AN INVESTIGATION OF (p, xn) AND (p, 2pxn) NUCLEAR REACTIONS ON SEPARATED TELLURIUM ISOTOPES

N. G. ZAĬTSEVA, M. Ya. KUZNETSOVA, MIN NAM BUK, and V. A. KHALKIN

Joint Institute for Nuclear Research

Submitted to JETP editor June 30, 1962

J. Exptl. Theoret. Phys. (U.S.S.R.) **43**, 1672-1677 (November, 1962)

The excitation functions of (p, xn) and (p, 2pxn) reactions on separated tellurium isotopes Te^{125} and Te^{126} at bombarding proton energies from 120 to 660 MeV are studied radiochemically. With energy increase from 120 to 300 MeV the cross section for (p, xn), $1 \leq x \leq 4$, decreases considerably and then remains constant within error limits to 600 MeV. Within experimental error the cross sections for (p, 2pxn), $1 \leq x \leq 6$, remain constant in the entire energy range. The (p, 2p) cross section is practically constant from 120 to 480 MeV but at 660 MeV increases by about the factor 1.5.

INTRODUCTION

THE results obtained in investigations of high-energy nuclear interactions [1-5] agree on the whole with Serber's cascade-evaporation mechanism. [6] Metropolis et al [7] have used the Monte Carlo method to calculate the cascade stage of Serber's reaction model. Dostrovsky et al [8] have performed general calculations of the evaporation stage. Satisfactory agreement has been found between the calculated cross sections [3,4,5] and the experimental results for the (p, 2pxn), (p, pxn), and (p, xn), $x > 1$, reactions.

A special position is occupied by the so-called simple reactions such as (p, pn), (p, 2p), (p, n), ($p, p\pi^+$) etc. The experimental energy dependences of cross sections for these reactions do not always agree with the calculations, [9] the experimental values being usually several times greater than the theoretical results. [1-5,10,11] It has been suggested [1,2,10] that the discrepancies result from the inadequacy of a nuclear model based on constant nucleon density. Other investigators [12,13] have used ideas based on the shell model to account for the observed cross sections for simple reactions.

A correct understanding of the simple-reaction mechanism requires more experimental data for both simple reactions and those of the types (p, xn), (p, pxn), and (p, 2pxn), $x > 1$. The present work was performed to obtain data on the (p, n), (p, 2p), (p, xn), and (p, 2pxn) reactions by irradiating separated Te^{125} and Te^{126} isotopes with protons having energies from 120 to 660 MeV.

EXPERIMENT

The targets were $24 \times 7 \times \sim 1.5$ mm plates prepared by compressing a homogeneous mixture of finely dispersed tellurium metal powder (3% by weight) and aluminum powder (97%). The quantity of tellurium irradiated in each run was 15—20 mg. Table I gives the isotopic and chemical compositions of impurities contained in the Te^{125} and Te^{126} samples. It can be assumed without large error that only Te^{125} or Te^{126} participated in the (p, xn) and (p, 2pxn) reactions.

The targets were irradiated by the internal proton beam of the synchrocyclotron of the Joint Institute for Nuclear Research during periods of 30 to 40 min at energies from 120 to 660 MeV. The proton beam was monitored internally by the Na^{24} yield from Al in the reaction $Al^{27}(p, 3pn)Na^{24}$. [14]

The radioactive iodine isotopes produced in the (p, xn) reactions were separated 12 hours following irradiation. During this time the short-lived iodine isotopes ($T_{1/2} \leq 2$ hrs [15]) decayed and no daughter isotopes of tellurium were accumulated in the iodine. The target was dissolved in 3M HNO_3, 10 mg of an iodine carrier was added, and the iodine was separated and purified by distillation and extraction. [16] Targets to be used for measurements were prepared in the form of a PdI_2 deposit.

The radioactive antimony isotopes produced in (p, 2pxn) reactions were separated 2 to 3 hours following irradiation. During this time there could not have been any appreciable accumulation of Sb^{119} from Te^{119} ($T_{1/2}$ = 13 hours and 4.5 days, respec-

Table I

Isotopes	Te^{125}, %	Te^{126}, %	Isotopes	Te^{125}, %	Te^{126}, %
Te^{120}	0.03	<0.05	Te^{125}	92.0	0.4
Te^{122}	0.03		Te^{126}	5.4	98.0
Te^{123}	0.03		Te^{128}	1.4	1.3
Te^{124}	0.5		Te^{130}	0.7	0.3

Impurities: 0.05% Fe_2O_3 and 0.01% CuO.

tively[15,17]). The target was dissolved in concentrated HCl, and an antimony carrier was added (15 mg Sb^{III} in 6M HCl). After the aluminum was dissolved, bromine was added to dissolve the tellurium and to oxidize the antimony to Sb^{V}. The antimony was extracted by diisopropyl ether, after which tellurium, arsenic, molybdenum, and tin impurities were removed.[18] The targets used in measurements were prepared out of antimony metal obtained by reducing Sb^{III} in a hydrochloric acid solution of 1M $CrCl_2$. The Na^{24} samples were prepared from the solution remaining after the iodine or antimony had been separated.

The radioactivities of the iodine and antimony samples were measured with an MST-40 end-window Geiger counter. Beta rays and x rays were separated by means of a beryllium absorber;[19] x rays and hard gamma rays were separated by means of a lead absorber. The x-ray counting coefficient determined from I^{124} ($\beta^+/K = 40/60$[20]) equalled 45 for the iodine isotopes ($\lambda = 0.494$ Å), and 37 for the antimony isotopes ($\lambda = 0.455$ Å). In calculating the absolute cross sections for I^{125} and Sb^{119} it was assumed that each decay event produced a single 35- or 24-keV gamma ray, respectively.[21]

The treatment of the measurements took into account the decay schemes and self-absorption in the target.[22] In the case of x rays corrections were introduced for absorption in beryllium and for counter efficiency. No corrections were introduced for self-scattering, scattering in air, absorption in the counter window, or absorption in the air layer between the sample and the window.

RESULTS

Table II gives the cross sections for the production of radioactive iodine and antimony isotopes in (p,xn) and (p,2pxn) reactions on separated tellurium isotopes for different incident proton energies. Most of the given values are the averages of two determinations. The absolute values of the cross sections for I^{124}, I^{126}, Sb^{122}, and Sb^{124} are given with 25% error; for I^{123} and Sb^{120} the error is 35%, and for I^{125} and Sb^{119} the error is at least 40%.

DISCUSSION OF RESULTS

(p,xn) reactions. Table II shows that the (p,xn) cross sections of Te^{125} agree within experimental error with the corresponding cross

Table II. Cross sections for (p,2pxn) and (p,xn) reactions on Te^{125} and Te^{126} (mb)

Reaction	E_p				
	120	200	300	480	660
$Te^{126}(p, 2p6n)Sb^{119}$	5.6	6.4	6.8	6.8	5.7
$Te^{125}(p, 2p5n)Sb^{119}$	9.1	—	6.8	5.1	6.8
$Te^{126}(p, 2p5n)Sb^{120}$	9.4	12.1	10.2	9.2	8.6
$Te^{125}(p, 2p4n)Sb^{120}$	10.6	—	7.6	6.8	10.2
$Te^{126}(p, 2p3n)Sb^{122}$	18.1	14.0	21.1	22.0	21.6
$Te^{125}(p, 2p2n)Sb^{122}$	20.0	—	17.6	15.4	22.1
$Te^{126}(p, 2pn)Sb^{124}$	11.6	12.7	15.0	18.2	18.0
$Te^{125}(p, 2p)Sb^{124}$	9.5	—	11.0	12.6	20.0
$Te^{126}(p, 4n)I^{123}$	15.6	5.5	2.2	2.0	1.8
$Te^{125}(p, 3n)I^{123}$	20.0	—	2.4	—	1.8
$Te^{126}(p, 3n)I^{124}$	15.4	5.5	2.8	1.9	2.2
$Te^{125}(p, 2n)I^{124}$	13.3	—	2.5	2.2	2.3
$Te^{126}(p, 2n)I^{125}$	13.0	4.6	2.3	1.2	1.8
$Te^{125}(p, n)I^{125}$	7.2	—	1.2	—	—
$Te^{126}(p, n)I^{126}$	8.5	~3.0	1.1	0.8	1.2
$Te^{125}(p, ?)I^{126}$	2.2	—	0.3	—	0.4
$\sigma(p, 2p)/\sigma(p, 2n)$ for Te^{125}	0.71	—	4.4	5.72	8.7

sections of Te^{126}. The cross sections diminish up to about E_p = 300 MeV, after which they remain constant. Similar behavior has been observed for these reactions on other elements.[23]

In the investigated proton energy range the (p, 4n), (p, 3n), and (p, 2n) reactions on tellurium have identical cross sections within experimental error. No predominance of any one of these reactions was observed, unlike the case for similar reactions on yttrium.[24] It is difficult to make a similar comparison for other elements because of insufficient systematic experimental data. A comparison of the cross sections for different (p, xn) reactions on various elements[24] reveals no systematic dependence on the atomic number of the target nucleus.

The (p, n) cross section of tellurium is somewhat smaller than that for (p, xn), x > 1, but the excitation functions are similar.

A rough estimate of the cross section for Te(p, n)I based on a calculation of the nuclear cascade for ruthenium and cerium[7] gives ~ 6 mb (E_p = 82 MeV) and ~ 2 mb (E_p = 286 MeV), which are close to the experimental results at 120 and 300 MeV.

Our measurement of the (p, n) cross section diminishes considerably more steeply with increasing energy than the total cross section for a p-n interaction on intranuclear nucleons calculated from Goldberger's formula[25] and using the cross sections for free p-n interactions. It follows that the fraction of residual nuclei with small excitation energies grows with decreasing proton energy below 300 MeV.

Table II gives the cross sections for I^{126} production from the bombardment of Te^{125}. In this case it is difficult to assign the iodine production to any specific reaction in Te^{125}. Reactions on isotopic impurities (Te^{126}, Te^{128}, and Te^{130} in Table I) are possible and secondary reactions are also probable.

(p, 2pxn) reactions. Table II shows that the cross sections for (p, 2pxn), $0 \le x \le 6$, with the exception of (p, 2p) and possibly (p, 2pn), do not depend on proton energy in the investigated interval. The largest yield from tellurium at $E_p \le 300$ MeV comes from reactions involving the emission of two neutrons. At E_p = 660 MeV we have $\sigma(p, 2p) = \sigma(p, 2pn) = \sigma(p, 2p2n) = \sigma(p, 2p3n)$. The cross section diminishes only with the emission of a fourth neutron. The (p, 2pxn) reactions on other elements vary differently as the proton energy is increased.[23] It is therefore difficult to arrive at any conclusions regarding a systematic dependence of (p, 2pxn) cross sections and their excitation functions on the atomic number of the target nucleus.

The (p, 2p) reactions are of special interest. The experiments show that the ratio $\sigma(p, 2p)/\sigma(p, 2n)$ increases with E_p; at E_p = 120 MeV the ratio equals 0.7, while at E_p = 660 MeV it equals 8.7. According to Winsberg,[3,27] this cross section ratio should be considerably greater than unity, because the (p, 2p) reaction can occur in one step whereas the (p, 2n) process requires two steps.

On the basis of the foregoing discussion and the experimental data it can be assumed that at E_p = 120 MeV an appreciable role in the reaction $Te^{125}(p, 2p)Sb^{124}$ is played by the knocking-out of a single proton followed by the evaporation of another proton, while at higher energies (> 300 MeV) the reaction is predominantly a cascade process.

In order to evaluate the cross section for the production of Sb^{124} from Te^{125} in the cascade stage of (p, 2p) alone we can use the cascade calculation for Ce^{140} at E_p = 460 MeV.[28] If $r_0 = 1.3 \times 10^{-13}$ cm the cross section will be 10 ± 4 mb; for $r_0 = 1.5 \times 10^{-13}$ cm we have σ = 13 ± 5 mb. These values are very close to the experimental (p, 2p) cross section of Te^{125} (σ_{exp} = 12.6 mb). However, since the calculated (p, 2p) cross sections of Te^{125} and Ce^{140} are close, while the experimental results differ widely (σ_{exp} for Ce^{140} equals 50.9 mb at E_p = 440 MeV[29]) it cannot be claimed that the calculation is in good agreement with experiment. It is obvious that the calculations of the cascade stage by the Monte Carlo method, using the model of a degenerate uniformly dense Fermi gas of nucleons in a nuclear potential with radius $r_0A^{1/3}$,[7] does not fully represent the actual process.

It has recently been suggested[2] that simple reactions are especially sensitive to the character of the nuclear surface; the calculations by Metropolis et al.[7] did not take this into account.

A different approach to account for simple reactions has been proposed by Benioff, based on the shell model.[12,13] It is here considered that at sufficiently high energies (p, pn) and (p, 2p) are only knock-on reactions, and that, consequently, the residual nucleus possesses excitation energy smaller than the binding energy of the most loosely bound particle in the residual nucleus. Only an entirely definite number of neutrons and protons (the so-called "available" nucleons) can participate in the reactions.

It can be expected that at the given energies and in a certain limited portion of the periodic table

Table III

E_p, MeV	Target	$\sigma(p, 2p)$, mb	n	$\sigma(p, 2p)/n$	E_p, MeV	Target	$\sigma(p, 2p)$, mb	n	$\sigma(p, 2p)/n$
300	Ce	30.4	8	3.8	400	Ce	54.3	8	6.8
300	Te	11.0	2	5.5	440	Ce	50.9	8	6.4
350	Ce	47.6	8	6.0	480	Te	12.6	2	6.3

the total (p, 2p) cross section divided by the number of available protons will remain constant.

It is interesting to compare the data (Table III) for tellurium and cerium in the range 300—500 MeV[29] when tellurium has n = 2 available protons and cerium has n = 8, i.e., the number of available protons equals the number outside the closed shell of 50 protons.

Table III shows that for Te and Ce the (p, 2p) cross sections in the 300—500-MeV range differ by factors of 3 or 4, whereas $\sigma[\mathrm{Te}(p, 2p)\mathrm{Sb}]/2 = \sigma[\mathrm{Ce}(p, 2p)\mathrm{La}]/8$ within experimental error in the entire range. The same behavior is not observed at lower energies, where a considerable contribution to the (p, 2p) reaction can possibly come from the evaporation process (p, Pp). In this case the foregoing comparison of the cross sections per available proton would be invalid.

The authors wish to thank V. N. Mekhedov for discussions.

[1] J. M. Miller and J. Hudis, Ann. Rev. Nuclear Sci. **9**, 159 (1959).

[2] B. G. Harvey, Progr. in Nuclear Phys. **7**, 89 (1959).

[3] I. M. Ladenbauer and L. Winsberg, Phys. Rev. **119**, 1368 (1960).

[4] D. R. Nethaway and L. Winsberg, Phys. Rev. **119**, 1375 (1960).

[5] N. T. Porile, Phys. Rev. **125**, 1379 (1962).

[6] R. Serber, Phys. Rev. **72**, 1114 (1947).

[7] Metropolis, Bivins, Storm, Turkevich, Miller, and Friedlander, Phys. Rev. **110**, 185 (1958).

[8] Dostrovsky, Rabinowitz, and Bivins, Phys. Rev. **111**, 1659 (1958).

[9] Markowitz, Rowland, and Friedlander, Phys. Rev. **112**, 1295 (1958).

[10] H. P. Yule and A. Turkevich, Phys. Rev. **118**, 1591 (1960).

[11] Gusakow, Legoux, and Sergolle, Compt. rend. **251**, 70 (1960).

[12] P. A. Benioff, Phys. Rev. **119**, 316 (1960).

[13] P. A. Benioff, Phys. Rev. **119**, 324 (1960).

[14] E. Bruninx, High-Energy Nuclear Reaction Cross Sections, CERN 61-1, 1961.

[15] Zaĭtseva, Kuznetsova, Levenberg, and Khalkin, Radiokhimiya (Radiochemistry) **2**, 451 (1960).

[16] Kuznetsova, Mekhedov, and Khalkin, JETP **34**, 1096 (1958), Soviet Phys. JETP **7**, 759 (1958).

[17] Zaĭtseva, Kuznetsova, Levenberg, Pokrovskiĭ, and Khalkin, Izv. AN SSSR, Ser. Fiz. **24**, 1083 (1960), Columbia Tech. Transl. p. 1090.

[18] C. W. Stanley and L. F. Glendenin, in Radiochemical Studies: The Fission Products (C. D. Coryell and N. Sugarman, eds.), McGraw-Hill, New York, 1957, vol. 3, paper 271, p. 1592.

[19] M. Lindner and I. Perlman, Phys. Rev. **78**, 499 (1950).

[20] M. Ya. Kuznetsova and V. N. Mekhedov, Izv. AN SSSR, Ser. Fiz. **21**, 1020 (1957), Columbia Tech. Transl. p. 1021.

[21] Strominger, Hollander, and Seaborg, Revs. Modern Phys. **30**, 697 and 705 (1958).

[22] A. H. W. Aten, Nucleonics **6**, 68 (1950).

[23] E. Bruninx, High-Energy Nuclear Reaction Cross Sections, CERN 62-9, 1962.

[24] A. A. Caretto and E. O. Wiig, Phys. Rev. **115**, 1238 (1959).

[25] M. L. Goldberger, Phys. Rev. **74**, 1269 (1948).

[26] W. Hess, Revs. Modern Phys. **30**, 368 (1958).

[27] L. Winsberg, Bull. Am. Phys. Soc. **2**, 380 (1957).

[28] A. A. Caretto and G. Friedlander, Phys. Rev. **110**, 1169 (1958).

[29] P. P. Strohal and A. A. Caretto, Phys. Rev. **121**, 1815 (1961).

Translated by I. Emin
290