Mirror Nuclei and Charge Symmetry

by Thomas A. Tombrello, Jr.

Some highlights in the study of energy levels and reactions of light nuclei.

Soon after the nucleus was discovered, it became obvious that the mass of the atom was largely concentrated in its nucleus and that this mass was approximately an integral multiple of the mass of a hydrogen nucleus (proton). Since the nuclear charge was less than the charge on that number of protons, it was proposed by Rutherford in 1920 that one of the nuclear constituents would have about the same mass as the proton but with no electric charge (the neutron). The discovery of this object by Chadwick in 1932 led to a model of the nucleus consisting of neutrons and protons that is still in vogue today.

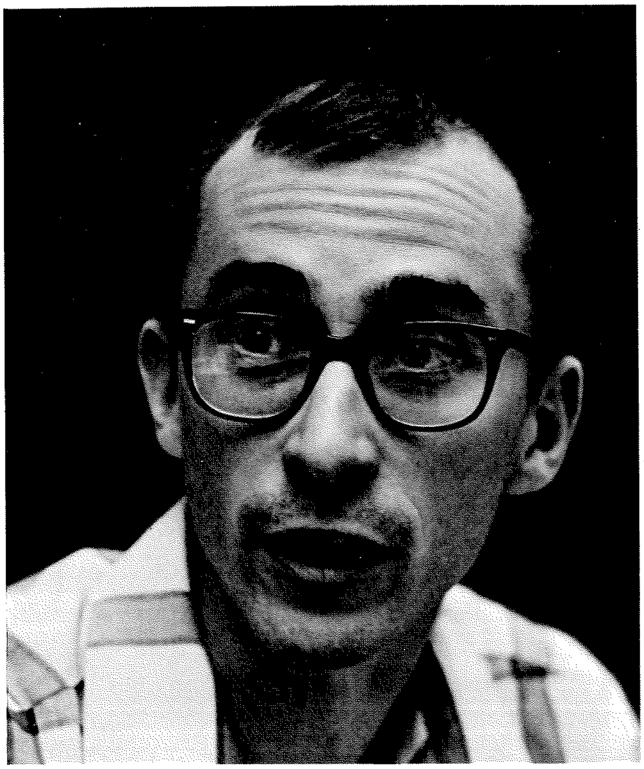
A particular nucleus of Z protons and N neutrons would then have a charge equal to Z (the atomic number) times the proton charge and have a mass approximately equal to that of Z protons and N neutrons. The mass equivalence is only approximate, because different nuclei have different binding energies —the effect of binding being to reduce the mass by $\triangle m$ according to Einstein's relation: binding energy $= \triangle mc^2$. Since the overall mass is still approximately $A = N + Z$ times the mass of a hydrogen atom, we call A the atomic mass number.

Early experiments showed that the low-energy scattering of protons from protons, and neutrons from protons, were virtually identical for the same angular momentum states, if one removed the effects produced by the electric repulsion of the charged protons. This led to the postulate that the nuclear force between proton pairs, neutron pairs, or a neutron and a proton were equal. This idea was called "charge independence" and was the first of the internal symmetries (exclusive of the space and time coordinates) proposed for the strong (or nuclear) interaction. To be slightly more precise, the equality of the proton-proton and neutron-neutron nuclear forces is called "charge symmetry," and the further equality with the appropriate part of the neutron-proton force is called "charge independence."

Soon after the proton-proton scattering measurements the Kellogg Laboratory became involved indirectly in this problem. W. A. Fowler, L. A. Delsasso, and C. C. Lauritsen had been using the early high-voltage machine to make radioactive nuclei that decayed by the emission of electrons (e^-) or positrons (e^+). The major part of their work reported in 1936 was concerned with what seemed to be a confirmation of the Konopinski-Uhlenbeck theory of nuclear beta-decay. As it turned out eventually, the theory was completely incorrect; the data contained unsuspected errors that were typical of all such experiments of that period. However, in the last few paragraphs of their paper the authors noted that in all the positron decays studied the mass difference (and hence the binding-energy difference) of the decaying nucleus and the nucleus it became after the decay could be explained by considering only the difference in the electric repulsion among the protons. The parent nucleus formed had Z+1 protons and Z neutrons; in the decay one proton becomes a neutron with the emission of a positron and a neutrino (ν). This is written schematically as:

$$^{2Z+1}_{Z+1}X \rightarrow {}^{2Z+1}_{Z}Y + e^+ + \nu$$

where $^{2Z+1}_{Z+1}X$ is the nucleus of the element X which has Z+1 protons (atomic number, Z+1) and an atomic mass of 2Z+1. We notice that the initial nucleus, X, has Z+1 protons and Z neutrons; the final nucleus, Y, has Z protons and Z+1 neutrons. Because of the equality of the neutron-neutron and proton-proton forces we see that the only difference in the binding forces in X and Y is produced by the



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electrostatic interaction of the extra proton with the rest. Thus, Fowler, Delsasso, and Lauritsen had shown that the neutrons and protons in nuclei also obeyed the same charge symmetry principle that had been observed for free neutrons and protons. One should not underestimate that result, because it provides not only a very strong confirmation of the symmetry principle itself but also reflects on the overall validity of the neutron-proton model of the nucleus.

Related pairs of nuclei like X and Y in our example have come to be known as "mirror nuclei," because the role occupied by neutrons in one nucleus is given to protons in the other, and vice versa. Thus, neutrons and protons could be thought of as mirroring one another in the structure of the two nuclei.

Following this discovery, theoretical work by Wigner indicated that such mirror pairs of nuclei would not only have similar binding energies, but all their excited states would be similarly located with virtually identical energy spacing. Not until after the war was this extended theory of mirror symmetry confirmed experimentally. Again, the lead in this area was in Kellogg, where the development of precise techniques of measuring particle energies with magnetic and electrostatic analyzers was actively pressed.

The key experimental example was the study of the lowest excited states of ^{7}Li (3 protons, 4 neutrons) and ^{7}Be (4 protons, 3 neutrons) by A. B. Brown, C. W. Snyder, W. A. Fowler, and C. C. Lauritsen. (It is worth noting that one of the techniques developed for this experiment was again put to use recently in the alpha-scattering experiment that was landed on the lunar surface.) The energy level diagrams for these mirror nuclei are below right. The excitation energies of the various states (in MeV), their angular momenta (J) and parities ($\pm$) are given. Also shown are the energies corresponding to the possible decay modes; e.g., all the excited states of ^{7}Be above 1.587 can decay into a ^{3}He nucleus plus a ^{4}He nucleus (alpha particle); states above 5.608 can also decay into a proton plus a ^{6}Li nucleus. The data shown are taken from the most recent and complete experimental work available, a PhD thesis from Kellogg by R. J. Spiger (1966).

Note that though the lower excited states have the same order and the same approximate spacing, the spacings are not reproduced in detail. This is not due in this case to any breaking of the mirror symmetry, but reflects the presence of nearby decay modes (channels). This effect was first explained in another PhD thesis from Kellogg by R. G. Thomas (1951) for another mirror pair, ^{13}N and ^{13}C.

In the past few years it has been of considerable interest to look for methods to test more precisely the limits of the validity of charge symmetry. This has taken two different routes in Kellogg; the first is closely akin to that used originally by Fowler, Delsasso, and Lauritsen.

The electrostatic energy of a nucleus is proportional to the number of pairs of charged particles present; if there are Z protons, then there are Z(Z-1) possible pairs. If we generalize slightly, we can say that the contribution from the interaction of the charges alone is a quadratic function of Z. Thus, we find within a set of mirror nuclei that for each nuclear mass, M:

$$M = cZ^2 + bZ + a$$

where c, b, and a are the same for all members of the set.

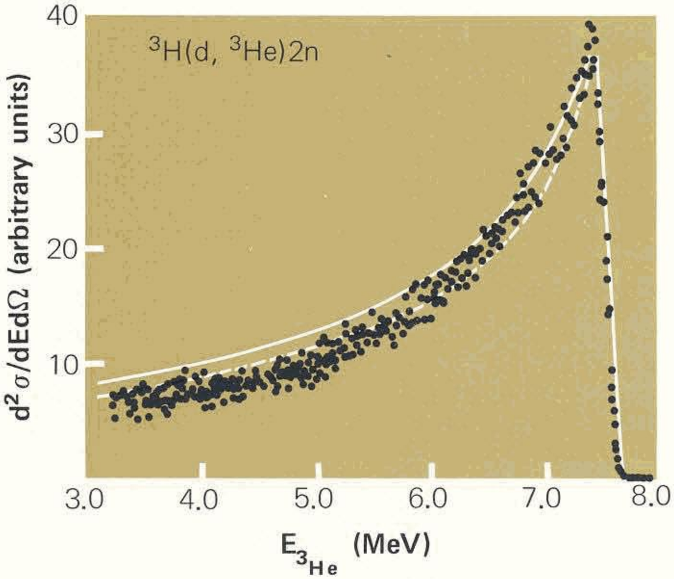
By our generalization we now have three parameters to determine, so that to check the validity of mirror symmetry we must have at least four pieces of data. Therefore, a mirror pair of nuclei will no longer be sufficient; we now need a mirror quartet. The only example that has been studied in sufficient detail—in Kellogg, of course—is composed of ^{9}Li, the corresponding excited states of ^{9}Be and ^{9}B, and ^{9}C. The masses of these nuclei and excited states were determined to about one part in two million, and they allow the only accurate check now available for the quadratic formula. The results show a definite breakdown of the formula, but this occurs at such a low level that it is impossible to say whether the discrepancy is due to a true violation of the symmetry or to higher order corrections to the electrostatic interaction itself.

The second approach to investigating charge symmetry attacks the foundations of the original postulate. Since the neutron is unstable, it has been impossible to actually observe the scattering of neutrons from neutrons. Thus the assumption of charge symmetry remains unchecked in its most fundamental form. It is just barely possible that the scattering could be studied directly using underground nuclear explosions, but the high cost together with the large chance of failure have so far prevented its serious consideration.

So we are forced to a less direct and less precise approach. We have considered reactions such as:

$$^3H + d \rightarrow {}^3He + 2n,$$

where two neutrons together with another particle occur as the products of a nuclear reaction. If experimental conditions can be found in which the neutrons do not interact with the other particle (in our example the ^3He), then perhaps the interaction of the two neutrons can be deduced.

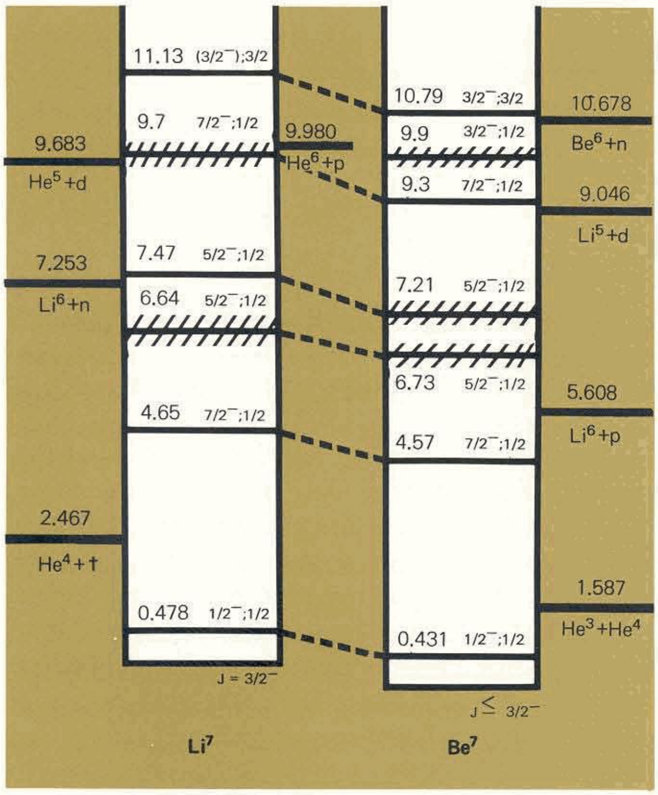


In the energy spectra of ^3He particles from the reaction $^3H(d, {}^3He)2n$, the pronounced peak shows the effect produced by the strong low-energy scattering of the two neutrons.

The criterion that the ^3He not be strongly involved with the neutrons can be fulfilled to a large extent. The chart above shows the energy spectrum of ^3He particles coming from the reaction. The lines give the simplest predictions one can make by assuming deviations of ± 1 percent from charge symmetry. These data are from another Kellogg thesis project by H. T. Larson (1969), but similar data have been obtained elsewhere for other reactions.

However, one still has the problem of assigning an overall uncertainty because of the indirect nature of the process. Larson's analysis has gone quite far in this direction, at least for the reaction he has considered. Unfortunately, the news is not promising; we seem to be limited to a minimum theoretical uncertainty of about $\pm$ 2 percent. Since this is not really good enough to say anything definite about the breakdown of charge symmetry, we are blocked in this direction for the moment.

So, the study of mirror nuclei and charge symmetry remains a significant challenge to our ingenuity. We have made progress, but in some areas we are in need of new ideas and techniques. We can safely predict that these studies begun over 30 years ago will be with us for some time to come.



Energy level diagram of the mirror nuclei ^7Li and ^7Be