

## New Isotopes of Einsteinium\*

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The new isotopes  $E^{249}$ ,  $E^{250}$ ,  $E^{251}$ , and  $E^{252}$  were produced by bombardment of  $Bk^{249}$  with helium ions. A recoil method was used to separate the bombardment products from the target material, so that the target could be used repeatedly.

Approximate excitation functions for the formation of the einsteinium isotopes were measured as well as their half-lives,  $\alpha$ -particle energies, and electron-capture branching ratios.

### INTRODUCTION

THE bombardment of heavy-element nuclei with charged particles leads mainly to fission.<sup>1</sup> The cross sections of reactions such as  $(\alpha, xn)$  are therefore much lower for target nuclei of  $Z > 90$  than they are for lighter elements. The excitation functions of several reactions of the  $(\alpha, xn)$  and  $(\alpha, xp \gamma n)$  types have been studied for target nuclei up to  $Cm^{244}$ .<sup>1,2</sup> It is of some interest to investigate similar reactions with even heavier targets to see whether the same pattern of competition between fission and spallation is maintained.

In the work described herein, the 280-day  $\beta^-$ -emitting  $Bk^{249}$  was bombarded with helium ions from 20 to 40 Mev, and reactions of the type  $(\alpha, xn)$  were studied radiochemically. Such reactions can produce four previously unobserved isotopes of einsteinium (symbol E, atomic number 99) with mass numbers from 249 to 252.  $E^{248}$  could presumably be produced by  $(\alpha, 5n)$  reaction at the highest energies, but in fact it was not observed.

The production of  $Bk^{249}$  by multiple neutron captures and  $\beta^-$  decays, starting with  $Pu^{239}$ , has already been described.<sup>3</sup> The amount of  $Bk^{249}$  available was only  $1.2 \times 10^{-8}$  g, or about  $3 \times 10^{13}$  atoms. Hence it was necessary to use all of it in each bombardment, and to use the highest available helium-ion beam density in the Crocker Laboratory 60-inch cyclotron.

These requirements were met by using a deflector-channel target assembly previously developed for the production of the new element mendelevium (atomic number 101).<sup>4</sup> The target material was deposited as a very thin layer over a rectangular area  $0.6 \times 6$  mm on a 0.005-cm-thick gold foil. (This small target area was chosen to match the area of the most intense helium-ion beam.) The target area was exposed to a collimated helium-ion beam whose intensity varied from about 20 to  $75 \mu a/cm^2$ , depending on how well the cyclotron was

adjusted. The beam passed first through the gold foil and then through the  $Bk^{249}$  target, so that nuclear reaction products were ejected from the target in the forward direction. They were caught on a 0.00025-cm-thick gold "catcher" foil placed about 5.5 mm from the target foil. By this method it was possible to bombard the  $Bk^{249}$  target a large number of times without the necessity of dissolving it. Some 45 bombardments, many of them for as long as 9 hours, were made with no loss of target material.

The energy of the helium ions was varied by inserting aluminum degrading foils into the beam ahead of the target. The helium-ion beam intensity was measured with a Faraday cup placed behind the thin gold catcher foil. The  $Bk^{249}$  target also contained a known amount of  $Cm^{244}$ , from which  $Cf^{246}$  was produced by the  $(\alpha, 2n)$  reaction. From the known cross section for this reaction<sup>5</sup> and the measured amount of  $Cf^{246}$  finally separated from the catcher foil, the over-all yield was calculated for each bombardment. The yield value obtained in this way included both the recoil collection efficiency and the chemical handling loss. In almost every case, yields between 60 and 90% were obtained.

### EXPERIMENTAL

#### 1. Target Preparation

The recoil of  $At^{211}$  atoms produced by bombardment of  $Bi^{209}$  with helium ions was investigated by Chetham-Strode.<sup>5</sup> For helium ion energies of 20 to 40 Mev, he found that high ejection yields of nuclear reaction products should be obtained if the density of the target deposit was less than about  $30 \mu g/cm^2$ . Since the target area was only  $0.036 cm^2$ , the total weight of target and impurities could not be allowed to exceed  $10^{-6}$  g. Preliminary experiments with targets of  $Cm^{244}$  showed that it was possible in practice to obtain ejection yields very close to 100% for the  $(\alpha, 2n)$  reaction. The  $Cf^{246}$  produced in this case was found to be projected forward into a rather narrow cone.

Radiochemically pure  $Bk^{249}$  was isolated by precipitation and ion-exchange methods, which have been de-

\* This work was done under the auspices of the U. S. Atomic Energy Commission.

<sup>1</sup> Glass, Cobble, Carr, and Seaborg, *Phys. Rev.* **104**, 434 (1956).

<sup>2</sup> Chetham-Strode, Choppin, and Harvey, *Phys. Rev.* **102**, 747 (1956).

<sup>3</sup> Thompson, Ghiorso, Harvey, and Choppin, *Phys. Rev.* **93**, 908 (1954).

<sup>4</sup> Ghiorso, Harvey, Choppin, Thompson, and Seaborg, *Phys. Rev.* **98**, 1518 (1955).

<sup>5</sup> A. Chetham-Strode, University of California Radiation Laboratory Report UCRL-3322, 1956 (unpublished).

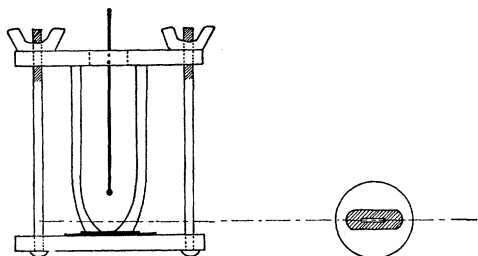


FIG. 1. Cell for electrodeposition of target.

scribed earlier.<sup>6</sup> At this point, a known amount of  $\text{Cm}^{244}$  was added. Final chemical purity was obtained by elution of the berkelium and curium with pure 6*M* hydrochloric acid through a bed, 4 cm by 0.3 cm in diameter, of purified Dowex-50 cation-exchange resin (4% cross-linked). By use of a very low flow rate of eluant, the berkelium and curium were eluted as a very sharp band in a volume of only about 0.1 ml. The solution was then evaporated to dryness.

The deposition of the mixture of  $\text{Bk}^{249}$  and  $\text{Cm}^{244}$  onto the gold target foil was made electrolytically. The Bk and Cm were dissolved in 6*M* ammonium chloride of high purity at a *pH* of about 2, and transferred to a cell in which the annealed gold target foil was the cathode. The bottom of the cell (Fig. 1) defined the area over which the target materials would deposit. A carefully cleaned platinum wire anode was used. A current density of about 1 amp/cm<sup>2</sup> of cathode surface, maintained for about 40 min, brought about the deposition of 80 to 90% of the target material onto the gold foil. After the ammonium chloride was rinsed off, the foil was washed with acetone and heated to a dull red to expel volatile substances. Finally it was fastened into a stainless steel holder (see Sec. 2) with Epon<sup>7</sup> resin.

The amount of  $\text{Bk}^{249}$  in the target was estimated by counting aliquots of the cell solution before and after the deposition. A windowless proportional counter was assumed to give a counting efficiency of 90% for the  $\beta^-$  particles from  $\text{Bk}^{249}$  mounted on thick platinum plates.

## 2. Cyclotron Probe

An expanded schematic view of the deflector-channel probe is shown in Fig. 2. The helium-ion beam was first collimated by means of the water-cooled copper and graphite collimator *A*. The second collimator *B* reduced the beam to the required size. The stainless steel holder *C* supported a 0.04-cm-thick duraluminum foil which sealed the rest of the probe assembly from the cyclotron vacuum. Aluminum absorber strips could be mounted behind the duraluminum foil. Holder *D* supported the target. The foils *C* and *D* were cooled by

means of rapid circulation of helium between them. The gold "catcher" foil *E* was mounted on the end of rod *F* with Scotch tape. The rod *F* terminated in a water-cooled aluminum block which served as the Faraday cup. The space between the target and the catcher foil was evacuated. The several cooling and vacuum systems were interlocked so that the cyclotron could not be operated until proper conditions were obtained.

The rod *F* could be very rapidly withdrawn after completion of a bombardment, so that no time was lost in examining the products. Holders *C* and *D* sealed into the assembly with O-rings so that they too could be readily withdrawn to permit a change of target or absorber.

The target and collimator *B* assembly could be moved vertically by remote control so that the most intense beam could be located. Cooling of the foils was adequate to permit a beam as large as 200  $\mu\text{a}/\text{cm}^2$  to be used over prolonged periods of time, but such intense beams were not commonly available.

## 3. Chemical Separations

At the end of a bombardment, the Faraday cup rod was removed and the catcher foil torn off. The foil was dissolved in a few drops of 8*M* hydrochloric acid containing a little nitric acid. The solution was then forced rapidly through a 5-by-0.3-cm bed of Dowex-1 anion-exchange resin. The resin bed was heated to 87°C by means of an outer jacket through which trichloroethylene vapor was circulated. Under these conditions, gold was very completely retained by the resin, while the tripositive actinide elements passed through. The resin bed was washed with a few drops of 8*M* hydrochloric acid.

The solution thus obtained was evaporated to dryness. The several actinide elements were then separated from one another by means of elution through a bed of Dowex-50 cation-exchange resin, with a solution of ammonium  $\alpha$ -hydroxy isobutyrate as eluant. This, and the other chemical procedures, have been fully described elsewhere.<sup>6</sup> The  $\alpha$  radioactivity of the separated actinide

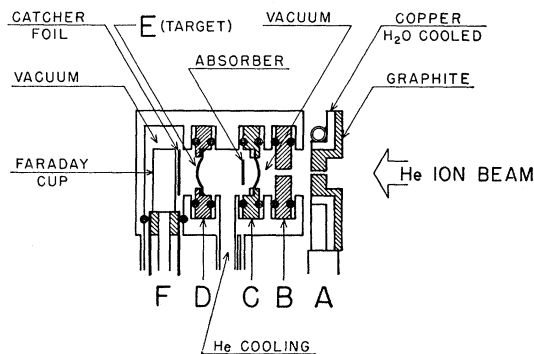


FIG. 2. Cyclotron target assembly (schematic).

<sup>6</sup> Thompson, Harvey, Choppin, and Seaborg, *J. Am. Chem. Soc.* **76**, 6229 (1954); Choppin, Harvey, and Thompson, *J. Inorg. Nuclear Chem.* **2**, 66 (1956).

<sup>7</sup> An epoxy resin supplied by Shell Development Company, Emeryville, California.

TABLE I. Nuclear properties of einsteinium isotopes.

Isotope	Type of decay <sup>a</sup>	Half-life	$\alpha$ -particle energy (Mev)	Ratio of electron capture to $\alpha$ branching
E <sup>249</sup>	E.C., $\alpha$	2 hr	6.76	760
E <sup>250</sup>	E.C., $\alpha$ ?	8 hr	Not observed	$\alpha$ not observed
E <sup>251</sup>	E.C., $\alpha$	1.5 days	6.48	190
E <sup>252</sup>	$\alpha$ , E.C.?	~140 days $t_{1/2}\beta^- > 20$ yr	6.64	E.C. not observed

<sup>a</sup> E.C. refers to electron capture.

element fractions was then examined with a gridded ionization chamber and pulse-height analyzer.

In experiments where the electron-capture activities were to be examined, further decontamination from radioactive impurities was required. The actinide element fraction from the Dowex-1 anion-exchange bed was purified by coprecipitation of the actinide elements with a carrier of lanthanum fluoride. The precipitate was redissolved in a saturated solution of boric acid. The actinide elements were further purified (and separated from the lanthanum carrier) by elution through a bed of Dowex-50 cation-exchange resin with saturated hydrochloric acid containing 20% ethyl alcohol.<sup>6</sup> The final separation of the actinide elements from one another was then made as described above. The full chemical procedure required about 2 to 2.5 hours.

#### NUCLEAR PROPERTIES OF EINSTEINIUM ISOTOPES

Four previously unobserved isotopes of einsteinium were produced in this work. Their mass assignments were made initially from the systematics of decay<sup>8</sup> and confirmed by means of excitation functions. Their properties are summarized in Table I.

The electron-capture decays were observed in a windowless proportional counter, for which a counting efficiency of 80% was assumed for thin samples mounted on platinum plates. It was not possible to measure the counting efficiency for any of the nuclides involved, but the assumed counting efficiency is based on the general experience of this laboratory.

The observed  $\alpha$ -particle energies (not necessarily ground-state transitions) of the known isotopes of californium and einsteinium are plotted against their mass numbers in Fig. 3. The einsteinium isotopes show a break associated with a neutron number of 152, which was first observed for the californium isotopes.<sup>9</sup> A similar break has also been observed for the isotopes of fermium.<sup>10</sup> (In Fig. 3, data are included for the recently discovered nuclides E<sup>248</sup> and Fm<sup>251</sup>.<sup>11,12</sup>)

<sup>8</sup> Glass, Thompson, and Seaborg, *J. Inorg. Nuclear Chem.* **1**, 3 (1955).

<sup>9</sup> Ghiorso, Thompson, Higgins, Harvey, and Seaborg, *Phys. Rev.* **95**, 293 (1954).

<sup>10</sup> A. Ghiorso *et al.* (unpublished); A. M. Friedman *et al.*, *Phys. Rev.* **102**, 585 (1956).

<sup>11</sup> A. Chetham-Strode and L. W. Holm, *Phys. Rev.* **104**, 1314 (1956), preceding paper.

<sup>12</sup> Harvey, Chetham-Strode, Holm, and Thompson (to be published).

The half-life measurements were most accurately made by resolution of proportional-counter decay curves such as that shown in Fig. 4. The decay of E<sup>252</sup>, however, was observed only by means of  $\alpha$ -pulse analysis, which yielded the decay curve shown in Fig. 5. The decay of the other nuclides was also studied by  $\alpha$ -pulse analysis to check the half-life values obtained in the proportional counter.

#### REACTION CROSS SECTIONS

The yields of the four new isotopes of einsteinium were measured in some experiments with a windowless proportional counter and in others by  $\alpha$ -pulse analysis. The accuracy of the cross-section measurements was limited to about  $\pm 30\%$  by (1) uncertainty in the amount of Bk<sup>249</sup> in the target (the very soft  $\beta^-$  activity of Bk<sup>249</sup> is not easy to count accurately, since the counting yield is very sensitive to the thickness of the sample), and (2) counting statistics in those experiments in which yields were measured by  $\alpha$ -pulse analysis. For example, less than 20 events of the 6.76-Mev  $\alpha$  particle of E<sup>249</sup> were usually observed.

The  $\beta^-$  decay of the Bk<sup>249</sup> produced Cf<sup>249</sup>, so that bombardment of the target yielded progressively larger amounts of Fm isotopes whose electron-capture decay produced further amounts of E<sup>250</sup>, E<sup>251</sup>, and possibly E<sup>249</sup>. Reactions such as Cf<sup>249</sup>( $\alpha, p2n$ )E<sup>250</sup> presumably also occurred.

The Bk<sup>249</sup> ( $\alpha, n$ ) and ( $\alpha, 2n$ ) reactions were studied at a time when the amount of Cf<sup>249</sup> in the target was negligible. The E<sup>250</sup> was produced by Bk<sup>249</sup>( $\alpha, 3n$ ), by Cf<sup>249</sup>( $\alpha, p2n$ ), and by Cf<sup>249</sup>( $\alpha, 3n$ )Fm<sup>250</sup>—E.C.—>E<sup>250</sup>. Although the atom ratio of Bk<sup>249</sup> to Cf<sup>249</sup> in the target was always larger than 2:1, a large fraction of the E<sup>250</sup> was probably produced by the Cf<sup>249</sup> ( $\alpha, p2n$ ) and ( $\alpha, t$ ) reactions, since reactions of this type appear to have unexpectedly large cross sections.<sup>13</sup> It was not possible

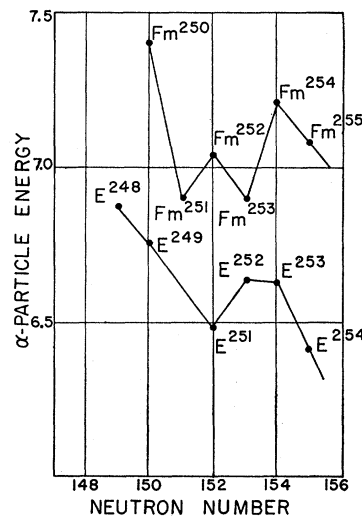


FIG. 3.  $\alpha$ -particle energy vs neutron number for  $Z=99$  to 100.

<sup>13</sup> W. A. Wade (private communication, 1956).

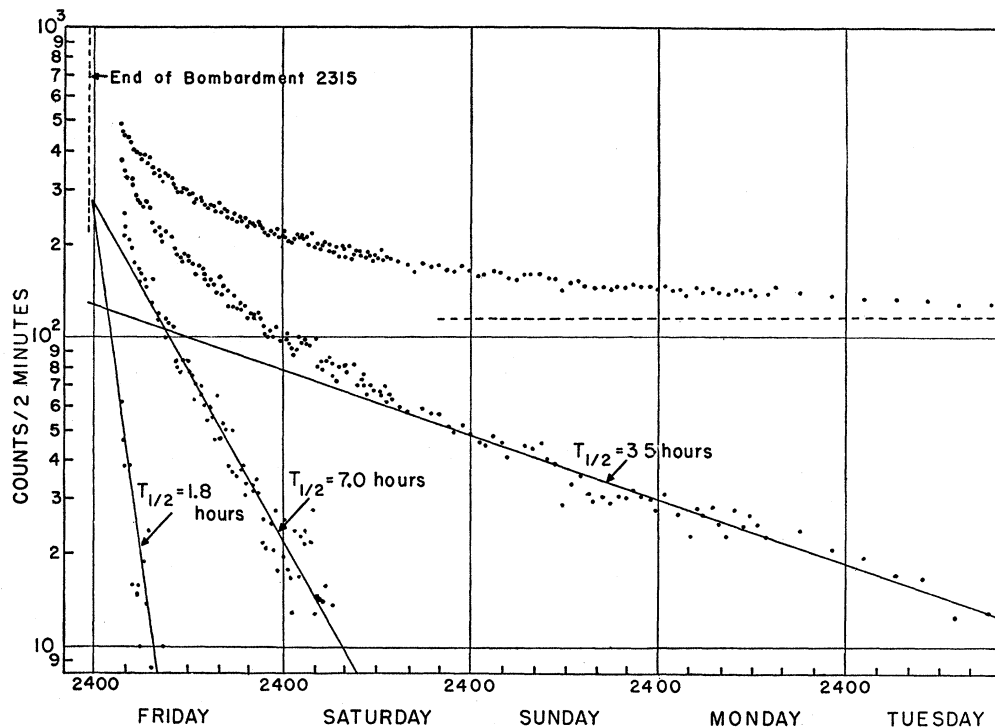


FIG. 4. Windowless proportional counter decay curve for sample containing  $E^{249}$ ,  $E^{250}$ , and  $E^{251}$ .

to distinguish between the various modes of production of  $E^{250}$ , so that the excitation curve shown in Fig. 6 is a sum of the cross sections and serves mainly to confirm the mass assignment of  $E^{250}$ . The cross sections given for the  $(\alpha, n)$  curve are based on the assumption that  $E^{252}$  is  $\beta$ -stable. This is almost certainly not true. Hence the cross sections for  $Bk^{249}(\alpha, n)E^{252}$  represent lower limits, but probably fairly close ones.

The  $(\alpha, n)$ ,  $(\alpha, 2n)$ , and  $(\alpha, 4n)$  curves in Fig. 6 are very similar in shape and magnitude to those obtained for other somewhat lighter nuclides such as  $Pu^{238}$  or  $Pu^{239}$ . The cross sections are comparable in magnitude, showing that fission is not rapidly superseding spallation as the  $Z$  and  $A$  of the target are increased. (For a more

detailed discussion, see reference 1.) The flatness of both the  $(\alpha, n)$  and  $(\alpha, 2n)$  curves is not readily to be explained by the usual compound-nucleus mechanism. To avoid fission or further particle evaporation, the residual nucleus must be left with less than about 6 Mev of excitation. This implies that much more energy is carried off by the neutrons in the  $(\alpha, n)$  and  $(\alpha, 2n)$  reactions than is required by an evaporation mechanism involving commonly accepted values for nuclear temperatures. The small peak in the  $(\alpha, 2n)$  curve might

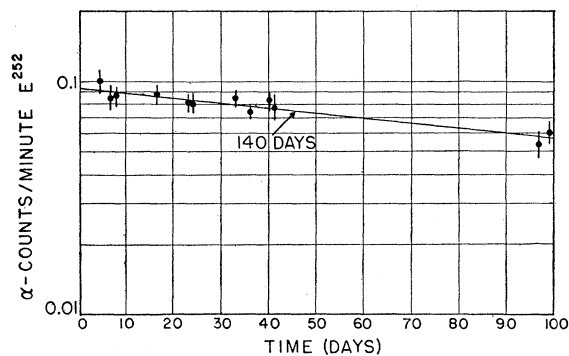


FIG. 5. Decay curve of 6.64-Mev  $\alpha$  activity of  $E^{252}$ .

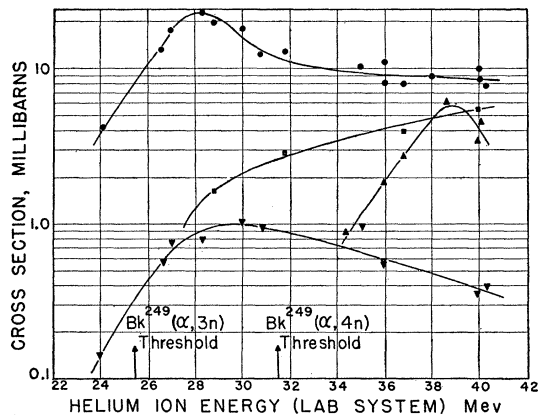


FIG. 6. Excitation functions for formation of einsteinium isotopes.  $\nabla$   $Bk^{249}(\alpha, n)E^{252}$ ;  $\bullet$   $Bk^{249}(\alpha, 2n)E^{251}$ ;  $\blacksquare$   $Bk^{249}(\alpha, 3n)E^{250} + Cf^{249}(\alpha, 3n)Fm^{250} \rightarrow E^{250} + Cf^{249}(\alpha, \beta 2n)E^{250} + Cf^{249}(\alpha, t)E^{250}$ ;  $\blacktriangle$   $Bk^{249}(\alpha, 4n)E^{249} + Cf^{249}(\alpha, \beta 3n)E^{249}$ .

then be attributed to a compound-nucleus-evaporation mechanism, while the long "tail" at higher energies must be due to a different mechanism—perhaps a direct interaction of the helium ion with one or two neutrons.

Such a non-compound-nucleus mechanism implies the transfer of less momentum to the reaction product, and hence implies that the recoil collection efficiency might be less than expected. However, the Bk<sup>249</sup> target deposit was sufficiently thin that recoils with much less than the full momentum would escape. (This was shown by measuring in several bombardments the small amount of Bk<sup>249</sup> ejected from the target by elastic and inelastic scattering processes, which gives a very sensitive measure of the thickness of the target.<sup>14</sup>) In addition, the

<sup>14</sup> A. Chetham-Strode (unpublished).

measurement of the yield of Cf<sup>246</sup> from the Cm<sup>244</sup> added to the target automatically compensated for any such effects insofar as they occurred equally for nuclear reactions of Bk<sup>249</sup> and for the ( $\alpha, 2n$ ) reaction of Cm<sup>244</sup>.

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We are especially indebted to Thomas C. Parsons for the production and primary purification of the Bk<sup>249</sup> target sample.

### Interaction of 1.0-, 1.77-, 2.5-, 3.25-, and 7.0-Mev Neutrons with Nuclei\*

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The differential cross sections for elastic scattering of 2.5-Mev neutrons by Al, Fe, Zr, Sn, Ta, and Bi were measured over the angular range from 15° to 160°. At 7.0 Mev similar measurements were made for Be, C, Al, Fe, Zr, Sn, Ta, and Bi at angles ranging from 12° to 150°. Inelastic collision cross sections were determined by sphere transmission measurements for a number of elements at 1.0-, 1.77-, 2.5-, 3.25-, and 7-Mev neutron energies.

By using an optical model of the nucleus, cross sections for elastic scattering and for compound nucleus formation were calculated. With suitable choices of the optical model parameters the calculated cross sections are in reasonable agreement with the experimental values.

#### I. INTRODUCTION

PREVIOUS measurements of fast-neutron interactions with nuclei have been interpreted with considerable success in terms of an optical model of the nucleus.<sup>1-4</sup> This model, which represents the nucleus by a complex potential well, can be used to calculate the total cross section, the differential cross section for elastic scattering, and the cross section for compound nucleus formation. Most calculations of this type have been done using a square potential well. Although the qualitative features of the cross-section variations with energy and with atomic weight were reproduced, this model failed in one notable respect. Namely, the cross sections for compound nucleus formation were significantly smaller than the experimental data indicated.<sup>2</sup> The source of trouble was thought to be the

sharp edge of the potential well, and rounding of the potential well was proposed. This refinement is identical to that introduced by Woods and Saxon<sup>5</sup> to interpret proton scattering experiments. The cross-section information available some time ago was extensive enough to indicate the limitations of the complex, square-well model. However, it has been apparent that additional cross-section data would be helpful in testing the more refined models of the nucleus since very often the available information has not been sufficient to define a unique set of nuclear parameters.

The investigation reported here was undertaken to measure differential cross sections for elastic scattering and inelastic collision cross sections in energy regions where experimental data were not available. Several measurements have been made in the past on the angular distributions of elastically scattered neutrons.<sup>2,6-9</sup> However, very limited experimental data

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<sup>1</sup> Feshbach, Porter, and Weisskopf, *Phys. Rev.* **96**, 448 (1954).

<sup>2</sup> M. Walt and J. R. Beyster, *Phys. Rev.* **98**, 677 (1955).

<sup>3</sup> Bjorklund, Fernbach, and Sherman, *Phys. Rev.* **101**, 1832 (1956).

<sup>4</sup> J. O. Elliot, *Phys. Rev.* **101**, 684 (1956).

<sup>5</sup> R. D. Woods and D. S. Saxon, *Phys. Rev.* **95**, 577 (1954); **101**, 506 (1956).

<sup>6</sup> W. D. Whitehead and S. C. Snowden, *Phys. Rev.* **92**, 114 (1953); **94**, 1267 (1954). Willard, Bair, and Kington, *Phys. Rev.* **98**, 669 (1955); A. Langsdorf and R. O. Lane, *Phys. Rev.* **99**, 621 (1955); W. J. Rhein, *Phys. Rev.* **98**, 1300 (1955); I. L. Morgan,