If now we compare this number to the total rest energy of the universe, Mc^2, lo and behold, we get the amazing result that $GM^2/R = Mc^2$, so that the total energy of the universe is *zero*. Actually, we don't know the density nor that radius well enough to claim equality, but the fact that these two numbers should be of the same magnitude is a truly amazing coincidence. It is exciting to think that it costs *nothing* to create a new particle, since we can create it at the center of the universe where it will have a negative gravitational energy equal to Mc^2.

In these estimates, it is the density of the universe that is the hardest to determine. We can see stars and galaxies, sure enough, but we have no clear idea of how many black stars there are, stars which have burned out. Neither do we know the density of intergalactic gas. We have some idea of the density of sodium in the space between galaxies, obtained by measuring the absorption of the D lines as they come from distant stars. But sodium is possibly a very tiny fraction of the total, and we would need to know the hydrogen density. By studying the motion of spiral arms of galaxies, and of globular clusters, it appears that galaxies have in their center a lump of dark mass. All of this fragmentary evidence does not allow us to get any reliable estimate of the average density of the universe. Eddington, for his estimates in the twenties, used the value 1 hydrogen atom per cm^3, for galaxies. The radio astronomers who have recently studied the galaxy in "hydrogen light" arrive at a value only slightly smaller, say 0.7 hydrogen atoms/cm^3. There is no evidence for the density of intergallactic material; the cosmologists have guessed at values some 10^5 times smaller, 10 hydrogen atoms per cubic meter. With this estimate, we get the exciting result that the total energy of the universe is zero. Why this should be so is one of the great mysteries—and therefore one of the important questions of physics. After all, what would be the use of studying physics if the mysteries were not the most important things to investigate?

All of these speculations on possible connections between the size of the universe, the number of particles, and gravitation, are not original but have been made in the past by many other people. These speculators are generally of one of two types, either very serious mathematical players who construct mathematical cosmological models, or rather joking types who point out amusing numerical curiosities with a wistful hope that it might all make sense some day.

1.3 QUANTUM EFFECTS IN GRAVITATION

In the next few lectures we shall start to construct a quantum theory of gravitation. It might be well for us to keep in mind whether there would be any observable effects of such a theory. Let us first consider the gravitation as a perturbation on the hydrogen atoms. Evidently, an extra

attraction between the electron and proton produces a small change in the energy of bound hydrogen; we can calculate this energy change from perturbation theory and get a value, ϵ. Now, the time dependent wave function of a hydrogen atom goes as $\psi = \exp(-iEt)$, with E of such a size that the frequency is something like 10^{16} cycles per second. Now, in order to observe any effects due to ϵ, we should have to wait for a time until the true wave function should differ from the unperturbed wave function by something like 2π in phase. But the magnitude of ϵ is so small that the phase difference would be only 43 seconds (of phase) in a time equal to 100 times the age of the universe T. So gravitational effects in atoms are unobservable.

Let us consider another possibility, an atom held together by gravity alone. For example, we might have two neutrons in a bound state. When we calculate the Bohr radius of such an atom, we find that it would be 10^8 light years, and that the atomic binding energy would be 10^{-70} Rydbergs. There is then little hope of ever observing gravitational effects on systems which are simple enough to be calculable in quantum mechanics.

Another prediction of the quantum theory of gravitation would be that the force would be mediated by the virtual exchange of some particle, which is usually called the graviton. We might therefore expect that under certain circumstances we might see some gravitons, as we have been able to observe photons. But let us recall that even though light has been observed very early in man's history (Adam did it) it was not until 1898 that electromagnetic waves were produced with conscious knowledge of their field nature, and that the quantum aspects of these waves were not observed until even later. We observe gravity, in that we know we are pulled to the earth, but classical gravitational waves have not as yet been observed; this is not inconsistent with what we expect—gravitation is so weak that no experiment that we could perform today would be anywhere near sensitive enough to measure gravitational radiation waves, at least, those which are expected to exist from the strongest sources that we might consider, such as rapidly rotating double stars. And the quantum aspect of gravitational waves is a million times further removed from detectability; there is apparently no hope of ever observing a graviton.

1.4 ON THE PHILOSOPHICAL PROBLEMS IN QUANTIZING MACROSCOPIC OBJECTS

The extreme weakness of quantum gravitational effects now poses some philosophical problems; maybe nature is trying to tell us something new here, maybe we should not try to quantize gravity. Is it possible perhaps that we should not insist on a uniformity of nature that would make everything quantized? Is it possible that gravity is not quantized and all the rest of the world is? There are some arguments that have been made in

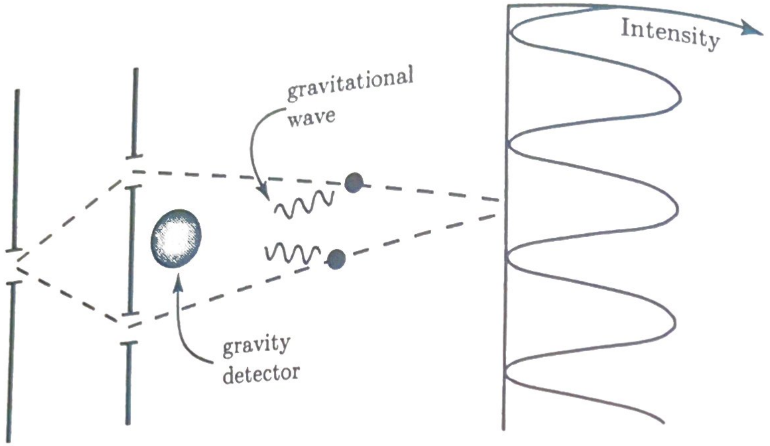

Figure 1.2

the past that the world cannot be one-half quantum and one-half classical. Now the postulate that defines quantum mechanical behavior is that there is an amplitude for different processes. It cannot then be that a particle which is described by an amplitude, such as an electron, has an interaction which is not described by an amplitude but by a probability. We consider a two-slit diffraction experiment, and insert a gravity detector, which may be assumed classical, which can in principle tell which slit the electron passed as illustrated in Figure 1.2. Let us imagine that the detector has not yet received a signal telling it which slit the electron passed; the position of the electron is described by an amplitude, half of which went through the upper slit, and half of which went through the lower slit. If the gravity interacts through a field, it follows that the gravity field must have an amplitude also; half of which corresponds to the gravity field of an electron which went through either slit. But this is precisely the characteristic of a quantum field, that it should be described by an amplitude rather than a probability! Thus it seems that it should be impossible to destroy the quantum nature of fields.

In spite of these arguments, we would like to keep an open mind. It is still possible that quantum theory does not absolutely guarantee that gravity *has* to be quantized. I don't want to be misunderstood here—by an open mind I do not mean an empty mind—I mean that perhaps if we consider alternative theories which do not seem *a priori* justified, and we calculate what things would be like if such a theory were true, we might all of a sudden discover that's the way it really is! We would never make this discovery with the attitude that "of course one must always entertain the possibility of doubt," but act and calculate with one prejudice only. In this spirit, I would like to suggest that it is possible that quantum mechanics fails at large distances and for large objects. Now, mind you, I do not say that I think that quantum mechanics *does* fail at large distances, I only say that it is not inconsistent with what we do know. If this failure of quantum

mechanics is connected with gravity, we might speculatively expect this to happen for masses such that $GM^2/\hbar c = 1$, of M near 10^{-5} grams, which corresponds to some 10^{18} particles. Now quantum mechanics gives silly answers for objects of this size; if we calculate the probability that a grain of sand should jump over a wall, we get answers like $10^{-260,000}$, which are ridiculous. We must therefore not neglect to consider that it is possible for quantum mechanics to be wrong on a large scale, to fail for objects of ordinary size. In this connection we might discuss how the theory of observation and measurement creates some problems. Let us for example talk about Schrödinger's cat paradox. It is not a real paradox, in the sense that there are two possible answers which can be arrived at by proper logic—it is a means of pointing out a philosophical difficulty in quantum mechanics, and each physicist must decide which side he prefers.

We imagine that in a closed box into which we cannot observe, we have placed a live cat and a loaded shotgun; the cat is confined so that if the shotgun goes off it dies. Now the shotgun is triggered by a Geiger counter, which counts particles from a radioactive source; let us suppose that the source is such that we expect one count per hour. The question is, what is the probability that the cat is alive one hour after we have closed the box?

The answer from quantum mechanics is quite easy; there are two possible final states that we consider, the amplitude is

$$\text{Amplitude} = \frac{1}{\sqrt{2}}\psi(\text{cat alive}) + \frac{1}{\sqrt{2}}\psi(\text{cat dead}).$$

When we think about this answer, we have the feeling that the cat does not see things in the same way; he does not feel that *he* is $1/\sqrt{2}$ alive and $1/\sqrt{2}$ dead, but one or the other. So that what may properly be described by an amplitude to an external observer, is not necessarily well described by a similar amplitude when the observer is part of the amplitude. Thus the external observer of the usual quantum mechanics is in a peculiar position. In order to find out whether the cat is alive or dead, he makes a little hole in the box and looks; it is only after he has made his measurement that the system is in a well-defined final state; but clearly, from the point of view of the internal observer, the results of this measurement by the external observer are determined by a probability, not an amplitude. Thus we see that in the traditional description of quantum mechanics we have a built-in difference between a description including an external observer, and a description without observation.

This kind of a paradox crops up each time that we consider the amplification of an atomic event so that we recognize how it affects the whole universe. The traditional description of the total quantum mechanics of the world by a complete Monster Wavefunction (which includes all observers) obeying a Schrödinger equation

$$i\frac{\partial\Psi}{\partial t} = \mathbf{H}\Psi$$

implies an incredibly complex infinity of amplitudes. If I am gambling in Las Vegas, and am about to put some money into number twenty-two at roulette, and the girl next to me spills her drink because she sees someone she knows, so that I stop before betting, and twenty-two comes up, I can see that the whole course of the universe for me has hung on the fact that some little photon hit the nerve ends of her retina. Thus the whole universe bifurcates at each atomic event. Now some people who insist on taking all quantum mechanics to the letter are satisfied with such a picture; since there is no outside observer for a wavefunction describing the whole universe, they maintain that the proper description of the world includes all the amplitudes that thus bifurcate from each atomic event. But nevertheless, we who are part of such a universe know which way the world has bifurcated for us, so that we can follow the track of our past. Now, the philosophical question before us is, when we make an observation of our track in the past, does the result of our observation become real in the same sense that the final state would be defined if an outside observer were to make the observation? This is all very confusing, especially when we consider that even though we may consistently consider ourselves always to be the outside observer when we look at the rest of the world, the rest of the world is at the same time observing us, and that often we agree on what we see in each other. Does this then mean that my observations become real only when I observe an observer observing something as it happens? This is a horrible viewpoint. Do you seriously entertain the thought that without the observer there is no reality? Which observer? Any observer? Is a fly an observer? Is a star an observer? Was there no reality in the universe before 10^9 B.C. when life began? Or are *you* the observer? Then there is no reality to the world after you are dead? I know a number of otherwise respectable physicists who have bought life insurance. By what philosophy will the universe without man be understood?

In order to make some sense here, we must keep an open mind about the possibility that for sufficiently complex processes, amplitudes become probabilities. The fact that it is amplitudes that are being added could be detectable only by processes which detect phase differences, and interferences. Now the phase relations for very complicated objects could be enormously complex, so that one would observe an interference only if the phases of all parts of a complicated object were to evolve in a very, very precise fashion. If there were some mechanism by which the phase evolution had a little bit of smearing in it, so it was not absolutely precise, then our amplitudes would become probabilities for very complex objects. But surely, if the phases did have this built-in smearing, there might be some consequences to be associated with this smearing. If one such consequence were to be the existence of gravitation itself, then there would be no quantum theory of gravitation, which would be a terrifying idea for the rest of these lectures.

These are very wild speculations, and it would be little profit to keep discussing them; we should always keep in mind the possibility that quantum mechanics may fail, since it has certain difficulties with the philosophical prejudices that we have about measurement and observation.

1.5 GRAVITATION AS A CONSEQUENCE OF OTHER FIELDS

Let us return to a construction of a theory of gravitation, as our friends the Venutians might go about it. In general we expect that there would be two schools of thought about what to do with the new phenomenon. These are:

1. That gravitation is a new field, number 31.
2. That gravitation is a consequence of something that we already know, but that we have not calculated correctly.

We shall take up the second point of view for a little while, to see whether it has any possibilities. The fact of a universal attraction might remind us of the situation in molecular physics; we know that all molecules attract one another by a force which at long distances goes like $1/r^6$. This we understand in terms of dipole moments which are induced by fluctuations in the charge distributions of molecules. That this is universal is well known from the fact that *all* substances may be made to condense by cooling them sufficiently. Well, one possibility is that gravitation may be some attraction due to similar fluctuations in something, we do not know just what, perhaps having to do with charge.

If we worry about the fact that quantum mechanics fails in that very often infinities crop up in summing over all states, we might look for a connection between gravity, the size of the universe, and this failure of quantum mechanics. The infinities always occur when we sum over denominators $\sum_n 1/(E - E_n)$. Now, it is conceivable that if we were to consider that whole universe, we would not be summing over virtual states in the usual fashion, but that we should sum only over those virtual states for which we could borrow enough energy from the rest of the universe. A theory that would not allow virtual states if the energy violation were larger than the total energy of the universe would be slightly different from the usual one, which assumes this total energy is essentially infinite.