THERMODYNAMICS, ENERGY, MATTER, AND FORM

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Appendix: Conservation of Mass and of Energy

It is convenient, in discussing conservation both of mass and of energy, to consider how these notions arose.

Conservation of Mass

This notion belongs really to chemistry, and was established by experiments such as the following.

Suppose that a suitable vessel were divided, internally, into two compartments. A suitable reagent might be put into each compartment, the vessel sealed, and the whole weighed. The the reagents would be let mix, maybe by tipping the vessel. When the reaction had finished, the whole would be weighed again, and it would be found that the weight had not changed. In other words, it was conserved.

Conservation of Energy

It is sometimes said that energy is ability to do mechanical work. Here mechanical work is taken in the usual sense: the magnitude is given by the product of the force acting on something, and the distance which the thing moves while the force is acting.

However, the word "ability" is perhaps not entirely felicitous; also, such a definition may leave room for difficulties due to the limitations expressed in the second law of thermodynamics. It is suggested that it is better to say that the energy of an object or of a system in a given situation, state, position, etc., is equal to the work which was done, or might have been done, to get it into that state, etc..

If the state is one of motion, the work done, against inertia, in getting it into motion at a certain speed, is called the kinetic energy, as is well known. Whereas energy which an object can have although stationary is called potential. Such, for instance, is that associated with the work done in raising an object against gravity.

Suppose, then, than an object were held at some height above the ground. It would be said to have a certain potential energy: 1,000 foot-pounds, for instance, for a 100 pound object 10 feet above the ground. This figure could be converted into other units, as desired. The kinetic energy, in this situation, would be zero, since the object was at rest.

Now let the object be let fall. As it fell, the potential energy would decrease. But it would speed up its motion, so the kinetic energy would increase. And, both kinds having been expressed in consistent units, it would be found that the sum, potential and kinetic, remained constant at the original 1,000 foot-pounds. The sum might be called the total energy, and it remains constant: it is conserved.

Of course, the argument used here would apply only until the object struck the ground. Then it would be necessary to take heating, for instance, into account.

It could be said that there is nothing remarkable here in the conservation. For the things concerned, especially the kinetic energy, were set up so as to be conserved. As Ritz remarked, in another connection: " . . . *la conservation de l'energie n'est plus une loi, mais une convention.*"[8]

The utility comes in when it is found, by experiment, that the principle extends much more widely. It is found that a certain amount of mechanical work, wasted against friction, will always cause a certain amount of heat, expressed in calories, for instance. Conversely, a certain amount of heat used (if it can be used; the second law of thermodynamics comes in again) in a heat engine, causes a certain amount of mechanical work, done by the engine. So heat can be identified with energy, and conservation applies to that energy.

Likewise, mechanical work may be done by chemical, electrical, etc., actions, and vice versa; and it is found that there, too, there is a fixed relation between the amounts. So chemical, electrical, etc., energy may be identified; and it is found that conservation applies to these forms of energy too.

So the real reason why the conservation of energy is an important principle lies in its extremely wide range of applicability.

Examples Cited for Joint Conservation

It is often said that in nuclear reactions, for instance, conservation of mass and of energy do not apply separately, but only when both are considered jointly. Actually, as Warren has pointed out, there is nothing unique about a nuclear reaction in this respect.[9] The same effects would happen with a chemical reaction, although in that case there would probably be no hope of measuring them. But, in fact, (and Warren noted this, too) the whole notion needs investigation.

A typical reaction might be that in which uranium 235, when bombarded by neutrons, breaks up into lanthanum and bromine, and more neutrons. The fact that more neutrons come out than went in is what makes a chain reaction possible.

Suppose that one gram of uranium 235 were used. Ideally, 0.00429 gm. of neutrons would be needed to bring about the complete reaction. The result would be: 0.6295 gm. of lanthanum, 0.3611 of bromine, and 0.01287 of neutrons.

Thus for 1.00429 gm. of reagent put in, so to speak, only 1.0035, (rounded a bit) would come out. Apparently 0.0008 gm., approximately, disappeared.

This, as is well known, is identified with the energy produced by multiplying it by the square of the speed of light. Thus this says that 7.2×10^{17} ergs, about 20,000

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kilowatt-hours, of energy would be released, by the disintegration of the gram of uranium 235.

Notice, though, that the masses of the resulting materials were, presumably, determined when those results were at rest, or not moving very energetically. Suppose, now, that the reaction could be accomplished in a sufficiently strong vessel, one, moreover, which was well insulated thermally. Immediately after the reaction, the fragments, the lanthanum, etc., would be flying around at great speeds inside the vessel. And they would be heavier because of that motion, according to the theory of relativity. In fact, the amount by which each fragment would be heavier than if at rest would be given by its kinetic energy divided by the square of the speed of light. So the results altogether would be heavier by an amount equal to the total kinetic energy divided by the square of the speed of light. But the total kinetic energy is just the 7.2×10^{17} ergs mentioned above. And this amount, from what was said, is equal to the (apparent) loss of the 0.0008 gm. multiplied by the speed of light. So when this is taken into account, the mass in the vessel remains exactly what it was before the reaction: the mass was indeed conserved.

So, of course, was the energy. The 7.2×10^{17} ergs would be there, in the form of kinetic energy of the rapidly moving fragments. So it appears that mass and energy have been conserved separately. The 7.2×10^{17} ergs could, before the reaction, have been considered a sort of nuclear chemical energy of the uranium.

Of course, no insulation is perfect. Eventually, the vessel and its contents would cool off. From a microscopic viewpoint, the fragments from the reaction would slow down in their motion. In so doing, they would, according to the theory of relativity, become lighter. And indeed, eventually the contents of the vessel would be found to be lighter by the 0.0008 gm mentioned previously; and the 7.2×10^{17} ergs of energy would have radiated away. It might appear that the transformation of mass into energy was only delayed.

But the loss of energy, by radiation, (probably infrared), needs to be examined a little more closely. According to the present views, the radiation comes off in quanta, or photons. Associated with each photon is a certain amount of energy. There is also associated with it a certain amount of mass, just as if it were a material object; and the magnitude of the mass is given by that of the energy divided by the square of the speed of light. (Which number, in terms of centimeters and seconds, is 9×10^{20}.) So the mass of the radiation radiated by the experiment in cooling would be 7.2×10^{17} divided by 9×10^{20}, which gives 0.0008 gm.. So the mass, which was at first supposed to be missing, was neither destroyed nor converted into anything else. It was merely scattered around in radiation. So even in the long run mass and energy were separately conserved. Here it is necessary to consider the radiation to see that both are conserved, that is all.

An Analogy

The following analogy may be of some interest. Suppose that, to determine the heat of reaction (say) of some chemical reaction, one were to let it proceed in an insulated vessel. The idea would be to measure how much the temperature rose, and to calculate the heat of reaction by the usual methods of calorimetry. Suppose that the reaction was one in an aqueous solution. Suppose also that the vessel were open to the air at the top, although direct loss of heat might be prevented by shields and baffles.

Immediately after the reaction, it would be found that both mass and energy had been conserved. I.e., the mass would be the same as before; and the thermal energy, found by calorimetry, would be equal to the chemical energy represented by the reagents before the reaction. Such, of course, is the result expected in such cases.

A while later, however, things would be different. The contents of the vessel would have cooled somewhat; hence it might appear that energy had been lost somehow.

Moreover, it would be found that the contents of the vessel were now a little lighter.

Would one say, then, that in this case mass had been transformed into something else? Of course not. What happened was simply this. Because of the heating, some of the water evaporated. And in escaping as vapor, it took with it energy, in amount given by the latent heat of evaporation of the water. I.e., along with each gram of water which escaped as vapor, energy amounting to about 550 to 600 calories of heat escaped, as latent heat of vaporization. (The latent heat depends somewhat on the temperature, being about 540 calories per gm., at 100 °C, and somewhat more at lower temperatures.)

So here, too, mass and energy were separately conserved, but they came away together. Is the situation with the radiation not analogous? Only there the figure connecting mass and energy is not a latent heat (although perhaps it might be called one, by stretching the analogy a bit), but it is rather the square of the speed of light, as has been noted.

Conclusion

It is concluded, then, that even in nuclear reactions, mass is not converted into energy. Both are separately conserved, as in other cases. But they come off together in radiation, always a certain amount of mass along with a certain amount of energy.

A Caution

There has been some discussion, as to whether the relation between mass and velocity, used above, applies universally, or only for charged elementary particles. For something of the sort can be shown by electromagnetic theory to apply to charged particles, without any need to appeal to relativity.[10]

As for the present discussion, either the relation mentioned applies generally or it does not. If it does, the conclusions reached would seem to be valid. If not, then the problem disappears; there never was any reason to suppose that mass and energy were not conserved separately.

It might be remarked, also, that the relation between radiation and mass may at least be made plausible from

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