BIRTH AND DEATH OF ELEMENTARY PARTICLES

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Laws of Motion

The physical universe around and within us is constantly changing, yet there are permanent aspects to it. When the heavens change we recognize that much of the change is motion: the relative positions change. We see this on the terrestrial scale too. Automobiles and people move, birds fly and flags flutter in the wind. It is then the identity in change: the abstract entity that takes on different positions that is the subject of study of the physical discipline of mechanics. Modern physics traces to Galileo and Newton the precise formulation of the principles of mechanics. In Newton's hands the mathematical formulation became adequate to treat the motion of heavenly bodies, the tides in the sea and the falling apple as well as a host of other phenomena like the propagation of sound in a gas.

The equation of motion states

$$\frac{dp}{dt} = F$$

where the lefthand side of the equation is the rate of change of momentum of the particle while the righthand side is the force acting on the particle. When there are a number of particles the mutual interactions of the particles obey the principle of action and reaction and are equal and opposite.

The grand design of mechanics however seemed to be leaving out chemical changes as well as dissipative processes. In the first, the material itself undergoes a chemical change, a change in species so that we can no longer consider the changes to be due to motion. For simple dissipative processes like friction or viscosity one appealed to the existence of subunits, the "particles" which changed the nature of their collective motion into more disorderly motion and which manifested as a dissipative process. Here we may recognize the enigma of the Second Law of Thermodynamics, the propensity of disorder developing spontaneously and thus providing an arrow of time: from order to disorder.

A quantitative measure of the disorder is given by the thermodynamic quantity of "entropy". The second law of thermodynamics may be formulated as the tendency of entropy to increase with time while the first law states that the energy remains constant.

Chemical changes could be brought under the scheme of physics of permanent matter changing its configuration by invoking the atomic theory. The Greeks had the notion of atoms as indivisible permanent objects which constituted the observed matter. For each kind of matter there was a different kind of atom. But then we still do not have an understanding of chemical change. It is better to use the older *Vasisśesika* doctrine of atoms with qualities and the possibility of forming

two or three atom complexes. This theory was reinvented by Dalton in a quantitative form. The chemical compounds were various combinations of a few elementary atoms. In a chemical reaction the atoms may change associations, dissociate or recombine.

The burning of carbon to produce carbon dioxide is given by the chemical equation

$$C + O_2 \rightarrow CO_2,$$

while the combination of hydrogen and oxygen to form water is given by

$$2H_2 + O_2 \rightarrow 2H_2O.$$

Sodium combines with chlorine from hydrochloric acid to create sodium chloride and then release hydrogen:

$$2Na + 2HCl \rightarrow 2NaCl + H_2.$$

The precipitation of calcium carbonate from calcium chloride mixed with carbonic acid

$$HCO_3 + CaCl \rightarrow CaCO_3 + HCl.$$

In all these chemical equations we see that the atomic specificity is preserved but their associations are changed.

If we are willing to enlarge the notion of the configuration of a physical system to include the state of association between atoms we could consider the laws of chemical processes to be part of the equations of motion of physical systems. The atoms now become the elementary objects of the theoretical framework.

Emission of Light by Atoms: Decay of Excited Atoms

But atoms have other properties. They emit and absorb light. For example, the excited atom of an hydrogen atom deexcites with the emission of a light quantum γ.

$$A^* \rightarrow A + \gamma$$

and equally well excitation by absorption of light:

$$A + \gamma \rightarrow A^*.$$

The states of the system thus include the vacuum (no particles), atom, atom + one light quantum, atom + two light quanta etc. Since the light wave that is emitted or absorbed has a wavelength several hundred times the size of the atom the light is not inside the atom after it is absorbed or before it is emitted. Instead we do have a changed state of the atom, and excited state with more energy than the ground state of the atom. The absorption of light by atoms is therefore of a different kind of process from a chemical change where the atoms remain intact, but only change their associations. But many mechanical attributes are preserved under the transitions: the energy, the momentum and the angular momentum. What is preserved in

the transition are not the constituents but only such attributes. If we want to include these transitions also in our enlarged framework of "motion", we must consider the groundstate atom *plus* light on the one hand and the excited atom on the other as both states of a single system. This single system is not an atom, but a more abstract object which have these different kinds of states.

Birth and Death of Particles

In the search for deeper and deeper levels of matter we do come across a large number of particles like pions, nucleons and strange particles which also undergo such dramatic changes. For example nucleons are of two kinds, the positively charged "protons" and the electrically neutral "neutron". The pions come in three varieties, the positive, the neutral and the negative pions. In studying their reactions we can have processes like proton plus negative pion go to neutron plus neutral pion.

$$\begin{aligned} p + \pi^- &\rightarrow n + \pi^0 \\ p + \pi^+ &\rightarrow p + \pi^0 + \pi^+ \\ p + \pi^- &\rightarrow p + \pi^0 + \pi^- \end{aligned}$$

It is useful and advantageous to consider both neutron and proton as different states of the "nucleon"; to consider the three kinds of pions as different states of the "pion".

In Newton's mechanics the equations of motion described the rates of change of position of a particle and its velocity. The object of discussion is an abstract "particle" which may take on one position and velocity or the other. The particle with the attributes of position and velocity is the concrete object, but the framework discusses the abstract object. When we come to modern particle physics we carry the level of abstraction much further to associate a family of particles as the concrete realization of an abstract particle.

Decay as Change of State

Already at the level of emission and absorption of light by atoms we see an asymmetry: an excited atom can spontaneously emit a quantum of light and go to the ground state. The excited atom "decays". Decay is a change of state: a single object is transmuted into two or more particles. This is a spontaneous transformation. The reverse transformation of recombination of the decay product can be induced under suitable conditions, thus recreating the decaying entity. Decay and creation are two aspects of the same process. New objects appear when old objects disappear.

This process can be quantified and described in a formalism where both the old and the new states enter on an equal footing. The aim of the theoretical framework would be to calculate the rate of transition into the various possible decay products.

In the realm of high energy physics decaying particles dominate the scene. There are only a few particles: the proton, the light quantum, the electron and the neutrino, which are stable. All the others decay with a time scale from a few minutes for the neutron to a millionth of a millionth second or even shorter at the other end.

The neutron decays into a proton, electron and neutrino by a weak interaction:

$$n \rightarrow p + e^- + \bar{\nu}$$

while the pion and the muon have decays:

$$\begin{aligned} \pi^+ &\rightarrow \mu^+ + \nu_\mu \\ \pi^0 &\rightarrow \gamma + \nu \\ \mu^+ &\rightarrow e^+ + \nu + \bar{\nu}_\mu \end{aligned}$$

but not all reactions take place:

$$\mu^+ \not\rightarrow e^+ + \gamma.$$

The lifetime, which is the time it takes for the survival probability for the particle, is approximately one third.

The laws of decay are statistical. Given a collection of identical unstable particles within a given time interval some of them would decay and some would not decay. Individual decays cannot be predicted but the probability that any one particle will decay can be calculated. The method follows the application of quantum mechanics to the spontaneous alpha radioactive decays of atomic nuclei and the emission of light by excited atoms. This method gives a quantitative understanding of various decay processes and the underlying laws governing them.

Quantum Theory of Decay

Quantum theory is a mathematical model of physical processes which describes the amplitudes for various processes. These amplitudes obey equations of motion which enable us to compute them as functions of time. The growth of the amplitude for the decay products and the decline of the amplitude for the decaying object take place gradually very much like a rotating vector has one of its components increase and another decrease or a polaroid photograph gradually manifests. In fact the mathematical theory envisages an abstract vector in an infinite dimensional space of states gradually evolving.

Since the decay is a physical process it is also subject to the principal of relativity. So the apparent law changes somewhat when we go to a moving frame. In fact, a moving unstable particle decays at a slower rate than the same particle at rest; and the ratio by which it gets changed is a computable universal function of the velocity with which the particle moves.

If the lifetime at rest is τ_0, the lifetime of a particle moving with the velocity v is τ related to τ_0 by the formula:

$$\tau = (1 - (\frac{v^2}{c^2}))^{-\frac{1}{2}}\tau_0$$

where c is the velocity of light. Moving particles live longer.

It also follows that when the quantum theory is strictly applied, very frequent observations on the decaying particle can inhibit its decay. This is called the Zeno effect and has been verified by

experiments in atomic physics. There are other consequences of the strict application of quantum theory to the decay amplitude. The amplitude is an analytic function of time, stemming from the existence of a lowest energy state for a generic system, which in turn is in accordance with the second law of thermodynamics. This has the further consequence that for very long times the survival amplitude no longer dies down exponentially with time but becomes only as an inverse power of time.

Birth of Particles

The possibility that particles can decay is compensated for by the possibility that such unstable particles can be created. The light quantum is born at the decay of the excited atom. The pions are born in high energy nuclear collisions and subsequently decay. The charge pions decay into muons and neutrinos, and the muons decay into an electron and neutrinos. The more exotic shortlived particles of high energy physics are born in extremely high energy collisions between particles in a collider and live for a very short time and then decay into other particles. It is in the nature of the principles of quantum theory that if the particles can decay they can be created and vice versa. The more interacting the particle, birth and death are all the more inevitable for the particle: and hence the study of birth and death of the particles is a good way to study its interaction with other particles.

Role of Birth and Death in Nucleogenesis

The processes of birth and death of particles play a very important role in the observed processes. The spontaneous emission and induced absorption of light by atoms is responsible for bodies to glow as their temperatures rise; when a body is properly isolated the light in its vicinity per unit volume rises as the fourth power of its absolute temperature independent of the specific nature of the material. But this equilibrium state is brought about by the decay of excited atoms and the birth of the excitations by interaction with the light. X-rays are produced by high energy electrons suddenly decelerating and emitting short wavelength "light". When primordial matter undergoes nucleosynthesis, the higher atomic number elements are brought about by capture and radioactive decay in collusion.

Our understanding of the forces between particles is in terms of "virtual particle exchange" between them. Nucleons exchange pions or gluons between them; these virtual particles emerge from one particle and merge into the other. This birth and death of the exchanged quantum then serves to produce a force between the source and the sink. This idea has been so fruitful that we tend to view all forces between particles as due to such processes.

Cosmology and the Laws of Interaction

In all these stages we have acted as if the properties of the particle which is born and which dies and its interaction with the other particles are fixed once and for all. Modern cosmology proposes extreme conditions of energy density and temperature in early stages of the universe and even at the present time in the interior of a very dense heavenly object. In such situations the properties of the particles may change. In particular massive particles could become massless and the interactions they mediate may become stronger. This interface between cosmology and

particle physics is an extremely fertile field for new results and possible clues to the nature of matter itself.

Concluding Remarks

In summary we may say that a natural development of physics is to go beyond particles as immutable to particles undergoing birth and death of production and decay. In this context we must consider a substratum of which the presence of the particle and the absence of the particle are merely distinct states of this substratum. This substratum is the quantized field. We may need states of not one but many particles to describe spontaneous decay. The laws of birth and death derived from quantum mechanical principles involving transition amplitudes is inherently statistical.

The need to go beyond the obvious to find the substratum reminds me of the verse from Ramayana:

rāmam daśaratham viddhi
māṁ vidhi janakātmajāṁ.

(When one transcends limitations of perception, time is recognized as a chariot; but one whose perception is limited cognizes progenitor and offspring.)

Birth and death of elementary particles is an interplay of the harmonious evolution of the physical state and of the incompatible observational criteria we put on. It is a challenge to us to proceed beyond habitual perception of the superficial and look for a deeper structure.