Neutron capture cross sections of even-mass tellurium isotopes

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Neutron capture by the stable even-mass Te isotopes ($A = 120$ to 130) produces in the neighboring odd-neutron isotopes a low-spin ground state ($1/2^+$ or $3/2^+$) and a high-spin ($11/2^-$) isomeric state. Following neutron irradiation of samples of Te of natural isotopic abundance, thermal cross sections and resonance integrals have been determined for all of the odd-mass radioactive ground states and isomers produced in the capture process. By comparing Cd-shielded and unshielded irradiations, it was possible to correct for the effect of capture by epithermal neutrons and so obtain consistent values for the thermal cross sections. Half-lives have been remeasured for ^{121g,m}Te, ^{127m}Te, and ^{131m}Te. The previously observed systematic behavior of the thermal cross sections leading to the low-spin and high-spin states in Sn does not appear for the similar states in the Te isotopes.

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I. INTRODUCTION

Radiative neutron capture by the even-mass isotopes of Sn ($Z = 50$) with mass numbers 116, 118, 120, 122, and 124 leads eventually to an $11/2^-$ state, which is the ground state in (radioactive) ^{123,125}Sn and an excited isomeric state in ^{117,119,121}Sn. In ^{117,119}Sn the ground state is $1/2^+$, in ^{121}Sn the ground state is $3/2^+$, and in ^{123,125}Sn there is a low-lying $3/2^+$ isomeric state. In a recent publication [1] we reported the measurement of the thermal cross sections and resonance integrals for several of these neutron capture processes and pointed out the remarkable uniformity of the thermal cross sections over this range of isotopes: All captures leading to the $11/2^-$ states have thermal cross sections in the range of 2–4 mb, whereas captures leading to the $1/2^+$ and $3/2^+$ states have cross sections in the range of 0.11–0.22 b. (Capture by ^{112}Sn and ^{114}Sn to $1/2^+$ ground states gives cross sections with similar values [2,3]). There is no discernible isotopic effect over this range of mass numbers. The thermal cross sections remain quite constant despite the addition of 12 neutrons to the nucleus ($N = 62$ to 74).

The behavior of the even-mass Te isotopes ($Z = 52$), only two protons away from Sn, seems at least superficially similar. Neutron capture by Te isotopes with mass numbers 120, 122, 124, 126, 128, and 130 leads to either an $11/2^-$ isomeric state or a low-spin ground state ($1/2^+$ in ^{121,123,125}Te and $3/2^+$ in ^{127,129,131}Te). Previously reported values [2,3] of the thermal cross sections for radiative neutron capture by Te isotopes appear to show none of these systematic behaviors. These measurements have been reported by a variety of laboratories using different measuring techniques. Many of these results are reported only as total cross section for the ground state plus isomer or else as the ratio of the ground-state and isomeric cross sections. To more fully explore any possible systematic behavior in Te, we have measured the cross sections for radiative capture by all of the stable even-mass Te isotopes. Captures by these 6 isotopes lead to a total of 12 ground and low-lying isomeric states. Ten of the 12 are radioactive (all except the ^{123,125}Te ground states) and thus accessible to measurement using the activation technique. The present paper contains the results of these measurements and a comparison with the corresponding results in Sn.

The use of high-resolution Ge detectors to study the γ emissions from irradiated samples enables the characteristic γ rays from many different radioactive isotopes to be observed from a single sample. This has the advantage of permitting the simultaneous determination of cross sections from several isotopes, thus lending confidence to the search for systematic behavior. Our goals in these experiments were to (1) follow the decays of all radioactive isotopes present in each irradiated sample to enable this simultaneous determination of the cross sections; (2) irradiate samples in facilities with widely differing thermal and epithermal neutron fluxes to serve as internal cross-checks of the results; (3) determine separately the values of the cross sections for each isotope's ground state and isomer; and (4) use Cd-shielded irradiations to determine the (often considerable) effect of captures by epithermal neutrons, which permits a more reliable measurement of the contributions to the capture by the thermal component of the neutron flux.

Figure 1 shows a schematic view of the neutron capture process by the even-mass Te isotopes. The capture proceeds through high-lying resonance states (mostly $1/2^+$, corresponding to s-wave captures, but also occasionally $3/2^-$, corresponding to p-wave captures). Following the emission of several (unobserved) primary and secondary γ rays, the capture process populates the excited $11/2^-$ isomeric state or the ground state, which is either $1/2^+$ or $3/2^+$. The long-lived isomeric states decay both by γ transitions (with competing internal conversion) to the ground state and by electron capture or negative β decay to the neighboring Sb or I isotopes, except for ^{123m,125m}Te, which decay only through isomeric γ transitions. The radioactive ground states likewise β decay to Sb or I. Table I summarizes the properties of the Te isotopes used in the present work [4–7].

The determination of the cross sections from the observed γ-ray intensities depends critically on the precise knowledge of the isotopic abundance and the half-life of the radioactive decay. Recommended values of the Te isotopic abundances have been given by Rosman and Taylor [7]. We have chosen to use their "representative" isotopic abundances rather than their "best" values, which introduces an additional uncertainty into the calculation of the cross sections for ^{120g,m}Te and

TABLE I. Properties of Te isotopes used for cross-section measurements.

A	Abundance (%)[a]	Capture to	J^π	$t_{1/2}$		Isomeric state[b]		Analyzing γ rays[b]
				Previous work[b]	Present work	E (keV)	$I_{\gamma+e}$ (%)	
120	0.09 *1*	121*g*	$1/2^+$	16.78 *35* d, 19.16 *5* d	19.2 *1* d	294.0	88.6	573.1 (80.3%)
		121*m*	$11/2^-$	154 *7* d	164.2 *8* d			212.2 (81.4%)
122	2.55 *12*	123*g*	$1/2^+$	∞				
		123*m*	$11/2^-$	119.7 *1* d, 119.2 *1* d		247.4	100	159.0 (84.0%)
124	4.74 *14*	125*g*	$1/2^+$	∞				
		125*m*	$11/2^-$	57.40 *15* d		144.8	100	109.3 (0.274%)
126	18.84 *25*	127*g*	$3/2^+$	9.35 *7* h				360.3 (0.135%), 417.9 (0.99%)
		127*m*	$11/2^-$	109 *2* d	106.1 *7* d	88.3	97.6	360.3 (0.131%), 417.9 (0.97%)
128	31.74 *8*	129*g*	$3/2^+$	1.160 *5* h				459.5 (7.70%), 487.3 (1.42%)
		129*m*	$11/2^-$	33.6 *1* d		105.3	64	695.8 (2.99%), 729.5 (0.70%)
130	34.08 *62*	131*g*	$3/2^+$	25.0 *1* m				149.7 (68.8%), 452.3 (18.2%)
		131*m*	$11/2^-$	30 *2* h, 33.25 *25* h	32.48 *11* h	182.4	25.9	773.7 (36.8%), 852.2 (20.3%)

[a]Isotopic abundances from Rosman and Taylor [7].
[b]Spectroscopic data from Refs. [4–6].

(to a somewhat smaller extent) ^{122m,124m}Te. Because our experiments involved tracking the decay of each sample over at least two half-lives, for some of the isotopes we were able to determine half-lives that are more precise than the previously accepted values. These cases are listed in Table I and are discussed later in this paper.

II. EXPERIMENTAL DETAILS

Samples of Te of 99.99% metallic purity and natural isotopic abundance were irradiated in the Oregon State TRIGA reactor (OSTR) [8]. Four different irradiation facilities were used: a thermal column (TC, with nominal thermal and epithermal neutron fluxes of, respectively, 6.4×10^{10} and 1.8×10^8 neutrons cm^{-2} s^{-1}), an in-core irradiation tube (ICIT, with fluxes of 8.9×10^{12} and 1.2×10^{12} neutrons cm^{-2} s^{-1}), a cadmium-lined in-core irradiation tube (CLICIT, with fluxes of 0 and 1.2×10^{12} neutrons cm^{-2} s^{-1}), and a fast pneumatic transfer facility ("rabbit", with fluxes of 1.0×10^{13} and 3.5×10^{11} neutrons cm^{-2} s^{-1}). The rabbit samples could also be enclosed in a Cd box (0.5 mm wall thickness) to isolate the epithermal component. Ten samples were employed, with two separate irradiations in each of the five configurations (TC, ICIT, CLICIT, and rabbit with and without Cd). All Te irradiations were accompanied with flux monitors. Primary flux monitors were Au and Co as dilute (respectively, 0.134% and 0.438%) alloys in thin Al metal foils.

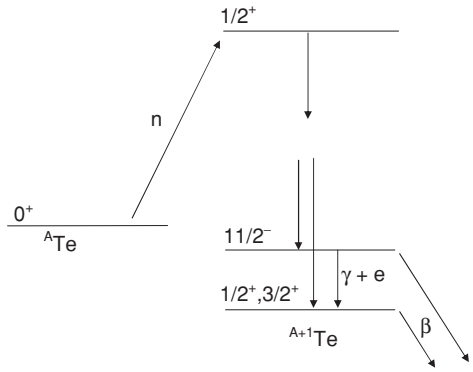

FIG. 1. Schematic diagram of processes involved in thermal neutron capture by even-mass isotopes of Te. The capture process is dominated by s-wave ($1/2^+$) resonances, but p-wave ($3/2^-$) resonances may also contribute.

The Te polycrystalline samples were typically 0.4–0.5 mm in thickness and several millimeters in length and width. Sample masses ranged from 7 to 130 mg. Irradiations in the ICIT, CLICIT, and TC lasted 2–3 h, and counting of the samples began several hours following the irradiations; rabbit irradiations were 1–10 min and the samples were counted within about 30 min following the irradiations. Self-shielding of samples in the neutron irradiations was estimated to amount to less than 0.2% for thermal neutrons and less than 1% for epithermals. The small neutron attenuation occurs because the stable isotopes with the largest cross sections have the smallest abundances.

All samples were initially counted for periods ranging from several hours to several days after the irradiations, and then recounted periodically over at least two decay half-lives of each of the Te activities. The γ rays were observed with a high-purity Ge detector (with a nominal volume of 169 cm^3,

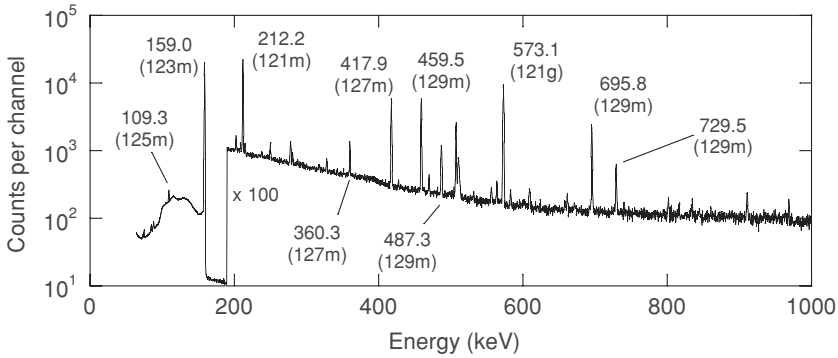

FIG. 2. Long-lived component of γ-ray spectrum of irradiated Te, obtained several months following irradiation. The prominent peaks used in the present study are labeled with their energies in keV.

an efficiency of 35% compared with NaI at 1332 keV, and a resolution of 1.68 keV at 1332 keV). Source-to-detector distances were generally 10 to 20 cm, for which coincidence summing effects are negligible. The signals were analyzed with a digital spectroscopy system connected to a desktop computer. Peak areas of the γ-ray lines, which were well isolated from neighboring peaks, were determined with the MAESTRO software [9].

Attenuation of γ rays from absorption within the samples was estimated by using the half-thickness of the sample as a representative absorption distance. For the most sensitive case (109.3 keV), the loss in intensity in the thickest sample was about 20%. Absorption for the 149.7- and 159.0-keV γ rays was at most 10%, for 212.2 keV it was at most 5%, and for higher energy γ rays it was less than 1%.

Efficiency calibrations were done with standardized sources of ^{133}Ba and ^{152}Eu. The calibration below 200 keV was also characterized by using reactor-produced sources of ^{160}Tb, ^{169}Yb, and ^{182}Ta. Sample γ-ray spectra from the long-lived and short-lived Te activities are shown in Figs. 2 and 3. In addition to the Te, the irradiated samples showed activity from 8.0-d ^{131}I, daughter of ^{131}Te.

III. RESULTS

For each Te isotope, the activity was determined from the γ-ray intensities by using the peaks listed in Table I. A half-life correction was applied to compensate for decay from the end of bombardment to the time of counting. The end-of-bombardment activity a depends on the cross sections according to

$$a = N(\sigma\phi_{\text{th}} + I\phi_{\text{epi}})(1 - e^{-\lambda t_i}), \quad (1)$$

where N is the number of stable Te target nuclei in the irradiated sample, ϕ_{th} and ϕ_{epi} are the thermal and epithermal neutron fluxes, and t_i is the irradiation time. In Eq. (1), σ represents the effective thermal cross section (i.e., the 2200 m/s value). Because there are no broad or low-lying neutron resonances known for any of the Te isotopes considered in the present work, the cross section closely follows the $1/v$ behavior below about 1 eV [2,10]. The effective resonance integral I includes a small contribution from the $1/v$ region [2]. Assuming the Cd cutoff energy to be about 0.5 eV gives for this contribution a value of about 0.45σ; the corrected resonance integral I' is then

$$I' = I - 0.45\sigma. \quad (2)$$

Because the resonance integral is usually larger than the thermal cross section (about an order of magnitude larger for most of the Te isotopes), this correction is small and in almost all cases within about one standard deviation of the values of the resonance integrals. However, it is important to make this correction for the Au and Co flux monitors to avoid introducing additional systematic uncertainties in the flux determinations. For our flux monitors we have assumed the following cross sections [2]:

$$\sigma(\text{Au}) = 98.65 \pm 0.09\,\text{b}, \quad I(\text{Au}) = 1550 \pm 28\,\text{b},$$
$$\sigma(\text{Co}) = 37.18 \pm 0.06\,\text{b}, \quad I(\text{Co}) = 74 \pm 2\,\text{b}.$$

Tables II and III summarize the thermal cross sections and resonance integrals determined from the present work. With the exception of the short-lived ^{129g,131g}Te, each resonance integral was determined from both CLICIT and rabbit data, and each thermal cross section was determined from ICIT, TC, and rabbit data. Generally, the TC value gets the most weight in the thermal cross section determination, because the

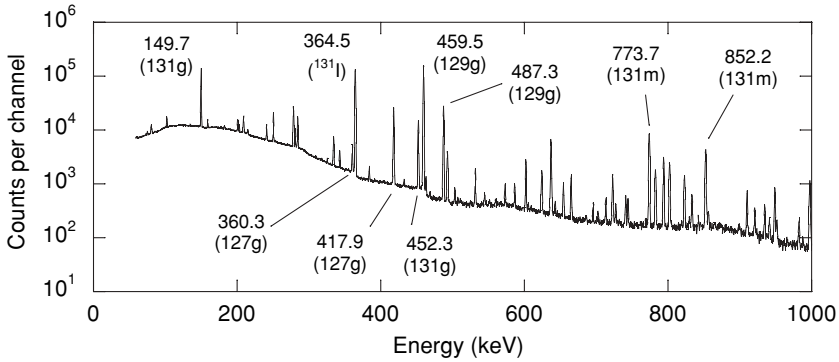

FIG. 3. Short-lived component of γ-ray spectrum of irradiated Te, obtained within 3 h following irradiation. Peaks used in the analysis are labeled with energies in keV. Essentially all other peaks visible in this spectrum are due to ^{129g,131g,131m}Te and ^{131}I.

TABLE II. Thermal cross sections of Te isotopes.

Target A	Capture to	Thermal cross section σ (b)	
		Present results	Previous results
120	121g	0.558 (67)	2.0 (3)[a]
	121m	0.098 (12)	0.34 (6)[a]
122	123g	–	
	123m	0.418 (27)	0.44 (3)[b]
124	125g	–	
	125m	0.851 (61)	1.12 (7),[b] 0.040 (25)[c]
126	127g	0.325 (14)	0.78 (16),[d] 1.03 (16)[e]
	127m	0.056 (3)	0.0625 (56),[b] 0.073 (15)[d]
128	129g	0.181 (10)	0.133 (27),[d] 0.178 (27),[e] 0.200 (8)[f]
	129m	0.026 (2)	0.0273 (20),[b] 0.015 (3),[d] 0.0161 (7)[f]
130	131g	0.186 (11)	0.27 (6),[a] 0.222 (44),[d] 0.161 (24)[e]
	131m	0.0106 (4)	0.04 (1),[a] <0.008(3)[d]

[a]Sehgal [14].
[b]Alpatov *et al*. [16].
[c]Gvozdev and Khazov [18].
[d]Seren *et al*. [21].
[e]Mangal and Gill [22].
[f]Maxia *et al*. [25].

ICIT and rabbit values are more sensitive to the uncertainties in the resonance integral. The epithermal flux is so small in the TC (a factor of 400 smaller than the thermal flux) that even a resonance integral an order of magnitude larger than the thermal cross section has only a very small effect.

Uncertainties in the cross sections depend on a number of measurement-related factors, including the flux determinations, detector efficiency calibrations, counting statistics, and relative branching ratios. Overall these factors combine to give a minimum uncertainty in the range of 4–5% in our cross sections. Uncertainties in isotopic abundances contribute

TABLE III. Resonance integrals of Te isotopes.

Target A	Capture to	Resonance integral (b)		
		Present results		Previous results[a]
		I	I'	
120	121g	20.7(9)	20.5(9)	
	121m	3.95(17)	3.91(17)	
122	123g	–	–	
	123m	9.95(42)	9.76(42)	5.08 (36),[b] 7.6 (16)[c]
124	125g	–	–	
	125m	7.74(43)	7.36(43)	1.40 (11)[b]
126	127g	2.69(10)	2.54(10)	8.0 (6)[d]
	127m	0.541(25)	0.516(25)	0.637 (42)[b]
128	129g	1.57(7)	1.49(7)	1.59 (6),[d] 1.48 (13)[e]
	129m	0.244(10)	0.232(10)	0.207 (12),[b] 0.0774 (52)[e]
130	131g	0.376(18)	0.292(19)	0.34 (3),[d] 0.48 (14)[f]
	131m	0.047(3)	0.042(3)	

[a]Uncorrected resonance integral I except where indicated.
[b]Alpatov *et al*. [16].
[c]Anufriev *et al*. [17].
[d]Van der Linden *et al*. [24].
[e]Maxia *et al*. [25].
[f]Ricabarra *et al*. [28]; value is corrected resonance integral I'.

at about the 10% level for ^{120}Te, 3–5% for ^{122,124}Te, and less than 0.2% for ^{126,128,130}Te. The uncertainties quoted in Tables II and III do not include a possible contribution from the systematic uncertainties in the absolute γ-ray intensities (owing primarily to the lack of definite information on the β branching to the ground states), which are significant only for ^{127g,m}Te ($\pm$10%), ^{129g}Te ($\pm$6.5%), and ^{129m}Te ($\pm$36%). Our quoted results for the ^{129m}Te cross sections are based on the intensities of the ^{129m}Te decay γ rays, but also on the γ rays emitted following the ^{129m}Te isomeric decay through ^{129g}Te. These analyses give identical cross sections, so the values quoted in Tables II and III for ^{129m}Te may be influenced only by the $\pm$6.5% systematic uncertainty of the ^{129g}Te decays rather than the $\pm$36% systematic uncertainty of the ^{129m}Te decays.

Our results for the ground-state cross sections represent processes leading directly to the ground state with the contributions of the isomeric state subtracted out. In all cases in the present work this contribution is small, partly because of the smaller cross section of the isomeric state and partly because of its longer half-life.

A. ^{120}Te → ^{121}Te

The print [4] and on-line [5] versions of the *Table of Radioactive Isotopes* both quote a value of 16.78 ± 0.35 d for the half-life of ^{121g}Te, whereas the on-line Evaluated Nuclear Structure Data File [6] adopts the more recent value of Siegert [11], 19.16 ± 0.05 d. We have followed the decay of our Te samples over more than 40 d to determine this half-life; our value is 19.2 ± 0.1 d, in excellent agreement with Siegert's result. The only reported determination of the ^{121m}Te half-life is 154 ± 7 d by Bhattacharyya and Shastry [12]. We have followed the decay of our samples over more than 10 months to enable us to obtain its half-life,

$$t_{1/2}(^{121m}\text{Te}) = 164.2 \pm 0.8\,\text{d}.$$

For the duration of the counting of this sample, we also compared our values of the half-lives of ^{123m}Te (119.7 ± 0.4 d) and ^{125m}Te (58.0 ± 0.4 d) with the accepted values quoted in Table I. The good agreement with previous values for these two cases lends confidence to our new values for ^{121g,m}Te. The cross sections leading to ^{121g}Te and ^{121m}Te quoted in Tables II and III use the revised half-lives for both isotopes.

Pomerance [13] reported a measurement of the total ^{121}Te cross section of $\sigma(g+m) = 68 \pm 68$ b; the large experimental uncertainty of this value overlaps our results. Cross section ratios have been previously determined by Sehgal [14], who obtained $\sigma(g)/\sigma(m) = 6.2 \pm 1.5$, and by Gangrsky *et al.* [15], who obtained $\sigma(m)/\sigma(g) = 0.18 \pm 0.02$. From our values for $\sigma(g)$ and $\sigma(m)$ we obtain $\sigma(g)/\sigma(m) = 5.7 \pm 0.5$ and $\sigma(m)/\sigma(g) = 0.176 \pm 0.016$. These values are in excellent agreement with the less-precise previous values. Sehgal also determined the separate values of $\sigma(g) = 2.0 \pm 0.3$ b and $\sigma(m) = 0.34 \pm 0.06$ b, based on a comparison with the cross section for the production of ^{123m}Te, which was taken to be 1.1 b. Using instead our cross section for ^{123m}Te as the reference value, Sehgal's results would scale down, respectively, to 0.76 ± 0.11 and 0.13 ± 0.02 b, bringing them into better agreement with our results.

B. ^{122}Te → ^{123}Te

Our result for the thermal cross section leading to the isomeric state is in excellent agreement with the value reported by Alpatov *et al.* [16], although the agreement with their value of the resonance integral is not good. Another determination of the resonance integral was done by Anufriev *et al.* [17] based on a calculation from the measured neutron resonance parameters; their value is roughly midway between our result and Alpatov's.

C. ^{124}Te → ^{125}Te

Previous results [16,18] for the ^{124}Te thermal cross section leading to ^{125m}Te vary widely. Alpatov *et al.* [16] and Gvozdev and Khazov [18] both used the activation technique with the 109-keV transition, in common with the present work, but γ rays were observed in the former and conversion electrons in the latter. More recent studies of primary and secondary gammas in the capture by ^{124}Te (discussed in Sec. IV) are consistent with a value close to 1 b, in agreement with the present work and that of Alpatov, but in conflict with the currently available compilations of cross sections [2,3], which list the much smaller value of Gvozdev and Khazov as the recommended value. (A previous discussion of this disagreement was given by Honzátko *et al.* [19], whose data suggest a thermal cross section for the isomer in the range 1.0–5.3 b.)

D. ^{126}Te → ^{127}Te

The currently accepted value of the half-life of ^{127m}Te is 109 ± 2d, derived from data reported by Andersson *et al.* [20]. We have followed the decay of the 417.9-keV γ ray for a period of 10 months to obtain a half-life of

$$t_{1/2}(^{127m}\text{Te}) = 106.1 \pm 0.7\,\text{d}.$$

Our result for the ground-state thermal cross section is a factor of 2–3 smaller than the previous results [21,22], but our value for the isomeric cross section is in good agreement with the previous values. Because we used the same γ rays to analyze the decays of the ground state and the isomer, the agreement with previous work for the isomeric cross section eliminates uncertainties in the branching ratios or detector efficiencies as a source for the disagreements in the case of the ground-state thermal cross section. Moreover, our cross sections yield a value for the isomeric-to-total ratio, 0.147 ± 0.010, that is in good agreement with previous measurements of this ratio: 0.15 ± 0.01 by Gangrsky *et al.* [15] and 0.149 ± 0.004 by Reifarth and Käppeler [23] (whose results include a 5.5% contribution from epithermal neutrons, which affects the ratio by only a few per cent).

For the resonance integral, our values are smaller than previously measured ones both for the ground state [24] and the isomer [16]. Van der Linden *et al.* [24] characterize their measurement for the ground state in terms of the ratio $I/\sigma = 8.9 \pm 0.7$ from which they deduce I using the accepted

TABLE IV. Comparison of cross sections deduced from activation and (n, γ) studies.

A	Activation		(n, γ)	
	$\sigma(g+m)$ (b)	$\sigma(m)/\sigma(g+m)$	$\sigma(g+m)$ (b)	$\sigma(m)/\sigma(g+m)$
120	0.656 (68)	0.149 (24)		
122	4.32 (40)[a]	0.097 (11)[a]	4.0 (6)[b]	0.17 (3),[b] 0.123 (20)[f]
124	7.15 (70)[a]	0.119 (14)[a]	6.1 (7)[b]	0.167 (17),[b] 0.138 (12)[f]
126	0.381 (14)	0.147 (10)	0.55 (6)[b]	0.157 (16)[b]
128	0.207 (10)	0.130 (12)	0.24 (3),[b] 0.186 (21)[c]	0.111 (10)[b]
130	0.197 (11)	0.054 (4)	0.24 (2),[b] 0.193 (20),[d] 0.186 (13)[e]	0.059 (4)[b]

[a]Calculated from present results for $\sigma(m)$ and tabulated [2] values of $\sigma(g)$.
[b]Tomandl *et al.* [33].
[c]Wirth *et al.* [31].
[d]Honzatko *et al.* [29].
[e]Tomandl *et al.* [32].
[f]Bondarenko *et al.* [30].

value of σ. Our results for the independently determined I and σ yield $I/\sigma = 8.3 \pm 0.5$, in excellent agreement with Van der Linden *et al.*, which suggests that the apparent discrepancy in the values of the resonance integrals can in fact be traced to the thermal cross sections. As is discussed in the following, we agree very well with the results of Van der Linden *et al.* for the resonance integrals leading to ^{129m}Te and ^{131m}Te.

E. ^{128}Te → ^{129}Te

In the case of thermal captures by ^{128}Te our results for both the ^{129}Te ground state and isomer are in reasonable agreement with previous work [16,21,22,25]. Our values for the cross sections yield an isomer-to-total ratio of 0.126 ± 0.012, which can be compared with measured values of 0.074 ± 0.015 (Bishop *et al.* [26]), 0.127 ± 0.010 (Alpatov *et al.* [16]), 0.080 ± 0.008 (Gangrsky *et al.* [15]) and, 0.124 ± 0.008 (Reifarth and Käppeler [23], again with an epithermal contribution that contributes less than the experimental uncertainty).

The present results agree reasonably well with the previously measured resonance integrals [16,24,25]. Browne and Berman [27] report $I(g+m) = 1.098 \pm 0.105$ b obtained by summing over the known resonances. The results of Maxia *et al.* [25] give values for both the thermal cross section and resonance integral leading to the isomer that are substantially smaller than our values (despite the agreement in both values for production of the ground state). The disagreement may perhaps be traced to the γ-ray branching ratios; Maxia *et al.* (who used NaI detectors) underestimated the total intensity of the 460- and 487-keV transitions by about 10% and also assumed the same decay intensities for the 460- and 487-keV transitions in both the ground-state and isomeric decays, but according to the presently accepted decay scheme (Table I) 36% of the isomeric decays proceed through a β transition that produces only negligible amounts of those γ rays. These corrections account for most of the difference between our results and those of Maxia *et al.*

TABLE V. Comparison of Sn and Te thermal cross sections.

Neutron number	Sn[a] Low spin $(1/2^+, 3/2^+)$	Sn[a] High spin $(11/2^-)$	Te[c] Low spin $(1/2^+, 3/2^+)$	Te[c] High spin $(11/2^-)$
64				
66	0.14 (3)	0.0035 (5)		
68	0.22 (5)[b]	0.010 (6)[b]	0.558 (67)	0.098 (12)
70	0.14 (3)[b]	0.0019 (4)[b]	3.9 (4)[b]	0.418 (27)
72	0.138 (10)	0.0041 (12)	6.3 (7)[b]	0.851 (61)
74	0.114 (10)	0.0033 (8)	0.325 (14)	0.056 (3)
76			0.181 (10)	0.026 (2)
78			0.186 (11)	0.0106 (4)

[a]Krane and Sylvester [1], except where indicated.
[b]Values from Mughabghab [2].
[c]Present work, except where indicated.

F. ^{130}Te → ^{131}Te

The previously accepted value of the ^{131m}Te half-life (30 ± 2 h) was revised by Reifarth and Käppeler [23] to 33.25 ± 0.25 h. We have followed the decays of several samples, monitoring the γ rays listed in Table I along with several others over periods of roughly 2.5 days following the irradiations. Fitting our decay data gives a half-life of

$$t_{1/2}(^{131m}\text{Te}) = 32.48 \pm 0.11\,\text{h}.$$

Previous values [14,21,22] for the ground-state and isomeric cross sections are overall less precise than but in otherwise fairly good agreement with the present results.

By summing over the known resonances, Browne and Berman [27] obtained $I(g+m) = 0.258 \pm 0.032$ b, which is somewhat smaller than our results. The resonance integral leading to ^{131g}Te is the only case among the Te isotopes in which there is a correction for the $1/v$ component that is significantly outside of the experimental uncertainty. Ricabarra *et al.* [28] quote a somewhat larger value for the corrected resonance integral, but they base their analysis on a larger value of σ (0.26 ± 0.08 b). Had they used a thermal cross section closer to our value, the corrected resonance integrals would be in very good agreement.

IV. DISCUSSION

The present results show the benefits of producing a self-consistent set of measurements of thermal neutron cross sections by (1) using a mixed isotopic sample to observe a range of isotopes and (2) systematically correcting for the effects of capture by epithermal neutrons. With a high-resolution counting system, the individual γ rays from each isotope can be easily identified and separately measured.

Several recent studies have reported the Te cross sections based on measurement of the primary and secondary γ transitions from the capture states. [29–33]. Results of these studies are generally reported either as the total cross section $\sigma(g+m)$ or as the isomer ratio $\sigma(m)/\sigma(g+m)$. To facilitate a comparison between the activation and the (n,γ) results, we have converted our values for $\sigma(g)$ and $\sigma(m)$, with the inclusion of the tabulated [2] values for the stable ^{122,124}Te ground states, to values of $\sigma(g+m)$ and $\sigma(m)/\sigma(g+m)$. The results of this comparison are listed in Table IV. Although there are one or two small disagreements, the overall agreement is quite satisfactory (within one standard deviation in most cases). There certainly appear to be no systematic differences between the two data sets. This gives confidence to the reliability of these two sets of results derived from very different techniques, in the one case relying on the intensities of the radiations *emanating from* the ground and isomeric states, and in the other on the intensities of radiations *leading to* those states.

It is interesting to compare the results of the present work with those of our previous similar study of the Sn isotopes [1]. The low-lying structures of the odd Sn and Te isotopes are very similar—the ground state and the isomeric state are separated by 300 keV or less; one has high spin ($11/2^-$) and the other low spin ($1/2^+$ or $3/2^+$), as expected from the shell-model states available to odd-neutron nuclei with neutron numbers between 64 and 82 ($d_{3/2}$, $s_{1/2}$, $h_{11/2}$). The Sn nuclei with this structure show a surprising consistency in the thermal cross sections of the low-spin states and also in the high-spin states (Table V). The Sn cross sections leading to the low-spin state cluster around 0.14 b and those leading to the high-spin state are in the range of 2–4 mb, giving a low-spin to high-spin ratio typically about 40. The individual values of the cross section reflect the complicated resonance structure, but the ratio involves the relative difficulty of reaching the low-spin and high-spin states through primary and secondary γ rays from the resonances ($1/2^+$ and $3/2^-$).

The values for Te are markedly different. The low-spin to high-spin ratio is about 6–9 for most of the isotopes and rises only to about 18 for capture by ^{130}Te, which most resembles Sn in the magnitudes of the cross sections (especially the small cross section for the high-spin state). The implication is that the low-spin resonances can decay to the high-spin isomer relatively more easily in Te than in Sn. One possible path for this decay would be for the resonances to decay first to low-spin negative-parity states built on the $h_{11/2}$ structure, and then to decay within the $h_{11/2}$ multiplet eventually to reach the isomeric state. Such low-spin states associated with the $h_{11/2}$ structure have been investigated through (n,γ) and single-neutron transfer reactions leading to odd Te isotopes ($A = 123$ [30], $A = 125$ [34], $A = 129$ [31], and $A = 131$ [32]). However, the information about the locations and decays of the low-spin members of the $h_{11/2}$ family and about contributions from competing low-spin negative-parity orbitals is not sufficiently detailed to enable a calculation of the relative decay probabilities. Moreover, contributions from direct capture [31,32] are likely to be significant in nuclei near closed shells, such as Sn and Te.

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