Disintegration of Ba^{139}†

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The nuclear radiations from Ba^{139} have been investigated with the help of a magnetic lens spectrograph and scintillation counters in coincidence. Beta rays of energy 2.380, 2.227, and 0.822 Mev have been found together with an internal conversion line from a gamma ray of energy 0.163 Mev. The photoelectron spectrum, taken in the lens, showed gamma rays of energies 0.163 and 1.43 Mev. Beta-gamma coincidence experiments, performed with scintillation counters, showed that the 2.23-Mev beta-ray group is in coincidence with the 0.163-Mev gamma ray. The 0.163-Mev line has a $K/(L+M)$ ratio of 7.0 and an internal conversion coefficient α_K of 0.22, both of which correspond to an $M1$ transition. The connection with the shell model is discussed.

1. INTRODUCTION

A NUMBER of investigations of the radiations from Ba^{139} (85 min) have been carried out in the last few years, but none has led to a complete understanding of the disintegration scheme. Shepperd and Hill[1] used a magnetic lens spectrometer to measure the particle spectrum. They found a beta-ray distribution having an end-point energy of 2.27±0.02 Mev together with a K and an L internal conversion line for a gamma ray of energy 0.163 Mev. In addition they found a weak gamma ray of higher energy. Using a counter and absorption methods they estimated the energy of this gamma ray to be approximately 1.05±0.1 Mev. Shepperd and Hill made a Fermi plot of their data which appeared to support the idea of a single beta-ray group.

In the meantime, this element had been under investigation in this laboratory off and on, since 1948. The high-energy gamma ray was measured in a magnetic lens spectrometer, using the photoelectrons from a lead converter, and an energy of 1.46 Mev was found. The internal conversion line at 0.163 Mev was found in the investigation of the beta-ray spectrum. However, the Fermi plot of the beta rays did not give a straight line and it was surmised that there were several groups present. Coincidence work, done with ordinary counters, appeared to show that there were no gamma-gamma coincidences but that there were beta-gamma coincidences dependent on energy. In order to clear up these various difficulties it was decided to reinvestigate the spectrum of Ba^{139}.

2. EXPERIMENTAL RESULTS

Sources were prepared by bombarding barium metal with 11.5-Mev deuterons in the Indiana University cyclotron. The material was purified chemically, was separated, and used as $BaCrO_4$.

The beta-ray spectrum was investigated in a magnetic lens spectrometer. Since the half-life is 85 minutes the entire spectrum could not be investigated with one source. A number of separate runs were therefore taken and each was monitored to some convenient point on the beta-ray spectrum. The results of the investigation are shown in Fig. 1. A casual inspection of the beta-ray spectrum shows that it must be complex.

A Fermi analysis of the data was then made, and the results are shown in Fig. 2. The analysis suggests that there are two beta-ray groups having end-point energies around 2.3 Mev and differing by something of the order of magnitude of 0.150 Mev. In addition there is a group of considerably lower energy. The end-point energies, relative agundances, and values of log ft for the various groups are given in Table I.

The internal conversion line was measured carefully. Figure 3, in which the number of counts/min is plotted against the current in the lens, shows the profile of the line. The energy of the gamma ray responsible for the line is 0.163±0.001 Mev. From a plot of N/I *versus* I the value of $K/(L+M)$ was found to be 7.0±0.3. The

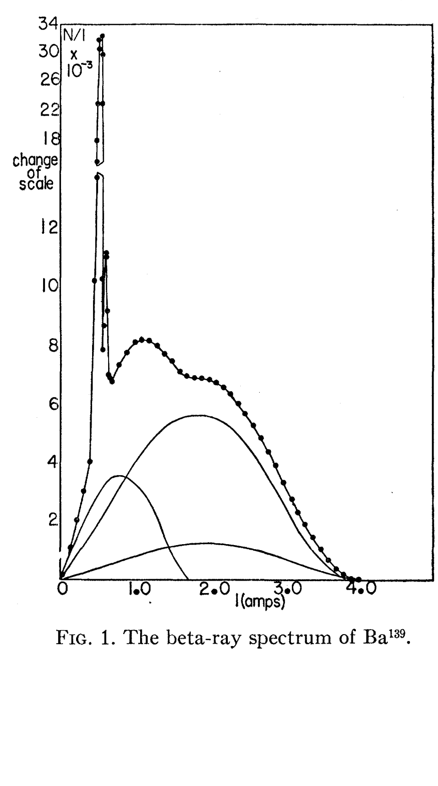

FIG. 1. The beta-ray spectrum of Ba^{139}.

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[1] L. R. Shepperd and J. M. Hill, Nature **162**, 566 (1948).

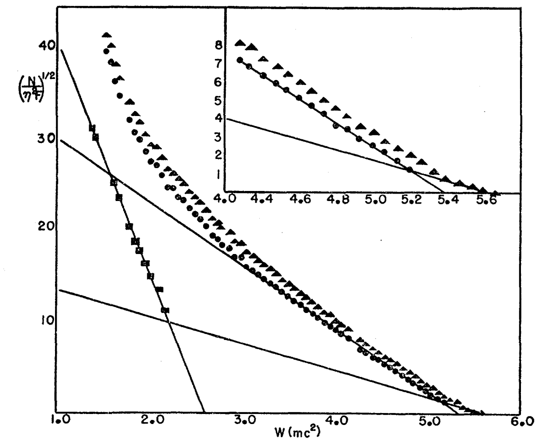

FIG. 2. Fermi plot of the beta rays of Ba^{139}.

determination of the internal conversion coefficient will be discussed in connection with the disintegration scheme.

The energy of the high-energy gamma ray was reinvestigated using a uranium radiator. Weak K and L photolines were found corresponding to a gamma ray of energy 1.43 ± 0.03 Mev.

3. EXPERIMENTS WITH SCINTILLATION COUNTERS; COINCIDENCE EXPERIMENTS

The gamma rays were also measured on a scintillation counter using a NaI(Tl) crystal, a Dumont 6292 photomultiplier tube, and a differential pulse-height analyzer. The pulse-height spectrum showed a high-energy gamma ray and the gamma ray at 0.163 Mev and no other gamma rays between these energies.

In order to check the results of the beta-ray analysis which showed that there are two high-energy beta-ray groups differing in energy by approximately the energy of the internally converted gamma ray, arrangements were made to do beta-gamma coincidence experiments using scintillation counters. The gamma rays were measured with the help of a NaI(Tl) crystal and photomultiplier tube. The beta rays were measured using an anthracene crystal and photomultiplier tube. The scintillation spectrometers were connected as shown in Fig. 4. Each branch of the circuit contained a preamplifier, linear amplifier, and differential pulse-height analyzer. The two branches were then fed to a coincidence circuit which had a resolving time of 0.2 microsecond. Arrangements were made to feed the singles output of either branch or the coincidence output to a fast scalar. The NaI(Tl) crystal used was a cylinder of 1-inch diameter and 1-inch height, and was canned in MgO. The anthracene crystal was a cube 2 cm on an edge.

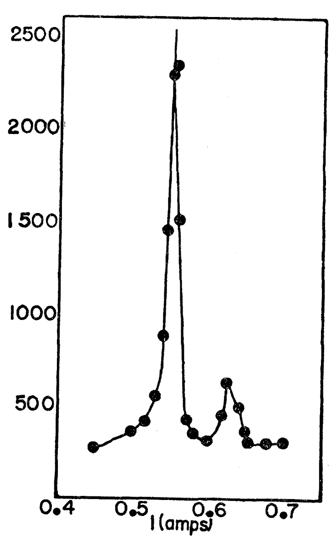

FIG. 3. Internal conversion line in Ba^{139}.

The use of an anthracene scintillation counter as a device for measuring beta-ray distributions was tested by measuring the beta-ray distribution from Cs^{137}. The experiments showed, in addition to the beta-ray spectrum, the internal conversion line corresponding to the gamma ray at 661 kev. The scintillation counter gives the number of particles in a given energy range $N(E)$. Since the resolving power of the scintillation

TABLE I. Beta rays of Ba^{139}.

End point energy Mev	Relative abundance percent	log ft
2.380	15.2	7.60
2.227	65.7	6.81
0.822	19.1	5.67

spectrometer goes like $(\epsilon)^{-\frac{1}{2}}$, where ϵ is the dial setting in volts associated with a given energy E, it follows that

$$N(E)=\epsilon^{\frac{1}{2}}N(\epsilon). \qquad (1)$$

A Fermi plot can therefore be made from the information obtained from $N(E)$ *vs* E. The energy calibration of the instrument is made from a measurement of the internal conversion line of Cs^{137}. The Fermi plot of the beta-ray distribution of Cs^{137} made in this way shows the well-known forbidden shape.

In order to measure coincidences between the gamma ray at 0.163 Mev and the high-energy beta rays of Ba^{139}, certain additional precautions had to be taken. Since the main interest in the experiment is in the neighborhood of the end point of the beta-ray spectrum (2.3 Mev) enough coincidences had to be obtained between the 0.163-Mev line and the beta rays to give statistically significant results. This entails the possibility that the high-energy end of the beta-ray spectrum may be distorted by pulse pileup from the large number of low-energy beta rays emitted by the source. In order to obviate this effect, an aluminum absorber, thick enough to stop all electrons of energy less than 1.1 Mev, was placed between the source and the anthracene scintillation spectrometer. In order to carry out the experiment it is necessary to know the number of chance coincidences in a given experiment, i.e., the resolving time of the apparatus. The resolving time was measured both with a double pulse generator and by measuring chance coincidences from a Cs^{137} source.

The experiments on Ba^{139} consisted in placing the source between the two scintillation counters. Channel 1, the NaI(Tl) scintillation spectrometer, was set on the 0.163-Mev line, while the scintillation spectrometer using the anthracene crystal was swept through various pulse-height settings in the neighborhood of the end point of the beta-ray spectrum. The coincidence counting rate was corrected for chance coincidences and the quantity $N_{\beta\gamma}/N_\gamma$ was used for making a Fermi plot of the coincidences. The results of the Fermi plot are shown in Fig. 5 together with a Fermi plot for the singles spectrum in the same region. It will be seen that the Fermi plot for the singles counts has a somewhat higher end point than that for the coincidence counts, showing that the 0.163-Mev gamma ray is in coincidence with the lower of the two high-energy groups. The actual end points obtained were 2.195 Mev for the singles and 2.050 Mev for the coincidences, giving a difference of 0.145 Mev. The actual values of the end points obtained are, of course, not as accurate as those obtained in the lens spectrometer, their actual values being dependent on the calibration with Cs^{137}. However, the difference between these two end points is significant. In this paper the more accurate values as determined by the magnetic lens spectrometer will be used.

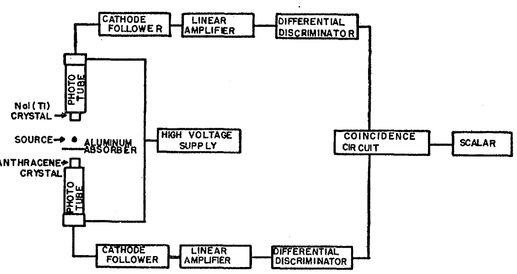

FIG. 4. Block diagram of scintillation spectrometers for beta-gamma coincidence work.

4. DISCUSSION OF RESULTS

The results of the investigations are embodied in the disintegration scheme of Fig. 6. The experiments showed that the highest-energy beta-ray group has an end point of 2.380 Mev and that the next lower beta-ray group, of energy 2.227 Mev, is in coincidence with the 0.163-Mev gamma ray. The difference in energy between these two beta-ray groups is, within the experimental error, equal to the energy of the 0.163-Mev gamma ray. The third beta-ray group feeds the high-energy gamma ray which presumably leads to the ground state.

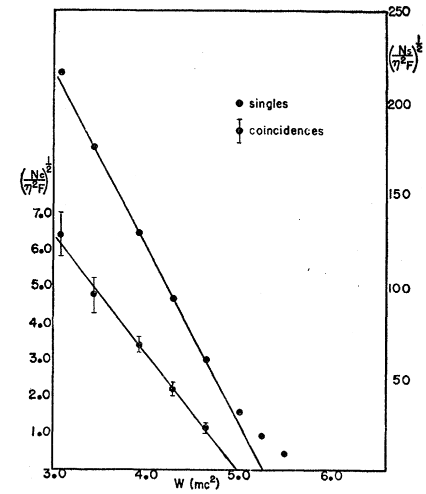

FIG. 5. Fermi plot for beta-gamma coincidences in Ba^{139}.

With the help of the disintegration scheme, it is now possible to calculate the internal conversion coefficient for the 0.163-Mev line. Knowing that the second beta-ray group feeds the line at 0.163 Mev, one can calculate the internal conversion coefficient in the K shell, α_K, from the ratio of the number of K-conversion electrons to the total number of electrons in the second group. The result gives $\alpha_K=0.22$. From the tables of Rose, Goertzel, and Perry[2] one finds that the value of $\beta_1=0.24$ agrees most closely with the measured value. Hence the 0.163-Mev line is magnetic dipole ($M1$). The value of the K/L ratio (7.0) also agrees quite well with that predicted from the empirical curves of Goldhaber and Sunyar[3] for $M1$ radiation ($K/L=7$).

It is now of interest to correlate these findings with what is to be expected from considerations of the shell model. The spin of the ground state of the product

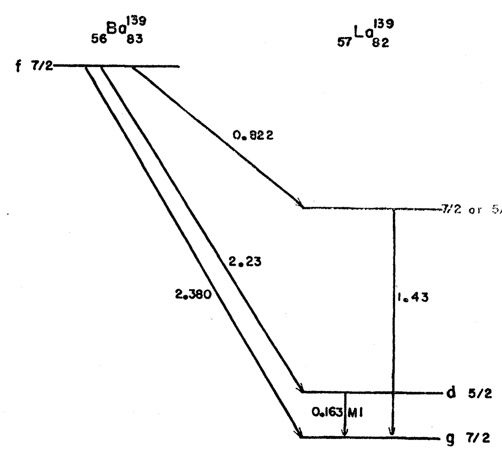

FIG. 6. Disintègration scheme of Ba^{139}.

[2] Rose, Goertzel, and Perry, Oak Ridge National Laboratory Report ORNL-1023, 1951 (unpublished).
[3] M. Goldhaber and A. W. Sunyar, Phys. Rev. 83, 906 (1951).

nucleus La^{139} has been measured and is 7/2, and the state is characterized as $g_{7/2}$. The log ft value for the 2.38-Mev group implies $\Delta I=0$, 1 yes. Taking the first possibility, the ground state of Ba^{139} is $f_{7/2}$. The fact that the internal conversion line at 0.163 Mev is $M1$ and that the log ft value for the second group is 6.8 definitely established that the first excited state of La^{139} is $d_{5/2}$. The beta-ray group of energy 0.822 Mev appears to be allowed, which would imply that the state at 1.43 Mev is odd and has a spin of 5/2 or 7/2. It is interesting to note that in the region of 57 protons the $g_{7/2}$ and $d_{5/2}$ states have nearly the same energy. In the present case the $d_{5/2}$ state lies above the $g_{7/2}$ by 0.163 Mev.

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Scattering of 14.1-Mev Neutrons in Helium, Hydrogen, and Nitrogen*

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Cloud-chamber studies have been made of the scattering of 14.1-Mev neutrons in helium, hydrogen, and nitrogen. For each of these gases the angular distribution of the elastically scattered neutrons has been obtained. The angular distribution in helium shows a minimum at about 110° in the center-of-mass system, with a large maximum representing forward scattering and a smaller maximum for backscattering. The hydrogen angular distribution is isotropic. Elastic scattering in nitrogen resembles diffraction scattering, showing a strong forward scattering maximum and smaller maxima at 70° and 180°, with minima close to 60° and 130°. Inelastic scattering in nitrogen does not depart from spherical symmetry by more than a factor of two. The elastic scattering cross section for nitrogen is 0.82 barn and the inelastic scattering cross section is 0.48 barn. Cross sections for two- and three-particle disintegrations are 270 and 16 millibarns, respectively.

I. INTRODUCTION

STUDIES of the scattering of neutrons by nuclei are important for the information they yield relative to the nuclear forces involved. Such studies can be made by observing the recoil nuclei. In the scattering of fast neutrons by light nuclei the recoil nucleus can receive an appreciable part of the energy of the incident neutron. The recoil energy is related to the energy of the incident neutron by the equation

$$E_r=E_n\{2\cos^2\phi+(1+1/M)Q/E_n\pm 2\cos\phi \times[\cos^2\phi+(1+1/M)Q/E_n]^{\frac{1}{2}}\}M/(M+1)^2, \quad (1)$$

where E_n is the energy of the incident neutron and E_r and M are the energy and mass, respectively, of the recoil nucleus, and ϕ is the angle of the recoil with respect to the incident neutron direction. Q is the energy released in the reaction and is negative for inelastic scattering, zero for elastic scattering.

When the target nuclei are contained in the gas of a cloud chamber, the paths of the recoils are made visible as tracks whose length and direction can be measured directly. If the range-energy relation for the recoil nucleus is known, the length of the track gives the energy of the recoil. The remaining unknown in (1) is Q, which is the negative of the excitation energy of the residual nucleus. Thus a cloud-chamber experiment makes possible a study of the inelastic scattering as well as the elastic scattering.

The present work is a cloud-chamber study of the scattering of 14.1-Mev neutrons in helium and hydrogen, where only elastic scattering is possible, and in nitrogen, where there is considerable inelastic scattering at this energy.

II. EXPERIMENTAL ARRANGEMENT

Monoenergetic 14.1-Mev neutrons were obtained from the $H^3(d,n)He^4$ reaction. The unresolved beam of deuterons from the Rice Institute Cockroft-Walton accelerator was used to bombard a target[1] of tritium absorbed in a 300-μg/cm² film of zirconium evaporated onto a tungsten disk. The accelerator was operated at about 160 kev. Molecular ions comprised approximately 80 percent of the beam, so that most of the deuterons incident on the target had energies of 80 kev. An aperture 5 mm in diameter was placed over the target to restrict the diameter of the beam and consequently the size of the neutron source. In each experiment the cloud chamber was placed at 90° to the deuteron beam. The energy spread over the angle subtended by the chamber was less than 0.1 Mev.

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† National Science Foundation predoctoral fellow.
‡ Now at Phillips Petroleum Company, Atomic Energy Division, Idaho Falls, Idaho.

[1] A. B. Lillie and J. P. Conner, Rev. Sci. Instr. 22, 210 (1951).