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Thick-Target Yields of Iodine Isotopes from Proton Interactions in Te, and the Double-β Decay of $^{128,130}Te$

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We report thick-target yields of $^{126,128,130}I$ from the bombardment of natural Te targets with 15-, 30-, 45- and 50-MeV protons, together with the iodine production cross sections for 1.85- and 5.0-GeV protons. With these data, we have estimated the relative cosmic-ray induced production of ^{126}Xe, ^{128}Xe and ^{130}Xe in Te ores. These quantities affect the ratio of double-β decay half-lives of ^{130}Te and ^{128}Te. A revised correction of cosmic-ray induced xenon can change the half-life ratio by as much as 10%, from $(3.52\pm0.11) \times 10^{-4}$ to $(3.88\pm0.14) \times 10^{-4}$.

1. INTRODUCTION

The double-β decay half-lives of $^{128,130}Te$ have been recently measured by Bernatowicz *et al.* (1992,1993), using the geochemical method. A recent review by Moe (1993) emphasizes the discrepancy between the half-life values obtained by Bernatowicz and those from previous results, where the half-life of ^{130}Te decay was measured relative to that of ^{82}Se, from ores containing minerals of both elements. However, the half-life ratio $t_{1/2}(^{130}Te)/t_{1/2}(^{128}Te)$, which is independent of the age of the minerals and of the retention of the daughter atoms in the mineral, was very precisely measured by Bernatowicz *et al.* They measured the number of atoms and isotopic abundances of Xe present in samples collected from several tellurium ores. Deviations from the isotopic abundances of atmospheric Xe, in the form of excesses of some of the isotopes, were found, and are attributed to several processes in addition to double-β decay: (i) fission products, (ii) neutron capture on Te, (iii) $^{127}I(n,\gamma)$, (iv) α-particle-, (v) neutrino-, (vi) cosmic-ray muon- and secondary-proton reactions. After correcting the measured excesses for the mechanisms (i-v), there still remained a small excess of ^{126}Xe, which is not a double-β decay product, which they attributed to muon- and proton induced reactions.

Bernatowicz *et al.* considered muon-induced reactions, and also those caused by secondary protons (i.e. protons produced in the muon-induced nuclear spallation), showing that these contributions do not affect the inferred value for the ^{130}Te double-β decay half-life, because they account for only 10^{-5} of the measured ^{130}Xe excesses. However, the same calculations indicate that the cosmic-ray reactions could affect the deduced ^{128}Te half-life by as much as 10%. The correction to the ^{128}Xe excess for this mechanism depends critically on how we scale the ^{128}Xe excess from that of ^{126}Xe, the "cosmic-ray detector". Because these corrections are model-dependent, we decided to address them by measuring iodine yields from proton reactions on tellurium targets, to better estimate the contribution of secondary protons and that of direct muon reactions to the production of Xe in Te ores.

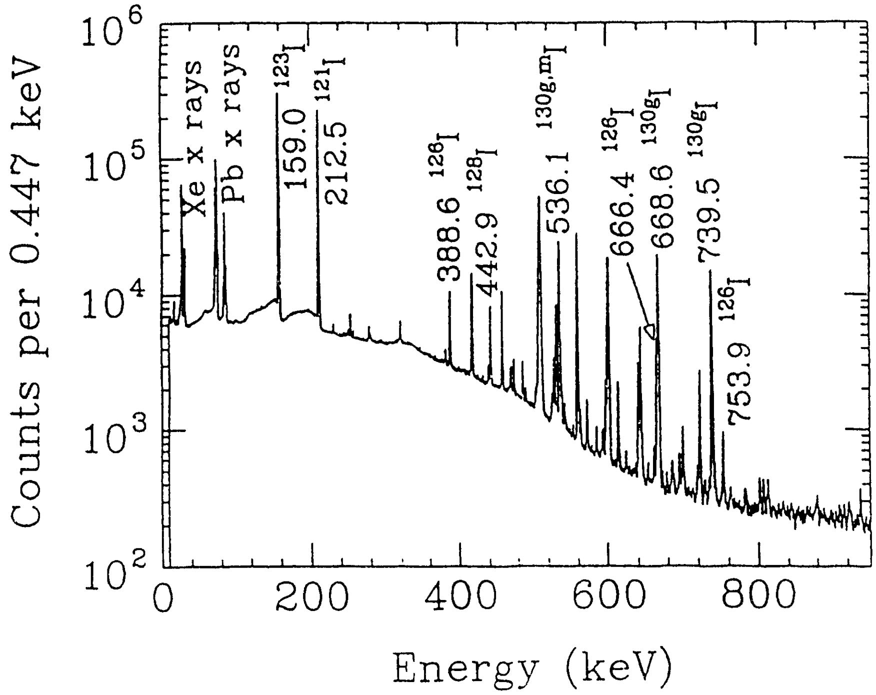
2. EXPERIMENT

The Te targets were made of 99.99% purity metallic tellurium, purchased from Johnson Matthey. Tellurium pieces were crushed and pressed at 120°C for 4 min, to form the targets. For the low-energy activations (<50 MeV) the beam was stopped in the targets.

The low-energy proton activations were performed at the 88-Inch Cyclotron at Lawrence Berkeley Laboratory; those at high-energy were performed at the LBL's Bevatron accelerator. At the Bevatron, the targets were held in air, with the Te slabs assembled in a stack, together with Polycast acrylic plastic sheets (polymethyl methacrylate, $[C_5O_2H_8]_n$) to monitor the integrated beam exposure, through the production of ^{11}C. The 15-, 30- and 50-MeV proton activations were done with bombardment times of ~10 min for the first two, and one hour for the last one, each having an integrated current of 10 μC. The 1.85- and 5.0-GeV proton experiments were done with bombardment times of approximately one hour, with integrated currents of 60 and 5 nC, respectively. To check for iodine losses during the activations, due to the target heating, one of the activated targets was heated on a hot plate, for a period corresponding to the bombardment time. No loss of radioactivity was detected.

Following the irradiations, the targets were γ-counted with a 100 cm^3 coaxial HPGe detector inside a 5-cm thick lead shielding. Due to the widely different half-lives of the iodine isotopes under study: ^{126}I (13 days), ^{128}I (25 min), ^{130m}I (9 min), and ^{130g}I (12 hours), three different sizes of time bins were used for counting: 5-min bins during the first hour, 1-hour bins during the next 24 hours, and then several 6-hour bins. Some of the sources were measured two weeks later, to confirm the amount of radioactivity attributed to the 13-day component. All half-lives measured were in agreement with the corresponding adopted values, indicating no loss of iodine from the targets during the measurements. Figure 1 shows a spectrum obtained from the 50-MeV activation, with some of the photopeaks identified.

Fig. 1: Spectrum from the 50-MeV activation.



3. RESULTS AND DISCUSSION

Table 1 shows our results for the iodine thick-target yields and the production cross sections for the high-energy experiments. Table 2 contains the relative Xe yields inferred from the data in Table 1 and data at lower proton energies (3 to 6 MeV) from Roughton *et al.* (1979).

TABLE 1: Our results for the $^{126,128,130}I$ thick-target yields, in 10^{-4} nuclei/proton.

E_p(MeV)	^{126}I	^{128}I	^{130g}I	^{130m}I
15	1.31(2)	1.08(1)	0.42(1)	0.70(1)
30	13.5(1)	11.0(1)	1.04(3)	0.98(2)
45	23.6(5)	13.8(1)	1.1(1)	0.90(6)
1850*	6.0(20)	3.9(3)	1.0(1)	
5000*	13(5)	6.7(11)	1.6(3)	

*For these energies we quote (p,xn) cross sections, in mb, and the values for ^{130g}I contain 83% of the ^{130m}I yield, corresponding to the isomeric transition branch.

TABLE 2: Relative Xe production from iodine thick-target yields, ^{126}Xe=1. The data for proton energies below 15 MeV come from Roughton *et al.* (1979).

E_p(MeV)	^{128}Xe	^{130}Xe
3.029	0.75	2.15
3.346	3.70	4.43
3.934	2.34	3.61
4.292	2.93	4.07
4.645	2.00	2.92
5.049	1.75	2.80
5.687	2.42	3.86
6.082	2.81	3.17
6.360	1.87	3.51
15	1.68(3)	1.86(4)
30	1.67(2)	0.32(1)
45	1.23(12)	0.19(2)
50	1.0(2)	0.16(3)
1850	1.4(5)	0.39(13)
5000	1.1(5)	0.28(12)

To make a statement about the proton-induced xenon excesses, Bernatowicz *et al.* used a simple model. They assumed that only (p,n) reactions take place and that they all have the same cross section. Then, the relative yields of the Xe isotopes depend only on the Te isotopic abundances in the ores and on the β-decay branching ratios of the produced iodine to the Xe. The relative yields predicted by this model are shown in Table 3. Because $^{128,130}Te$ could also be contributing to the ^{126}Xe excess, through the (p,3n) and (p,5n) reactions respectively, we also show in Table 3 the mass ratios caused by them, in addition to that from (p,n). Bernatowicz *et al.* assumed $M(^{128}Xe)/M(^{126}Xe)=3.47$.

If we assume that (p,xn) reactions are the sole source of iodine and xenon in the ore, we would expect the relative Xe yields to be roughly given by the experimental ratios in Table 2. However, this is dependent on the proton energy spectrum. Table 2 shows that even for energies between 3 and 6 MeV, the 3.47 ratio is only achieved in a very narrow energy range, a more appropriate value lying between 1 and 3. The low-energy bombardments we did provided information on the separate contribution of the (p,n), (p,3n) and (p,5n) reactions.

TABLE 3: Relative Xe mass production in the simple model, with (p,xn) reactions, $^{126}Xe=1$.

A	x=1	x=1,3	x=1,3,5
128	3.47	2.69	1.62
130	4.01	1.50	0.90

If instead of 3.47 we use 1.0 as the excess ratio, the ratio of the ^{130}Te to ^{128}Te half-lives changes from $(3.52 \pm 0.11) \times 10^{-4}$ (Bernatowicz 1992,1993) to $(3.88 \pm 0.14) \times 10^{-4}$. Thus, we see that the deduced half-life ratio can change as much as 10%, depending on the induced secondary-proton spectrum underground.

The muon reaction $^{A}Te(\mu^{+},\mu^{+}\pi^{-})^{A}I$ is the equivalent of a (p,n) reaction. Bernatowicz *et al.* estimate that proton- and muon-induced reactions contribute with roughly equal amounts of Xe.

We can take into account direct muon reactions, and keep as 3.47 the mass ratio from their contribution. Using 1.0 for the xenon mass ratio coming from secondary proton reactions, yields a total ratio of 1.78, assuming equal reaction rates of muons and protons. In this case, the half-life ratio becomes $(3.77 \pm 0.13) \times 10^{-4}$, its 1-$\sigma$ interval almost touching that found by Bernatowicz *et al.*

Concluding, the effect of not knowing the ratios of cosmic-ray induced excesses of ^{126}Xe and ^{128}Xe can be as large as 10%, or approximately three to four times the standard deviation quoted by Bernatowicz *et al.* for the double-β decay half-life ratio. Since the mass excess ratios of ~1 and ~3 look more like the edges of the possible range of values, we think that the value for the $^{128,130}Te$ double-β decay half-life ratio should reflect this fact.

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