

鈾、鉛、金、鉑、鎢等元素被 21 Mev. 中子 打擊時的分裂截面的最高限度*

何澤慧

(中國科學院近代物理研究所)

照相乳膠的技術用來定 21 Mev. 中子打擊重元素時的分裂截面的最高限度, 這些元素的分裂截面比鈾²³⁸ 的分裂截面的 4×10^{-5} 還要小。

這個實驗結果與根據液球模型的分裂理論所推出的分裂閾, 不很符合, 但與錢三強簡單討論所推出的分裂時所需要的最低中子能力比較符合。

1. 引 論

根據原子核的液球模型, Bohr 與 Wheeler 由理論上曾推出比鈾更輕的元素被適當能力的中子打擊, 也會與鈾一樣的發生分裂現象, 並且可以算出對於每一種元素發生分裂現象所需要的最低的中子能力。

若鈾、鉛、金、鉑、鎢, 捉到一個中子後組成“組合核”, 組合核的分裂所需要的最低能力為 V . 如最後一個中子的結合能為 U , 則使這個組合核發生分裂現象所需要的最低的中子能力為

$$E_n = V - U$$

按 Bohr 與 Wheeler 的計算¹

$$V = \{10.18 (1-x)^3 - 4.62 (1-x)^4\} A^{2/3} \text{ Mev.}$$

$$x = 0.0209 Z^2 / A.$$

這裏的 A 是組合核的核子總數, Z 為此元素之質子數。

U 可以根據每個核子的結合能的半經驗公式算出², 如 ϵ 為每個核子的結合能

*中國科學院近代物理研究所論著叢刊甲集第七號。

$$\epsilon_A = 14.66 \left[1 - 1.40 \left(\frac{N-Z}{A} \right)^2 \right] + 15.4 A^{-1/3} + 0.602 A^{-4/3} Z^2$$

這裏 E 的單位是 Mev. N, Z, A , 是原子核中的中子數, 質子數, 和核子總數。這個公式中的原子核半徑是

$$R = 1.42 \times 10^{-13} A^{1/3} \text{ cm.}$$

它與由 Gamov 的 α 綫蛻變學說所計算出來的最重的那些原子核的半徑很符合。

如 M_A 為含 N 個中子和 Z 個質子的原子核的原子質量

$$M_A = N M_n + Z M_p - A \epsilon_A \begin{cases} + \frac{1}{2} \delta_A & (N \text{ 為奇數 } Z \text{ 為奇數}) \\ - \frac{1}{2} \delta_A & (N \text{ 為偶數 } Z \text{ 為偶數}) \\ 0 & (N \text{ 為偶數 } Z \text{ 為奇數}) \\ 0 & (N \text{ 為奇數 } Z \text{ 為偶數}) \end{cases}$$

δ 是 N, Z 的函數, 其數值由 Bohr 與 Wheeler¹ 估計出為

A	Z_A	δ_A (MEV)
180	72.9	1.2
190	76.4	1.1
200	80	1.1
210	83.5	1.1

加進一個中子後, 總質量為 $M_A + M_n$, 這個中子加入後, 組成組合核, 組合核的最穩定狀態的原子質量為

$$M_{A+1} = (N+1)M_n + Z M_p - (A+1) \epsilon_{A+1} \begin{cases} 0 & (N \text{ 奇. } Z \text{ 奇.}) \\ 0 & (N \text{ 偶. } Z \text{ 偶.}) \\ + \frac{1}{2} \delta_{(A+1)} & (N \text{ 偶. } Z \text{ 奇.}) \\ - \frac{1}{2} \delta_{(A+1)} & (N \text{ 奇. } Z \text{ 偶.}) \end{cases}$$

最後一個中子的結合能則為

$$U = M_A + M_n - M_{A+1} = (A+1)\epsilon_{A+1} - A\epsilon_A \begin{cases} +\frac{1}{2}\delta_A & (N \text{ 奇}, Z \text{ 奇}) \\ -\frac{1}{2}\delta_A & (N \text{ 偶}, Z \text{ 偶}) \\ -\frac{1}{2}\delta_{A+1} & (N \text{ 偶}, Z \text{ 奇}) \\ +\frac{1}{2}\delta_{A+1} & (N \text{ 奇}, Z \text{ 偶}) \end{cases}$$

計算得下列各原子核的 V , U , E_n 如下：

原子核	$V(\text{Mev})$	$U(\text{Mev})$	$E_n(\text{Mev})$
${}_{83}\text{Bi}$ 209	9.3	5.9	4.4
206	10.0	5.9	4.1
${}_{82}\text{Pb}$ 207	10.4	6.8	3.6
208	10.7	5.6	5.1
${}_{79}\text{Au}$ 197	11.6	6.0	5.6
194	12.1	6.0	6.1
${}_{78}\text{Pt}$ 195	12.5	7.1	5.4
196	12.9	5.9	7.0
198	13.7	5.6	8.1
182	14.3	6.3	8.0
${}_{74}\text{W}$ 183	14.6	7.3	7.3
184	15.2	6.0	9.2
186	16.0	5.7	10.3

Broda 和 Wright³, Broda⁴ 曾用 900 Kev 的氘打擊鋰，產生最高能力的中子約為 14 Mev. 他們利用了這些中子去打擊鈾與鉛，結果並沒找到分裂現象。Perlman, Göckermann, Templeton, 與 Howland⁵ 利用了 Berkeley 184 吋的迴旋加速器中產生的 400 Mev 的 α 粒子，200 Mev 的氘和 100 Mev 的中子，打擊原子序數自 78 到 83 的元素，結果每種元素都發生了分裂。

Kelly 與 Wiegand⁶ 用平均能力為 84 Mev 到 63 Mev 的中子，使鉑到鈾的元素都得到了分裂現象；用平均能力為 50 Mev 的中子，只有鉑鉛和鈾等元素得到了分裂現象；中子平均能力為 35 Mev 時，鉛與鈾可以分裂；而中子平均能力為 30 Mev 以下，25 Mev 左右，只有鈾還可以產生一些分裂現象。在平均能力為 25 Mev 的中子羣，能力分佈曲線上半高值的寬度為 13.7 Mev，因為分裂的激起曲線可能自分裂閾起突然的增長，因此中子羣的能力寬度使分裂閾能不容易明確，觀察到的分裂現象可能是由於能力分佈的較高部份的中子

所產生，分裂截面在分裂閾附近可能對能力的變遷很敏銳。

Phillips, Rosen 和 Taschek⁷ 曾經利用單純能力的 14 Mev 的中子打擊自然界存在的幾種重元素，定出它們分裂截面的最高限度，但是由於這些物質中的鈾雜質含量不確定性，統計標準錯誤達 100%，在這種不準確的條件下，他們所量出的分裂截面實在是小得難以測量（小於鈾核截面一萬分之一）。

上述的一些工作是最近關於原子量低於 83 的重元素的分裂可能性的研究，大多數都是沒有看到分裂現象，有些是不很確定，只有很高能力的中子才給了明確的分裂現象，我們感到值得試一試是否在 21 Mev 中子能力以下，可以使上述諸元素達到分裂閾；若是可以達到，則量一量它們的分裂截面。這個工作是在 Kelly 與 Wiegand 和 Phillips, Rosen 與 Taschek 的工作以前作的。

2. 實驗過程

我們用的照相板是 Ilford E₁，乳膠厚度為 20 μ ，這種照相版可以記錄分裂碎片的痕跡，但對於 α 粒子與質子的靈敏性很小，將這些照相版浸入下列各種元素的鹽的飽和溶液內：

乳酸 鈹
 醋酸 鉛
 綠化 金
 四綠化 鉑
 鎢酸 鈉

這些鹽在水中的溶解度不同，照相版在攪動的溶液中浸 30 分鐘，然後用蒸溜水洗過（但乳膠面不洗），使它乾，用這種方法，那些溶解度比較小的鹽，在乾後多少還黏在乳膠的表面上。

作為比較的標準照相板是用同樣的方法將照相板浸入 1% 的硝酸鈾裏。

每種元素在乳膠的單位面積上的濃度是用稱量法估計的，標準版的鈾量還用 α 粒子的計數作為校正。

⁸³ Bi	0.07 mg/cm ²	~ 3.4 × 10 ⁻⁷ gm - atom / cm ²	
⁸² Pb	0.28 ,,	~ 13.5 ,,	,,
⁷⁹ Au	0.16 ,,	~ 8.1 ,,	,,
⁷⁸ Pt	0.23 ,,	~ 11.8 ,,	,,
⁷⁴ W	0.12 ,,	~ 6.5 ,,	,,
⁹² U	0.02 ,,	~ 0.84 ,,	,,

重金屬的鹽浸入乳膠後，有時有一種減少照相板靈敏度的作用，因此我們必須知道，如有分裂碎片，是否那些浸了鹽的照相版還可以看得出，為了保證照相乳膠對於分裂碎片的靈敏性，我們另外作了一套與我們作實驗同樣浸鹽液的照相版，不過每片中再加了一些微量的鈾鹽，這些片受到中子打擊後，可以看出鈾分裂碎片的痕跡。

作實驗的那些照相版同時放在法國法蘭西學院迴旋加速器裏鐳靶的後面，游子是 7 Mev 的氬核，游子電流平均為 $10 \mu A$ ，照相版被中子射擊時間為 30 分鐘，這些照相版是裝在一個鐳的盒子裏，在鐳靶與它中間放了 5 cm 厚的鉛片，使 γ 線的作用減少。

3. 結 果

每片照相版在高倍顯微鏡下找了 1000 個視野，結果沒有看到一根分裂碎片的痕跡，在鈾標準版中每視野平均有六個分裂現象，假定那些版中 1000 個視野有少於一的分裂現象，那麼我們求得每種元素的分裂截面 (σ) 的最高限度當為：

$$\sigma < \sigma_{U^{238}} \frac{C_U}{C} \frac{N}{N_U}$$

$\sigma_{U^{238}}$ 為 U^{238} 的分裂截面

C_U 為鈾量在照相板上的濃度

N 為每一視野所產生的分裂碎片的痕跡數

N_U 為鈾標準版在每一視野所產生分裂碎片的痕跡數

$$\sigma_{Bi} < \frac{.84 \times 10^{-7}}{3.4 \times 10^{-7}} \times \frac{.001}{6} < 4.1 \times 10^{-5} \sigma_{U^{238}}$$

$$\sigma_{Pb} < \frac{0.84 \times 10^{-7}}{13.5 \times 10^{-7}} \times \frac{.001}{6} < 1.0 \times 10^{-5} \sigma_{U^{238}}$$

$$\sigma_{Au} < \frac{0.84 \times 10^{-7}}{8.1 \times 10^{-7}} \times \frac{.001}{6} < 1.7 \times 10^{-5} \sigma_{U^{238}}$$

$$\sigma_{Pt} < \frac{0.84 \times 10^{-7}}{11.8 \times 10^{-7}} \times \frac{.001}{6} < 1.2 \times 10^{-5} \sigma_{U^{238}}$$

$$\sigma_W < \frac{0.84 \times 10^{-7}}{6.5 \times 10^{-7}} \times \frac{.001}{6} < 2.1 \times 10^{-5} \sigma_{U^{238}}$$

4. 討 論

在我們的試驗中，用了能力比 21 Mev 小的中子打擊原子序數為 83 到 74 的原子核，結果沒有看到分裂現象，假如其中任何一原質的分裂閾在中子動能 21 Mev 以下，那麼雖然中子羣中只有十分之一的能力在 21 Mev 附近⁸，但是它的強度也應該够大，使我們可以看到分裂現象。Bohr 與 Wheeler 的計算指出 10 Mev 的中子動能已足够使所有這些元素發生分裂了（見表 1. 圖 2.）根據最近 Frankel 與 Metropolis⁹ 的計算，分裂閾所需要的中子動能推高了一些（見表 1. 圖 2. 這些數值是由 Frankel 與 Metropolis 計算出的鈾附近的元素分裂閾的曲線外推而估計出的）然而除鎢以外，其餘的元素分裂閾所需要的中子動能仍是該小於 20 Mev，這一點與實驗不符合。

為瞭解這個差異，錢三強¹⁰ 曾用分裂所能放出的能力與分裂碎片的動能的關係來解釋，他的解釋如下：

組合核 ${}_{92}\text{U}^{236}$ 分裂時所產生的碎片的動能最大實驗數值¹¹ 為 180 — 190 Mev。

另一方面在 $A = 50 - 150$ 的範圍內，Amaldi 和他的同工作者¹² 曾從實驗導出原子核的半徑應為

$$R = (1.52 A^{1/3} + 0.692) \times 10^{-13} \text{ cm} \quad (1)$$

我們知道 ${}_{92}\text{U}^{236}$ 分裂碎片最大可能性的數值¹³ 是

$$\left. \begin{array}{lll} A = 138 & Z_1 \sim 52 - 54 & R_1 = 8.6 \times 10^{-13} \text{ cm} \\ A = 96 & Z_2 \sim 38 - 40 & R_2 = 7.7 \times 10^{-13} \text{ cm} \end{array} \right\} \quad (2)$$

R_1, R_2 , 係由 (1) 式算出。

假定 A_1 與 A_2 為兩個球體，在未離開前，兩球相切，它們之間靜電排斥能力為

$$E_{\text{排斥}} = \frac{Z_1 Z_2 e^2}{R_1 + R_2} \sim 188 \text{ Mev}$$

這個數值與碎片的最大動能的實驗所得值非常符合，根據這點，我們可以說碎片的最大動能相當於最低激起狀態的碎片間的靜電排斥能力。

將這個結論，引用到我們的問題中，我們可以利用 Amaldi 的原子核半徑公式 (1) 求出鈾核等分裂時的碎片動能 (圖 1. E_{kin})。因為我們不知道它們如何分裂，為簡單起見，當它們是對稱分裂 ($A_1 = A_2$)。

另外根據質譜實驗的數據¹⁴，我們可以推算出，加進一個動能為零的中子後，鈾核等對稱分裂時可放出的能力，(圖 1. $E_{lib} + U$)。 U 為最後一個中子的平均結合能力，不管 N 和 Z 奇數偶數的關係。

在 E_{kin} 中減去 $E_{lib} + U$ 即得圖 2. 綫 (Tsien)。這線表示若是要使分裂所放出的能力真真能用，必需達到分裂時的動能，為要達到這個動能，我們最低限度必需加進綫 (Tsien) 所指出的中子動能。

綫 (Tsien) 是根據對稱分裂與 U 的平均數值而得，實際上很可能不是對稱分裂，各核的各種個別數值與平均數值會有些差異，這些因素可能使這個綫的數值錯誤到 5—10 Mev，但是在圖 2. 中，這曲線和 Bohr-Wheeler (B & W)，Frankel-Metropolis (F & M) 的曲線同時與實驗相比，我們覺得錢氏 (Tsien) 的曲線比較和實驗符合。在 $A = 200$ 附近，曲線 (Tsien) 有一個最高值，這是因為在 $A = 90 - 105$ 範圍內，“束緊分數”的圖綫的斜度比 $A = 180 - 210$ 時大一倍的關係^{14,15}。

這個工作的實驗部份是作者在巴黎的法蘭西學院原子核化學研究室中作的，作者對於研究室主任若利歐居里教授的領導及他給予種種研究方便，表示深忱的謝意。中國科學院近代物理研究所所長錢三強先生對此問題感覺興趣，作者對於他的有用的討論致謝。

UPPER LIMITS OF THE FISSION CROSS-SECTIONS OF BISMUTH, LEAD, GOLD, PLATINUM AND TUNGSTEN FOR 21 MEV NEUTRONS*

By HO ZAH-WEI

Institute of Modern Physics, Academia Sinica, Peking.

(Received March 11, 1951)

ABSTRACT

The emulsion technique was used to set certain upper limits for the fission cross sections of some naturally occurring heavy elements bombarded with 21 Mev neutrons. It is established that the fission cross-sections for these elements (Bi, Pb, Au, Pt and W) are less than 4×10^{-5} of that of U^{238} . These results are in disagreement with the fission threshold derived from the theory of fission based on the liquid drop model for heavy nuclei, but support a simple argument about the minimum neutron energy required to produce fission by Tsien San-Tsiang.

I. INTRODUCTION

Bohr and Wheeler¹ have shown, by theoretical considerations based on the liquid drop model for heavy nuclei, that it ought to be possible to cause fission by bombarding elements of atomic number 83 or less with neutrons of sufficiently high energy. Numerical calculation² based on Bohr and Wheeler's theory gives for the threshold energy V for the compound nucleus (formed by neutron capture) to fission the following relation

$$V \text{ (in Mev)} = \left\{ 10.18 (1-x)^3 - 4.62 (1-x)^4 \right\} A^{2/3}$$

where $x=0.0209 Z^2/A$,

Z and A referring to the compound nucleus. The minimum kinetic energy E_n required to produce fission is therefore given by $E_n=V-U$, where the binding energy U for the last neutron of the compound nucleus can be calcula-

* Contributions from the Institute of Modern Physics, Academia Sinica, Series A, No. 7.

1. Bohr and Wheeler, *Phys. Rev.* **56** (1939), 426.
2. Mattauch and Fluegge, *Kernphysikalische Tabellen* (Berlin 1942).

ted from² the semiempirical formula for the binding energies of heavy nuclei as follows:

The mass M_A of a nucleus with mass number $A=N+Z$ containing N neutrons (each of mass M_n) and Z protons (each of mass M_p) is given by²

$$M_A = NM_n + ZM_p - A\epsilon_A \begin{cases} + 0.5\delta_A & (N \text{ odd}, Z \text{ odd}) \\ 0 & (N \text{ odd}, Z \text{ even}) \\ 0 & (N \text{ even}, Z \text{ odd}) \\ - 0.5\delta_A & (N \text{ even}, Z \text{ even}) \end{cases}$$

where the binding energy ϵ_A per particle is given by² (in Mev)

$$\epsilon_A = 14.66 \left\{ 1 - 1.40 \left(\frac{N-Z}{A} \right)^2 \right\} + 15.4 A^{-1/3} + 0.602 Z^2 A^{-4/3}.$$

The expression for the nuclear radii corresponding to the above formula for ϵ_A is $R=1.42 \times 10^{-13} A^{1/3}$ cm, which is in good agreement with Gamow's theory of α -decay. The values for δ_A have been estimated by Bohr and Wheeler¹ as follows:

$\delta_A=1.2$ Mev for $A=180$, $\delta_A=1.1$ Mev for $A=190, 200$ and 210 .

Now, by applying the above semiempirical formula to the capture of a neutron by the initial nucleus of mass number A , so as to form a compound nucleus of mass number $A+1$, we get, for the binding energy U of the last neutron, the expression

$$U = M_A + M_n - M_{A+1} = (A+1)\epsilon_{A+1} - A\epsilon_A \begin{cases} + 0.5\delta_A & (N \text{ odd}, Z \text{ odd}) \\ + 0.5\delta_{A+1} & (N \text{ odd}, Z \text{ even}) \\ - 0.5\delta_{A+1} & (N \text{ even}, Z \text{ odd}) \\ - 0.5\delta_A & (N \text{ even}, Z \text{ even}) \end{cases}$$

Values for V , U and E_n thus calculated for the heavy nuclei used in the present experiment are tabulated below.

The body of experimental evidences, however, shows very poor agreement with the above theoretical prediction. Broda and Wright³, also Broda⁴,

3. Broda and Wright, *Nature* **158** (1946), 871.

4. Broda, *Nature* **158** (1946), 872.

TABLE 1. Values for E_n , according to Bohr and Wheeler's theory

Initial nucleus	V (Mev)	U (Mev)	E_n (Mev)
$^{209}_{83}\text{Bi}$	9.3	5.9	4.4
$^{206}_{82}\text{Pb}$	10.0	5.9	4.1
$^{207}_{82}\text{Pb}$	10.4	6.8	3.6
$^{208}_{82}\text{Pb}$	10.7	5.6	5.1
$^{197}_{79}\text{Au}$	11.6	6.0	5.6
$^{194}_{78}\text{Pt}$	12.1	6.0	6.1
$^{195}_{78}\text{Pt}$	12.5	7.1	5.4
$^{196}_{78}\text{Pt}$	12.9	5.9	7.0
$^{198}_{78}\text{Pt}$	13.7	5.6	8.1
$^{182}_{74}\text{W}$	14.3	6.3	8.0
$^{183}_{74}\text{W}$	14.6	7.3	7.3
$^{184}_{74}\text{W}$	15.2	6.0	9.2
$^{186}_{74}\text{W}$	16.0	5.7	10.3

bombarded Bi and Pb with neutrons produced by 900 kev deuterons hitting a lithium target. The maximum value for the energy of the neutrons thus produced is about 14 Mev, but they found no positive evidence of fission of Bi or Pb. Perlman, Goeckermann, Templeton and Howland⁵, by using particles from the 184-inch cyclotron at Berkeley, namely 400 Mev α -particles, 200 Mev deuterons and 100 Mev neutrons, did observe fissions of all elements with atomic number Z between 78 and 83. Kelly and Wiegand⁶ also observed fission of elements from Pt to Bi when neutrons with their mean energy about 84 Mev. With neutrons with mean energy of 50 Mev, fissions were observed only for Tl, Pb and Bi, while with neutrons with mean energy of 35 Mev, fissions were observed only for Pb and Bi, and with neutrons with energy below 30 Mev and about 25 Mev, fissions were observed only for Bi. Here the energy distribution of the neutrons used possessed a rather broad maximum, for example, the total energy width at half-maximum being 13.7 Mev for the neutrons with mean energy about 25 Mev. Since the true excitation curve might rise abruptly from zero yield at a certain energy of the neutron, the threshold point would be obscured by the spread in the energy distribution of the neutron beam used, because the number of fissions observed might come from the high energy tail of the neutron energy distribution. Phillips, Rosen and Taschek⁷ attempted to determine the upper limits of

5. Perlman, Goeckermann, Templeton and Howland, *Phys. Rev.* **72** (1947), 351.

6. Kelly and Wiegand, *Phys. Rev.* **73** (1948), 1135.

7. Phillips, Rosen and Taschek, *Phys. Rev.* **75** (1949), 919.

the fission cross sections of certain naturally occurring heavy elements below radium by bombarding these with a 14 Mev monoenergetic neutron source. They concluded, in view of the uncertain uranium contamination, that the fission cross sections at 14 Mev neutron energy for these elements are less than 10^{-4} of that for uranium.

In what follows we shall present some similar negative results obtained in 1947 by the present writer, for neutrons of 21 Mev energy.

2. EXPERIMENTAL PROCEDURE

The plates used were Ilford E_1 plates of emulsion thickness 20μ . Such plates records fission tracks and has a low sensitivity to α -particles and protons. The plates were loaded with salts of the following elements,

- Bi as Bismuth lactate,
- Pb as Lead acetate,
- Au as Gold chloride,
- Pt as Platinum tetrachloride,
- W as Sodium tungstate.

All these salts are more or less soluble in water. The plates were immersed in saturate solutions of the above salts for 30 minutes with agitation, then rinsed in distilled water (but not the emulsion surface) and dried. By this process, the less soluble salts would remain more or less on the surface of the emulsion. For comparison, monitor plates were made by impregnation with uranyl nitrate one percent solution.

The area concentration of the above heavy elements for the various plates was estimated gravimetrically. The concentration of uranium for the monitor plate was also checked by making an α -particle count. The results obtained for the area concentration are as follows, where conversion from the salts to the elements have been made already.

Conc. of <i>Bi</i>	= 0.07 mg/cm ²	= 3.4×10^{-7} gm-atom/cm ²
„ „ <i>Pb</i>	= 0.28 „	= 13.5 „ „ „ „
„ „ <i>Au</i>	= 0.16 „	= 8.1 „ „ „ „
„ „ <i>Pt</i>	= 0.23 „	= 11.8 „ „ „ „
„ „ <i>W</i>	= 0.12 „	= 6.5 „ „ „ „
„ „ <i>U²³⁸</i>	= 0.02 „	= 0.84 „ „ „ „

It was found that emulsions loaded with heavy metals were somewhat desensitized. Hence a special check was applied to find whether fission tracks would be visible in the loaded plates. Plates identical with those in the main experiments but containing small amounts of uranium in addition were exposed to neutrons, and the presence of the fission tracks was established.

The plates were irradiated simultaneously with neutrons from the lithium target of the College de France cyclotron, bombarded with 7 Mev, $10 A\mu$ deuterons, for half an hour. The plates were held in a cadmium box put behind a 5 cm lead shield to diminish the γ -ray fog.

3. RESULTS

In each plate 1000 fields of view were searched for fission tracks, but none was found. The number of fission tracks in the monitor plate was found to be about six tracks per field of view. The fission cross section for the heavy elements investigated can be determined, relative to the fission of U^{238} , by using the simple formula

$$\frac{\sigma}{\sigma_U} = \frac{N C_U}{N_U C},$$

where σ denotes the fission cross section for a certain element, C denotes the concentration of this element in the emulsion, and N denotes the average number of fission tracks found per field of view. The suffix U refers to the element U^{238} . With $N_U=6$, $N<.001$, and the various values for the concentration of the elements given above, we get

$$\sigma_{Bi} / \sigma_U < 4.1 \times 10^{-5}$$

$$\sigma_{Pb} / \sigma_U < 1.0 \times 10^{-5}$$

$$\sigma_{Au} / \sigma_U < 1.7 \times 10^{-5}$$

$$\sigma_{Pt} / \sigma_U < 1.2 \times 10^{-5}$$

$$\sigma_W / \sigma_U < 2.1 \times 10^{-5}$$

4. DISCUSSION

In this experiment, elements of atomic number varying from 83 to 74 have been bombarded by neutrons of energy $E_n \leq 21$ Mev, in which about 10 per cent neutrons are with energy about 21 Mev⁸. If any one of the elements

8. Richards, *Phys. Rev.* **59** (1941), 796.

investigated has a threshold E_n for fission below 21 Mev, fission tracks should have been observed.

According to Bohr and Wheeler's calculation, 10 Mev neutrons are sufficient to make all the elements investigated here fissionable, (cf. Table 1, also the curve marked with B & W, fig. II). Frankel and Metropolis⁹, extending Bohr and Wheeler's calculation with the aid of an electronic calculator, have pushed the fission threshold a little higher, (cf. the curve marked with F & M, fig. II. These values are estimated by extrapolation of the fission threshold for nuclei near uranium.) But the minimum neutron energy required to cause fission in elements of atomic number higher than that of tungsten is still below 20 Mev, being only about 10 Mev for Pb and Bi. These theoretical predictions are not in agreement with the negative experimental results obtained by Broda and Wright, by us, and by Phillips, Rosen and Taschek.

Tsien¹⁰ has given an explanation for the higher neutron energy required to cause fission. The argument is briefly as follows. Suppose on fission the compound nucleus splits itself into two daughter nuclei in contact which separate subsequently from each other by Coulomb repulsion. If this picture is correct, the total kinetic energy of the two fission fragments after separation will equal the Coulomb energy of the two daughter nuclei initially in contact. Now for the slow neutron fission of U^{235} , the experimental value for the total kinetic energy of fission fragments is about 180–190 Mev¹¹. For the fission products, in the region of $A=50$ to 150, we may use the empirical formula for the nuclear radii deduced by Amaldi and his coworkers¹² from other experiments.

$$R = (1.52 A^{1/3} + .692) \times 10^{-13} \text{ cm}$$

For the daughter nuclei, we take, using the most probable fission fragments¹³,

$$A_1 = 138, Z_1 \sim 52 - 54, \text{ so } R_1 = 8.6 \times 10^{-13} \text{ cm},$$

$$A_2 = 96, Z_2 \sim 38 - 40, \text{ so } R_2 = 7.7 \times 10^{-13} \text{ cm},$$

R_1 and R_2 being calculated from the above formula. Assuming approximately spherical shape for the daughter nucleus, the Coulomb energy before separation is calculated to be

9. Frankel and Metropolis, *Phys. Rev.* **72** (1947), 914.

10. Tsien San-Tsiang, *J. de Phys. et Rad.* **9** (1948), 6.

11. Jentschke, *Zeits. f. Physik*, **120** (1943), 165; Flammersfeld, Jensen and Gentner, *Ibid.*, 450.

12. Amaldi and Cacciapuoti, *Phys. Rev.* **71** (1947), 739; Amaldi, Bocciairelli, Cacciapuoti and Trabacchi, *Nuovo Cimento*, **3** (1946), 203.

13. Plutonium plant, *Rev. Mod. Phys.* **18** (1946), 441.

$$\text{Coulomb energy} = Z_1 Z_2 e^2 / (R_1 + R_2) \sim 188 \text{ Mev,}$$

in excellent agreement with the experimental value for the total kinetic energy of the fragments after separation. The above picture for fission is thus justified for the compound nucleus U^{236} .

If we assume the above picture of fission also for the compound nucleus formed by neutron capture from Bi, or Pb, . . . , we can similarly derive, with the help of Amaldi's formula of nuclear radii, the total kinetic energy E_{kin} of the fission fragments after separation. For simplicity, calculation is made for symmetrical fission, $A_1 = A_2$, and the results are plotted in Fig. 1.

From the experimental data¹⁴ obtained with mass spectrograph, we can deduce the energy liberation for a symmetrical fission of the compound nucleus formed by the capture of a neutron of zero kinetic energy. The results are plotted in Fig. 1, marked with $E_{lib} + U$.

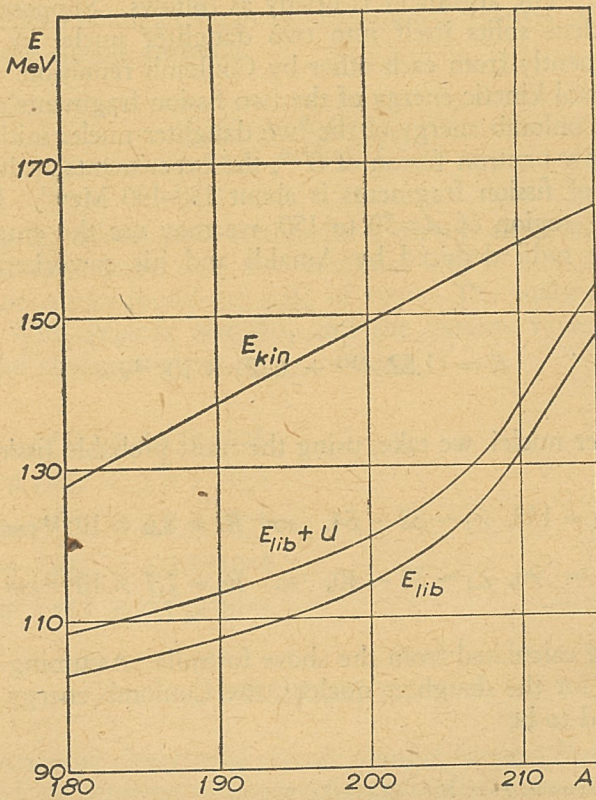


Fig. 1

14. Dempster, *Phys. Rev.* **53** (1938), 869; Hahn, Flugge and Mattauch, *Physik. Zeit.* **41** (1940), 1.

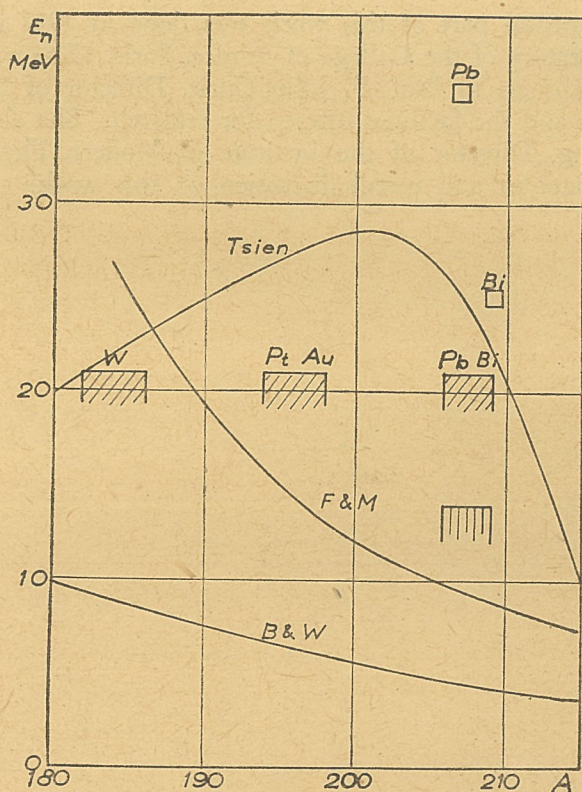


Fig. 2

- Fission observed (Kelly and Wiegand)
- ▨ Fission not observed (Ho Zah-Wei)
- ▩ Fission not observed (Broda and Wright, Phillips, Rosen and Taschek)

The difference between E_{kin} and $E_{lib} + U$ gives the minimum kinetic energy E_n of the neutron required for producing fission in accordance with Tsien's picture. This is plotted in Fig. 2, marked with Tsien, for comparison with Bohr and Wheeler's theory and the various experimental results. Considering that the fission is very probably asymmetrical, and that experimental data for a particular nucleus generally deviate from the average trend, the curves of Fig. 2 might at places be in error by 5 to 10 Mev. All the same, it seems that Tsien's curve agrees better with all the experimental results obtained so far. The appearance of a maximum in Tsien's curve near $A=200$ is due to the fact that the slope of the packing fraction curve in the region of $A=90-150$ is twice as big¹⁵ as that in the region of $A=180-210$.

15. Feenberg, *Rev. Mod. Phys.* **19** (1947), 239.

The experimental part of this work was done in 1947 in the Nuclear Chemistry Laboratory of the College of France, Paris. The author wishes to express her indebtedness to Prof. F. Joliot-Curie, Director of the Laboratory, for his direction and the facilities offered for research. She also thanks Prof. Tsien San-Tsiang, Director of the Institute of Modern Physics, Academia Sinica, for his interest and useful discussion on this work.