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ATOMIC WEAPONS RESEARCH ESTABLISHMENT

AWRE REPORT No. O - 58/61

Light Mass Yields in the 14 MeV Neutron Fission of U-235

D. G. Vallis

uranium

A. O. Thomas

January, 1962

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United Kingdom Atomic Energy Authority

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Light Mass Yields in the 14 MeV Neutron Fission of U-235

D. G. Vallis
A. O. Thomas

Summary

    By irradiating targets of highly enriched U-235 with
14.7 MeV neutrons produced by D,T reaction in the
Aldermaston Cockroft-Walton accelerator, the fission yields
of Br-82, Br-83, Br-84, Se-81m, As-77, Ga-73, Zn-72 and Ni-66
were determined relative to that of Mo-99. A determination
of the absolute fission yield of Mo-99 was made under the
same experimental conditions by irradiating mixtures of iron
and U-235 solutions followed by measurement of the activities
of Mo-99 and Mn-56 produced by fission and (n,p) reaction
respectively. A value of 5.2 ± 0.5% was obtained in good
agreement with the previously published figure of 5.17%.

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1. INTRODUCTION

The latest compilation of fission product yields, that of Katcoff [1], gives the known fission yields in the 14 MeV neutron fission of U-235. Although the yields in the peak and trough regions have been determined by several workers [2 - 4] yields of the light masses below mass 82 have not been measured previously. Katcoff drew a fission yield curve, which when extrapolated to light masses, using the single known point at mass 83, exhibits an increase in the most asymmetric modes of fission compared with the curve for thermal neutron fission of U-235.

Ford et al. [2] and Wahl [3] measured fission yields by the "R-value" method in which the ratios of fission products from the 14 MeV neutron fission were compared with the corresponding ratios from thermal fission. This method has the advantage that if parallel measurements of yields in the two types of fission are carried out, the necessity for absolute counting is avoided. However, in the present work, the various product yields have been compared with that of Mo-99. The decay schemes of the nuclides of interest are fairly well known and it is therefore possible to calculate counter efficiencies using a generalised function of efficiency versus average energy appropriate for a given counter. Furthermore, the low-yield fission products in the thermal neutron fission of U-235 have received somewhat less attention than the high yield products and any errors in their values would be reflected in the corresponding values for 14 MeV neutron fission if the "R-value" method were used. Finally, the value of the absolute fission yield of Mo-99 in 14 MeV neutron fission has been determined previously and the value obtained was confirmed in the present work under the same conditions of experiment as for the measurement of the other yields. The method used was to compare the disintegration rates of Mo-99 formed in fission and of Mn-56 formed by (n,p) reaction in the same target solution and therefore in the same 14 MeV neutron flux.

2. EXPERIMENTAL

2.1 Irradiations

The source of 14 MeV neutrons was a "thick" Zr-T target bombarded by 200 kV deuterons in the Aldermaston Cockcroft-Walton accelerator. The neutrons produced in the H-3(d,n)He-4 reaction entered the U-235 specimen over a solid angle of nearly 2π about the axis of the deuteron beam.

The close proximity of neutron source and U-235 was necessary
to overcome the disadvantage of the low neutron output, i.e.,
$5 \times 10^9 - 2 \times 10^{10}$ n/s. Furthermore, in some experiments
it was necessary to irradiate large masses of U-235, i.e.,
100 mg - 1 g in order to obtain sufficient activities of
the low-yield fission products.

In each experiment, U-235 was irradiated as uranyl
nitrate or chloride in nitric or hydrochloric acid solution
contained in a thin-walled 2 ml capacity Perspex cell. The
approximate dimensions of the disc-shaped cavity containing the
liquid were 25 mm diameter by 3 mm thick with a wall thickness
of 0.5 mm. The cell was placed in front of the accelerator
drift tube so that its cavity was concentric with and separated
from the Zr-T target by an air-gap of about 0.5 mm. During
irradiations cold air was blown through this gap to prevent
damage to the Perspex cell by the hot target.

The average energy of the neutrons entering the
uranium was calculated from the data of Benveniste and
Zenger [5]. By integrating the function for $E_I.(E_o, \varphi)$
with respect to φ between $-\pi/2$ and $+\pi/2$ the average

neutron energy in the above experimental arrangement was
found to be 14.7 ± 0.2 MeV, where φ is the lab. angle made
by the velocity vector of the neutrons with beam direction
and E_o is the incident deuteron energy in MeV.

During irradiations the neutron flux was monitored
at frequent intervals by counting the α particles emitted in
the D-T reaction in a small geometry at an angle of 177° to
the deuteron beam. Although it was not necessary to determine
the absolute value of the neutron flux in order to obtain
fission yields relative to Mo-99, the α counting results gave
a measure of the slow decline of the flux during irradiation.
The greatest rate of the decline observed during any experiment
was about 12% of the initial flux per hour. Usually it was
found that the decline in flux was an exponential function
with respect to time. Two main reasons are usually given
for this apparent "poisoning" of the target during irradiation.
Firstly, progressive deposition of carbonaceous material
on the Zr-T target produces a degradation of deuteron energy.
This effect decreases the depth of the site of resonance
adsorption of deuterons in the target. Secondly, tritium
may diffuse through and evaporate from an overheated target.
Both of these effects probably occur simultaneously making
it difficult to predict the flux decay rate theoretically.
However, using the observed half-life for the flux decay
in each experiment it was possible to make small corrections
to the observed fission product yields. Clearly, the

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induced fission product activity may be considered to be the daughter of a long-lived parent, i.e., the declining neutron flux, rather than the product of a constant-rate reaction.

The isotopic composition of the enriched U-235 was as follows:- U-235, 92.86; U-238, 5.76; U-234, 1.20; and U-236, 0.18 atoms %. The uranium was purified by adsorption of the chloride in 7M HCl on an anion exchange column of Amberlite CG400 resin followed by elution at 0.5 M HCl. After ignition of the chloride to U_3O_8, the uranium was extracted into diethyl ether as uranyl nitrate from saturated NH_4NO_3 solution 0.5N to HNO_3. The uranyl nitrate was ignited to U_3O_8 in a tared silica crucible and a stock solution of uranyl chloride of accurately known uranium concentration was prepared from the weighed oxide.

2.2 Radiochemical Purification Procedures

Well-known procedures are only described briefly. In all cases, radiochemical separations were carried out using 1 mg of carrier element.

Bromine

The method used was that of Feldman et al. [6]. The final aqueous extract containing Br^- in the presence of $NaHSO_3$ was made alkaline with 1N NaOH and sources were prepared from known weights of this solution. Portions of the remaining solution each containing 20 - 100 µg bromine were analysed for the determination of chemical yield using a micropotentiometric tritration of Br^- with $AgNO_3$ between silver/silver bromide and calomel electrodes.

Radiochemical purification was not commenced earlier than 15 min from the end of the irradiation in the 32m Br-84 measurements so that the 3m Se-84 could decay completely. Similarly, chemical treatment was delayed by 3 h in the 2.3 h Br-83 measurements to allow nearly complete decay of its precursor: 25 m Se-83.

Arsenic

Arsenic carrier was added to the fission product solution as sodium arsenate. The solution was allowed to stand 3 days to allow complete growth of 39h As-77 from 12h Ge-77. As^V was reduced to As^{III} in 1N HCl solution by bubbling SO_2 through the solution. (Molybdenum was removed by precipitation of the α-benzoin oxime complex.) After boiling off SO_2 and extracting excess α-benzoin oxime with $CHCl_3$, As_2S_3 was precipitated by bubbling H_2S gas. The

sulphide was washed with water and redissolved in 6M NH_4OH and a few drops of 30% H_2O_2 solution. After boiling, the solution was made 2N to both HCl and HI and arsenious tri-iodide was extracted into $CHCl_3$. Arsenic was then back-extracted into 1M H_2SO_4. The solution was transferred to a small distillation flask (Figure 1) where it was made strongly alkaline by the addition of a few pellets of sodium hydroxide. A piece of pure aluminium was then dropped into the vessel and nitrogen slowly bubbled through the solution. Upon warming the solution, arsine was evolved and carried in the stream of nitrogen into the electrically heated portion of a silica tube. A narrow black band of arsenic appeared in the silica tube just beyond the heating element and the complete transfer of arsenic to the tube occurred in about 5 min. The arsenic was dissolved in 6M HNO_3 and evaporated to dryness. The final solution of arsenious oxide in 1N NH_4OH was used for source preparation and spectrophotometric determination of chemical recovery. Weighed portions of the solution containing 20 - 60 μg arsenic were analysed by a method depending on the molybdenum blue colour obtained by reduction of the arsenomolybdate complex [7].

Selenium

Selenium was purified by the method of Winsberg and Glendenin [8] involving distillation of the bromide and repeated precipitations of the element by SO_2 gas from the 6M HCl solution. The purification procedure was started after a sufficient time, i.e., 3 h, had elapsed from the end of the irradiation for primary 18m Se-81, 69s Se-83 and 25m Se-83m to have decayed to negligible proportions. From the final metal precipitate a solution was prepared in 1M H_2SO_4 for source preparation and chemical yield determination. To a portion of the solution containing 40 - 80 μg selenium as H_2SeO_3 was added 20% KI solution and the excess iodine was back-titrated with 0.01 N $Na_2S_2O_3$ solution to a colourless end-point in the presence of starch indicator.

Manganese

Manganese was separated by passing the fission product solution in 4M HCl through an anion exchange column of Amberlite CG400 resin. Molybdenum, iron and uranium were retained by the column. The effluent containing manganese was evaporated to dryness and fumed with concentrated perchloric acid. The manganese was then extracted as the diethyldithiocarbamate complex from a solution 0.5M to HCl and 1.5M to ammonium acetate. After thorough washing with a 0.5M HCl:1.5M NH_4Ac mixture, the complex was destroyed by evaporation with aqua regia. A solution of the manganese

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in 1M HCl and 6M NH₄Cl was scavenged with neodymium and zirconium by precipitating their hydroxides by the addition of 6M NH₄OH solution. H₂S was then bubbled through the solution to precipitate MnS. The ion-exchange separation was repeated by passing the manganese through the column in 9M HCl and after evaporation of the effluent to dryness the manganese was redissolved in a mixture of 1M HCl and 6M NH₄Ac. 1 mg of cadmium carrier was added and precipitated by the passage of H₂S through the solution. The manganese in the supernatant solution was converted once more to the diethyldithiocarbamate complex and extracted into CHCl₃. After washing the organic layer as before, the complex was destroyed with aqua regia and the manganese was dissolved in 1M HNO₃ for counting and chemical yield determination. The yield was determined by a spectrophotometric method depending on the permanganate ion colour [9].

Molybdenum

The procedure employed alternative precipitations of the α-benzoin complex from 1M HCl solution and scavenging precipitations of iron and neodymium carriers in 1N NaOH solution. The final oxime precipitate was fumed with concentrated $HClO_4$ and HNO_3. The residue of MoO_3 was dissolved in 0.1N NH₄OH solution for source preparation and measurement of recovery by a spectrophotometric method depending on the colour of the molybdenum thioglycollate complex [10].

Gallium

The active solution was evaporated with gallium carrier to dryness with concentrated $HClO_4$. The residue was dissolved in 7.5M HCl and the solution passed through an anion exchange column similar to those already described. Gallium was eluted with 1M HCl and three molybdenum scavenges were performed on the eluant by precipitating 1 mg quantities of molybdenum carrier with α-benzoin oxime. Gallium ferrocyanide was precipitated, washed with water, and fumed to dryness with concentrated $HClO_4$ then with concentrated HBr solution. The gallium was then extracted as the chloride from 7.5M HCl into diethyl ether from which it was back-extracted into water. Two scavenges each with 1 mg iron and 1 mg neodymium were carried out in 0.1N NaOH solution. Gallium was finally precipitated by bubbling CO_2 through the slightly alkaline solution. The hydroxide was dissolved in 0.1M HCl.

The chemical recovery was determined by a method quoted by Sandell [7] and modified by Herrington (AWRE private communication) in which gallium hydroxyquinolate is measured

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spectrophotometrically at a wavelength of 395 mμ.   The
sample weights of gallium for these determinations were in
the range 20 - 100 μg.

Zinc

Zinc was first adsorbed on an anion exchange
column of Amberlite CG400 resin from 2M HCl.   The column
was washed with 1M and 0.5M HCl and the zinc eluted with
0.02M HCl.Zn was then precipitated as the mercuric thiocyanate
complex from the weakly acid effluent.   The precipitate was
washed with the ammonium mercuric thiocyanate reagent and
dissolved in the minimum quantity of concentrated HCl.
Addition of more reagent reprecipitated the zinc complex
which was again washed with reagent and fumed to dryness
with concentrated $HClO_4$ and concentrated HBr.   The residue
was dissolved in 1M HCl and made neutral to methyl red
indicator by the dropwise addition 1M NaOH.   10% aqueous
quinoline α-carboxylic acid solution was added to precipitate
the zinc complex which was washed firstly with reagent and
then with water and finally dissolved in 6M HCl.   The zinc was
adsorbed from the 6M HCl solution on an anion exchange
column similar to the one previously used and the same series
of elutions carried out.   To the final effluent containing
the zinc was added 1M Na_2CO_3 solution.   The precipitate
of $ZnCO_3$ thus formed was washed with water and dissolved in
0.1M HNO_3 for source preparation.   The zinc recovery was
determined by a micro-coulometric method of Steed and Monk (AWRE
private communication).   A mercury-EDTA solution containing
the zinc sample (5 - 20 ug) buffered at pH 10.5 with ammonia
solution was electrolysed at constant current using a mercury
cathode.   The end point was detected by a sharp rise in the
potential difference between a pair of polarised mercury
electrodes.   The elapsed time of electrolysis was proport-
ional to the amount of zinc present.

Nickel

The nickel diethyldithiocarbamate complex was
first extracted into $CHCl_3$ from ammoniacal citrate solution.
The organic layer was washed repeatedly with ammoniacal
citrate solution and the complex was destroyed with aqua
regia.   A sulphide scavenge from a 0.3M HCl solution of
palladium, silver and cadmium was then performed and the
supernatant liquid containing nickel was passed straight
through an anion exchange column similar to those used in
the previous procedures.   Pyridine and 10% NH_4CNS solution
were added to the effluent from the column.   The precipitate
of nickel pyridine thiocyanate was dissolved in $CHCl_3$, the
solvent layer washed with 1% NH_4CNS solution and the nickel

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back-extracted into 2M HCl. The diethyldithiocarbamate
extraction procedure was then repeated followed by destruction
of the complex with aqua regia. The residue was dissolved
in 1M HCl, neodymium scavenge was added and the solution
made alkaline with 10% (NH₄)₂CO₃ and 6M NH₄OH solutions.

The Nd(OH)₃ precipitate was rejected and the
extraction of nickel as the diethyldithiocarbamate complex
was repeated. After destruction of the complex with
aqua regia the nickel was extracted as the α-furyldioxime
complex from ammoniacal citrate solution into CHCl₃. The
organic layer was then washed with water, acidified with
1M HCl and thoroughly mixed with 10% sodium diethyldithio-
carbamate solution. The organic layer was washed with
water and the complex again destroyed with aqua regia.
The nickel was dissolved in 0.1M HCl. The chemical
recovery was determined using a spectrophotometric method
[7] depending on the colour of the oxidised nickel
dimethylglyoxime complex.

2.3 Preparation of Iron-Uranium Solution Mixtures

A spectrographically standardised iron rod,
obtained from Johnson Matthey and Company Ltd., was cleaned
by abrasion and washed with alcohol. Approximately 5 g.
of the iron was cut off, weighed and dissolved in 7M HCl to
give a solution containing 91.90 mg iron/g. Because the
work was carried out over a period of several months the
iron concentration in the solution was checked gravimetrically
at a later date.

The method used was precipitation of the hydroxide
and ignition to Fe₂O₃. The mean result of these analyses
was 91.40 ± 0.20 mg iron/g. It was assumed, therefore,
that the strength of the solution had remained the same
throughout the period of investigation.

In each of the four irradiations in which the
Mo-99 fission yield was determined, accurately weighed
quantities of each of the iron and U-235 solutions were
mixed and quantitatively transferred to the iradiation cell.

2.4 Counters and Counting Techniques

The counters and counting techniques used in this
laboratory have been described by the authors [11] in a
separate report. Two types of end-window β counter were
used; the low background Van Duuren type and a flow proport-
ional counter. Both counters were calibrated over a wide
range of β energy against 4π and βγ coincidence counting
techniques. Counter efficiencies for the activities of

interest were calculated from the efficiency versus average energy curves and the known decay schemes as in the method of Bayhurst and Prestwood [12]. For Mo-99 and Mn-56, however, the proportional counter was calibrated by comparison with a 4π counter.

2.5 Method of Calculation

The fission yield of the product studied is given by

$$Y_B = Y_A \frac{I_B}{I_A} \cdot \frac{(1 - e^{-\lambda_A t})}{(1 - e^{-\lambda_B t})} , \qquad \dots (1)$$

where Y_B is the yield of the species to be calculated;

Y_A is the yield of Mo-99, in this work taken to be 5.17%;

I_A is the observed activity, at the end of irradiation, of Mo-99 in d/m;

I_B is the observed activity, at the end of irradiation, of the species to be calculated, in d/m;

λ_A is the disintegration constant of Mo-99 in m^{-1};

λ_B is the disintegration constant of the species to be calculated in m^{-1};

t is the irradiation time in min.

Corrections must be applied to take account of the observed exponential flux decay and the amounts of species A and B formed by fission of the U-238 component in the enriched U-235. Owing to the small abundances of U-236 and U-234 in the uranium, the effect of fission of these isotopes has been neglected. Some of the yields of the corresponding fission products in the 14 MeV neutron fission of U-238 were estimated by extrapolation to light masses of data in the Katcoff compilation [1]. Below and including mass 77, where it is difficult to extrapolate the known data, the yields in U-235 and U-238 fission were assumed to be equal.

Equation (1) then becomes

$$Y_B = \frac{I_B}{I_A} \cdot \frac{\lambda_A}{\lambda_B} \cdot \frac{(\lambda_B - \lambda_C)}{(\lambda_A - \lambda_C)} \cdot \frac{(e^{-\lambda_C t} - e^{-\lambda_A t})}{(e^{-\lambda_C t} - e^{-\lambda_B t})} \cdot \frac{(\sigma_1 Y_A + \sigma_2 X Y_A')}{\sigma_1}$$

$$- \frac{(\sigma_2 X Y_B')}{\sigma_1}, \qquad\qquad\qquad \dots (2)$$

where λ_C is the apparent "disintegration constant" of the neutron flux;

σ_1 is the fission cross-section in cm^2 for U-235 with 14.7 MeV neutrons;

σ_2 is the fission cross-section in cm^2 for U-238 with 14.7 MeV neutrons;

Y_A' is the fission yield of Mo-99 in the fission of U-238 by 14.7 MeV neutrons, taken to be 5.70% in this work;

Y_B' is the fission yield of the species to be calculated, in the fission of U-238 by 14.7 MeV neutrons;

X is the ratio of U-238 to U-235 by atoms in the uranium used in the experiments.

In those experiments in which the yield of Mo-99 (Y_A) was calculated from the yield of Mn-56 in the Fe-56 (n,p)Mn-56 reaction, equation (2) becomes:-

$$Y_A = \left[\frac{I_A}{I_D} \cdot \frac{\lambda_D}{\lambda_A} \cdot \frac{(\lambda_A - \lambda_C)}{(\lambda_D - \lambda_C)} \cdot \frac{(e^{-\lambda_C t} - e^{-\lambda_D t})}{(e^{-\lambda_C t} - e^{-\lambda_A t})} \frac{N_3 \sigma_3}{N_1 \sigma_1} \right] - \frac{(N_2 \sigma_2 Y_A')}{(N_1 \sigma_1)}$$

$$\dots (3)$$

where N_1 is the number of U-235 atoms bombarded;

N_2 is the number of U-238 atoms bombarded;

N_3 is the number of Fe-56 atoms bombarded;

I_D is the activity in d/m of Mn-56 at the end of irradiation;

λ_D is the disintegration constant of Mn-56 in m^{-1};

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σ_3 is the Fe-56(n,p)Mn-56 cross-section in cm^2 at 14.7 MeV.

All other symbols have the same meanings as in equations (1) and (2).

In the Br-83 determinations the irradiation time (t) was 15 min in one experiment and 2 h in the other. If the Br-83 yield is calculated using equations (1) or (2) there is an inherent assumption that its precursor has a half-life negligibly small compared with the value of t. This would be the case if 69s Se-83m were the sole precursor. However, if K_1 is the fractional yield of 69s Se-83m and K_2 that of 25m Se-83, the ratio of the fission yield calculated by assuming complete formation of Br-83 from Se-83m to that calculated taking the branching mechanism into account, is given by

$$\frac{1 - e^{-\lambda_3 t}}{K_2\lambda_3 \left[1 - (\lambda_2 e^{-\lambda_3 t} - \lambda_3 e^{-\lambda_2 t}) \; (\lambda_2-\lambda_3)\right] + K_1(1 - e^{-\lambda_3 t})},$$

where λ_2 is the disintegration constant in m^{-1} of Se-83;

λ_3 is the disintegration constant in m^{-1} of Br-83;

and the neutron flux is assumed to be constant.

From the Katcoff [1] tables K_2/K_1 is 0.76 for the thermal neutron fission of U-235. Croall and Willis (AERE, private communication) obtained a value for this ratio of 0.62 for thermal neutron induced fission and 1.41 for 20 MeV proton induced fission. In the present 14 MeV neutron work, K_2/K_1 was not determined, but it probably falls between these two values. However, the thermal neutron fission value (0.62) was taken to make the small correction to the Br-83 yields found in this work. The accuracy of the yield results depends on the validity of this assumption and it is estimated that the Br-83 results have an error of about ± 15% of the quoted values.

3. RESULTS

Table 1 shows the results of the fission yield determinations. If more than one determination was made, the "best value" is the median, except for Br-84 results where lower values are given less statistical weight. The latter were derived from short irradiations, i.e., 5 and 10 min, whereas the first value was derived from a 2 h irradiation in which the precursor activity Se-84, with uncertain half-life of the order 2 - 3 min attains saturation activity early in the irradiation.

In Figure 2 the fission yield curve is plotted to include the new yield values. Also shown are the "mirror" or "reflected" points obtained in the heavy mass region. The mass for symmetric fission used to obtain the reflected points was 115.7 given by

$$\text{sym. mass} = \frac{(235 + 1 - v)}{2}.$$

A value of v for 14 MeV fission of U-235 of 4.7 ± 0.5 was obtained by Protopopov and Blinov [13]. Summation of the whole fission yield curve gave 204.8% fission yield.

The accuracy of the determination of the absolute fission yield of Mo-99 by the irradiation of mixed iron and U-235 solutions depended on the values of the cross-sections for fission of U-235 and for the Fe-56(n,p)Mn-56 reaction used in the calculations. A value of 2.30 barns was used for the fission cross-section in the initial calculations.

Chittenden et al. [14] have recently published a list of values for the (n,p) cross-section obtained by several workers using neutrons of energy in the range 14.1 - 15 MeV. There is a considerable variation in the published results, but the median value is about 114 mbarns which was also used in the initial calculations. Values of 4.82, 5.18, 5.18 and 5.61% were obtained for the Mo-99 yield in the four experiments, giving a mean value of $5.2 \pm 0.5\%$. A more recent value of 2.15 barns for the fission cross-section has become available during the course of this work, obtained from the excitation function of fission of U-235 by fast neutrons published by Adams, Batchelor and Green [15]. In order to obtain good agreement between our Mo-99 yield results and the previously published result of 5.17% the (n,p) cross-section should now be 107 ± 5 mbarns, which is in close agreement with 105 ± 5 mbarns obtained from the excitation function curve of Hughes and Schwartz [16] probably the best evaluation of all available data. These experiments have therefore demonstrated the facility with which an absolute fission yield may be determined by radiometric comparison of rates of fission and n,p reaction in the same medium. This technique would be of value in the measurement of the yields of a short-lived fission product which is difficult to determine relative to that of another "standard" fission product when formation of the latter, by β-decay of its precursor activities, is disturbed by the necessarily early chemical treatment.

4. CONCLUSIONS

It may be seen from Figure 2 that the new fission yields lie on a smooth continuous curve in the light mass region of the yield mass distribution. This curve "reflected" in the heavy mass wing nearly superimposes the single existing point for the yield of Eu-156, although the fission product yields of the rare earth elements are required to complete the curve.

The total chain yield for mass 82 may be found by interpolation of the fission yield curve and a value of $0.50 \pm 0.05\%$ obtained. Using the observed independent yield of Br-82 of $(5 \pm 1) \times 10^{-4}\%$ the fractional chain yield is found to be $(1.0 \pm 0.2) \times 10^{-3}$. This value agrees reasonably well with the value of 1.6×10^{-3} obtained by Ford et al. [2] using the "R-value" method. Ford et al. found that the known fractional chain yields for the 14 MeV neutron fission of U-235 including those obtained by Wahl [3] for I-131, Te-131m, Te-131, I-132, I-133, Te-133 and I-134, could be fitted to a fractional chain yield versus $Z-Z_p$ curve similar to the curve for thermal neutron fission. The assumptions were made that the Equal Charge Displacement Hypothesis [17] holds for both thermal and 14 MeV neutron fission, that the distribution of charge is independent of fragment mass and that one neutron is emitted from each fragment in thermal neutron fission whereas in 14 MeV neutron fission 2 neutrons are emitted from the light fragment and 3 neutrons are emitted from the heavy fragment. This latter assumption is reasonable in view of the fact that the values of ν in thermal and 14 MeV neutron fission are approximately 2 and 5 respectively.

The total chain yield for mass 81 may also be obtained by interpolation and is found to be 0.35%. It may be concluded, therefore, that the yield of Se-81 is the difference between the total chain yield for mass 81 and the observed yield of Se-81m, i.e., 0.30%. The ratio of the yields of Se-81 to Se-81m is then 5.9. Considering also the values obtained by Croall and Willis for this ratio in other types of fission it may be seen from Table 2 that the result for 14 MeV neutron fission confirms the trend in increasing yield of the high-spin isomer with increasing energy of fission.

5. ACKNOWLEDGMENTS

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bombardments.   We also acknowledge the co-operation of Mr. J. Gray and the other members of the operating staff of the accelerator.   Valuable assistance was also given by Mr. K. C. Steed who determined the chemical yields in the radiochemical analyses.

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TABLE 1

Yields Relative to Mo-99 Yield (=5.17%)

Product	Fission Yield, %	Best Value
32m Br-84	1.03	1.03
	0.99	
	0.93	
2.3h Br-83	0.86	0.83
	0.80	
35.9h Br-82	6.0×10^{-4}	5×10^{-4}
	4.0×10^{-4}	
57m Se-81m	0.071	0.051
	0.053	
	0.048	
	0.044	
39h As-77	0.072	0.068
	0.064	
5h Ga-73	0.0115	0.0115
	0.0114	
49h Zn-72	0.0078	0.0078
56h Ni-66	4.0×10^{-4}	4.0×10^{-4}

TABLE 2

Ratios of Yields of Se-81 Isomers for Different Modes of Fission

Fissile Isotope	Particle	Se-81/Se-81m
U-235	Thermal neutrons	28
U-233	Thermal neutrons	~23
U-235	14 MeV neutrons	~5.9
U-235	20 MeV protons	1.75

Labels in figure: SILICA TUBE, As, HEATING COIL, N₂, N₂+As H₃
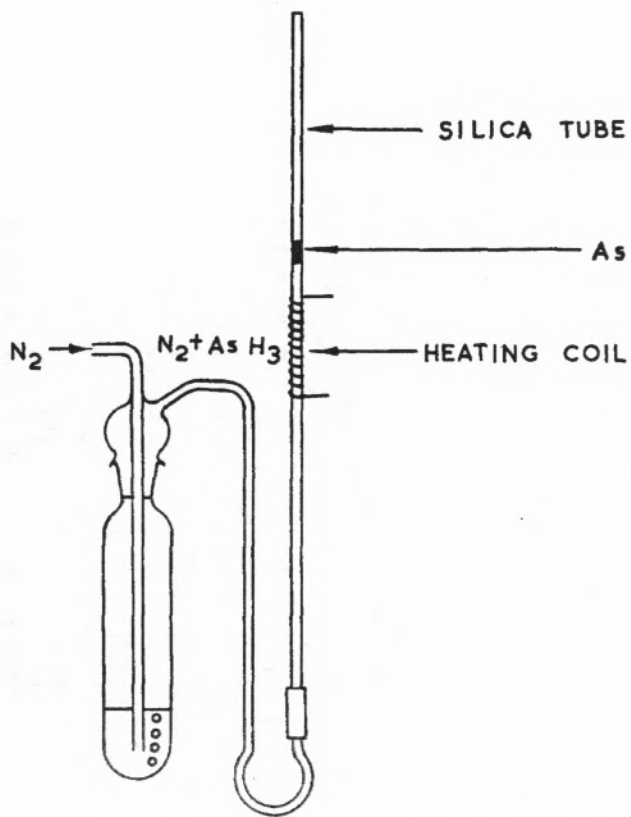
FIGURE I. ARSINE APPARATUS
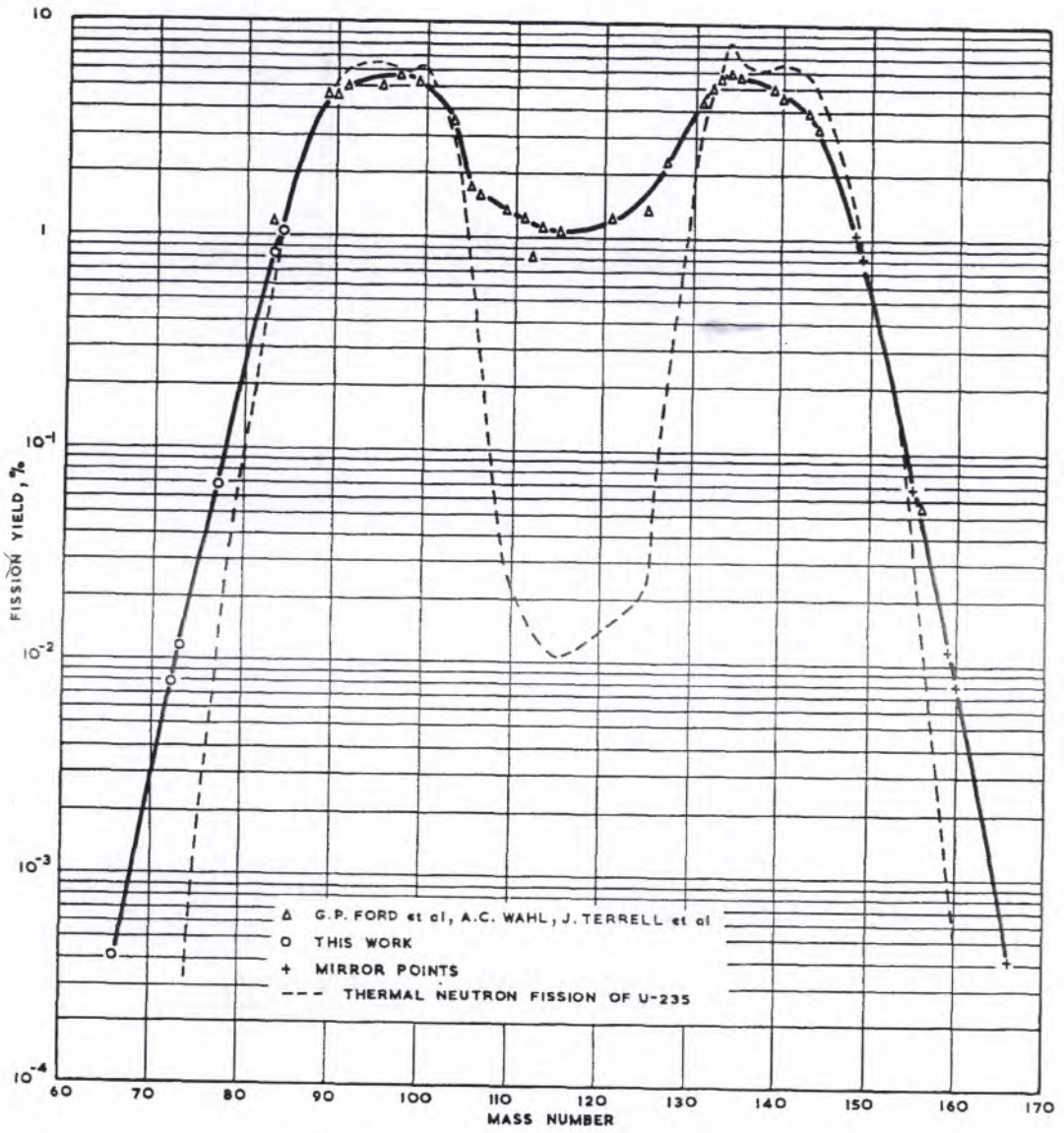
FIGURE 2. 14 MeV NEUTRON FISSION OF U-235

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