on such a surface will then differ importantly from that of figures on a flat surface. On a spherical surface we can not, of course, draw a straight line in the usual meaning of that term; but we can draw one after Euclid's definition: the shortest distance between two points; and, as every navigator knows, this will be an arc of a great circle. There is a name used in general for such a shortest line traced on a curved surface of any kind: it is called a geodesic line. Its actual shape will, of course, depend on the way the surface is curved and the direction in which the line is drawn. On a cylinder, for instance, a geodesic may be a straight line, an arc of a circle or some intermediate form, according as it is drawn parallel, perpendicular or oblique to the axis of the cylinder.

On our spherical surface the three angles of a triangle (constructed of geodesics) will exceed 180° by an amount proportional to the area of the triangle. And upon such a surface two arcs of great circles will always intersect each other if sufficiently produced; that is to say, through a given point no geodesic (or "straight") line can be drawn parallel to (that is, not meeting) a given geodesic. A surface possessing these geometrical properties is called a surface of positive curvature.

On such a water-surface a floating particle, if set in motion, and free from the action of all forces, frictional, attractional or otherwise, would travel by the shortest, "straightest" path it could find, obeying Newton's first law of motion with the added condition of being confined to the spherical surface; that is to say, on a curved surface, the natural path of a body moving under the action of no force is a geodesic.

Surfaces of negative curvature may be constructed, on which the geometry is just the opposite of that on a surface of positive curvature; for on such a negatively curved surface the three angles of a triangle sum up to less than 180°, and through a given point more than one geodesic can be drawn parallel to (*i.e.*, never meeting) a given geodesic. Examples of such surfaces are the stem of a wine glass, a saddle or a mountain pass. On such a surface the geodesic, from a Euclidean point of view, would be a curiously twisted line.

Returning now to our flat surface of water, let us render it non-Euclidean by curving it in still another fashion. By careful manipulation it is possible to lay upon the surface of the water a particle of a heavy body such as lead, or even gold, so that it will float. The only thing necessary is to avoid breaking through the surface. The particle then lies supported by the unbroken water surface bent into a cusp or depression. Here we have a surface, normally two dimensional, bent or depressed slightly in the direction of a third dimension in the vicinity of a particle of matter. If we examine the geometry of figures traced upon the curved portion of the water surface, we shall find it non-Euclidean, and of negative curvature. The geodesic of this part of the surface will be a curved line of some kind; but if continued well beyond the cusp in either direction the geodesic will soon be indistinguishable from an ordinary straight line, and the geometry of these distant portions of the surface will be Euclidean.

Suppose now a comparatively heavy particle thus floating and forming a rather deep and widely extended cusp. At a great distance, in a Euclidean region of the surface, suppose a much smaller and lighter particle, which hardly produces any cusp, moving freely along the surface in a direction that will carry it past the heavy particle at a short distance, well within the latter's cusp. The path of the moving particle, at first a straight line, will as it enters the cusp gradually assume the curved or geodesic form proper to the space in which it finds itself. Assuming no attractive force to exist between the particles, the moving particle will pass on and out of the cusp, its path again becoming straight; but on account of the brief twist to which it was subjected in passing through the cusp the final straight portion of the path will not in general be a continuation of the first straight portion. The particle will have suffered a permanent deflection.

An observer watching the motion of the particle through what we may call Euclidean-Newtonian spectacles, which do not show him the curvature of the water surface, will say: ''Yes, on passing the heavy particle the light particle seems to have suffered a force of attraction of some kind, and to have been deflected from its straight path.'' But let him replace these glasses by others of Einsteinian make, and he will say: ''No, I see now that there was no force of attraction at all. It was purely the inertia of the moving particle combined with the peculiar curvature of the surface which it had to traverse that produced the change in its path.''

In the later development of Einstein's theory there is to be found a tendency to say not that a particle of matter has a space-cusp surrounding it, but that the cusp itself constitutes what we call a material particle. On this view the equivalence of matter and energy follows easily. Matter is static, an initial distortion in ''space''; energy is kinetic, the spreading ripple into which the initial distortion is converted when whatever is holding it lets go. On this view there is little to choose between the old concept of an ether and Einstein's concept of space. If space can be bent it may be straightened, and if this process be repeated frequently enough the space may be said to vibrate. Endow Einstein's ''space'' with resiliency as well as deformability, and we have something which strangely resembles the old-fashioned ''ether.''

But what happens when energy is reconverted into matter, as we have seen must take place in the electrolysis of water, or in any process which involves an increase in the potential energy of the system? It is not inconceivable that if the amplitude of the energy waves reaches a certain intensity the medium which carries them, call it space, ether or what you will, may acquire a permanent or quasi-permanent distortion, like a body which has been strained beyond its elastic limit. Such a distortion may slowly straighten out again under the stimulus of passing waves, perhaps by discrete jumps, as the quantum theory demands, much as a pile of cannon balls may be conceived to disintegrate under the influence of a mild and continuous earthquake, one ball at a time being dislodged and rolling down. In particular, such an intensity might conceivably be reached if our space has a slight positive curvature, analogous to that of a sphere; for then radiation starting from any point must eventually converge to the opposite ''pole'' of the universe, where its intensity must be as great as at the starting point. It is a curious idea, this of matter distilling, so to speak, from one pole and condensing at the other, through the intermediate phase of radiant energy. It possesses at least this recommendation, that it holds out a way of escape from the intellectually intolerable position of having to suppose that the ultimate fate of radiant energy is to travel, like the Wandering Jew, onward for ever.

''Upon this supposition of a positive curvature,'' said Clifford, fifty years ago,[5] ''the whole of geometry is far more complete and interesting. . . . In fact, I do not mind confessing that I personally have often found relief from the dreary infinitudes of homaloidal space in the consoling hope that after all this other may be the true state of affairs.''

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[5] ''The Postulates of the Science of Space''; Lectures and Essays.