The Excitation Function for ^{48}V from Tritons on Natural Titanium

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Natural titanium is used as a diagnostic charged-particle detector in nuclear-device tests making use of the reactions $^{48}\text{Ti}(p,n)^{48}\text{V}$, $^{48}\text{Ti}(d,2n)^{48}\text{V}$, and $^{47}\text{Ti}(d,n)^{48}\text{V}$. However the presence of tritons in the reaction environment can also produce ^{48}V from the reactions $^{46}\text{Ti}(t,n)^{48}\text{V}(Q=7.225 \text{ MeV})$, $^{47}\text{Ti}(t,2n)^{48}\text{V}(Q=-1.652 \text{ MeV})$ and $^{48}\text{Ti}(t,3n)^{48}\text{V}(Q=-13.278 \text{ MeV})$. The titanium isotopic abundances are respectively 8.0%, 7.3%, and 73.8%. Triton reaction cross sections for titanium are needed so that corrections to the proton and deuteron diagnostic data can be accurately calculated. In pursuit of this, we have measured the $\sum_{x=1,3} \text{Ti}(t,xn)^{48}\text{V}$ excitation function using targets of natural titanium. In addition we have measured $^{48}\text{Ti}(t,3n)^{48}\text{V}$ using targets of separated ^{48}Ti . Measurements on separated ^{46}Ti and ^{47}Ti are planned.

The measurements were made using the Van de Graaff at the Los Alamos National Laboratory (LANL). An analyzed beam was brought to our irradiation chamber located in the reaction room of the facility. The beam was defined by a 3/8 inch diam hole through a tantalum collimator. Our targets (1.0 inch diam foils) were mounted in a Faraday cup. The integral of the beam current was measured by an ORTEC 439 digital current integrator having a precision of 0.01% and an absolute accuracy of 0.2%.

The data are given in Tables 1 and 2 and are plotted in Fig. 1. They are identified by numbers, e.g. in No. T323H27-2 T, stands for tritons, 323 for the day of the year, H27 for the number of the foil-stack holder used in the irradiation, and -2 for position in the stack. The day-323 data were obtained using titanium foils $\sim 11 \text{ mg/cm}^2$ thick interspersed with both aluminum catcher foils and degraders. The catcher foils catch those ions that recoil out the back of the primary foil. The activity in the catchers can be several percent of the total and thus their count must be included in the total count.

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The data identified by T079P1 are for a second run using 3.6 mg/cm^2 targets which were made by evaporating titanium onto thick aluminum backings by the Materials Fabrication Division of Lawrence Livermore National Laboratory (LLNL). These targets were used to measure the excitation function in the rapidly varying region at low energies.

A third run was made with foils of separated ^{48}Ti (99.81%) covering the range 2 to 18 MeV. The main reason for this run was to determine ^{46}Sc and ^{47}Sc cross sections, and thus only three points were obtained for the $^{48}\text{Ti}(t,3n)^{48}\text{V}$ reaction, which has a threshold at 14.113 MeV. These data are given in Table 2.

To get accurate cross section measurements the areal densities of the target foils must be known accurately. The foil densities were determined by weighing. We then used fluorescent x-ray analysis to establish that the density variation of the 11 mg/cm^2 foils was in the order of $\pm 1\%$ or less by the masking off portions of the foils. The 3.6 mg/cm^2 foils, also analyzed by fluorescent x-ray analysis, cross-compared closely in density with the thicker foils and were found to be uniform to $\pm 2\%$. The ^{48}Ti foils were not analyzed but a previous usage showed them to be of excellent quality.

The counting was started at LANL and completed at LLNL. The data at LANL were analyzed using the code RAYGUN. The analysis at LLNL was done using the code GAMANAL.¹ With a 15.974 d half-life there was no problem in obtaining cross comparisons between samples counted and analyzed at the two laboratories. Quite consistently we find the LANL count to be $1.02x$ that of the LLNL count (checked using other gamma activities for energies from 150 to 1800 keV). Gunnink² claims a 2% calibration accuracy for the LLNL system. We have arbitrarily reduced the LANL counts by 2% before making the final averages. The uncertainties given in column four of Table 1 are due to counting statistics only. They represent averages of about six counts.

The dE/dx values for tritons are large enough at 1 to 3 MeV that a significant energy variation of the tritons occurred as they passed through the foils. In the region of the rising excitation function, this can introduce inaccuracies if we associate the measured cross section (column four of Table 1) with the average energy of the projectile in the foil. To correct this, we have made energy resolution corrections. To obtain the corrected value of σ we use a procedure that depends on knowing only the relative variation of the cross section with energy which we obtain from a polynomial

fit to the uncorrected data. Experimentally, we obtain an average of σ over the foil thickness Δx . We call the experimental value σ_{exp} and the corresponding calculated value σ_{av} . By definition

$$\sigma_{\text{av}} = \frac{1}{\Delta x} \int \sigma(x) dx$$

from which we can write

$$\sigma_{\text{av}} = \frac{1}{\Delta E} \int \frac{\sigma(E) dE}{\frac{dE}{dx} \left(\frac{dE}{dx} \right)_{\text{av}}} .$$

Note that the term in the denominator inside the integral corrects for the fact that as dE/dx increases, less of the foil thickness is subject to irradiation for a given energy. The correction for the dE/dx variation over the foil thickness has a minor effect except for the thickest foils, where ΔE was ~ 1 MeV. We fit the data (we used $\ln \sigma$) in the rising portion of the excitation function (excluding T323H25-2) to a polynomial in $\ln E$. For each data point, we calculated σ_{av} and $\sigma(E_{\text{av}})$ from the polynomial. Corrected experimental values were obtained from $\sigma_{\text{exp}} \times \sigma(E_{\text{av}})/\sigma_{\text{av}}$. These values are given in column five and are to be associated with E_{av} . The results are quite insensitive to the details of the fitting. Whether we used three points and a three-term polynomial or ten points and a five-term polynomial (piece-wise continuous) the results are about the same. As a test of our procedure, we then used the new data points as inputs and recalculated $\sigma(E_{\text{av}})$ and σ_{av} (using ΔE). The values are given in parentheses in columns five and four respectively and should compare well with the original data. Using three data points and a three-term polynomial, our ability to calculate the original experimental points is quite good. For the results shown, the polynomial was over determined by several points. With the polynomial over determined, inaccuracies in E_{av} affect the fits. We note that our code makes allowances for straggling, but the inclusion of this effect had little effect on the final result except when ΔE was quite large (>1 MeV).

For T323H25-2, the agreement with the other data is not as good as we would like. The discrepancy is probably due to inaccuracies in energy and may reflect the dE/dx values used since raising E_{av} by less than 0.1 MeV would

bring the value into good agreement with the rest of the results. We started with 5.2 MeV tritons into the T323H25 foil stack and had to calculate the energies for T323H25-2 in the 1.1 to 2.95 MeV range. The dE/dx values we used could be high in this range by several percent (3% is all that is needed). The other results are not affected significantly by possible errors in dE/dx . In addition to this possible error, the ^{47}Ti reaction has a threshold in this region. These factors all combine to make the resolution correction for this point inaccurate. Thus the T323H25-2 data should not be used as part of the final data set.

The initial triton energies as given by the Van de Graaff operators was subject to a small correction. L. Rowton (the facility manager) and staff made a measurement of a well-known proton resonance at 14.250 MeV to obtain the error in energy. Scaling the results by momentum, we obtain a correction for tritons $\frac{dE}{E} = -2.31 \times 10^{-3}$, which was applied to the data. Although the resonance was measured to ± 5 keV we doubt that the final corrected triton energies are known to better than ± 20 keV because of possible hysteresis effects in the analyzing magnets and uncertainties in dE/dx . However, the need for accurate energies occurs only in the rising portion of the excitation function. Generally, in the region where the thick foils were used, an energy uncertainty of even 200 keV would not be significant.

Note in Fig. 1 that the data are shown as bars of width ΔE . The corrected data points are shown below the respective ΔE 's in the rising region of the curve. The results up to ~ 15 MeV are due to only ^{46}Ti and ^{47}Ti . Above that we see the contribution from ^{48}Ti .

The ^{48}Ti data are shown in Table 2. Column four shows the initial experimental data and column five the results of energy resolution correction. The ^{48}Ti data were then used to subtract the ^{48}Ti contribution from the three highest energy points of σ_{nat} in Table 1. Corrections for the finite energy resolution ΔE , associated with σ_{nat} , were made in making the ^{48}Ti corrections.

Preliminary calculations of the (t, xn) reactions were made using the STAPRE code (used global parameters). The results are given in Table 3. These results, scaled for isotopic abundances, are included in Fig. 1. Their sum, for comparison with the experimental data, is also shown.

We find that the calculated curve $0.080\sigma_{^{46}} + 0.073\sigma_{^{47}}$ is 30 to 40% higher than experiment at the higher energies but is several times experiment in the rising portion of the excitation function. The difference is probably due to

breakup of the triton in the reaction entrance channel, as we have found for deuterons incident on chromium targets,^{3,4} but probably not to as large an extent. Also, our measurements⁵ of the reaction $^{48}\text{Ti}(d,2n)^{48}\text{V}$ clearly show the effects of deuteron breakup. Modeling the triton results should help in our understanding of breakup in the mass-50 region. Measurements with separated ^{46}Ti and ^{47}Ti will greatly complement this effort. In addition, measurements for $^{44}\text{Sc}^{g,m}$, ^{46}Sc , ^{47}Sc , and ^{48}Sc production which are being obtained, will provide further data for modeling in the mass-50 region.

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Table 1. The $\Sigma_{x=1,3}$ and $\Sigma_{x=2,3}^{Ti(t,xn)} {}^{48}V$ Excitation Functions

ID #	E_{av} (MeV)	ΔE (MeV)	σ_{nat} (mb) ^a	Corrected ^b σ_{nat}
T079P11	1.67	0.65	0.017 $\pm$ 0.0011 (0.018)	0.010 .012) ^c
T323H25-2	2.03	1.82	0.627 $\pm$ 0.014 (0.407)	0.155 0.091) ^c
T079P12	2.21	0.58	0.235 $\pm$ 0.007 (0.231)	0.199 0.190) ^c
T079P13	2.73	0.54	1.122 $\pm$ 0.015 (1.21)	1.049 1.13) ^c
T079P14	3.25	0.48	4.10 $\pm$ 0.034 (3.94)	4.01 3.86) ^c
T079P15	3.77	0.44	8.50 $\pm$ 0.040 (8.38)	8.46 8.37) ^c
T323H25-1	4.59	1.20	16.55 $\pm$ 0.040 (16.90)	16.49 16.37) ^c
T323H26-3	6.62	0.97	31.44 $\pm$ 0.12	
T323H26-2	8.13	0.84	37.32 $\pm$ 0.03	
T323H26-1	9.50	0.76	40.51 $\pm$ 0.12	
T323H27-3	10.91	0.69	42.75 $\pm$ 0.21	
T323H27-2	12.45	0.63	41.89 $\pm$ 0.24	
T323H27-1	13.88	0.58	40.36 $\pm$ 0.55	
T323H28-3	15.32	0.55	38.98 $\pm$ 0.15	(37.70) ^d
T323H28-2	16.54	0.51	42.99 $\pm$ 0.17	(33.86) ^d
T323H28-1	17.71	0.49	58.87 $\pm$ 0.26	(29.38) ^d

^a Data without the parentheses are uncorrected experimental data. Errors given are statistical. For an approximate overall error, add 3% in quadrature.

^b Data without the parentheses are resolution corrected data. The results are insensitive to the data fits.

^c These data were derived using the fit equations based on corrected results. The variation using different fits is typically a few percent.

^d The contributions from σ_{48} were removed using the data in Table 2.

Table 2. The $^{48}\text{Ti}(t,3n)^{48}\text{V}$ Excitation Function

ID #	$E_{av}(\text{MeV})^a$	$\Delta E(\text{MeV})$	$\sigma_{48}(\text{mb})^b$	Corrected ^c $\sigma_{48}(\text{mb})$
T079H35-3	15.04	0.27	0.822 ± 0.037	0.809
T079H35-2	16.55	0.25	12.30 ± 0.07	12.27
T079H35-1	17.85	0.26	44.71 ± 0.17	44.65

^a Threshold gives us an extra data point at 14.113 MeV.

^b Uncorrected experimental data. The quoted errors are statistical. For an estimate of the overall error add 3% in quadrature.

^c Energy resolution corrected.

Table 3. Results of STAPRE Calculations

$^{46}\text{Ti}(t,n)^{48}\text{V}$		$^{47}\text{Ti}(t,2n)^{48}\text{V}$		$^{48}\text{Ti}(t,3n)^{48}\text{V}$	
$E_{\text{lab}}(\text{MeV})$	$\sigma(\text{mb})$	$E_{\text{lab}}(\text{MeV})$	$\sigma(\text{mb})$	$E_{\text{lab}}(\text{MeV})$	$\sigma(\text{mb})$
1.96	2.2	2.14	0.1	14.92	0.46
3.03	53.	3.74	57.	15.98	7.2
4.09	126.	5.86	397.	17.04	32.
4.89	141.	7.99	625.	18.10	77.
5.96	132.	10.12	719.	18.95	124.
7.02	114.	12.25	747.	20.02	183.
8.09	94.	13.84	721.		
8.89	81.	15.97	634.		
9.95	66.	18.10	532.		
10.08	65.	20.23	436.		
12.21	44.				
13.81	34.				
15.94	24.				
18.07	19.				
20.20	15.

Fig. 1. Experimental results for the $x=1,3$ and $x=2,3$ $\text{Ti}(t, xn)^{48}\text{V}$ excitation functions. The experimental results are compared with theoretical results obtained from the STAPRE code. Note that all cross sections are given in terms of their natural abundance in titanium.