Hands-On Nuclear Physics

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Hands-On Nuclear Physics

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Nuclear science is an important topic in terms of its application to power generation, medical diagnostics and treatment, and national defense. Unfortunately, the subatomic domain is far removed from daily experience, and few learning aids are available to teachers. What follows describes a low-tech, hands-on method to teach important concepts in nuclear physics, including the quark model, anti-matter, nuclear binding energy, stability, the nuclear shell model, and the importance of symmetry, by making use of neodymium disc magnets.

There have been several papers presented in this journal that show pedagogic methods for teaching nuclear topics to introductory physics students. For example, Constan[1] shows a nice method for modeling the nucleus using magnetic marbles; however, his method omits the topics of quarks, symmetry, and the shell model. Jesse[2] shows a useful method of mathematically simulating radioactive decay using a spreadsheet; however, he omits all other properties of the nucleus.

Materials

The items required are large and small neodymium disc magnets: several dozen "regular" nickel-plated (silver-colored) 3/8-in diameter x 1/8-in thickness disc magnets, one dozen regular nickel-plated ¼-in diameter x 1/8-in thickness magnets, and one dozen epoxy-coated black ¼-in diameter x 1/8-in thickness magnets. These magnets are readily available online from various suppliers.[3] Also useful, though not required, is a tin box for stabilizing the models during assembly and while being displayed.

Modeling nucleons

The quark model shows nucleons as being composed of these fractionally charged particles, the proton being composed of two +2/3 e (1 e = 1.6×10^{-19} C) and one -1/3 e particle, and the neutron being composed of two -1/3 e and one +2/3 e. In this model, the 3/8-in diameter magnets will represent 2/3 e quarks and ¼-in magnets will represent the 1/3 e quarks. To assemble a "proton," take a 3/8-in disc and place it on a silver ¼-in magnet. Instruct the students that the clicking sound the magnets make when they snap together represents a release of binding energy. Then, place another 3/8-in magnet on the other side of the small one. This configuration equates to a "proton" (see Fig. 1).

A "neutron" is similarly constructed, with the difference being that the small black magnets are placed on either side of the larger sized magnet. This configuration creates an isomorphic relationship between the size of the charge and the size of the disc magnet. Also, producing the ends of the neutron in black helps differentiate their appearance from protons.

"Nucleosynthesis"

There are two basic rules to follow for modeling the nuclei: protons only bond to neutrons (and vice versa), and the resulting bonding arrangement most closely approximates the geometry of a sphere. This will become more obvious as larger nuclei are modeled.

To "synthesize" the deuterium nucleus (proton-neutron), the nucleons should be placed on a flat surface (such as the lid of a tin box) and slid toward each other. Inform students that if they repel one another, one of the nucleons is either an antineutron or antiproton and needs to be flipped over. The two particles will make a clicking sound (release energy) as they bond. To make tritium, slide a neutron to the "unbonded" side of the proton. Then ask the students to pick up the "tritium nucleus," at which point the students will notice that it flexes easily from side to side. Next, set the tritium model back down. To make the helium nucleus, slide another proton onto the end of the chain, and then wrap the proton around until it connects with the neutron on the far side of the chain.

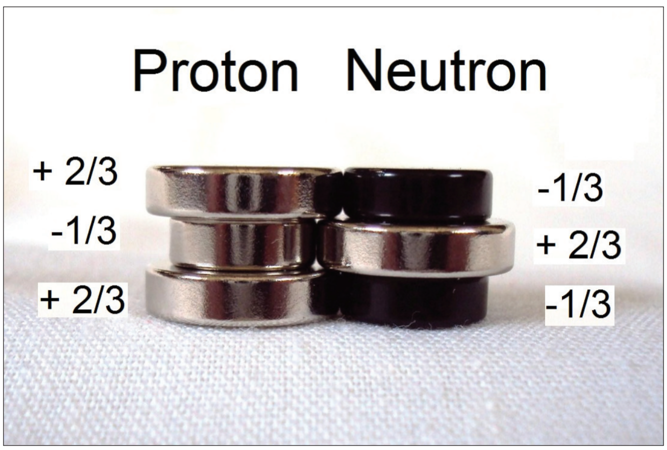

Fig. 1. Proton and neutron from quarks.

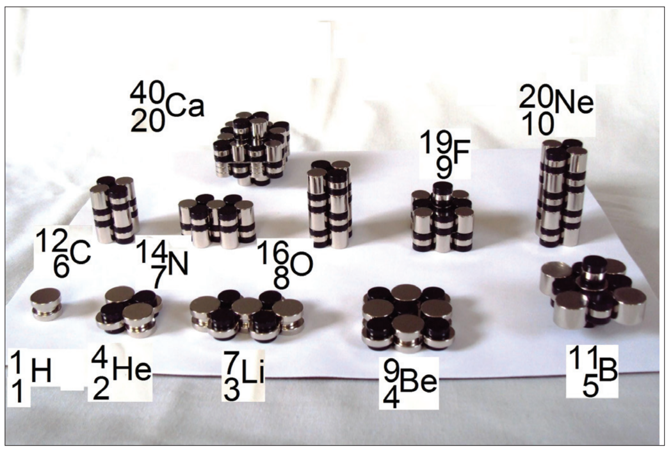

Fig. 2. Models of nuclei using magnets.

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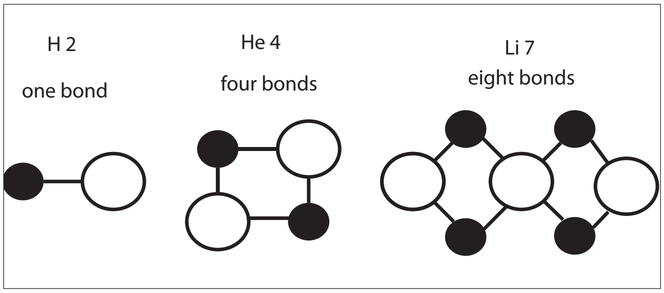

Fig. 3. Nuclei showing bonding patterns.

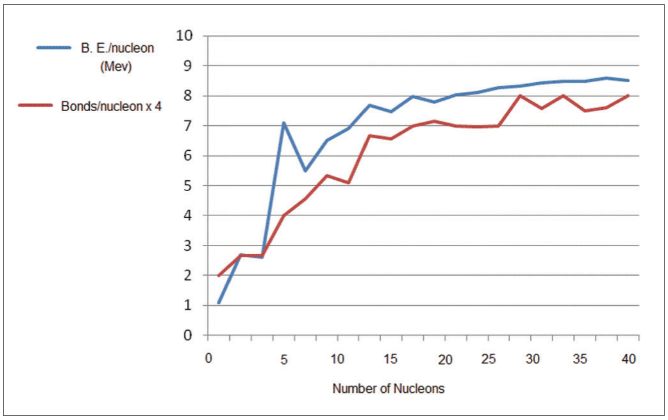

Fig. 4. Binding energy (B.E.)/nucleon and bonds/nucleon graph.

Table I. Data.

Nucleus	Total Bonds	# of nucle-ons	Bonds/ nucleon	(Bonds/ nucleon) x4	B.E./ nucleon
H 2	1	2	0.5	2.0	1.1
H 3	2	3	0.67	2.67	2.7
He 3	2	3	0.67	2.67	2.6
He 4	4	4	1.0	4.0	7.1
Li 7	8	7	1.14	4.56	5.5
Be 9	12	9	1.33	5.32	6.5
B 11	14	11	1.27	5.08	6.9
C 12	20	12	1.67	6.68	7.68
N 14	23	14	1.64	6.56	7.48
O 16	28	16	1.75	7.0	7.97
F 19	34	19	1.79	7.16	7.78
Ne 20	36	20	1.80	7.2	8.03
Na 23	40	23	1.74	6.96	8.11
Mg 24	44	24	1.75	7.0	8.26
Al 27	54	27	2.0	8.0	8.33
Si 28	53	28	1.89	7.57	8.44
P 31	62	31	2.0	8.0	8.48
S 32	64	32	1.88	7.5	8.49
Ar 36	75	36	2.08	8.33	8.52
Ca 40	80	40	2.0	8.0	8.50

Ask the students to pick up their helium nuclei, and they should notice that it is much more rigid (stable) than tritium. Stability in nuclei is important; it is associated with natural abundance, notably in the case of helium-4, which is a common decay product of radioactive nuclei. Using this method, one can construct models of the nuclei found on the periodic table. Figure 2 shows models of the first 10 elements of the periodic table plus calcium-40.

As a lab experiment, it may be convenient to have pairs of students build different nuclei and share their models using a document camera or overhead projector.

"Binding energy"

Once the models are assembled, ask the students to count the number of bonds between nucleons for their model (see Fig. 3) and record the number in a data table (see Table I). Note that the larger nuclei have several levels, and that proton-neutron bonding can occur between levels in addition to side-to-side bonding.

After the bond data are collected, ask students to divide the number of bonds by the number of nucleons in their model. This "bond per nucleon" ratio represents a measure of the nuclear binding energy. Have students input bonds per nucleon data and the binding energy per nucleon data into paired lists in a spreadsheet program or graphing calculator, and compute the correlation between the bonds per nucleon and the known binding energy per nucleon. Students should find that the correlation is approximately 0.94, showing the high correlation between the modeling technique and the properties of actual nuclei.

If time permits, have them multiply the bonds per nucleon data by a scaling factor of 4 and record the result in the next column. Then have them plot the bonds per nucleon data and the binding energy per nucleon data on the same graph. This should appear similar to Fig. 4.

Magic numbers and the shell model

In nuclear physics, a magic number is a number of nucleons such that they are arranged into complete shells. The first three magic numbers are 2, 8, and 20. In the models, students may notice the highly symmetric 4x4 structures of helium-4, oxygen-16, and calcium-40, at which point it can be suggested that these structures are termed "doubly magic" nuclei and represent, according to the nuclear shell model, "filled shells" with especially high binding energy. They may also notice the 3x3 symmetry of beryllium, boron, and aluminum; it can then be explained that this coincides with the favoring of an additional neutron compared to helium-4, carbon-12, oxygen-16, etc. Also, for an additional challenge, instruct students to build their nuclei with different geometric forms. They will likely discover that their deviations are less symmetric, less stable, and less conforming to an approximation of a sphere than the examples provided.

If students are interested in a further challenge, they can

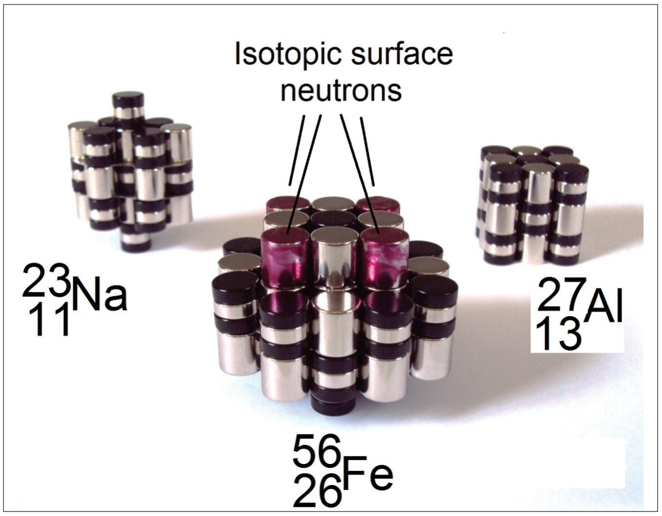

Fig. 5. Iron-56 (showing isotopic neutrons in red), sodium-23, and aluminum-27.

design and model larger nuclei such as sodium-23, aluminum-27, and iron-56, as shown in Fig. 5. Also, once these larger nuclei have been built, it can be explained that a "neutron" skin could be added to the surface of the large models. Make sure to attach neutrons only to the surface protons.

This modeling technique fits the experimental data regarding binding energy and stability quite nicely. Do, however, make sure to remind students that this experiment is simply a macroscopic *model* of the nucleus. It does not address the mathematical complexities of the quantum-mechanical description.

References

1. Zach Constan, "Learning nuclear science with marbles," *Phys. Teach.* **48**, 114–117 (Feb. 2010).
2. Kenneth E. Jesse, "Computer simulation of radioactive decay," *Phys. Teach.* **41**, 542–543 (Dec. 2003).
3. Neodymium disc magnets are available at Applied Magnets Inc., www.magnets4less.com, or K&J Magnetics Inc., www.kjmagnetics.com.

Jeff Whittaker *teaches honors physics at the Dearborn Center for Math, Science and Technology. He is the founder of the award-winning website PhysicsLessons.com and inventor of magnetic climbing technology, which can be seen on the website of the company Jeff founded at www.spiderclimbing.com. Currently, he is preparing a paper explaining the theory that inspired the nuclear modeling method shown in the present work.*
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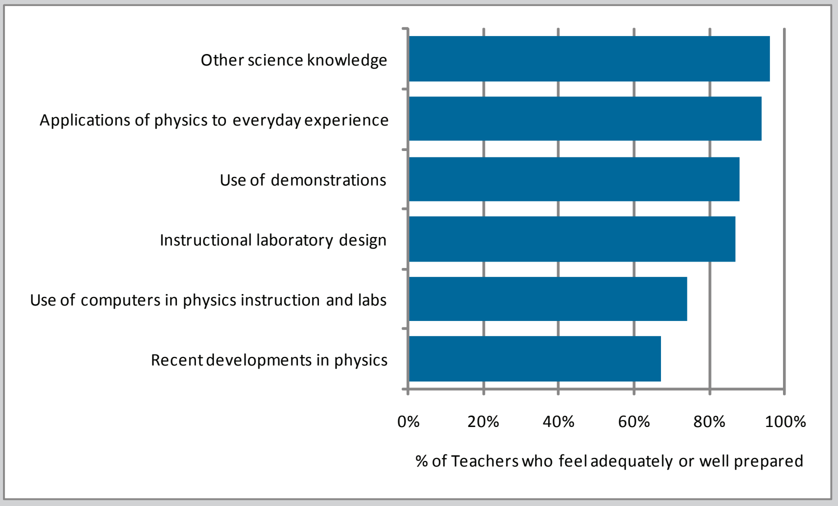
Teachers' self-assessed level of preparation

We asked high school physics teachers to assess their level of preparation across a number of domains. Almost all (98%) reported feeling adequately or well prepared in terms of their basic physics knowledge. The chart presents teachers' responses to their self-assessed level of preparation in six different areas. Almost all feel at least adequately prepared with respect to their science knowledge in other areas and the applications of physics to everyday experience. However, only two-thirds feel adequately or well prepared in recent developments in physics.



In the April issue, we will look at physics teachers' assessment of students' preparation. Susan White is Research Manager in the Statistical Research Center at the American Institute of Physics; she directs the Nationwide Survey of High School Physics Teachers. If you have any questions, please contact Susan at swhite@aip.org. DOI: 10.1119/1.4792016