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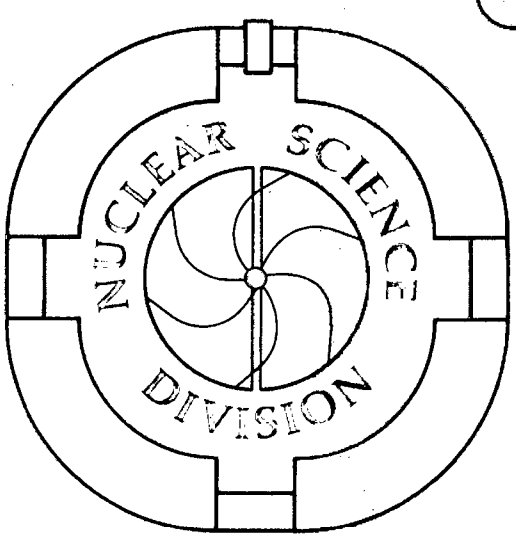

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ALPHA SPECTROSCOPY OF NUCLIDES PRODUCED IN THE INTERACTION OF 5 GeV PROTONS WITH HEAVY ELEMENT TARGETS*

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ABSTRACT

Alpha particle energies were redetermined to an accuracy of 2 to 5 KeV for a group of 40 neutron-deficient nuclides with atomic numbers ranging from 65 to 88. Improved half life values were measured for 10 of these nuclides. Weightless samples containing mixtures of these activities were prepared by use of the helium jet transport technique to remove spallatian and fragmentation products recoiling from targets of U, Th, Au and Ta bombarded with 5 GeV protons in the Bevatron. Experimental and calibration techniques are discussed in detail. Implications of the results for the mechanism of reaction of 5 GeV protons with complex targets are briefly discussed.

I. INTRODUCTION

In this paper we present redetermined values of the α-particle energies of about 40 α-emitting nuclides comprising chiefly isotopes of rare earth elements and isotopes in the platinum through radium group of elements. The opportunity for this redetermination came about as a result of a study of the α-emitting nuclides produced in targets of uranium, thorium, gold and tantalum by bombardment with 5 GeV protons. It is a characteristic of reactions with GeV protons that nearly all known nuclear species with mass below that of the target isotope are produced in yields which are typically 0.1 mb to

10 mb. By use of the helium jet transfer techniques to be discussed below it was possible to prepare weightless samples of these products and to measure the energy of the α particles emitted by the substantial number of products which underwent radioactive decay by alpha emission. The complexity of the α spectra, which contained 50 to 70 peaks, made the tasks of peak position determination, half-life analysis, and nuclidic identification difficult. The reward for overcoming these difficulties was the unique opportunity to measure so many species at one time under identical experimental conditions, which made it possible to make a precise determination of their relative energies. Furthermore, a number of the peaks occurring in the spectra have energies that have been precisely measured by magnetic or by semiconductor spectrometry. It was possible to improve substantially the energy determination of about 40 α emitters by comparing their position in the spectra with the positions of the precisely known lines. A dramatic improvement was made for the rare earth α emitters where errors were reduced from about 20 KeV to about 3 KeV.

The principal experimental tool in this research was the helium jet transfer technique which we and our collaborators[1] had used for some years with considerable success at the SuperHILAC to study new alpha emitting species produced in reactions induced in heavy element targets by heavy ion projectiles with energies of a few MeV per nucleon.

In this technique the target is enclosed in a small chamber through which helium gas is streaming. The reaction products are ejected from the target, slowed down in the helium and then swept from the target chamber by the stream of helium gas which is pumped out through a

capillary tube. The external orifice of this tube is positioned close to a metallic surface upon which the α-emitting products impinge and stick. The collector surface is located close to an α-detector of semiconductor silicon, which records the α-particles later emitted by the deposited reaction products. The helium jet transfer technique permits the removal of reaction products from the reaction zone and their deposition as a weightless sample some distance away in a radiation quiet zone where radiation detectors can be used without serious interference from primary and secondary beam particles or radiations.

Because of our previous experience with the helium jet technique we thought it would be interesting to explore its applicability to reactions induced by 5 GeV protons at the Bevatron. This required very extensive redesign of the apparatus as is discussed briefly in the experimental section to follow. A major necessity in this redesign was to effect a transfer of the reaction products through 15 feet of concrete shielding in order to get to a radiation quiet area instead of the few centimeters needed in the SuperHILAC experiments.

Following the experimental section we show the resulting α spectra and the procedures we used to identify the many contributors to the complex mixture of α peaks. Once the peaks were identified, the next goal was to refine the process of calibration of the energy scale and to generate a table of improved α-particle energies. We conclude the paper with a brief discussion section.

Similar experimental techniques based on a gas jet transport system were later independently developed by Dautet et al.[2] to study

yields of α-emitters in several medium mass targets (Ho, Tm, Re, Ta, Au) bombarded with 450 MeV protons.

II. EXPERIMENTAL METHODS

A. Reaction Cell and Helium Jet System

The experiments were performed on-line in one of the external beam lines of the LBL Bevatron at a time when 5 GeV protons were routinely available. The Bevatron is a pulsed accelerator with a beam burst in the external beam line every 6 seconds and a beam spill of 0.5 to 1.0 seconds. The beam area was typically a few centimeters in diameter but a low-intensity halo of primary and secondary particles extended many centimeters from the beam center. These beam characteristics dictated a reaction cell diameter of 7.5 centimeters instead of the 0.5 centimeters we had utilized previously at the SuperHILAC. The associated large radiation fields made it impossible to operate silicon detectors within a few tens of centimeters from the beam and necessitated the transport of the activity through the concrete shielding; the transport distance was 18 feet. The transport time was of the order of 0.5 seconds.

The recoil momentum of the α-emitting reaction products in the bombardment of heavy elements with 5.0 GeV is not known and was not measured in this work, but owing to the fragmentation or spallation nature of the formation process the recoil momentum is low. We used targets of infinite thickness compared to the expected recoil ranges but of slight thickness compared to the range of the 5 GeV protons which entered the target from its rear surface.

The aluminum reaction cell (7.5 cm i.d.) was placed directly in the beam. The heavy-element metallic foil was glued to the inside surface of the entry plate made of .027 inch aluminum. The distance between the target foil surface and the aluminum exit plate of the chamber could be varied between 4 and 20 mm. The reaction chamber was filled with helium to a pressure of 2 atmospheres. It entered through a wide bore copper tube on one side of the chamber, passed through the cell parallel to the target surface and exited through a stainless steel capillary fitted on the opposite side of the chamber. Capillary tubes of dimensions varying from 0.016 inch i.d. x 8 inch length to 0.035 inch i.d. x 24 inch length were used. The capillary tube was connected to an 18 foot length of thick walled tygon, teflon or polyethylene tubing. A typical internal diameter for this tubing was 0.041 inch. The helium with its cargo of radioactive reaction products traveled through this 18 foot length of plastic tubing until it reached a vacuum chamber housing for the sample collector and α-detector system. This vacuum chamber was a 15 inch x 15 inch x 12 inch high aluminum tank with a plexiglass cover plate. The dimensions and design of this chamber were not critically important. The tubing entered this chamber through a side port and the end of the tubing was fitted with a short capillary of stainless steel or glass to constrict the helium flow to a fine jet just before it struck a metallic collector plate. The heavy nuclides of the non volatile elements stuck to this collector plate, while the helium and the volatile nuclides were pumped away. The distance between the tip of the capillary and the surface of the collector was critical; the best distance was 3 to 4 mm.

The driving force for the helium flow in this whole system was a high capacity pump connected to the vacuum chamber housing the collector and detector system. This was a Leybold-Heraeus pump consisting of a E-250 single stage, rotary piston mechanical pump (147 cubic feet per minute displacement) and a WA-1000 Roots-type Blower (685 cubic feet per minute displacement). This system was connected to the vacuum chamber through a 6 foot stainless steel bellows. The pump system typically pumped helium at the rate of 10 cubic feet per hour maintaining a vacuum chamber pressure of 200 to 500 microns against a 2 atmosphere pressure in the reaction cell.

B. Sample Collection and Detector System

All α-particle measurements in this study were made with commercially available gold-plated silicon surface-barrier detectors operated in connection with commercial electronics. Generally we employed Ortec detectors with surface areas of 50 mm^2 and a thickness of 100 microns. The Ortec electronics system consisted of a Model 109A preamplifier, Model 451 main amplifier, and a Model 444 biased amplifier. The biased amplifier furnished a signal to a 4096 channel analog-to-digital converter (ADC) of LBL design which in turn transmitted a digitized signal to a computer. The energy scale for the digitized signals was calibrated with standards: ^{234}U, ^{241}Am, ^{244}Cm, ^{252}Cf, and the active deposit from a ^{228}th source (i.e., 10.64 hr ^{212}Pb in equilibrium with ^{212}Bi and ^{212}Po; these latter two nuclides emit 6.051 and 8.785 MeV α-particles, respectively.)

A stationary catcher foil was adequate for exploratory measurements of single parameter spectra over short periods of time (up to an hour

or two). However, when the collection time extended over many hours up to a maximum of 24, there were problems connected with the increasing prominence of long-lived activities and consequent obscuring of some of the low intensity peaks of short half life and with deterioration of peak resolution because of the build up of an oil or impurity deposit on the collector surface. We reduced these problems by use of two collector systems.

In one system, which we called the flipper system, the α-emitting nuclides were deposited on the edge of an aluminum disc. After a preset collection time (usually of 30 seconds, 2 minutes or 10 minutes) the disc was rotated a few degrees by a mechanical drive to position the radioactivity in front of a silicon semiconductor detector. The α-particle pulses were recorded for the same preset period, while a fresh sample was being collected on a different spot on the aluminum collector disc. As this period came to a close the disc rotated again which terminated the α-registration on one sample and initiated the measurement on the fresh sample. This cycle was repeated for whatever length of time (usually several hours) was needed to build the total number of recorded pulses to a satisfactory level.

An essential feature of the recording system was that each digitized α-pulse amplitude was recorded on magnetic tape together with a time pulse specifying the time elapsed since the collector disc was flipped from the collection to the counting position. This time pulse was valuable for the measurement of the half-life of specific α-peaks, as described below.

The second sample collection and detector positioning system was based on a tape drive system. We determined that the α-activity carried by the helium jet would deposit on the surface of magnetic tape. We then obtained an acoustic recorder magnetic tape deck and extensively modified it for incremental motion and for operation in a vacuum. This apparatus was placed inside the aluminum tank vacuum chamber discussed above. The sequence of operation for this system was similar to that for the flipper system. The α-activity was collected as the helium jet impinged on the surface of the magnetic tape. After a preset interval, the deposited activity was moved a few centimeters to a position in front of a silicon detector where the detector could record the emitted α-particles. At the end of the preset interval a fresh sample was moved into position in front of the detector. This system eliminated all problems with the buildup of a visible deposit or of long lived α-activity because a virgin tape surface was always used for sample collection.

C. Data Collection and Reduction

Data collection, display, and read out to magnetic tape were controlled by an on-line system consisting of a minicomputer with 12K words of core memory, a bulk storage disc, a magnetic tape drive, an oscilloscope display system, a teletype and a high speed matrix printer. Details of the hardware and software are not given.

Data were collected using a two parameter system which stored each digitized α-pulse height together with a time code specifying its time of arrival relative to the beginning of the counting period (flip time). These event pairs were stored in raw data buffers, which, when full,

were read out as separate records to magnetic tape. After the experiment these data could be recalled for sorting to arrive at a series of spectra representing successive counting intervals. The net peak area could be derived for a peak of interest in each spectrum of the series and the results analyzed in the usual way to arrive at a value of the half life for the selected α-peak.

The off line data analysis consisted of four phases: α-peak position determination, α-peak half life determination, peak identification, and finally a redetermination of α energies using peak positions and the precisely known energies of some of the α peaks appearing in the spectra. Figure 1 shows a typical α spectrum used in the analysis. These data were taken with a 30 sec flipper period. All of the strong peaks have been identified and most of them have been used in the energy analysis. Only muliplets which could not be unambiguously resolved were excluded from the α energy redetermination. Figure 2 shows α-spectra of the products of the interaction of 5 GeV protons with U, Th, Au and Ta.

Alpha peak positions were determined by fitting the spectra with the computer program SAMPO.[3] This program was used at the LBL central computer center on the data recorded in the magnetic tape files by the online computer. SAMPO allows the α-line shape to be determined from strong isolated peaks. This line shape is then used to fit multiplets of unresolved or partially resolved peaks. The total number of peaks that was needed to describe a spectrum such as is shown in Fig. 1 is approximately 70. Nominal α energies were determined by linearly

interpolating or extrapolating peak positions between the 4.067 MeV ^{151}Dy peak and the 7.739 MeV ^{217}Rn peak.

Half lives were determined by observing the decay of the intensity of peaks with time. The zero of time was taken to be the moment at which a fresh sample was placed in front of the surface barrier detector by a flipper or tape drive mechanism. Figure 3 shows spectra prepared by time sorting the α-energy data into 1.2 minute time bins, separated by 4.4 minute intervals. Marked changes in the relative intensity of the peaks occur because of their differing half lives. More precise time sorting of individual peaks was carried out to get accurate information on the half lives of individual peaks. This information was very useful in peak identification and in some cases for derivation of improved half life values. Decay plots were prepared by placing an energy window at the position of each peak of interest and background windows at energies above and below each peak; the taped data were then sorted according to time. The decay plots gave the number of decays, corrected for background, versus the time since sample rejuvenation.

Figure 4 shows the decay of the 5.030 MeV α particle peak from ^{154m}Tm. These data were taken with a 30 second flipper period and a ^{181}Ta target.

The computer code which was used to analyze the decay data for the many peaks was a least squares fitting program which decomposed the decay into a superposition of exponentially decaying components. In some cases, possible resolutions into one, two or three components were examined. The chi square values of the selected fits were consistent with counting statistics in all cases used for half life determination.

III. DATA REDUCTION AND RESULTS

A table listing all known α-emitting nuclides together with their energies and half lives was prepared from data given in several review articles.[4] This table was stored in the memory of a CDC 6600 computer. For each α line occurring in our spectrum, this table was searched to find all known α emitters which had a prominent α-particle energy near the line of interest. The candidates were then studied to see if one had a half life which was in agreement with our observed half life. In some cases it was found that the decay rate that we observed corresponded to that of a parent or grandparent activity. Identification of most lines was made on the basis of quantitative agreement of both α energy and decay half life. The fact that we recorded data with several choices for sample collection and counting time was useful because we could examine the data set with the flipper period best matched to the decay time of each peak that was used in the half life analysis. In addition, the presence or absence of a product nuclide for targets heavier or lighter than the product activity itself served to corroborate the identification. For a few weak α lines where it was not possible to determine a half life, identification was made on the basis of α energy alone. Our identification and half life results are summarized in Table I where the α energies and half lives of the strong peaks are given. In many cases the half lives which we determined have uncertainties comparable to or better than those previously reported.

When the above process was complete we had a table of some 40 well identified peaks. The statistical errors in the nominal energies of

these peaks, given by the statistical error in determination of the peak positions, was typically 1 KeV or less. We therefore undertook to make a self consistent determination of the energies of all of the well identified and well resolved peaks in our spectrum.

In order to eliminate the possibility that a thick deposit of pump oil or other contaminants had built up on the flipper plate and degraded the energies of the long lived α activities relative to those with short lifetimes, we performed comparison experiments on samples collected by the mechanical flipper and by the tape drive system. The experiments showed that the relative position of long and short lived activities was the same for the flipper system and the tape drive system. In order to fix with certainty the identity and energy of a prominent line which appears at the low energy end of all our spectra and which we believed to be correctly assigned to ^{150}Dy we performed an experiment to fix with precision the energy calibration in the vicinity of the 4.233 MeV[6] ^{150}Dy line. A high quality surface barrier detector was selected and the energy per channel was determined using a ^{212}Po (Th C') source (8.785 MeV) and a ^{150}Gd source (2730 MeV[7]). A sample of 7.1 minute ^{150}Dy was prepared immediately after the calibration by the bombardment of a ^{181}Ta target with 5.5 GeV protons and transporting the ^{150}Dy to the tape drive system with the helium jet. The shorter lived activities were allowed to decay. Immediately after calibration, the separation of the well known[6] 3.967 ± 0.003 MeV ^{149}Tb α line and the line assigned to ^{150}Dy was measured. Our result for its energy is E (^{150}Dy) = 4.233(3) MeV. We used this line as an anchor point in the internal calibration of our spectra.

The first step in the computation of improved α energies was the selection of lines to be used as standards. Each line was selected according to the following criteria:

1) The identification of the line should be certain.

2) Its position in our spectrum should be well determined.

3) Its energy should be well known.

Twenty lines were found to meet these criteria. They are the nuclides listed in Table II for which literature references are given. We then performed polynomial fits to the positions of these lines using their known energies. It was found that the quality of the polynomial fits improved in going from a straight line to a parabola but a cubic or higher polynomial was not statistically better than a parabolic fit. We chose to base our energy determination on the cubic fit for which the Chi squared per degree of freedom was 0.7. The energies of other lines were then determined by using the peak position peak energy relationship given by the cubic polynomial. The uncertainties in the energies were obtained as the quadratic sum of the uncertainty of the position of each peak and the uncertainty in the coefficients of the cubic polynomial. The results of this redetermination are given in table II.* Note that the energies of some of the peaks used as standards have been improved by the requirement of internal consistency. For many peaks, particularly in the rare earth region, uncertainties have been reduced from tens of KeV to a few KeV.

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*Note that these values were reported in preliminary form in Lawrence Berkeley Laboratory report, LBL-1666. 1972. They were abstracted in the 7th edition of Table of Isotopes, edited by C. Michael Lederer and Virginia S. Shirley, Wiley-Interscience, New York, 1978. (ref 8)

IV. REACTION MECHANISM IMPLICATIONS

The pattern of observation and non-observation of known neutron-deficient, alpha-emitting isotopes which was observed in this study can be discussed in terms of the current understanding of nuclear reactions induced by protons of high energy. There is a rich literature on the characteristics of the products resulting from the interactions of GeV protons with complex nuclei*.

Many radiochemical and instrumental techniques have been used to identify the products of these reactions and to measure formation cross sections, the kinetic energy spectra and other characteristics of these products. From these properties individual products can be categorized more or less clearly as spallation residues, fission products, evaporated particles, cascade particles, or fragmentation products.

In the case of 5 GeV protons interacting with uranium, the products falling in the rare earth group of elements, or in the elements somewhat higher in atomic number, can be classed either as fission products or as fragmentation products. Fission products have an excess of neutrons and high kinetic energy whereas fragmentation products are neutron deficient and have substantially lower kinetic energy. In some elements the yield distribution as a function of neutron number has a distinct two-humped distribution corresponding to this separation into two reaction classes.

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* See references 25-31 and the papers cited therein.

This knowledge of the pattern of cross sections for rare earth isotopes was one of the original motivations for starting this experimental investigation of the alpha spectra of the fragmentation group of rare earth products. An additional motivation was the knowledge that the measurement of alpha emitting species would be a sensitive test of how far away from the line of beta stability one could observe significant yields of fragmentation products. Furthermore, if the splitting of the uranium nucleus with 5 GeV protons were sufficiently violent it might be possible to produce and identify previously-unknown alpha emitters of neutron-deficient rare earth elements or of heavier elements such as hafnium, tungsten, rhenium. The successes and disappointments related to these motivations are summarized in figure 5.

Alpha emitting nuclides which were produced in sufficient yield to be identified in our spectra are shown by light shading in figure 5. It can be noted that these products are located some distance away from the line of beta stability. One way to state this distance quantitatively is to define a function Z_A-Z where Z is the atomic number of an observed nuclide of mass A and Z_A is the minimum of the appropriate mass parabola defined by a plot of mass data for all nuclides of mass A. (See discussion in ref. 26). When the Z_A-Z values are computed for the observed Tb, Dy, Ho and Er alpha emitters, they fall in the range of -2.9 to -5.8. For example, the values for ^{149}Tb, ^{155}Ho, and ^{154}Tm are -2.9,-3.1, and -5.5, respectively. There are no observed products with more negative values of Z_A-Z than 5.8. In figure 5 there appear a number of nuclides, such as ^{156}Lu and ^{158}Hf, which are known to decay by α-emission with α-branching ratios, α half lines, and

α-particle energies which would have made them prime candidates for observation by our helium jet technique had they been produced with reaction yields close to those of the observed products. The Z_A-Z values for all these nuclides are large; for example, the values for ^{156}Lu and ^{158}Hf are -6.8 and -7.0 respectively. Thus, we conclude that these two nuclides, as well as the other nuclides shown in labeled blank squares in fig. 5, are located too far from the valley of beta stability to be produced in the fragmentation of uranium target nuclei with BeV protons. The fragmentation reaction is a violent one and leads to a broad spectrum of products but there are definite limits to the distribution of yields. It is possible that low yields of some of these nuclides were produced in the fast step of the initial reaction but with such high excitation energy that the subsequent evaporation of nucleons (dominated by proton emission) resulted in the production of final nuclei much closer to stability.

These results are in agreement with those of Chu et.al.[26] who studies the interaction of uranium with protons of the much higher energy 28GeV. These authors found that yields of neutron-deficient rare earth products had cross section values of a few millibarns when Z_A-Z = -6.

Many of the α-emitters indicated by labeling in the blank squares were undiscovered at the time our study was conducted and have been studied since by reactions induced by heavy ions. A good summary of these results was published by Gauvin et al.[33]

In the case of the tantalum target the observed products can be described as spallation residues left from the intranuclear cascade

initiated by the incident proton. In the work of Dautet et al[2] done with 451 MeV protons a similar set of products was observed. They found agreement between their measured yields and cascade calculations.

In the case of gold targets we and Dautet et al.[2] see a similar set of rare earth products and we both conclude that fragmentation is the main mechanism for their formation. There is one striking difference in the α spectrum published by Dautet et al.[2] and our spectrum in Figure 1. The dominant peaks in their spectrum are the nuclides ^{178}Pt, ^{176}Pt, and ^{179}Au made by such spallation reactions as $^{197}Au(p,2p18n)^{178}Pt$.

In our spectrum the ratio of these peaks to the prominent rare earth peaks is down by two orders of magnitude. We believe this difference is due mainly to a strong increase in the yield of fragmentation products when the proton energy increases from 481 MeV to 5 GeV. Such an increase is well documented [25] in the case of the nearby element, bismuth.

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Table 1

Nuclide	Energy previous work[a] (Kev)	$T_{1/2}$ lit[a]	$T_{1/2}$ this work
		s = sec m = min h = hour ms = millisec s = microsec	
^{149}Tb	3967(3)[b]	4.10(.05)h	Long
^{151}Dy	4068(5)	17.7(.5)m	19.8(.5)m
^{154}Er	4166(5)	3.75(0.12)m	3.6(.2)m
^{150}Dy	4233(3)[b]	7.2(.1)m	7.3(.1)m
^{152}Ho	4345(15)	142(5)s	161.8(3)s
^{152m}Ho	4450(15)	52(.5)s	49.7(.4)s
^{151}Ho	4510(15)	35.6(.4)s	35.2(.1)s
^{151m}Ho	4600(15)	47(2)s	47.9(1.3)s
^{153}Er	4670(15)	36(2)s	37.1(.2)s
^{152}Er	4800(10)	10.7(.5)s	10.3(.1)s
^{154}Tm	4960(15)	5(1)s	8.3(.3)s
^{154m}Tm	5040(15)	3.0(.2)s	3.35(.05)s
^{153}Tm	5110(20)	1.6(.15)s	1.5(.3)s
^{179}Pt	5150(10)	33(4)s	54(4)s
^{155}Yb	5210(20)	1.6(.2)s	1.7(.2)s
^{183}Au	5343(5)	42(4)s	76(9)s
^{178}Pt	5440(20)	21.2(0.8)s	21(1)s
^{177}Pt	5525(20)	11(2)s	11(1)s
^{176}Pt	5750(15)	6(.5)s	11(.2)s
^{211}At	5866(2)	7.21h	Long

Table 1 (Cont.)

Nuclide	Energy previous work[a] (Kev)	$T_{1/2}$ lit[a]	$T_{1/2}$ this work
		s = sec m = min h = hour ms = millisec s = microsec	
^{199m}Po	5952(2)	5.2(.1)m	5.9(.1)m
^{198}Po	6178(5)	1.8(.05)m	1.8(.1)m
^{212}Fr	6338(3)	19(1)m	10 m
^{197m}Po	6387(8)	26(2)s	40(10)s
^{213}Fr	6773(5)	34.7(.3)s	35(.3)s
^{212}Ra	6896(5)	13(.2)s	13(1)s
^{204}Fr	6973(5)	2.1(0.2)s	Too weak to extract
^{222}Ac	7000(20)	66(3)s	Too weak to extract
^{217}At	7068(4)	32.3(.4)ms [4.81m]*	Too weak to extract*
^{218}Rn	7127(10)	35(1)ms [38s]*	43(4)*s
^{219}Fr	7310(10)	20(2)ms [2.21m]*	2.2(.5)*m
^{211}Po	7450(3)	.52 ms [7.2h]*	10 m*
^{214}Po	7687.1	.164 ms [38s]*	50(5)s*
^{217}Rn	7742(4)	.54(.05)ms [30s]*	28(2)s and 12(2)5*
^{216}At	7800(10)	.30(.03)ms [27.5s]*	30(2)s*
^{218}Fr	7851(10)	.7(0.6)ms [66s]*	60(10)s*

Table 1 (Cont.)

Nuclide	Energy previous work[a] (Kev)	$T_{1/2}$ lit[a]	$T_{1/2}$ this work
		s = sec m = min h = hour	
		ms = millisec	s = microsec
^{215}At	8010(10)	.10(.02)ms [2.2m]*	2(.05)m*
^{213}Po	8374(4)	4.2(0.8) s [30s, 8.0m, 58m]*	24(3)s* and 20(3)m*
^{212}Po	8785(1)	.3 s [60.6m]*	>6 m*
^{214}At	8802(10)	2 s [66s]*	60(4)s*
^{211m}Po	8880(20)	25.5(0.3)s	28(1)s

*Parent activity halflife; literature value given in brackets

[a]Reference 8

[b]Reference 6

Table II. Energies and Identities of Selected Peaks.

Nuclide*	Energy, this work† (keV)	Energy, previous work† (keV)	Nuclide*	Energy, this work† (keV)	Energy, previous work† (keV)
^{149}Tb	3972(5)	3967(3)	^{198}Po[i]	6183(3)	6178(5)
^{151}Dy[a,b]	4067(3)	4068(5)	^{212}Fr[j]	6339(3)	6338(3)
^{154}Er[c]	4166(3)	4166(5)	^{197m}Po[h]	6385(3)	6387(8)
^{150}Dy[d,e]	4233(3)	4232(3)	^{213}Fr[k]	6775(2)	6773(5)
^{152}Ho	4387(3)	4380(20)	^{212}Ra[l]	6901(2)	6896(5)
^{152m}Ho	4453(3)	4450(20)	^{204}Fr[k]	6970(3)	6973(5)
^{151}Ho	4517(3)	4510(20)	^{222}Ac	7013(2)	7010(10)
^{151m}Ho	4607(3)	4600(20)	^{217}At[m,n]	7071(2)	7068(4)
^{153}Er	4671(3)	4670(20)	^{218}Rn[o]	7133(2)	7127(10)
^{152}Er	4799(3)	4800(20)	^{219}Fr	7317(4)	7310(30)
^{154}Tm	4955(3)	4960(30)	^{211}Po[c]	7448(2)	7450(3)
^{154m}Tm	5030(3)	5040(20)	^{214}Po	7692(5)	7687(1)
^{153}Tm	5103(3)	5110(20)	^{217}Rn[p]	7739(2)	7742(4)
^{179}Pt[f]	5156(3)	5150(10)	^{216}At	7800(3)	7810(10)
^{155}Yb	5191(5)	5210(20)	^{218}Fr[q]	7867(2)	7870(10)
^{178}Pt[f]	5440(3)	5440(20)	^{215}At	8026(4)	8010(10)
^{177}Pt[f]	5510(3)	5510(10)	^{213}Po[n]	8376(3)	8377(5)
^{211}At[g]	5865(3)	5868(5)	^{212}Po[r]	8785(1)	8785(1)
^{176}Pt	5743(4)	5740(10)	^{214}At	8819(4)	8810(10)
^{199m}Po[h]	6060(3)	6064(4)	^{211m}Po	8885(5)	8880(20)

footnotes on following page

Table II. (Continued)

*A literal reference by a nuclide indicates that its energy was used as an internal standard in the fitting procedure.

†The number in parentheses is the error (in keV) of the measurement.

[a]Reference 9
[b]Reference 10
[c]Reference 11
[d]This work
[e]Reference 6
[f]Reference 12
[g]Reference 13
[h]Reference 14
[i]Reference 15
[j]Reference 16
[k]Reference 17
[l]Reference 18
[m]Reference 19
[n]Reference 20
[o]Reference 21
[p]Reference 22
[q]Reference 23
[r]Reference 24

REFERENCES

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1. K. Valli and E. K. Hyde, Phys. Rev. 176, 1377 (1968); J. Borgreen, K. Valli and E.K. Hyde, Phys. Rev. C 2, 1841 (1970).
2. H. Dautet, G. Bischoff, J. M. D'Auria, and B. D. Pate, Can J. Phys 58, 891 (1980).
3. J. T. Routti, Univ. Calif. Radiation Laboratory Report, UCRL-19452 (1969).
4. C. M. Lederer, J. M. Hollander, and I. Perlman, Table of Isotopes (Wiley, New York, 1967); K. Valli, in Proceedings of the Third International Conference on Atomic Masses, Winnipeg (1967), p. 296; P. Eskola, Arkiv fur Fysik 36, 477 (1967) and various original articles.
5. A. H. Wapstra, Nucl. Phys. 57, 48 (1964).
6. Izvestia Akademia Nauk. SSSR Ser. Fiz. 31, 1618 (1967); Bulletin Acad Science USSR--Physical Series 31 1657 (1967).
7. Ann. Acad. Sci. Fennicae Sec. A.VI, 109 (1962).
8. Table of Isotopes, Seventh Edition, C. Michael Lederer and Virginia S. Shirley, editors, John Wiley & Sons, Inc., New York (1978).
9. S. Mahunka, L. Fron, J. Fenyes, and A. V. Khalkin, Joint Institute of Nuclear Research, Dubna, USSR, JINR-P-2553 (1966).

10. N. A. Golovkov, S. K. Khran, and V. G. Chumin, Proceedings of Int. Symp. Nucl. Structure, Dubna (1968).

11. N. A. Golovkov, Sh. Guetkh, B. S. Dzhelepov, Yu. V. Norseev, V. A. Khalkin, and V. G. Chumin, Bull. Acad. Sci. USSR Phys. Ser. 33, 1489 (1969).

12. A. Siivola, Nucl. Phys. 84, 385 (1966).

13. R. W. Hoff, Univ. Calif. Radiation Laboratory Report, UCRL-2325, (1953).

14. E. Tielsch-Cassel, Nucl. Phys. A100, 425 (1967).

15. W. Treytl and K. Valli, Nucl. Phys. A97, 405 (1967).

16. K. Valli and E. K. Hyde, Univ. Calif. Radiation Laboratory Report, 16580 (1966).

17. K. Valli, E. K. Hyde, and W. Treytl, J. Inorg Nuc. Chem. 29, 2503 (1967).

18. K. Valli, W. Treytl, and E. K. Hyde, Phys. Rev. 161, 1284 (1967).

19. R. J. Walen, Compt. Rend. 255, 1604 (1962).

20. K. Valli, Ann. Acad. Sci. Fennicae, Ser A, VI, No. 165, 1 (1964).

21. F. Asaro and I. Perlman, Phys. Rev. 104, 91 (1956).

22. C. P. Ruiz, Univ. Calif. Radiation Laboratory Report, UCRL-9511 (1961), adjusted according to the redetermination of Po^{214} α_0 in ref. 24.

23. K. Escola, Phys. Rev. C5, 942 (1972).

24. A. Rytz, Helva. Phys. Acta 34, 240 (1961).

25. J. M. Miller and J. Hudis, Ann. Rev. Nuclear Science 9, 159 (1959).

26. G. Friedlander, p. 265 in Physics and Chemistry of Fission, Vol. II, Inter. Atomic Energy Agency, 1965.

27. Y. Y. Chu, E. M. Franz, G. Friedlander and P. J. Karol, Phys. Rev. C 4 2202 (1971).

28. G. Friedlander, L. Friedman, B. Gordon, and L. Yaffe, Phys. Rev. 129 1809 (1963).

29. V. P. Crespo, J. B. Cumming, A. M. Poskanzer, Phys. Rev. 174 1455 (1968).

30. A. M. Poskanzer, G. W. Butler and E. K. Hyde, Phys. Rev. C 3, 882 (1971).

31. E. K. Hyde, G. W. Butler, and A. M. Poskanzer, Phys. Rev. C4, 1759 (1971).

32. G. D. Westfall, et al., Phys. Rev. C 17, 1368 (1978).

33. H. Gauvin, Y. LeBeyec, J. Livet, and J. L. Reyss, Ann. Phys. 9, 241 (1975).

FIGURE CAPTIONS

Fig. 1. α-spectrum of nuclides collected by the helium jet technique from a uranium target bombarded with 5 GeV protons. Intermittent collection and counting periods of 30 seconds were used. Total time of experiment 2 hours. The isotopic identification of all prominent peaks is given.

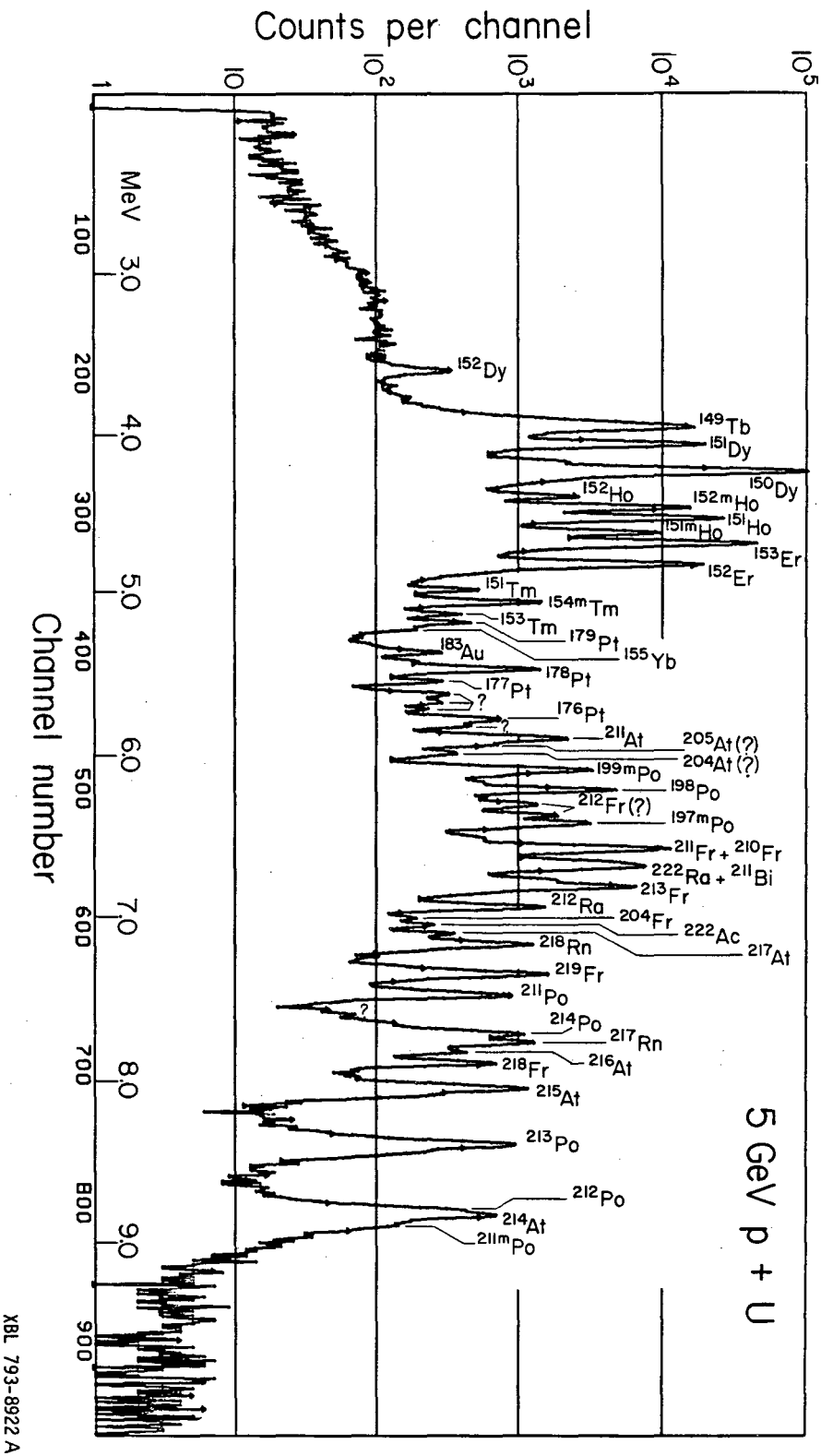
Fig. 2. α-spectra associated with products of interaction of 5 GeV protons with U, Th, Au, and Ta. Sample collection for 3 min followed by α registration for 3 minutes. Note that the same group of rare earth isotopes is produced in each target but the heavy element isotopes above Au and Ta are missing, as expected, from the spectra derived from the Au and Ta targets.

Fig. 3. Alpha spectra associated with products of interaction of 5 GeV protons with U. Sample collection for 10 min, followed by alpha counting for 10 min. The events recorded during three 1.2 sec intervals in the 10 min counting period are shown.

Fig. 4. Decay of 5.030 MeV peak assigned to ^{154m}Tm. Data were time sorted into 0.6 sec bins. Target-Ta. α-sample collection for 30 seconds followed by α-registration for 30 seconds. Derived half live of 3.35 $\pm$ 0.05 seconds.

Fig. 5. Section of Chart of the Nuclides showing region of alpha emitters of the neutron deficient isotopes of rare earth elements and heavier elements from hafnium through gold. Alpha activities identified in the present experiments are shown in light shading. Alpha emitters

which could have been observed had they been produced in significant yield are shown in labeled blank squares. Stable isotopes are shown in crosshatching.



XBL 793-8922 A

Fig. 1

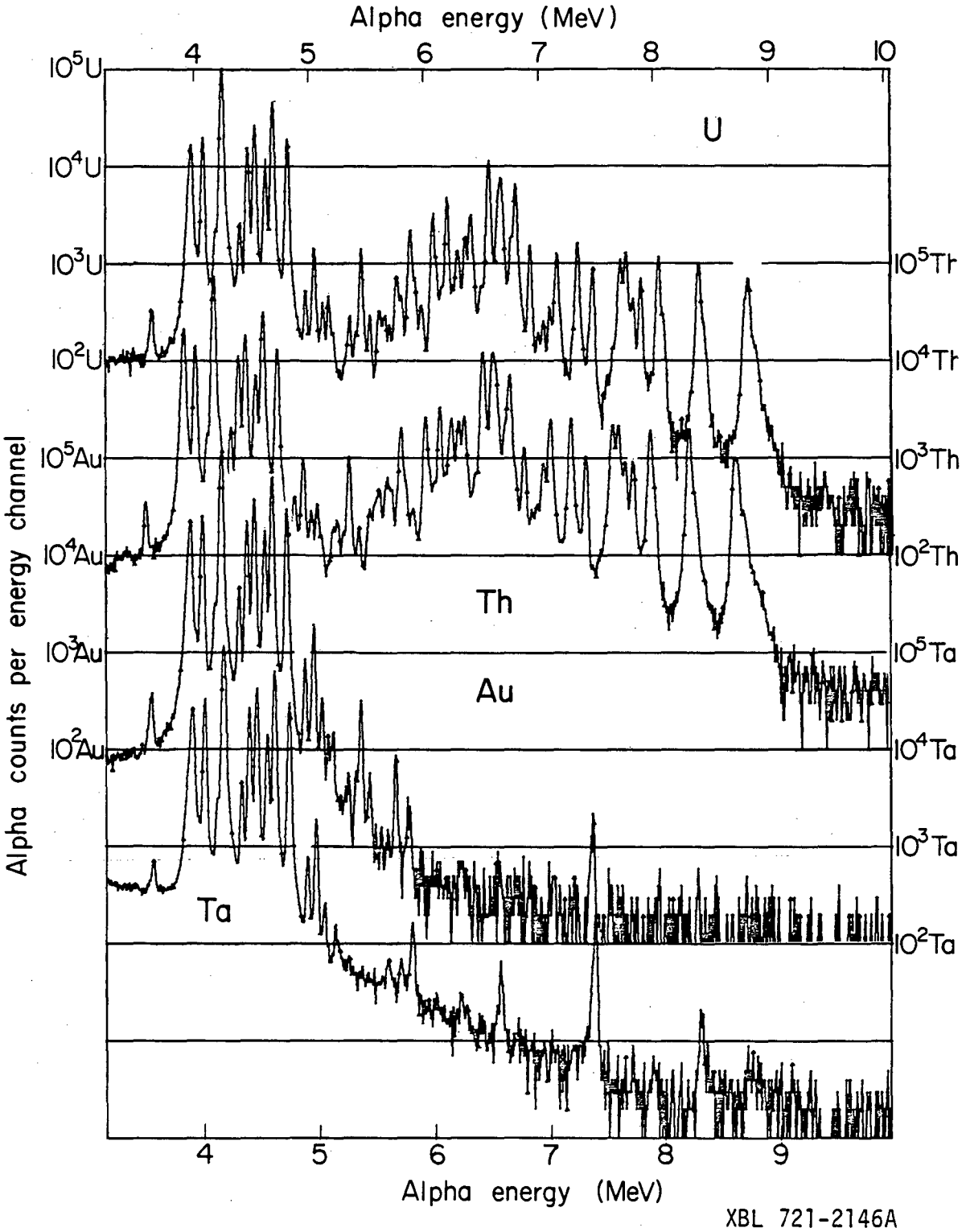
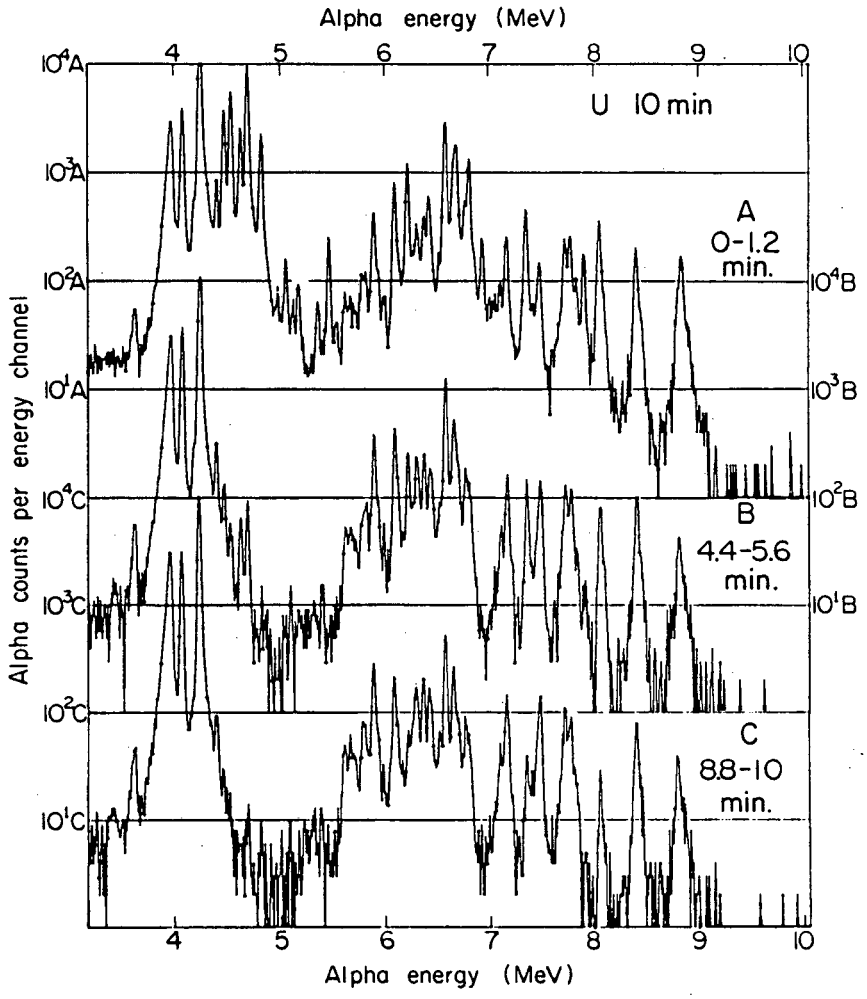

Alpha energy (MeV)
4
5
6
7
8
9
10
10^5U
10^4U
10^3U
10^2U
U
10^5Au
10^4Au
10^3Au
10^2Au
Th
Au
Ta
10^5Th
10^4Th
10^3Th
10^2Th
10^5Ta
10^4Ta
10^3Ta
10^2Ta
Alpha counts per energy channel
Alpha energy (MeV)
XBL 721-2146A

Fig. 2



XBL 718-2147A

Fig. 3

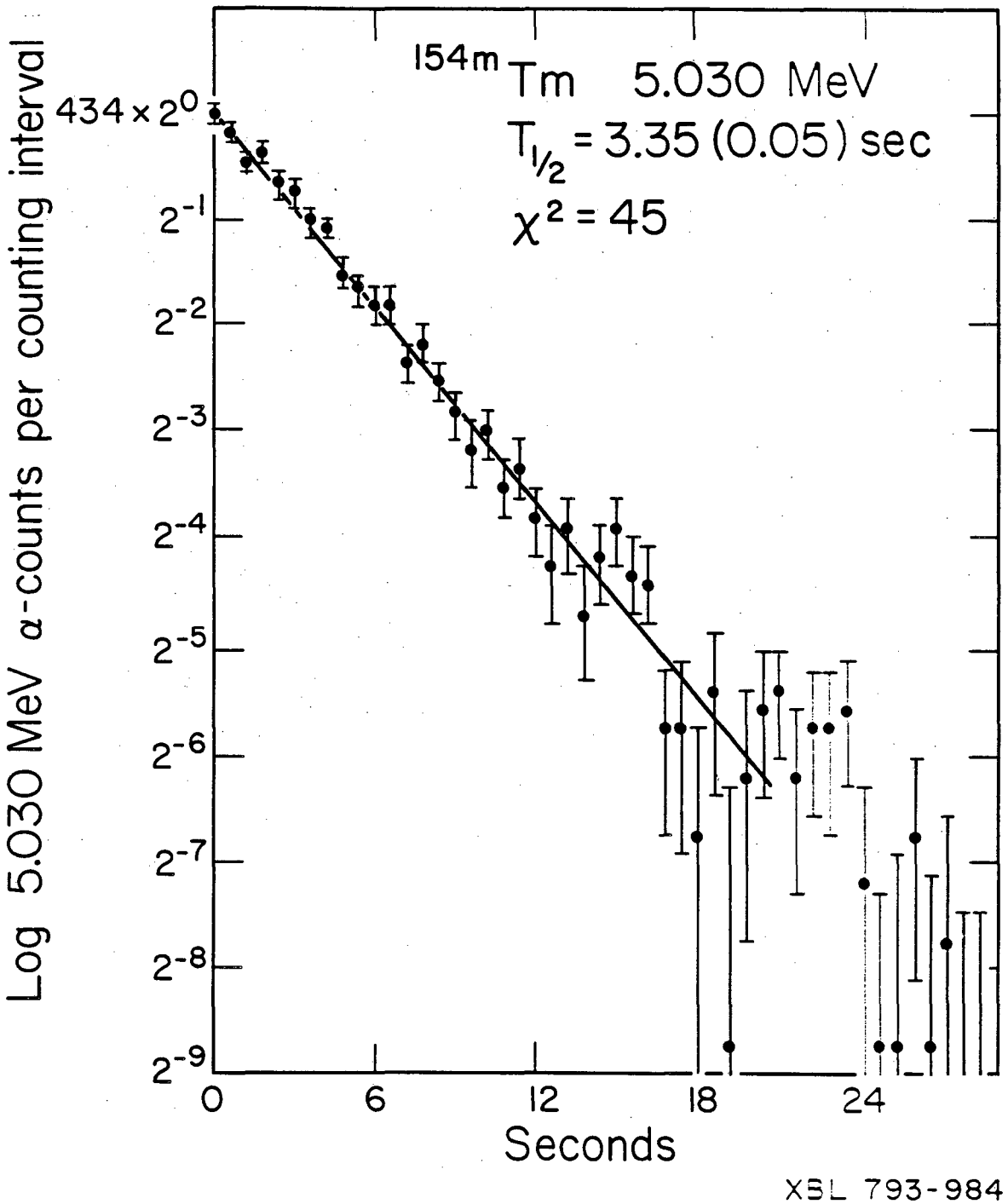
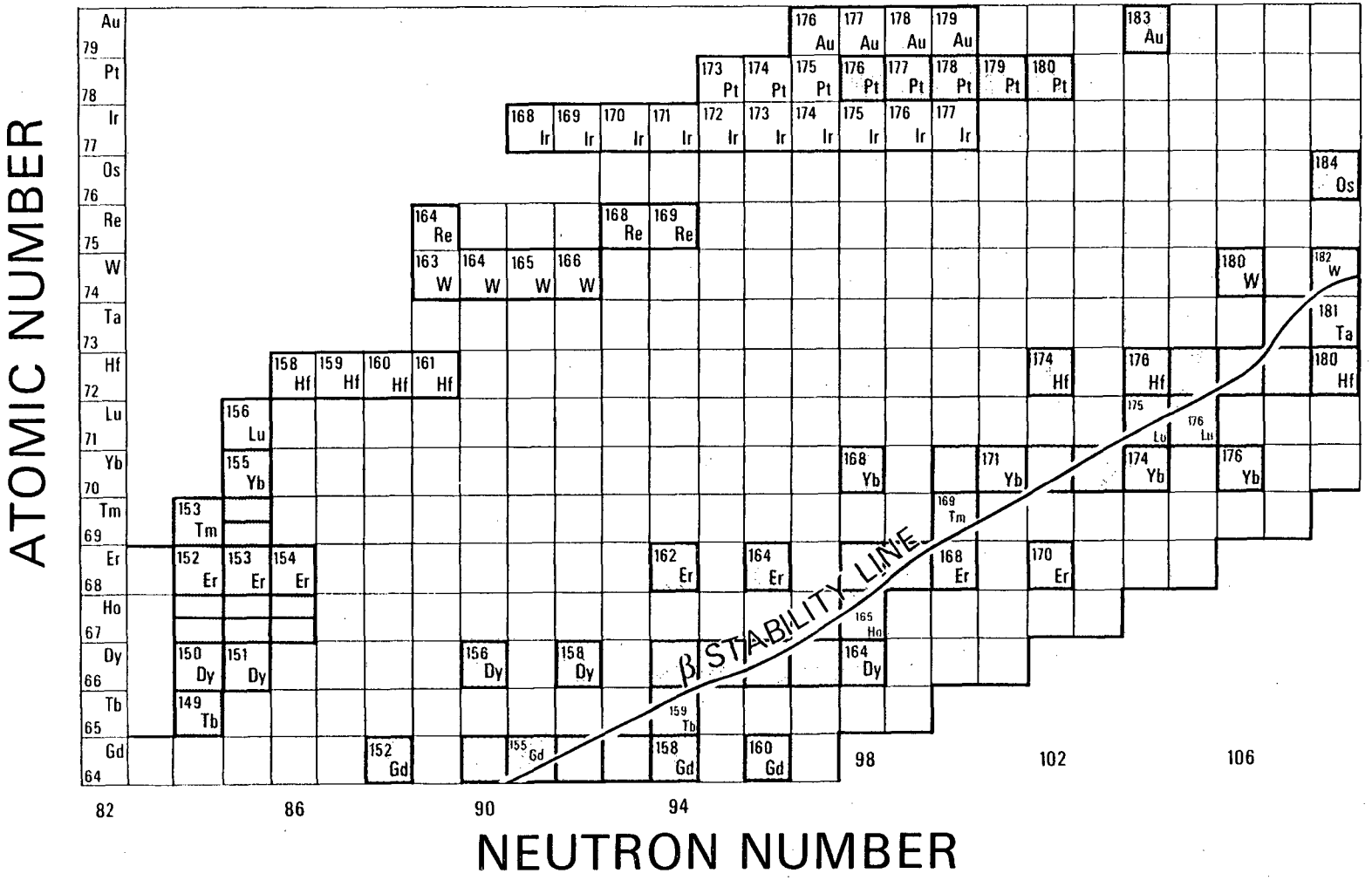

154m Tm 5.030 MeV
T1/2 = 3.35 (0.05) sec
χ² = 45
Log 5.030 MeV α-counts per counting interval
434 x 2⁰
2⁻¹
2⁻²
2⁻³
2⁻⁴
2⁻⁵
2⁻⁶
2⁻⁷
2⁻⁸
2⁻⁹
0
6
12
18
24
Seconds
XBL 793-984

Fig. 4



XBL 817-1027

Fig. 5

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