Students Method for Determining the Binding Energy of the Deuteron

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A recording spectrometer model 1820 manufactured by Nuclear Chicago with a sodium iodide crystal scintillator, a neutron source, water, and paraffin are used to determine the binding energy of H^2 by measuring the energy of the photons emitted when thermal neutrons are captured by H^1.

INTRODUCTION

NEUTRON capture gamma rays were first observed by Lea[1] who appears to have detected the gamma ray produced by the capture of neutrons in hydrogen using a Ra-Be neutron source and a Geiger counter as radiation detector. The experiment suffered from the disadvantage of using a very weak neutron source and a fairly insensitive radiation detecting device. However, more recently, Pringle[2] studied capture gamma rays with a weak Ra-Be neutron source and used a crystal scintillator spectrometer, a more sensitive detector.

The first accurate measurement of the energy of the hydrogen capture gamma ray was made by Bell and Elliot[3] using thermal neutrons from a reactor. The reported value was 2.23 Mev for the binding energy of the deutron.

A number of illustrative students laboratory experiments in neutron physics using a Pu-Be neutron source and commercially available instruments have been developed as part of a sequence of experiments constituting a nuclear and reactor physics laboratory. Measuring the binding energy of the deuteron is one of the simple experiments. The procedure and nature of the resulting data will be discussed.

* Established by the U. S. Atomic Energy Commission as part of the Atoms for Peace Program and operated by the University of Puerto Rico.
[1] D. E. Lea, Nature 133, 24 (1934).
[2] R. Pringle, Phys. Rev. 87, 1016 (1952).
[3] R. E. Bell and L. G. Elliott, Phys. Rev. 79, 282 (1950).

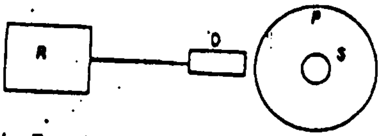

FIG. 1. Experimental setup. P—9-in.-diam paraffin cylinder S—PuBe neutron source, D—NaI scintillator detector, R—recording spectrometer.

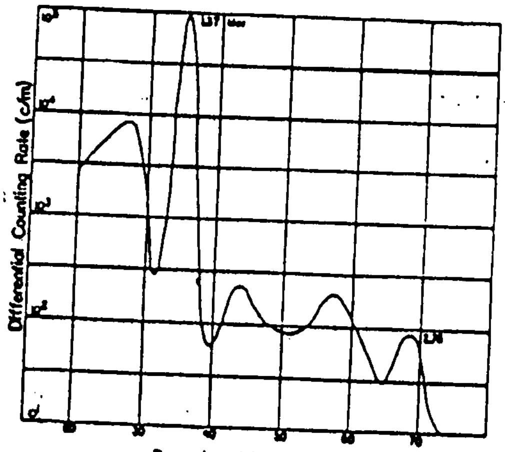

FIG. 2. Gamma spectrum of Na^{24}.

THEORY

The binding energy of a system of particles is the difference between the mass of the free constituents and the mass of the bound system. Thus the binding energy of the deuteron is

$$B(H^2) = M_a(n) + M_a(H^1) - M_a(H^2), \qquad (1)$$

where M_a refers to the atomic rest masses of the neutral atoms.

The binding energy of the deuteron can be determined experimentally by the measurement of the energy of the gamma rays which are emitted when thermal neutrons are captured by hydrogen. This is possible since the gamma-ray energy approximately equals the binding energy. The validity of this statement can be shown as follows:

The Q value of the nuclear reaction is given by

$$Q = M_a(n) + M_a(H^1) - M_a(H^2) \qquad (2)$$

or

$$Q = T(\gamma) + T(H^2) - T(n) - T(H^1), \qquad (3)$$

where T refers to the energy of the particles. Notice that the right-hand side of Eqs. (1) and (2) are the same. This means that the binding energy of the deuteron is equal to the Q value of the reaction. That is,

$$B(H^2) = Q. \qquad (4)$$

In as much as the energy of recoil of H^2, the energy of the slow neutrons and the energy of H^1 can be neglected with respect to the energy of the emitted gamma-ray photon, it follows from

Eq. (3) that the Q value of the reaction is approximately equal to the energy of the photon emitted.

That is,

$$Q \doteq T(\gamma) \qquad (5)$$

and from Eqs. (4) and (5) it follows that

$$B(H^2) \doteq T(\gamma). \qquad (6)$$

Equation (6) shows that the gamma-ray energy is approximately equal to the binding energy of the deuteron.

EXPERIMENT AND RESULTS

Figure 1 illustrates the experimental arrangement. A one curie Pu-Be neutron source is immersed in a container 15 in. in diameter and 12 in. high or inserted into the cavity of a cylindrical block of paraffin 9 in. in diameter and 10 in. high. Measurements of the neutron energy spectrum from this source has shown that most of the neutrons are fast. Upon elastic collision

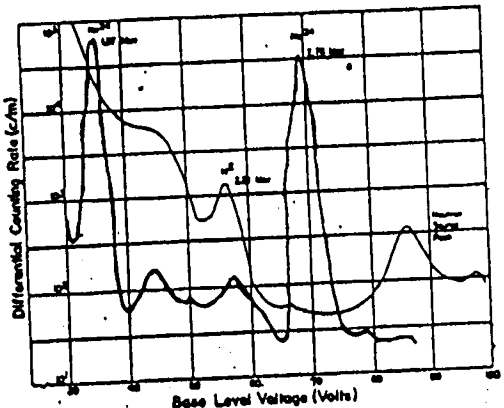

FIG. 3. Gamma spectra of Na^{24} and neutron source in water.

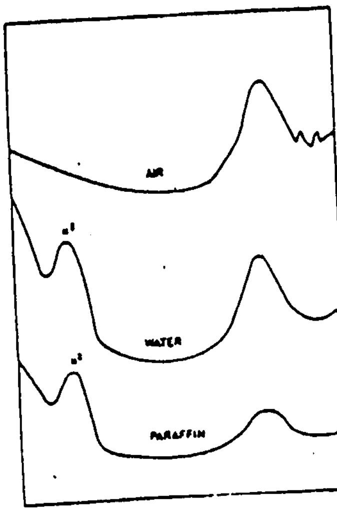

FIG. 4. Gamma spectra of neutron source in air, water, and paraffin.

with hydrogen atoms in water or in paraffin the neutrons are moderated to thermal energies. When the neutrons are thus thermalized they can be captured by H^1 with the emission of a gamma-ray photon. The gamma ray interacts with the NaI scintillator[4] and its energy recorded by the spectrometer.

Figure 2 shows the two gamma rays of 1.37 Mev and 2.76 Mev from Na^{24}. In as much as the binding energy of H^2 lies between the two Na^{24} gamma peaks it was decided to use this radioisotope to calibrate the spectrometer. The Na^{24} was prepared at the P.R.N.C. Swimming Pool Research Reactor.

Figure 3 shows a superposition of gamma-ray spectra from Na^{24} and the neutron source in water. The gain of the spectrometer was varied at about 2.5 Mev during the measurement of the Na^{24} spectrum. The energy of the deuteron peak was found by interpolation between the Na^{24} gamma peaks. The experimental value of the binding energy of H^2 so determined was 2.21 Mev.

The current best value for the binding energy of the deuteron which has evolved from a compilation of mass measurements and reaction data is 2.22 Mev.[5]

Figure 4 illustrates the gamma spectra of the neutron source in air, water and paraffin. The position of the H^2 peak which is seen in water and paraffin is characteristic of hydrogen containing matter.

CONCLUSIONS

This experiment has been a valuable teaching tool in our nuclear and reactor physics laboratory because:

(1) The student can calculate from the definition, the theoretical value of the binding energy of H^2 and then verify their calculation experimentally.

(2) In addition this experiment serves to acquaint the student with the theory and operation of a gamma-ray spectrometer.

(3) It demonstrates that an intense beam of thermal neutrons is not necessary to make a fairly accurate determination of the binding energy of H^2.

ACKNOWLEDGMENTS

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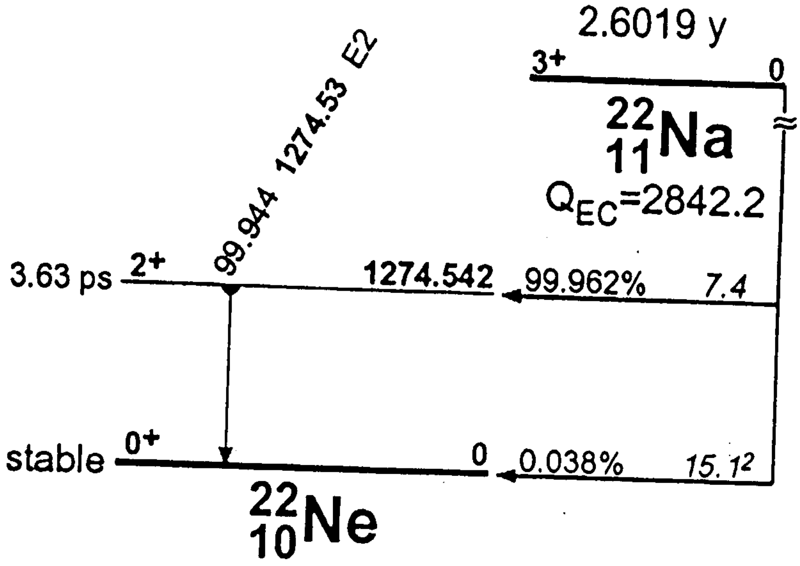
[4] K. Siegbahn, *Beta and Gamma Ray Spectroscopy* (North Holland Publishing Company, Amsterdam, 1955), Chap. 5.

[5] F. Everling *et al.*, Nuclear Phys. 15, 342 (1960).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3+
0
22
11
Na
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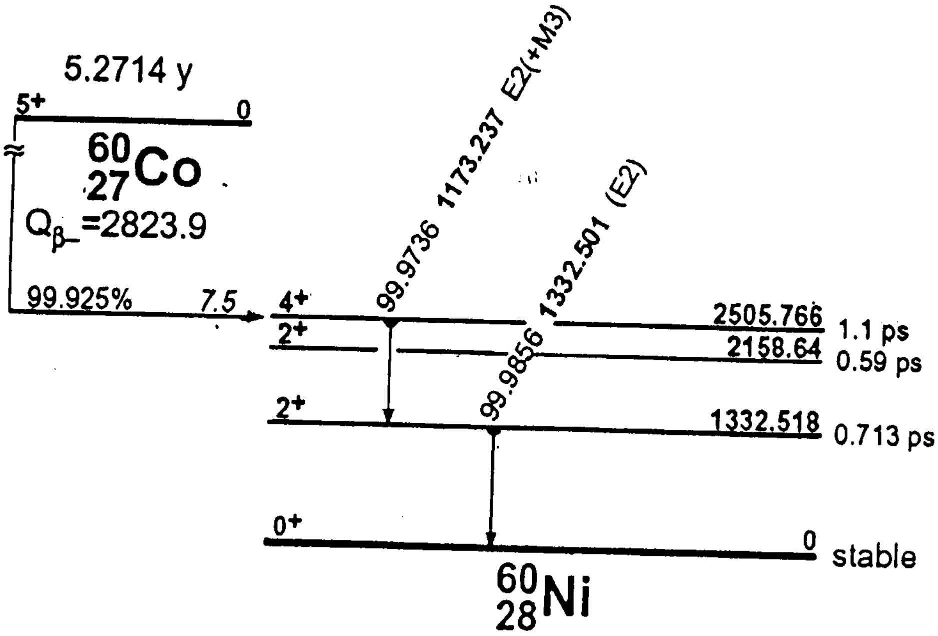
stable
0+
0
0.038%
15.12
22
10
Ne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27
Co
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7.5
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99.9856 1332.501 (E2)
4+
2505.766
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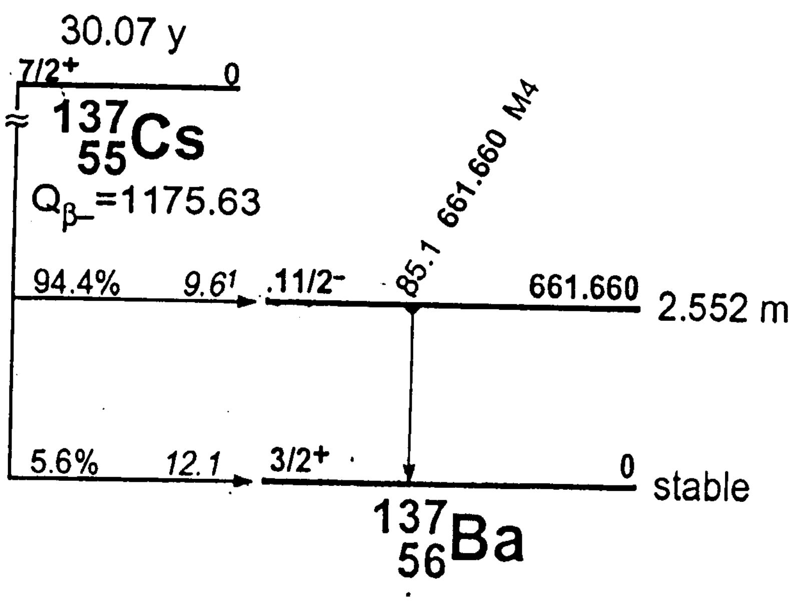
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55
Cs
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11/2−
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3/2+
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137
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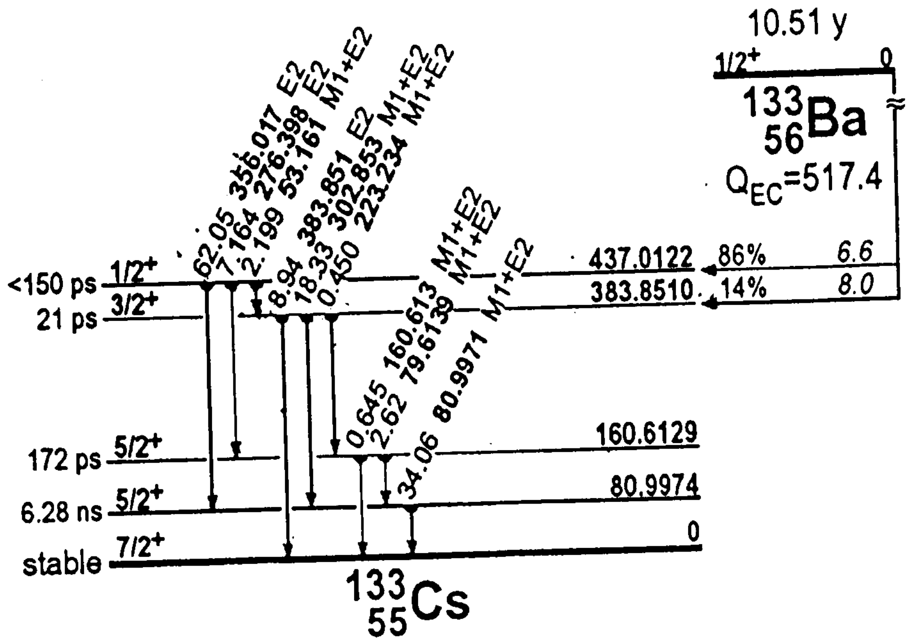
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14% 8.0
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383.8510
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0
<150 ps 1/2+
21 ps 3/2+
172 ps 5/2+
6.28 ns 5/2+
stable 7/2+
133 55 Cs
62.05 356.017 E2
7.164 276.398 E2
2.199 53.161 M1+E2
8.94 383.851 E2
18.33 302.853 M1+E2
0.450 223.234 M1+E2
0.645 160.613 M1+E2
2.62 79.6139 M1+E2
34.06 80.9971 M1+E2