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Nuclear Structure And Modern Research

By creating and studying in our laboratories the nuclear reactions and excitations that exist in quantity in the stars we are advancing our understanding of fundamental stellar processes and acquiring the benefits of nuclear technology.

by Victor F. Weisskopf

In the exploration of the structure of matter in the last decades we have witnessed three steps: first, the exploration of the electron shells of the atom; second, investigation of the structure of the nucleus; and third, the beginning of the exploration of the structure of the nucleon, the constituent of the nucleus.

Atom. The first step, beginning at the start of the century, has given us insight into a large body of phenomena. It enabled us to understand and describe the dynamics of electrons in the atom; it showed that all the tremendously heterogeneous and varied phenomena of the atomic world are based on the effects of the electrostatic attraction between the nucleus and the electrons. The interesting interplay of that attraction with the quantum mechanical properties of electrons gives rise to all that we usually see around us: atomic events, chemical events, the aggregation of atoms into solids, liquids, gases, plasmas, molecules and at the end, very probably, the world of living beings.

If one looks back at this achievement that, as we all know, was established in the 1920's, one may apply in a slight variation of the famous words of Churchill: Never have so few explained so much in so short a time. The realm that this world of atomic physics encompasses is essentially the realm of our terrestrial environment. It is a world where energy exchanges are taking place that are of the order of several electron volts or less, corresponding roughly to the temperature that we have here on earth and the kind of radiation that we receive from the sun.

Nucleus. The next step in exploration of the structure of matter was the exploration of the structure of the nucleus. Here a new force, a nuclear force dominates the scene. The energies here in play are of the order of millions of electron volts instead of electron volts as in the atomic world.

In many respects the world of nuclear structure is very similar to the world of atomic structure except, of course, in size and energy. We speak also of shells, nuclear shells; we have a nuclear spectroscopy that is using very much the same ordering principles as we find in atomic and molecular spectroscopy—angular momentum, rotational spectra, etc. We have nuclear chemistry; we have nuclear combustion, which is the analog to the chemical atomic combustion on yet a higher energy level.

But there is perhaps one characteristic difference; the atoms can aggregate to an extremely large variety of combinations of molecules, macromolecules, crystals and so on, whereas the nuclear entities do not show this great variety simply because the electrostatic repulsion prevents large accumulations of neutrons and protons. The accumulation of neutrons only would not give rise to electric repulsion. But a few neutrons are not stable although astrophysicists believe that large numbers are; they may form the neutron stars. So, in some ways nuclear chemistry is poorer in its realm of phenomena than atomic chemistry.

The nuclear phenomena, however, are dominated by a new kind of force which is the great attraction of this field. Here we have a new, natural force that can not be found in any other manifestation. It is not like the electric force, which we can find in our household world, and there are very good reasons: We can produce electric fields at large by an accumulation of many charges, for example, by rubbing some material and making it electrically charged.

We cannot produce such accumulations of the nuclear force because of a characteristic property of this force: its short range. Even if we have many sources assembled, the nuclear force will not add up because the force reaches only a short distance. In fact this distance is so short that two nucleons cannot get near enough together to add it up. Hence there is no classical analog to the nuclear force, and this is why the nuclear force is so interesting to us, but also this is why it is extremely difficult to get to this force and to establish the fundamental laws that govern it. I will come back to this second step in our development, but let me now consider the third step, the nucleon structure.

Nucleon. In high-energy physics we look into the structure of the nucleon itself, the internal dynamics of the proton and the neutron. We are not yet very far in this endeavor; we are just beginning. This structure is mostly unknown, but we see already on the horizon, in fact we see already in the laboratories, some features that are very similar to those of the previous two steps. We find a spectroscopy of excited states of nucleons; we find that we can order those excited states by ordering principles not so terribly different from the ones we have encountered before.

Some physicists even speak of subparticles, of which the nucleons are supposed to be made. I am referring to those hypothetical particles that carry the awkward name of "quarks." Now these quarks may not exist. In some ways I, personally, wish they do not, because if so, the whole story would be repeated over again and the real answer to the questions of "why" and "what"—why are there elementary particles and what really makes them fundamental—would then be postponed and probably would not be found in my lifetime.

Intensive or extensive?

Now let me go back to nuclear structure. It has a special interest and a special flavor because of its intermediate position. Whenever one speaks about the significance of a scientific field, one encounters two radical positions and also, of course, middle positions, but let me mention the radical positions first. For lack of any better words I would like to call them the positions of "intensivists" and "extensivists." The intensivists like to defend high-energy physics; they say, "Well, science is supposed to go for the first principles, the fundamental questions, the basic laws, and this is the only interesting thing; the rest is just application and reapplication of known principles and not of great interest."

The extensivists take a different view, perhaps best expressed in an article by Alvin Weinberg in PHYSICS TODAY (March 1964, page 42) in which he measures the importance of science by what I shall call its "usefulness." I do not mean by usefulness necessarily only technological usefulness, however, but also usefulness to other sciences. In other words, these latter people would measure the importance of a branch of science by its ramifications into the rest of man's activities, scientific and otherwise.

Here are two extreme positions. Clearly, high-energy physics ranks first for the intensive people. There one is asking directly—if you want to call it so—*the* last question: What are the fundamental particles of matter? The extensivists—and we have seen this in Weinberg's article—look at high-energy physics with a critical eye and say, "Well, this is of interest only to a small group of devoted people who talk to each other, and no other scientist is really interested in what's going on inside of inside of inside of the nucleus."

I do not want to defend one side against the other—I think both attitudes are important—but I would like to speak about nuclear structure because nuclear structure has, in a way, the enviable position to be in between, and therefore nuclear structure science should please both parties. Of course, it might also have the opposite effect, but I would like to make a very strong case that it could and should please both parties.

Questions of nuclear structure

Nuclear structure science asks what I have referred to as "last questions" in two ways: One, it attacks the phenomenon of the atomic nucleus. The atomic nucleus certainly is there; it is the center of all matter, here and in the universe; it exists; it must be understood; and it is one of the basic questions to ask not only what keeps it together—the nuclear force—but also: How is the nucleus constructed? How is it shaped? How does it behave? How do nuclei react? Why are they the way they are? And also the question: How did they come about? The "last questions" that nuclear structure is dealing with, are on the one side, concerned with the phenomenon of the nucleus itself and on the other side, raising a question of a basic law, namely, the nuclear force. Where does it come from? What are its properties? How does it work?

I would say, after looking at the whole picture, that nuclear structure so far, perhaps, did somewhat better on the first score than on the second. The phenomenon of the nucleus is understood today although vast fields are still obscure.

The phenomena of the nucleus manifests itself in the nuclear spectrum, in the excited states and in the vast array of nuclear reactions. What do nuclei do when they hit each other at various energies? In those two fields enormous progress has been made especially in the last two decades, but important questions remain left, and some of these questions are so fundamental that one is rather worried. For example, the question of the shape of the nucleus. True enough, the nucleus is sometimes a sphere and sometimes an ellipsoid, but we know very little about what the surface of the nucleus looks like. What is the surface? How does the nuclear matter go over into free space? Is the surface soft, hard? What does it consist of? Is it just the same thing as inside, only less dense? Or has the surface special properties, such that certain nucleon groups are formed? Here indeed our ignorance is vast. What kind of groups are there? Is the surface made of alpha particles? Is a deuteron surface, or is it just a Fermi gas of nucleons like inside?

The internal dynamics of a nucleus poses new problems such as the question of what happens when two nucleons come very near to each other.

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This is part of a general problem that physics faces not only in nuclear structure but in almost any other field, namely, the many-body problem. We are extremely ignorant in this respect although the many-body problem is obviously one that has a bearing on every piece of matter as we find it. In the nucleus we have not been able, yet, to devise a method to deal with this problem in a satisfactory way. This will be a theoretical development that I am sure will occur in the next 10 or 20 years; much of the drive and input material will come from nuclear-structure work.

Two kinds of answer

Looking at nuclear-structure research in the past, you will find two tendencies in regard to these problems. The first is that we would like to explain the phenomena—the nuclear reactions, the spectra, and so on—with as few as possible special assumptions about things we do not know so well, for example, nuclear force. And the second tendency is to go directly at those things we do not know so well, namely, at nuclear forces.

Let me make this clearer. The first tendency is to explain nuclear reactions or nuclear spectra on the basis of, for example, the compound-nucleus model, the independent-particle model, the statistical model or the rotational model. All these models are attempts, sometimes successful attempts, to understand what we see with as few assumptions as possible about unknown things, such as the nuclear force at small distances. It is as if we want to understand the properties of a solid on the basis of general assumptions by introducing a few elastic constants without yet worrying where these elastic constants come from. I think that nuclear physics was very successful in this area, and we now have excellent ways of predicting successfully behavior of nuclei and without knowing much about the details of nuclear dynamics.

The second tendency is to attack the problem the other way around. We look for phenomena in which the nuclear force is important; we try to find out something about the things we are ignorant of; we look for phenomena in which the nuclear force and those parts of the nuclear force that we do not know play an important role as in the near encounters of nucleons in nuclear matter or in surface phenomena or in the question of three-body interactions.

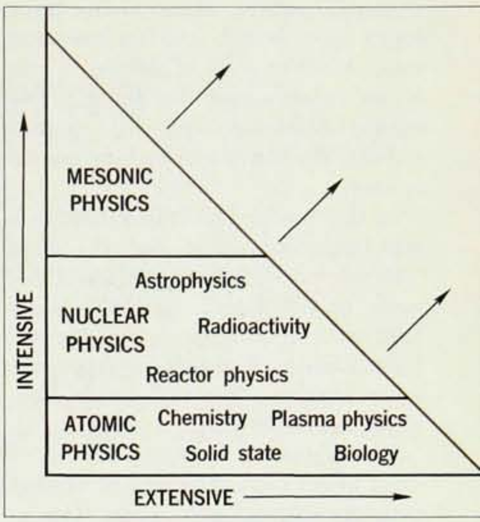
Nuclear physics was more successful in the first approach than in the second because we still have the problems with us: Does the nuclear force depend on velocity? How local is the force? Are there important three-body interactions within the nucleus? In this respect we surely will get more information from experiments.

There is, however, a difficulty that one should mention. It turned out from our experience that the nuclear force, the force between two nucleons, has a disagreeable property. It is rather different depending on whether the two nucleons have relative velocities that are small compared to light velocity or comparable with light velocity—that is, whether we deal with nonrelativistic or relativistic encounters. Nuclear structure gives us only information about the nonrelativistic region; there the nuclear force is relatively weak. (The weakness occurs because the force is transmitted by a pseudoscalar pion; but I do not want to go into these very interesting, formal questions.)

The point is that the nuclear force hides itself in an ordinary nucleus and does not show its full strength, which is about 100 times larger, except when two nucleons race by one another with velocities comparable to that of light and phenomena of nucleon-pair formation enter into the picture. This is the reason low-energy nuclear physics experiments have not been too helpful in exploring fundamental questions regarding nuclear forces. I say this, however, not to depreciate nuclear structure; on the contrary, I say this because I feel that it will be very important in nuclear structure to investigate the interaction of nuclei with very-high-energy projectiles. So I have to warn the chairman of the Atomic Energy Commission that nuclear-structure physicists will also come to him—I know they already do—to get machines of very high energy, of several hundred MeV and over a GeV.

Uses of nuclear physics

Now let me say a few words about



EXTENSIVENESS VS INTENSIVENESS showing the progress of the study of matter in atomic, nuclear and mesonic areas.

what I call "usefulness," in other words, the second aspect of the intermediate position of nuclear structure as a branch of science. Let me consider usefulness in its widest sense and make a few general remarks about usefulness and interrelation with other sciences. One can see the point if one looks at the development of our knowledge of the structure of matter in terms of the three steps that I indicated in the beginning.

Let us look at the figure. In this plot there are two coördinates; horizontally we plot extensiveness—we will see what that means—and vertically we plot intensiveness. The figure shows the three steps that our study of matter has taken: namely, the atomic step, the nuclear step and the mesonic step. I don't want to call it high-energy physics because high-energy physics will always be the highest step. A line is drawn at 45 deg, and the displacement of this line in the direction of the arrows is the progress of science. It is clear that the lower the field is in this intensive development, the more it is extended in the extensive direction. It means that it is more and more involved with other questions, with other scientific or technical activities.

For example, atomic physics started in the year 1912 or so—when it was the most esoteric field in the world, and the same arguments that are now leveled against high-energy physics by extensivists were then leveled against atomic physicists. Today atomic physics is very broad, and its extensive range includes a lot of things. There is not enough room for them in the figure; solid-state physics, plasma physics, chemistry and biology are examples.

In the nuclear field this extension is just beginning. You find the word "astrophysics" in the figure, and I will come to this later. In the mesonic field, of course, there is nothing, yet. I don't know what will be above mesonic physics. We will know more about that in 20 years.

Astrophysics. Now let me say a word about the connection of nuclear structure with other sciences. One of the greatest discoveries of our time is that stellar energy is furnished by nuclear processes. When one observes nuclear experiments in our laboratories, one gets the impression that nuclear physics is a man-made world. Nuclear processes occur rarely on earth by themselves. What we are doing here—apart from the practical applications—is spending many millions of dollars just to create the problem that we then proceed to solve.

After all, nuclei are not normally excited on earth. The phenomena of nuclear physics are effects of excited nuclei that we create with our accelerators. However, there are places in the universe where excited nuclei occur in large numbers; the natural habitat of nuclear structure physics is the interior of stars, and there are many stars; there are probably more stars than planets. Man has in fact created here on earth a cosmic environment, and this is what we are investigating. To have nuclear reactions going on in a laboratory—the same reactions that go on in the middle of the sun and the middle of Sirius—is far more impressive a human achievement than those trips to the moon now so much advertised.

The application of nuclear physics to celestial problems seems to me a very important issue that it is not enough recognized by the rank and file of nuclear physicists. All our present ideas as to the evolution of stars, the formation of elements, are based on nuclear processes, and there is much unfinished business here.

I am convinced it would help both the astrophysicists and the nuclear-structure physicists if there were more contact between them. The astrophysicists need a lot of cross sections that are not available. What they need are cross sections at relatively low energy, such as the cross section for the reaction between alpha particles and carbon going to oxygen much below the Coulomb barrier.

With the high beam intensities now available and with the precision with which cross sections can be measured, there are many problems that could and should be solved. We need to understand better what happens in a star, how and when different types of combustions set in—for example, when helium combustion takes over and hydrogen burning stops. These problems are fundamental and essential for knowledge of star development.

Another problem is the spallation process; what kind of lighter elements does one get when high-energy protons hit nuclei? This is probably one of the ways in which lighter elements are created, in particular those which you find in cosmic rays. All these are problems that more nuclear-structure research would help solve.

Not only would the astronomers be glad, but also the nuclear-structure people I think would profit from such a collaboration. It would add depth to their subject. Let me illustrate this: I come back now to the previous remark about the relative poverty of nuclear chemistry compared to atomic chemistry. In atomic chemistry we see an incredible wealth of different structures compared to the relatively limited number, let us say, of nuclear isotopes. But I think this is offset and perhaps even more than offset by the tremendous variety of stellar phenomena. All we see in the sky, strange stars, exploding stars, novas, quasars or galaxies, the previously mentioned neutron stars, are nuclear phenomena. They are a combination of nuclear and gravitational phenomena in which nuclear physics plays the essential, fundamental role as source of energy as far as we know.

It seems to me that here is a manifestation of a great variety of heterogeneous phenomena in the universe that is as rich or even richer than the variety of matter we find on earth, and here is where nuclear-structure research could help bring about a deeper understanding. The nuclear-structure people have done much work in order to understand nuclear models; let them now also help the astronomers to understand stellar models.

Technology. When I talk about usefulness, of course, I should also mention practical usefulness. There is no question that our diagram should contain reactor physics, artificial radioactivity and such fields in its second row. These are things that some pure physicists call "technological only" and find somewhat under their dignity—an attitude that is certainly wrong because understanding nature and making use of nature for better purposes must belong together. Also there is a certain greatness in making use of cosmic phenomena, in creating cosmic environments on our planet for the benefit of mankind.

I have tried to transfer to you some of my feelings of the fascination of this branch of science in which we are dealing with a most curious form of matter—nuclear matter—with its tremendous density. A matter, however, that is inert on earth but not at all inert in most other large accumulations of matter in the universe.

The dynamics of nuclear matter is probably much more essential to the life of the universe than our terrestrial atomic physics. After all, what is atomic physics? Atomic physics deals with electron shells around nuclei which are only formed at very low temperatures on a few outlying planets where conditions are just right—where temperature is not too high, low enough to form those electron shells but high enough to have them react with each other. These conditions are possible only because of the nearness of a nuclear fire. Under the influence of such a nuclear fire self-reproducing units were formed on earth. And after billions of years of benign radiation from the steady solar nuclear furnace, thinking beings evolved who construct machines and investigate those processes that are one step nearer to the heart of the universe than our daily world.

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This article is based on the Silliman Lecture delivered by the author at the dedication of the Yale University tandem electrostatic accelerator. □