Quantum Tunneling

One example may clarify how the "new" and "old" mechanics differ, namely the way George Gamow in 1928 explained alpha-radioactivity. As described in section #S-7 of "Stargazers" and in more detail in section #S-8 there, the atomic nucleus experiences opposing forces: the strong nuclear force holding its particles together must overcome the electric repulsion between positive protons sharing the nucleus, which tries to break it up. The nuclear force wins out at short distances, which is why nuclei exist at all, but since it falls off rapidly with distance, far away the electric repulsion dominates.

Consider a proton inside the nucleus. If something moves it a short distance away, the nuclear force pulls it right back, but if it somehow got far enough, the electric repulsion would push it away, never to return. An example is nuclear fission, possible in heavy nuclei of plutonium or uranium-235. Their nucleus contains so many protons trying to push it apart (with their electric repulsion), that adding just a modest amount energy--released when an extra neutron is allowed to be pulled into the nucleus--makes the entire nucleus break up into two positively charged chunks. These get separated far enough that they never come back again--instead, electric repulsion pushes them apart even more and releases a great amount of energy.

Such nuclei, and heavy nuclei close to them in mass, are all on the brink of instability, and even without externally added energy, they find a way to get rid of some of their disruptive positive charge. The forces on protons inside these nuclei resemble those on a bunch of marbles inside the "crater" of a volcano-shaped surface--smooth sloping sides outside, but a moderately deep crater on top (drawing). The outline of the "mountain" can be viewed as representing the total force on protons in a nucleus. Inside the crater the attraction predominates, holding the protons together, while outside it the repulsion predominates, pushing them away.

In the analogy of marbles inside a crater, if a marble could somehow get to the outside--say by carving a tunnel through the wall of the crater--this repulsion would make it roll away and it would release energy.

Newtonian mechanics provides no such tunnels: the proton is imprisoned inside the crater for all eternity. According to quantum mechanics, however, the proton's location is determined by a spread-out wave function. That wave is highest inside the "crater" of the nucleus, and if the proton materializes there, it stays trapped ("if" here just helps one imagine the process; in quantum physics, if a process--like this materialization--is unobservable, it is the same as saying it does not exist). The fringes of the wave, however, extend further out, and it always has a finite (though very small) strength beyond the crater, giving a finite chance for the proton to materialize on the outside and escape. It is as if quantum laws gave it a tiny chance to "tunnel" through the barrier to the slope outside.

Gamov (as well as Ronald W. Gurney, around that same time) proposed that such "quantum tunneling" did exist, and was the main cause of radioactivity in heavy elements. There was one modification: the most likely transition, requiring the least energy, was not the escape of a single proton, but of a helium nucleus--two protons and two neutrons bound together by the nuclear force, a very strong bond. Such
Energetic nuclei are known as "alpha particles" (α particles), a name introduced in the early days of research on radioactivity, after physicists found that some positively charged particles were emitted, but could not yet tell what they were.

It may take millions and even billions of years before an α particle manages to "tunnel" its way out, and such radioactivity is the source of much of the internal heating of the Earth (radioactive potassium also contributes). Other types of radioactivity in heavy elements often represent the re-adjustment of nuclei left unstable by α-particle emission, sometimes leading to the emission of additional α-particles.

Sooner or later, the α particle captures two electrons from its environment and becomes an ordinary atom of helium (and meanwhile the nucleus, having undergone α-emission, has reduced its positive charge and therefore must give up two electrons, preserving the electrical neutrality of matter as a whole). Nearly all of the helium found trapped in rocks or extracted from natural gas is in fact contributed by this process (we can tell this because it is deficient in a lighter form of helium, observed on the Sun and elsewhere). Thus the gas used to fill airships and balloons is almost entirely the product of radioactivity!

Conclusion

The study of gamma rays from radioactive nuclei suggests that nuclei, too, have energy levels. However, using quantum mechanics to calculate such levels is much harder here, because nuclear particles are much more tightly bound, and nuclear forces are more complicated. Still, at least in some approximation, quantum theory can be applied to many nuclear processes (as it was to α-radioactivity, above), also to fast collisions of particles and to nuclear fission.

Space physics deals with big objects--stars, plasmas, planets etc.--far above the sub-microscopic scale of most quantum processes. However, it still needs quantum mechanics, to account for atomic-scale processes involved in the behavior of such large objects. The energy of stars such as the Sun is mostly due to reactions between atomic nuclei, and most elements we know (excluding only the lightest ones) are apparently rapidly "cooked" in the catastrophic collapse of big stars, creating what is known as a "supernova." Indeed the matter of the original "big bang" seems to have lacked all the familiar elements from carbon and up, on which life (among other things) depends.

Other quantum processes determine

- the physics of the Sun's atmosphere
- the loss of trapped plasma produced in a magnetic storm (by "charge-exchange" collisions with the cloud of hydrogen atoms surrounding Earth)
- the chemistry of the upper atmosphere and ionosphere
- the colors produced by the polar aurora

and many other phenomena. The universe cannot be understood without quantum theory.
Almost all the preceding describes work done between 1900 and 1960. Much more was added since then, in particular about the way elementary particles interact in high-energy collisions (with application to the early universe, after the Big Bang). "Elementary particles" here means protons, neutrons and electrons, as well as unstable products of energetic nuclear collisions. That however lies far beyond the level of this overview, also it is quite beyond the writer's own expertise, two good reasons to stop here.