12 FEB. 1980

TRI-PP-79-42
Dec 1979

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Yield of deep spallation products of medium to heavy mass targets bombarded with 480 MeV protons*

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Abstract

Absolute cross sections for short-lived alpha emitting, very neutron deficient nuclei resulting from the interaction of 480 MeV protons with several medium mass targets (Ho, Tm, Re, Ta, Au) have been measured at the TRIUMF facility (Vancouver, Canada). Activities were transported using a gas jet system and relative transport efficiencies for products of various Z were measured. Calculations for the production of such deep spallation products were performed using the empirical Silberberg-Tsao method and the more fundamental, intranuclear cascade/evaporation model, and compared against the observed values.

(submitted to Canadian Journal of Physics)

*Funds provided in part by NSERC IEP Grant A0759.

CM-P00067047

Introduction

The interaction of intermediate energy protons with complex nuclei results in the production of a large number of nuclei, some of which are very neutron-deficient. A great deal of effort has been devoted to understanding the mechanism of such interactions through formulation of several models (1-5). These have generally been successful in predicting the yields of reaction product nuclei, particularly long-lived species near beta-stability. The purpose of the present study was to extend such measurements to those short-lived products (of half-life down to about 1 sec) that are remote from beta-stability. Cross sections for their production should represent independent rather than cumulative yields, and provide a more stringent test of the ability of the above reaction models to predict yields, especially of "deep" spallation reactions involving high initial energy transfer from projectile to target nucleus.

The key to yield measurements on such short-lived products was their transportation from their point of production to a shielded detection location (in a measured time of the order of 1.5 sec) by a gas jet recoil nucleus transport system.

2. Experimental Techniques

2.1 Techniques

The experiments were performed at the TRIUMF cyclotron facility (Vancouver, Canada) with 480 MeV protons and beam currents of about 500 nA. The targets were metallic foils of thicknesses and purities given in Table 1. Up to six of them could be mounted on a target holder and positioned remotely in front of a gas filled chamber 5 mm in

diameter and 4 mm in length which was part of the gas jet transport system (6-10), shown in Fig. 1.

The nuclear reaction products recoiling out of the target material were thermalized by the ethylene carrier gas flowing through the chamber (pressure about 10 Torr). The radioactive products attached to molecular clusters (6-8) present in the gas and were subsequently transported with the gas flow, through polyethylene tubing (4 mm inner diameter), to a collection chamber located approximately 20 m away.

At the exit of the tubing, the gas impinged on the surface of used computer tape, and the clusters carrying the nuclear reaction products adhered to it, forming a radioactive spot of a size (~4 mm) suitable for radiation measurements. The tape carrying the spot could be moved a pre-selected distance in front of one or more radiation detectors, on a pre-determined schedule as called for by a particular experiment.

Gas jet systems such as the present one are not very element-selective and many reaction products are transported with comparable efficiency. As a result, the identification of, for example, gamma-radiations measured from the radioactivity transported by the gas jet system is often difficult and brought with ambiguity. The necessary detection selectivity was achieved, in the present experiment, by taking advantage of the fact that most of the products of interest were alpha-emitters. Alpha radiations could be measured with good efficiency and resolution in the presence of an intense background of beta and gamma radiation using a 200 μ m Si surface barrier detector and were found easier to assign. Further, the use of ethylene gas provided thin sources, without significant deposit mass at the collection spot, that

were ideally suited for alpha-spectroscopy, as demonstrated by the spectrum in Fig. 2. The observed alpha energy resolution was 18 keV FWHM at about 6 MeV.

During a given experiment, collection of a radioactive spot continued for a pre-selected time; then tape movement positioned the spot in a known geometry with respect to the alpha detector. The alpha-radiations were recorded as a function of the elapsed time after the end of collection (in order to obtain decay information). Under computer control, the sequence of collection and counting was repeated until satisfactory statistics were obtained.

The chamber in which the detector was located was maintained at a higher pressure (~2 Torr) than the collection chamber (~0.2 Torr). This pressure difference minimized the possibility of organic vapors affecting the detector. A schematic representation of the collection end of the gas jet system is displayed in Fig. 3.

Alpha spectra were analysed for peak areas and energies using a modified version of the computer code, GAMANAL (11). The resulting energies and associated half-lives were compared with literature values in order to identify the observed radioactivities (see Tables 2-3).

To determine the absolute production cross sections of the various products from a particular target from the measured alpha radioactivity transported by the gas jet system required information on several experimental parameters, including the effective target thickness, the transit time in the gas jet system, and its efficiency for transporting the different elements in the relevant nucleide mass region. Separate experiments were required to evaluate these as described below.

2.2 Effective Target Thickness

The targets used ranged in thickness from 3 to 200 mg/cm². Such values exceed the maximum range of spallation products, and a measurement of the thickness of target material from which recoiling nuclei escaped was required. The method used was the thick target-thick catcher technique originated by Sugarman (12) and the results are displayed in Fig. 4 for the Ta and Au targets. The insert of Fig. 4 shows the experimental assembly used. The activities in the catcher foil and the target were assayed using gamma-ray spectroscopy techniques, following 30 min irradiations.

It was expected that a monotonic relationship would exist between the effective target thickness (R) and the mass number difference (ΔA) between the target and product nuclei (13-14). The data displayed in Fig. 4 are in reasonable agreement with this expectation, as are results obtained elsewhere (15,16) in this mass region. It was assumed for the present study that the dependence determined here for products close to stability applied to products of similar ΔA -value, but far from stability, for which a direct measurement of the effective target thickness was not possible.

2.3 Transit Time

In order to estimate the fraction of the various activities that had decayed before detection, the transit time of the gas jet system had to be measured. This was done by operating the TRIUMF cyclotron in a pulsed mode (with the proton beam on for 7 sec and off for 6 sec). A Be target was employed for most of the measurements to take advantage of the high production yield of the 844 msec alpha-emitter ⁹Li.

The gas jet system was operated with the gas flow kept constant, and the collection tape moving at constant speed so that a constant fraction of the collected activity was recorded. Thus the observed variation of the measured activity with time was due only to the modulation of proton beam intensity, and to the transport time of the gas jet system. The study was repeated for different ethylene gas-flow rates, and with a Ta target. [This latter provided results of lower statistical precision, but indicated that the (Be target) data applied to the mass-region of present interest].

Figure 5 displays typical results obtained, with the alpha particles counted for equal 50.0 msec time intervals, for a particular ethylene gas flow-rate.

The solid line corresponds to a fitting to the data via the least square procedure of the function

$$A(t) = 0 \quad : t < \tau$$

$$A(t) = C \frac{\lambda A}{(\lambda + A)} [\exp(-\lambda \tau)] \left\{ [1 - \exp [-(\lambda + A)(t - \tau)]] \right\} : t \geq \tau \quad (1)$$

where $A(t)$ is the activity measured at the time t

τ = the transport time through the capillary plus the collection tape transit time

λ = the decay constant of the radioactive species measured

A = inverse of the mean "turn-over" time of the gas in the production

chamber, obtained from the chamber volume (V) and gas flow-rate (ψ)

C = a factor that takes into account the gas jet transport efficiency, the beam intensity, and the effective target thickness.

This equation was derived under the assumptions that:

- (1) due to focussing of the clusters in the centre of the capillary, they all travelled with the same speed,
- (2) due to turbulence in the thermalisation chamber, the gas was well mixed in a time short compared to the "turn-over" time.

During the fitting procedure, the parameters τ and C were treated as variables. This analysis of the data indicated that the transport time in the capillary varied from 0.7 sec for an ethylene flow rate of $70 \text{ cm}^3 \cdot \text{s}^{-1} \text{ atm}^{-1}$ to 1.5 sec for a flow rate of $10 \text{ cm}^3 \cdot \text{s}^{-1} \text{ atm}^{-1}$. The total transport time, (that is including gas turnover in the production chamber), varied from 0.9 sec to 2 sec for the previously mentioned flow rates of gas.

Equation (1) was also employed to calculate the radioactive decay between production and detection of the many species studied. If the bombardment time exceeded several seconds, the equation simplifies. Thus, for example in the case of a one component decay with no growth from a parent activity, the activity after a collection time t_c would be

$$A_0 = \epsilon g N \sigma I \left(\frac{\lambda}{\lambda + \Lambda} \right) \left[\exp(-\lambda \tau) (1 - \exp(-\lambda t_c)) \right] \quad (3)$$

where

ϵ = gas jet transport efficiency

g = the detection efficiency of the alpha detector

N = the effective target thickness (atoms/cm²)

$\Lambda = \psi/V \text{ (sec}^{-1}\text{)}$

I = beam intensity (protons/sec).

2.4 Gas Jet Transport Efficiency

Ideally, determinations of the absolute transport efficiency should involve direct comparison of the numbers of product nuclei recoiling out of the target and of product nuclei collected at the end of the gas jet system. Again this was impossible for the short-lived alpha emitters of prime interest: instead, X-ray spectrum measurements were made of the generally longer-lived nuclides produced by 30 sec bombardments. Measurements made directly on the irradiated targets were compared with similar measurements made after gas jet transport. The X-ray measurements had the advantage that an average elemental transport efficiency was obtained, with the results shown in Table 4. It was assumed (and to some extent checked) that such efficiencies were valid for a range of isotope mixtures, and hence for the mixture of alpha-emitting isotopes of the same elements to be studied.

3. Experimental Results and Theoretical Calculations

3.1 Experimental Results

The production cross sections for the alpha-emitters identified in Tables 2 and 3 were calculated from the measured activities using Eq. (2) as described earlier, and values of the experiment parameters determined as described above. The results are presented in Tables 5-9.

The main source of error in the cross section values is the uncertainty in the efficiency of the gas jet system. Unfortunately it is difficult to estimate this precisely, and the same holds true for the effective target thickness. This difficulty is reflected in an estimated error of a factor two.

3.2 Theoretical Calculations

The above results were compared with two different predictions of yields in spallation reactions, namely, those from the semi-empirical approach of Rudstam (17) as modified and extended by Silberberg and Tsao (18), and those from the more fundamental intranuclear cascade model (5) plus statistical evaporation of various particles.

In the cascade calculations, the model of the nucleus used was that of a 8 step approximation to the nuclear shape with no reflection or refraction at the limits between regions of different densities. The pion⁰potential was constant with a value of zero and the isobar charge exchange reaction was not allowed. Neutrons and proton binding energies were extracted from the table of K. Takahashi *et al.* (20). Such a model was chosen over the more sophisticated versions as it has been shown (19) that there is little difference in calculated results between the different degrees of sophistication.

A comparison of the experimental data with results from the two calculations is shown for products from Ho and Au targets in Fig. 6 and 7. Cross sections are plotted against N-Z value of the nuclide in question, in order to facilitate the presentation of data covering a wide mass-number range.

4. Discussion

4.1 General Trends

It may be noted from Tables 5-9 and Figs. 6 and 7, first that most of the experimental data are not well predicted by the empirical procedure of Silberberg and Tsao (18), the latter's results being low often by several order of magnitude. This discrepancy may be

attributed to the fact that the parameters in the equations describing the spallation process had been adjusted to reproduce the experimental results previously available, none of which were for products as remote from stability as those measured in the present study.

Secondly, it is seen that the intra-nuclear cascade evaporation model (with the parameter choices indicated above) predicts reasonably well the bulk of the experimental results typically within a factor of two.

4.2 Special Reactions

1. $^{165}\text{Ho}(p, \pi^- \text{xn})^{153,154}\text{Tm}$

A possible route for the production in the observed small yields of $^{153,154}\text{Tm}$ from Ho targets is by means of the (α, xn) reaction induced by alpha-particles produced in the target. This has been studied experimentally by varying the target thickness from 20 mg/cm² to 100 mg/cm². It was found that this had no effect on the yield of these nucleides, showing that the secondary alpha induced reaction was not their source.

Another contribution could arise from impurities in the target material. Calculations based on the results obtained in this work indicate that in order for the nucleides in question to be produced with the observed yields, impurities such as Tm would have to be present in amounts of the order of 1%. However, the Ho target was known to be 99.9% pure and the amount of Tm present was only 0.071%.

The only other possible mode of production apparent is the $p, \pi^- \text{xn}$ reaction, and the agreement between the experimental results and the

predictions of intranuclear cascade plus evaporation calculations for production via this route is remarkably good.

2. Au(p,xp,yn)Dy,Tm,Ho

As mentioned previously the experimental results and those from the intranuclear cascade model are generally in good agreement, with the exception of Dy, Tm and Ho nucleides produced from a gold target. The predicted yields were too low to be calculated within the statistical production of the calculations (10^4 cascades per target-projectile combination). However, estimates were obtained by extrapolation of yield values as a function of mass-number. Experimental data are higher by a factor of the order of one hundred.

Such a disagreement is not typical of the data for other product nucleides. A reasonable explanation may be that these nucleides are not produced by the spallation process (as usually defined), but rather are residual nucleides left after fragment emission ($A \approx 20-50$) followed by evaporation. Fragment emission is a well established phenomenon, and the cross sections for it are large enough (21) for this process to be an important contributing factor in the production of the nucleides considered here.

5. Conclusion

These measurements indicate that gas jet systems can be used to measure cross section in intermediate energy proton reactions, provided some isotope selectivity can be obtained. Since "deep" spallation products are usually very short-lived, this approach could be used in other mass regions since elemental discrimination is minimal.

The comparison against the internuclear cascade model proved

reasonable, and the possible observation of products from a (p,n) process indicates that future studies could provide significant new information.

Acknowledgements

The efforts of the TRIUMF staff in operating the accelerator under unusual conditions is particularly acknowledged. In addition the assistance of W.J. Wieseahn with both computer calculations and technical advice with respect to the gas jet system is gratefully acknowledged.

References

1. H.W. Bertini, A.H. Culkowski, O.W. Hermann, N.B. Gove, and M.P. Guthrie. Phys. Rev. C17, 1382 (1978).
2. M. Blann, and F. Plasil. "Alice: a nuclear evaporation code". VSAEC Report 100-3494-10 (1973).
3. J.J. Griffin. Phys. Lett. 24B, 5 (1967).
4. J.R. Wu and C.C. Chang. Phys. Rev. C17, 1540 (1978).
5. G.D. Harp. Phys. Rev. C10, 2387 (1974).
6. R.D. MacFarlane, and Wm.C. McHarris in *Nuclear Spectroscopy and Reactions*, Vol. A (ed. by J. Cerny; Academic Press, New York) 1974.
7. H. Dautet, S. Gujrathi, W.J. Wieseahn, J.M. D'Auria, and B.D. Pate. Nucl. Instr. & Meth. 107, 49 (1973).
8. W.J. Wieseahn, J.M. D'Auria, H. Dautet, and B.D. Pate. Can. J. Phys. 51, 234 (1973).
9. H. Wollnik. Nucl. Instr. & Meth. 139, 311 (1976).
10. C. Weiffenbach, S.C. Gujrathi, J.K.P. Lee, and A. Haudayer. Nucl. Instr. & Meth. 125, 245 (1975).
11. R. Gunnink, and J.B. Niday; Computerized analysis by gamma-ray

spectroscopy. Vol. 1-UCRL-51061 (1972).

12. N. Sugarman, H. Münzel, J.A. Panontin, K. Wielgoz, M.V. Ramaniah, G. Lang, and E. Lopez-Menchera. Phys. Rev. 143, 952 (1966).
13. B. Neidhart and K. Bächmann. J. Inorg. and Nucl. Phys. 34, 423 (1972).
14. S.B. Kaufman, E.P. Steinberg, and M.W. Weisfield. Phys. Rev. C18, 1349 (1978).
15. W.R. Pierson, and N. Sugarman. Phys. Rev. 130, 2417 (1963).
16. N. Sugarman, M. Campos, and K. Wielgoz. Phys. Rev. 101, 388 (1956).
17. G. Rudstam. Z. Naturforsch. 21A, 1027 (1966).
18. R. Silberberg, and C.H. Tsao. "Partial cross sections in high energy nuclear reactions". Astrophys. Jour. Suppl. 25 315 (1973).
19. V.S. Barashenkov, H.W. Bertini, K. Chen, G. Friedlander, G.D. Harp, A.S. Iljinov, J.M. Miller, and V.D. Toneev. Nucl. Phys. A187, 531 (1972).
20. K. Takahashi, H. v. Groote, and E.R. Hiff. "Gross Theory of Nuclear Masses and Radii". IKDA 76/26(1976).
21. R.E.L. Green, private communication (1979).
22. E. Hagberg, P.G. Hanson, J.C. Hardy, P. Hornshøj, B. Jansen, S. Mattsson, and P. Tidemand-Petersson. Nucl. Phys. A293, 1 (1977).
23. J.D. Bowman, E.K. Hyde, and R.E. Epley. LBL Nucl. Chem. Ann. Report NLBL 1666 (1972).
24. H. Gauvin, Y. Le Beyer, J. Livet, and J.L. Reyss. Ann. Phys. 9, 241 (1975).
25. W. Seelman-Eggebert, G. Pfemming, and H. Münzel; Chart of Nuclides (1974).

Table 1. Target foils

Target element	Thickness (mg/cm ²)	Purity (%)	Typical impurities ^c (ppm)
Ho ^a	100.0	99.9	Er(200), Eu(100), Tm(170)
Tm ^a	200.0	99.9	Dy(100), Ho(100)
Ta ^b	12.5	99.96	W(10)
Re ^a	50.0	99.99	W(10)
Ir ^a	112.0	99.9	Pb(30)
Au ^b	24.0	99.999	
Bi ^b	3.5	99.9	

^aObtained from ALFA products, a division of Ventron corporation, 16207 South Carmentia Rd., Cerritos, California 90701. ^bObtained from Good-Fellow metals, Science Park, Milton Road, Cambridge, CB44DJ (UK). ^cImpurities which could have interfered with the results of these studies.

Table 2. Observed alpha activities from Ho, Tm, Ta, Re targets

Experimental data			
E_α (MeV)	Targets	$T_{1/2}$ (sec)	Assignment Ref.
5.199	Tm, Ta, Re	1.8 ± 0.3	^{155}Yb a
5.104	all	1.4 ± 0.3	^{153}Tm b
5.032	all	3.11 ± 0.3	$^{154}\text{Tm}^m$ b
4.957	Tm, Ta, Re	6.9 ± 1	^{154}Tm b
4.799	all	10.4 ± 0.6	^{152}Er b
4.673	all	36.3 ± 2	^{153}Er b
4.611	all	46 ± 3	$^{151}\text{Ho}^m$ b
—	all	19 ± 6	$^{151}\text{Er}^*$ c
4.518	all	35.1 ± 2	^{153}Er b
4.456	all	48.7 ± 6	$^{152}\text{Ho}^m$ b
4.388	Ho, Tm	150 ± 10	^{152}Ho b
4.233	Ho, Tm, Re	428 ± 18	^{150}Dy b
—		23 ± 5	$^{150}\text{Ho}^*$ d
4.172	Tm	>200	^{154}Er b
4.07	Ho, Tm	>300	^{151}Dy b
—		30 ± 12	$^{151}\text{Ho}^*$ b

aRef. (22)
bRef. (23)
cRef. (24)
dRef. (25)

*100% beta emitter, deduced from growth of daughter alpha emitter.

Table 3. Observed alpha activities from a Au target

E_α (MeV)	$T_{1/2}$ (sec)	Assignment	Ref.
6.125	2.5 ± 0.5	$^{177}\text{Au}, ^{180}\text{Hg}^*$	c
5.955	2.0 ± 0.4	^{175}Pt	c
5.929	3 ± 1	$^{178}\text{Au}, ^{181}\text{Hg}^*$	c
5.852	6.9 ± 0.3	$^{179}\text{Au}^*$	c
5.749	6.2 ± 0.2	^{176}Pt	c
5.672	2.0 ± 0.5	$^{173}\text{Ir}^*$	c
5.622	—	^{181}Au	c
5.521	10.0 ± 2	^{177}Pt	c
5.480	9 ± 1.5	^{177}Pt	c
5.449	22 ± 2	^{178}Pt	c
5.394	—	$^{175}\text{Ir}^*$	c
5.345	—	^{183}Au	c
—	—	$^{183}\text{Hg}^\dagger$	c
5.201	—	^{179}Pt	c
5.161	—	^{179}Pt	c
5.113	~ 10	$^{176}\text{Ir}^*$	c
		$^{176}\text{Pt}^\dagger$	c
5.038	3.5 ± 0.2	$^{154}\text{Tm}^m$	b
4.804	10.5 ± 1	^{152}Er	b
4.676	35 ± 5	^{153}Er	b
4.523	30 ± 5	^{151}Ho	b
4.457	~ 40	$^{152}\text{Ho}^m$	b

bRef. (23)
cRef. (24)

*Alpha branching ratio unknown.
†Deduced from growth of daughter activity.

Table 4. Gas jet system transport efficiency (%)

Products	Ho	Tm	Targets		Re	Au
			Ta			
Pm	17.0					
Sm	20.0 ± 5.0					
Eu						
Gd	17.0 ± 6.0					
Tb	18.0 ± 1.0	4.7 ± 0.3				
Dy	22.0 ± 1.0	4.0 ± 1.3	8.0 ± 2.0			
Ho	25.0 ± 2.0	8.0 ± 1.0	8.7 ± 1.0	14.0 ± 3.0		
Er		3.5 ± 1.0	6.6 ± 0.8	6.5 ± 0.5		
Tm		4.5 ± 1.0	6.2 ± 0.15	7.2 ± 0.4	2.9 ± 0.1	
Yb			6.7 ± 0.3	7.6 ± 0.4	2.5 ± 0.2	
Lu			6.0 ± 0.5	8.3 ± 0.4	2.5 ± 0.4	
Hf			6.7 ± 1.0	9.8 ± 0.3	2.9 ± 0.15	
Ta			5.1 ± 0.5	9.5 ± 1.0	3.6 ± 0.6	
W				9.2 ± 0.4	2.27 ± 0.05	
Re				5.4 ± 0.5	1.61 ± 0.02	
Os					1.73 ± 0.09	
Ir					1.9 ± 0.08	
Pt					1.2 ± 0.2	
Au					1.4 ± 0.2	

Table 5. Measured and experimental yields of products from a Ho target (in mb)

Product	Reaction*	Exp. cross section	Calculated cross section	
			(Cascade plus evaporation)	Silberberg and Tsao
$^{154}\text{Tm}^m$	(p, $\pi^{-12}\text{n}$)	1.5×10^{-2}	7.0×10^{-3}	
^{153}Tm	(p, $\pi^{-13}\text{n}$)	4.6×10^{-3}	4.0×10^{-3}	
^{153}Er	(p, ^{13}n)	2.8×10^{-1}	6.37×10^{-1}	
^{152}Er	(p, ^{14}n)	1.3×10^{-1}	5.6×10^{-1}	
^{151}Er	(p, ^{15}n)	2.4×10^{-1}	1.3×10^{-1}	
$^{152}\text{Ho}^m$	(p, ^{13}n)	3.32	3.31	7.9×10^{-1}
^{152}Ho		1.0×10^{-1}		
$^{151}\text{Ho}^m$	(p, ^{14}n)	3.32×10^{-1}	1.75	2.7×10^{-1}
^{151}Ho		1.50		
^{150}Ho	(p, ^{15}n)	9.6×10^{-1}	8.5×10^{-1}	6.25×10^{-1}
^{151}Dy	(p, ^{2p13}n)	5.7	6.84	1.64×10^{-1}
^{150}Dy	(p, ^{2p12}n)	4.34	6.08	3.6×10^{-1}

*No reaction mechanism necessarily implied.

Table 6. Measured and experimental yields of products from a Tm target (in mb)

Product	Reaction*	Exp. cross section	Calculated cross section	
			(Cascade plus evaporation)	Silberberg and Tsao
^{155}Yb	(p,15n)	1.9×10^{-2}	2.0×10^{-2}	
^{153}Tm	(p,p16n)	1.2×10^{-1}	2.2×10^{-1}	7.3×10^{-3}
$^{154}\text{Tm}^m$	(p,p15n)	3.1×10^{-1}	4.7×10^{-1}	2.6×10^{-2}
^{154}Tm		3.8×10^{-2}		
^{152}Er	(p,2p16n)	1.14	2.51	6.2×10^{-2}
^{153}Er	(p,2p15n)	2.47	3.61	1.6×10^{-1}
^{151}Er	(p,2p17n)	1.67	6.78×10^{-1}	1.1×10^{-2}
$^{151}\text{Ho}^m$	(p,3p16n)	7.1×10^{-1}	3.60	2.7×10^{-1}
^{151}Ho		2.75		
$^{152}\text{Ho}^m$	(p,3p15n)	6.16	6.22	7.5×10^{-1}
^{152}Ho				
^{150}Ho	(p,3p17n)	1.96	2.20	6.5×10^{-2}
^{150}Dy	(p,4p16n)	5.7	7.83	1.5

*No reaction mechanism necessarily implied.

Table 7. Measured and experimental yields of products from a Ta target (in mb)

Product	Reaction*	Exp. cross section	Calculated cross section	
			(Cascade plus evaporation)	Silberberg and Tsao
^{155}Yb	(p,4p23n)	4.2×10^{-2}	4.8×10^{-2}	4.3×10^{-4}
^{153}Tm	(p,5p24n)	7.5×10^{-2}	2.40×10^{-2}	8.4×10^{-4}
$^{154}\text{Tm}^m$	(p,5p23n)	3.0×10^{-1}	3.61×10^{-1}	3.0×10^{-3}
^{154}Tm		2.95×10^{-2}		
^{153}Er	(p,6p23n)	1.25	1.37	2.0×10^{-2}
^{152}Er	(p,6p24n)	5.05×10^{-1}	1.25	7.3×10^{-3}
^{151}Er	(p,6p25n)	5.8×10^{-1}	1.0×10^{-1}	1.3×10^{-3}
$^{151}\text{Ho}^m$	(p,7p24n)	3.03×10^{-1}	1.06	3.3×10^{-2}
^{151}Ho		1.72		
$^{152}\text{Ho}^m$	(p,7p23n)	2.72	1.83	9.4×10^{-2}

*No reaction mechanism necessarily implied.

Table 8. Measured and experimental yields of products from a Re target (in mb)

Product	Reaction*	Exp. cross section	Calculated cross section	
			(Cascade plus evaporation)	Silberberg and Tsao
^{155}Yb	(p,6p27n)	2.15×10^{-2}		2.77×10^{-4}
$^{154}\text{Tm}^m$	(p,7p27n)	7.4×10^{-2}	1.3×10^{-1}	1.88×10^{-3}
^{154}Tm		6.1×10^{-3}		
^{153}Tm	(p,7p28n)	2.42×10^{-2}	2.0×10^{-2}	5.29×10^{-4}
^{153}Er	(p,8p27n)	3.14×10^{-1}	1.9×10^{-1}	1.18×10^{-2}
^{152}Er	(p,8p28n)	1.19×10^{-1}	2.7×10^{-1}	4.48×10^{-3}
^{151}Er	(p,8p29n)	1.46×10^{-1}	2.0×10^{-2}	7.9×10^{-4}
$^{152}\text{Ho}^m$	(p,9p27n)	6.8×10^{-1}	3.4×10^{-1}	5.31×10^{-2}
$^{151}\text{Ho}^m$	(p,9p28n)	3.66×10^{-2}	1.7×10^{-1}	1.94×10^{-2}
^{151}Ho		4.6×10^{-1}		
^{150}Ho	(p,9p29n)	1.6×10^{-1}	4.0×10^{-2}	4.6×10^{-3}
^{150}Dy	(p,10p28n)	3.5×10^{-1}	1.1×10^{-1}	1.05×10^{-1}

*No reaction mechanism necessarily implied.

Table 9. Measured and experimental yields of products from a Au target (in mb)

Product	Reaction*	Exp. cross section	Calculated cross section	
			(Cascade plus evaporation)	Silberberg and Tsao
^{183}Hg	(p,15n)	3.22×10^{-1}	8.0×10^{-2}	
^{183}Au	(p,p14n)	1.64	1.5	2.9×10^{-1}
^{175}Pt	(p,2p21n)	2.17×10^{-2}	8.0×10^{-2}	1.64×10^{-4}
^{176}Pt	(p,2p20n)	1.09×10^{-1}	2.5×10^{-1}	9.94×10^{-4}
^{177}Pt	(p,2p19n)	2.4×10^{-1}	5.0	2.93×10^{-3}
^{178}Pt	(p,2p18n)	7.5×10^{-1}	1.75	1.56×10^{-2}
$^{154}\text{Tm}^m$	(p, $\Delta A=44$)	5.0×10^{-3}		4.1×10^{-4}
^{152}Er	(p, $\Delta A=46$)	8.5×10^{-3}		9.7×10^{-4}
^{153}Er	(p, $\Delta A=45$)	3.15×10^{-2}		2.6×10^{-3}
^{151}Ho	(p, $\Delta A=47$)	3.5×10^{-2}		4.2×10^{-3}
$^{152}\text{Ho}^m$	(p, $\Delta A=46$)	6.0×10^{-2}		1.1×10^{-2}

*No reaction mechanism necessarily implied.

Figure Captions

1. Displayed here is a schematic representation of the target chamber of the gas jet recoil transport system. The beam windows were essentially stainless steel of approximately 20 mg/cm² in thickness.
2. Summed alpha spectrum obtained from the irradiation of a Au target with 480 MeV protons (see text for details).
3. Displayed here is a schematic representation of the collection and counting chambers for the gas jet recoil transport system. The diameter of the transport tube (1) was 4 mm, which directed the radioactive products into a collection spot (2) on a movable tape (3) system. A thin (~70 mg/cm²) lucite window (5) was used in front of an X-ray spectrometer to minimize absorption effects. The distance (6) between the active spot and the detector collimator (4b) was 2 mm; the alpha detector (4a) was a 200 μ m Si surface barrier detector. A regulated air inlet (7) was used to maintain the pressure in the counting chamber to about 2 Torr. Not displayed is the pumping system used to evacuate the collection chamber to about 0.2 Torr.
4. Displayed here are the results of the thick target-thick catcher study (see text) to estimate the effective target thicknesses, a function of mass number difference (target A—product A). The insert displays the actual package used where (1) is the target foil (Ta,Au), (2,4) are the polyethylene catcher foils (~12 mg/cm²), (3) is a polyethylene holder, (5,5a) are aluminium foils used to monitor the beam intensity. The literature values are taken from Refs. 15 and 16.

5. The alpha activity observed as a function of time resulting from irradiation of ⁸Be target with 480 MeV protons is displayed here. Zero time corresponds to the start of a beam pulse hitting the target minus the time required (0.6 sec) for the tape to bring the radioactivity to the front of the detector.
6. Displayed here are the cross sections (log scale), both experimental (filled circles) and calculated (filled triangles and diamonds), as a function of N/Z for the various products, resulting from the interaction of 480 MeV protons with a Ho target. Products of the same element are indicated. The processes to produce the Tm products included a (p, π^- xn) mechanism (see text).
7. Similar to Fig. 6 for a Au target. The left figure corresponds to products which are due to spallation processes while the right figure could not be explained by spallation only. The calculations of isobar and eva do not provide numerical values for such products (see text).

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7