The Half-life of ^{130}Te Double β-decay

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(Z. Naturforschg. **21 a**, 84—90 [1966]; received 15 September 1965)

Dedicated to Prof. J. Mattauch *on his 70th birthday*

In order to determine the half-life of the ^{130}Te double β-decay, the amounts and isotopic composition of xenon extracted from tellurium ores, from the Oya gold mine in Japan, have been measured with a high-sensitivity mass spectrometer. Compared with atmospheric xenon an excess was definitely found at mass numbers 129, 130 and 131 in the extracted xenon. The excess of ^{130}Xe is predominant, the average amount in three samples being $(1.32 \pm 0.09) \times 10^{-11}$ ccSTP/g ^{130}Te. Attributing the excess ^{130}Xe to the double β-decay of ^{130}Te, the half-life is estimated to be $(8.20 \pm 0.64) \times 10^{20}$ years, assuming an age of $(9.06 \pm 0.29) \times 10^{7}$ years for the Te ores. The latter value is the K-Ar age of porphyrite, which is in close geological connection with the Te ores.

In order to investigate the other excesses than that of ^{130}Xe, isotopic analyses were also carried out on Xe from three other Te ores from the same mine. The ratios $(^{129}\text{Xe}/^{131}\text{Xe})_{\text{excess}} = 1.58$ and $(^{129}\text{Xe}/^{130}\text{Xe})_{\text{excess}} = 2.1$ were found to be the same for all samples. The origin of these excesses is discussed.

In addition a small excess of ^{128}Xe was found. If this is attributed to ^{128}Te double β-decay, the half-life of ^{128}Te is estimated to be 3×10^{22} years, a value shorter by about three orders of magnitude than the theoretically expected half-life. The above estimated half-life may be a lower limit of the ^{128}Te half-life.

The general tendency of the isotopic abundances (except for the above excesses), of the xenon extracted from Te ores seems to be to slightly increase in excess as one moves toward the lighter isotopes (as compared with atmospheric xenon).

In the mass Table there are about fifty nuclei for which double β-decay is energetically possible. ^{130}Te is one of them. The energy level scheme for its double β-decay [1] is shown in Fig. 1. Double β-decay has been studied theoretically by many physicists [2–8]. Accordding to their theoretical analyses, its probability is extremely small, with strong dependence on the decay energy. According to Primakoff and Rosen [8], the half-life of the ^{130}Te double β-decay is $2 \times 10^{21 \pm 2}$ years or $8 \times 10^{15 \pm 2}$ years for two-neutrino or no neutrino emission respectively. If it could be proven from a half-life determination that the double β-decay is accompanied by two-neutrino emission, the neutrino may be represented by the Dirac theory or the two component theory of the neutrino, and the total lepton number is conserved. On the other hand, if there is no neutrino emission, the neutrino may be represented by the Majorana theory, and the total lepton number is not conserved. The double β-decay may also yield information on the type of nucleon-lepton interaction, as well as the nature of the neutrino and the conservation of the total lepton number.

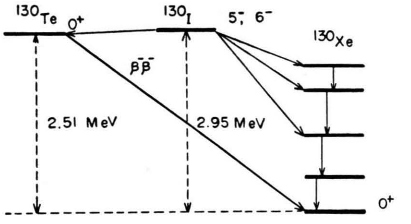

Fig. 1. Energy level scheme of ^{130}Te double β-decay [1].

Many experimental studies [9–19] of double β-decay have been undertaken using mass spectrometric methods, cloud chambers, photographic emulsions,

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or counters. However, none of these have given definite evidence of a double β-decay, except the mass spectroscopic studies on the ^{130}Te double β-decay of INGHRAM and REYNOLDS [13] and of HAYDEN and INGHRAM [14]. INGHRAM and REYNOLDS have given 1.4×10^{21} years for the half-life of the ^{130} Te double β-decay. HAYDEN and INGHRAM have obtained 3.3×10^{21} years as a lower limit of the half-life.

We have planned to determine the half-lives of as many possibly double β-decaying nuclei as possible by means of advanced mass spectrometric methods and to find the energy dependence of the half-life. In previous reports [20, 21] the half-life of the ^{130}Te has been studied preliminarily as part of the program using tellurium ores. In the work reported here the amount of ^{130}Xe was measured again by the isotope dilution method in order to improve the accuracy of the half-life determination. At the same time the abundance ratios of the xenon isotopes, extracted from tellurium ores taken from the same mine, were also measured to investigate excesses of xenon isotopes other than ^{130}Xe.

Experimental Procedures and Results

The mass spectrometer [22] used in the experiment is of the 90° deflection, single focusing type with a 20 cm radius. A 12-stage electron multiplier [23] of Cu-Be electrodes is used as a detector of ion currents, along with a vibrating-reed electrometer and an electronic recorder. At present, the detection limit for xenon is of the order of 10^{-13} ccSTP under static operation.

The extraction system and purification procedure was the same as described in the previous reports [20, 21], except that a titanium sponge was substituted for the calcium getter.

The four samples used in the experiments were tellurium ores taken from the Oya gold mine in Japan. They had been deposited as tetradymite Bi_2Te_2S in quartz veins embedded in the granite mass of the mine. The samples were prepared by finely crushing the quartz veins and separating the fraction of the tellurium minerals. The tellurium concentration was determined by a gravimetric analysis after extraction of the Xe. The age of the ore was assumed to be the same as that of coexisting porphyrite.

Prior to the extraction, the samples were heated at about 300 °C for several hours to drive out contaminating gases. Then the furnace temperature was gradually raised to about 1100 °C for about 3 hours. For the determination of the amount of ^{130}Xe a ^{128}Xe spike was added at the beginning of the extraction procedure. The ^{128}Xe used was produced by neutron-bombardment of potassium iodide in a nuclear reactor. The amount of the ^{128}Xe spike was determined as described in the previous reports [20, 21], by the isotope dilution using atmospheric xenon, the amount of which was calculated from the volume of the spike ampoule and the pressure of the xenon as measured with a KNUDSEN gauge. The amounts of ^{128} Xe spikes used are shown in Tab. 2. Purification of the extracted gases was carried out with a dry-ice trap, titanium sponge at 700 – 900 °C, a hot tungsten filament and a hot titanium filament. The purified gases were adsorbed on charcoal at liquid nitrogen temperature and then sealed up in a sample ampoule. The final purification was carried out with a hot tungsten filament and a hot titanium filament in the sample ampoule.

In mass spectrometric analysis of such extremely small amounts of xenon, it is most important and most difficult to remove the background of the apparatus in the xenon mass region. It was especially painstaking work to reduce a persistent memory effect for xenon in the mass spectrometer under static operation. But this effect could gradually be reduced by baking the mass spectrometer at about 150 °C and by bombarding the inner surface of the apparatus with intense beams of neon for a long time. An elevated pressure in the mass spectrometer always caused an increase of the memory effect for xenon. Usually the amount of argon contained in the ore is several orders of magnitude higher than that of xenon. As the introduction into the mass spectrometer of this argon always caused a considerable increase of the memory effect for xenon, the argon was separated from the xenon in the gas inlet part of the mass spectrometer by cooling a glass tube attached to that part at liquid nitrogen temperature, and by adsorbing the xenon on the glass tube while pumping out the argon sufficiently. Then

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the xenon was introduced into the mass spectrometer. The memory effect of xenon was practically eliminated as the result of separating out the argon.

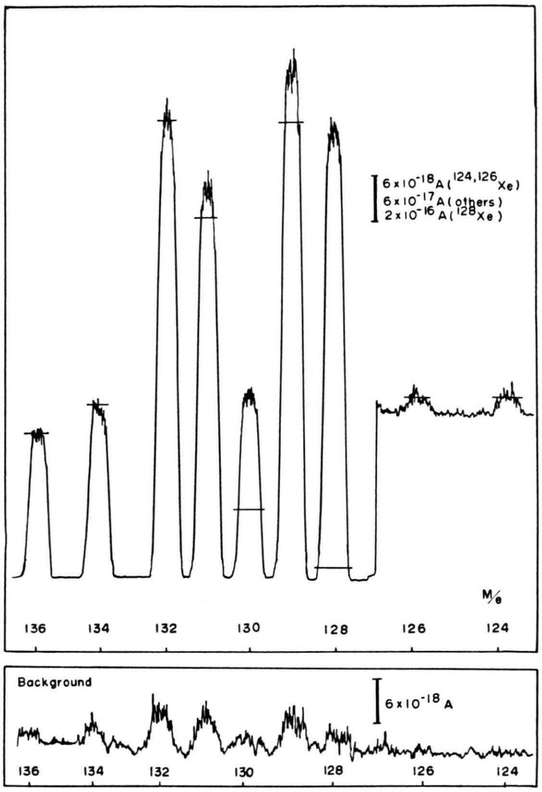

Fig. 2 (a). Mass spectrum of the mixture of the ^{128}Xe spike and the xenon extracted from Te ore (sample V), and background of the mass spectrometer taken at about the same time interval from the beginning of static operation as the sample measurement. Horizontal lines on mass peaks show the isotopic compositions of atmospheric xenon, normalized to ^{132}Xe.

An example of the mass spectrum of the mixture of the extracted xenon and the ^{128}Xe spike, and another example for the extracted xenon without the ^{128}Xe spike, are shown in Fig. 2, together with the backgrounds of the mass spectrometer. On the assumption that ^{132}Xe was due entirely to contamination by atmospheric xenon, the excess over the atmospheric xenon isotopes was obtained for each sample. Tab. 1 shows the isotopic compositions of the sample xenon and the atmospheric xenon normalized to ^{132}Xe, and the difference between them. As shown in Tab. 2, the amount of the excess ^{130}Xe per gram of ^{130}Te is in approximate agreement for each sample. As discussed in the following this suggests that the excessive ^{130}Xe originated from ^{130}Te.

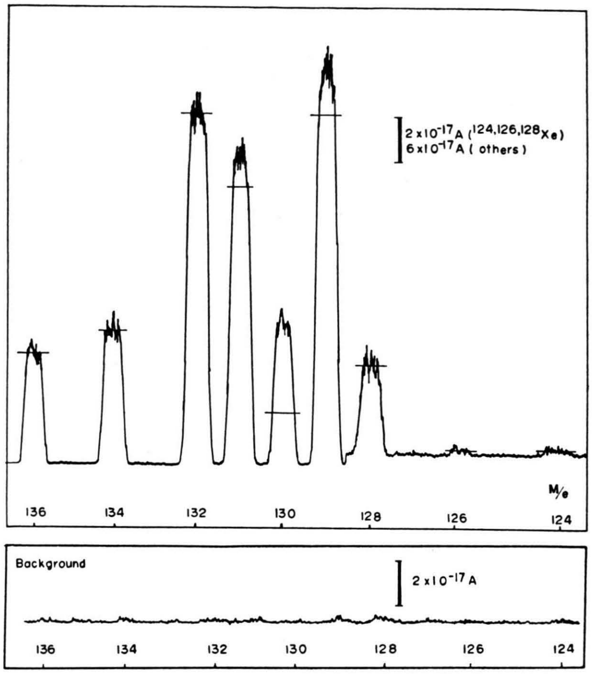

Fig. 2 (b). Mass spectrum of xenon extracted from Te ore (sample VIII), and background of the mass spectrometer taken at about the same time interval from the beginning of static operation as the sample measurement. Horizontal lines on mass peaks show the isotopic compositions of atmospheric xenon, normalized to ^{132}Xe.

Assuming the excess of $^{130}Xe = (1.32 \pm 0.09) \times 10^{-11}$ cc STP/g ^{130}Te to be due to the double β-decay of ^{130}Te the half-life can be calculated from the following equation:

$$T_{1/2} = (\ln 2)\,(N_p \cdot t/N_d)$$

where N_p is the number of parent nuclei ^{130}Te; N_d the number of daughter nuclei ^{130}Xe; and t the time interval for which the decay products accumulated in the ore. N_p was calculated from the tellurium concentration in the ore and the isotopic abundance of ^{130}Te. t was estimated to be $(9.06 \pm 0.29) \times 10^7$ years, i. e. it was taken to be the same as the K-Ar age of coexisting porphyrite. The experimental results involved in the half-life estimation are summarized in Tab. 2 together with the previous results[20, 21]. The calculated half-life was $(8.20 \pm 0.64) \times 10^{20}$ years on the average.

Discussion

The reasons why the excess ^{130}Xe was considered to be due entirely to the ^{130}Te double β-decay are as follows;

Isotope	Mixture xenon (1)	Atmospheric* xenon (2)	Difference between (1) and (2)
^{124}Xe	0.0047 ± 0.00014	0.0035 ± 0.00002	0.0012 ± 0.00014
^{126}Xe	0.0055 ± 0.0003	0.0033 ± 0.00001	0.0022 ± 0.0003
^{128}Xe	2.529 ± 0.0152	0.071 ± 0.0009	2.458 ± 0.0152
^{129}Xe	1.218 ± 0.0078	0.988 ± 0.0007	0.230 ± 0.0078
^{130}Xe	0.601 ± 0.0056	0.154 ± 0.0003	0.447 ± 0.0056
^{131}Xe	0.928 ± 0.0062	0.795 ± 0.0023	0.133 ± 0.0066
^{132}Xe	= 1.000	= 1.000	= 0.000
^{134}Xe	0.386 ± 0.0026	0.392 ± 0.0006	− 0.006 ± 0.0027
^{136}Xe	0.330 ± 0.0025	0.331 ± 0.0006	− 0.001 ± 0.0026

* Tank xenon.

Table 1 (a). Isotopic composition of mixture of extracted Xe and spike ^{128}Xe for sample III.

Isotope	Mixture xenon (1)	Atmospheric* xenon (2)	Difference between (1) and (2)
^{124}Xe	—	—	—
^{126}Xe	—	—	—
^{128}Xe	4.145 ± 0.069	0.071 ± 0.001	4.074 ± 0.069
^{129}Xe	1.209 ± 0.022	0.988 ± 0.001	0.221 ± 0.022
^{130}Xe	0.580 ± 0.016	0.154 ± 0.0003	0.426 ± 0.016
^{131}Xe	0.935 ± 0.029	0.795 ± 0.002	0.140 ± 0.029
^{132}Xe	= 1.000	= 1.000	= 0.000
^{134}Xe	0.400 ± 0.012	0.392 ± 0.001	0.008 ± 0.012
^{136}Xe	0.319 ± 0.023	0.331 ± 0.001	− 0.012 ± 0.023

* Tank xenon.

Table 1 (b). Isotopic composition of mixture of extracted Xe and spike ^{128}Xe for sample IV.

Isotope	Mixture xenon (1)	Atmospheric** xenon (2)	Difference between (1) and (2)
^{124}Xe	0.0042 ± 0.0001	0.0042 ± 0.00005	0.0000 ± 0.0001
^{126}Xe	0.0033 ± 0.0002	0.0040 ± 0.00003	− 0.0007 ± 0.0002
^{128}Xe	2.810 ± 0.008	0.078 ± 0.0003	2.732 ± 0.008
^{129}Xe	1.124 ± 0.007	0.999 ± 0.002	0.125 ± 0.007
^{130}Xe	0.405 ± 0.002	0.149 ± 0.001	0.256 ± 0.002
^{131}Xe	0.871 ± 0.004	0.790 ± 0.002	0.081 ± 0.005
^{132}Xe	= 1.000	= 1.000	= 0.000
^{134}Xe	0.386 ± 0.002	0.378 ± 0.001	0.008 ± 0.002
^{136}Xe	0.321 ± 0.002	0.316 ± 0.001	0.005 ± 0.002

** Xenon purified from a small amount of atmosphere by the same purification procedure as applied to the sample xenon.

Table 1 (c). Isotopic composition of mixture of extracted Xe and spike ^{128}Xe for sample V.

Isotope	Sample xenon (1)	Atmoshperic** xenon (2)	Difference between (1) and (2)
^{124}Xe	—	—	—
^{126}Xe	—	—	—
^{128}Xe	0.095 ± 0.003	0.073 ± 0.001	0.022 ± 0.003
^{129}Xe	1.101 ± 0.009	1.001 ± 0.003	0.100 ± 0.010
^{130}Xe	0.409 ± 0.008	0.154 ± 0.001	0.255 ± 0.008
^{131}Xe	0.867 ± 0.006	0.801 ± 0.004	0.066 ± 0.007
^{132}Xe	= 1.000	= 1.000	= 0.000
^{134}Xe	0.382 ± 0.004	0.381 ± 0.003	0.001 ± 0.005
^{136}Xe	0.316 ± 0.003	0.321 ± 0.001	− 0.005 ± 0.003

** Xenon purified from a small amount of atmosphere by the same purification procedure as applied to the sample xenon.

Table 1 (d). Isotopic composition of xenon extracted from sample VI.

Isotope	Sample xenon (1)	Atmospheric** xenon (2)	Difference between (1) and (2)
^{124}Xe	0.0045 ± 0.0003	0.0044 ± 0.00005	0.0001 ± 0.0003
^{126}Xe	0.0047 ± 0.0002	0.0042 ± 0.00004	0.0005 ± 0.0002
^{128}Xe	0.082 ± 0.001	0.078 ± 0.0002	0.004 ± 0.001
^{129}Xe	1.122 ± 0.007	0.996 ± 0.001	0.126 ± 0.007
^{130}Xe	0.427 ± 0.002	0.146 ± 0.001	0.281 ± 0.002
^{131}Xe	0.875 ± 0.003	0.792 ± 0.001	0.083 ± 0.003
^{132}Xe	= 1.000	= 1.000	= 0.000
^{134}Xe	0.389 ± 0.002	0.380 ± 0.0004	0.009 ± 0.002
^{136}Xe	0.327 ± 0.002	0.317 ± 0.001	0.010 ± 0.002

** Xenon purified from a small amount of atmosphere by the same purification procedure as applied to the sample xenon.

Table 1 (e). Isotopic composition of xenon extracted from sample VII.

Isotope	Sample xenon (1)	Atmospheric** xenon (2)	Difference between (1) and (2)
^{124}Xe	0.0039 ± 0.0002	0.0042 ± 0.00005	− 0.0003 ± 0.0002
^{126}Xe	0.0031 ± 0.0002	0.0040 ± 0.00003	− 0.0009 ± 0.0002
^{128}Xe	0.0762 ± 0.0006	0.0780 ± 0.0003	− 0.0018 ± 0.0007
^{129}Xe	1.131 ± 0.006	0.999 ± 0.002	0.132 ± 0.006
^{130}Xe	0.399 ± 0.002	0.149 ± 0.001	0.250 ± 0.003
^{131}Xe	0.873 ± 0.003	0.790 ± 0.002	0.083 ± 0.004
^{132}Xe	= 1.000	= 1.000	= 0.000
^{134}Xe	0.380 ± 0.001	0.378 ± 0.001	0.002 ± 0.002
^{136}Xe	0.321 ± 0.001	0.316 ± 0.001	0.005 ± 0.001

** Xenon purified from a small amount of atmosphere by the same purification procedure as applied to the sample xenon.

Table 1 (f). Isotopic composition of xenon extracted from sample VIII.

(i) If it were fissiogenic, the excess amount for heavier isotopes such as ^{134}Xe and ^{136}Xe should be larger than that for ^{130}Xe [24].

(ii) The excess ^{130}Xe per gram of ^{130}Te is approximately constant as shown in Tab. 2. As shown in Fig. 3, the xenon extracted from the tellurium ores shows the large excess of ^{130}Xe, but the xenon from the quartz vein does not (Fig. 4). These facts suggest that the excess of ^{130}Xe is closely related to Te, Bi and S included in the tellurium mineral. However, it is not known that some other processes, involving Bi and S, contribute significantly to ^{130}Xe. Also ^{130}Xe cannot be produced by the neutron capture of tellurium. So it is held that the excess of ^{130}Xe was due to the decay of ^{130}Te. However, since the successive single β-decay of ^{130}Te through ^{130}I is energetically forbidden judging from the latest mass data [1], it may be concluded that the major part of the excess of ^{130}Xe originated from ^{130}Te by double β-decay.

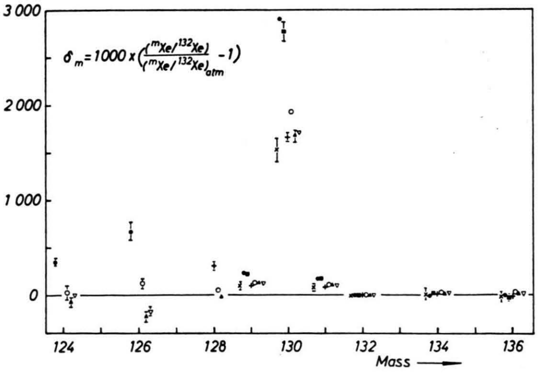

Fig. 3. Ratios of the excess of xenon isotopes from tellurium ores to the contaminating atmospheric xenon in ‰.

Sample	I	III	IV	V	VI	VII	VIII
Symbol	×	●	■	▽	+	○	▲

However, the half-life should be regarded as a lower limit, if it were confirmed in the future that some nuclear processes other than double β-decay had also been contributing to the excess ^{130}Xe. It may be necessary to say some more on the mineral age. If xenon loss from the tellurium ore should have been occurring during its life, the half-life estimated above would be an upper limit. The age

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[24] G. W. WETHERILL, Phys. Rev. **92**, 907 [1953].

	Sample (g)	Te-conc. (%)	^{130}Te (g)	^{128}Xe spike (10^{-10} ccSTP)	Excess of ^{130}Xe (10^{-11} ccSTP)	
					Total	per gram of ^{130}Te
Sample I[a]	17.5	33.8	2.08	17.3 ± 1.7	(2.09 ± 0.27)	(1.00)
Sample II[b]	10.9	13.2	0.605	1.28 ± 0.03	(1.01 ± 0.18)	(2.00)
Sample III	22.3	22.4	1.79	1.47 ± 0.04	2.56 ± 0.08	1.48
Sample IV	12.4	22.4	0.97	1.22 ± 0.03	1.27 ± 0.06	1.31
Sample V	10.9	29.8	1.14	1.42 ± 0.04	1.32 ± 0.04	1.16
Average						1.32 ± 0.09

[a] As the temperature of the electric furnace was not elevated to a sufficient degree that all the gases occluded in the ores were extracted completely, the result for "sample I" is not included in the average.
[b] As large memory effect of xenon disturbed the precise isotope analyses for the xenon of "sample II", the result for "sample II" is also not included in the average.

Table 2. Summary of results involved in half-life estimation of ^{130}Te double β-decay.

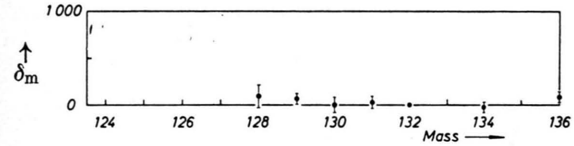

Fig. 4. Ratios of the excess of xenon isotopes from quartz vein to the contaminating atmospheric xenon isotopes in ‰.

$$\delta_m = 1000 \times \left[\frac{(^m\text{Xe}/^{132}\text{Xe})}{(^m\text{Xe}/^{132}\text{Xe})_{\text{atm}}} - 1 \right]$$

of the ore was estimated from the porphyrite by means of the K-Ar method. Therefore, the error caused by such a gas diffusion loss may be cancelled to some extent. If it exists, it may be smaller than the argon loss from the porphyrite in general. In such a case, the half-life estimated above would be a lower limit. But referring to many geological age determinations, the argon diffusion loss [25, 26] from minerals would not be so large without heavy metamorphism. Judging from such considerations, the half-life of the ^{130}Te double β-decay may not be grossly in error.

The half-life obtained, $(8.20 \pm 0.64) \times 10^{20}$ years, is in agreement with that given by INGHRAM and REYNOLDS (1.4×10^{21} years) and by HAYDEN and INGHRAM (3.3×10^{21} years) in its order of magnitude. This appears to support the two-neutrino theory for double β-decay.

The ratios of the excess ^{129}Xe to the excess ^{130}Xe and the excess ^{131}Xe were approximately constant for each sample as shown in Tab. 3. This suggests that the excess ^{129}Xe and ^{131}Xe originated from the tellurium ores as well and perhaps were produced by the same nuclear processes. The excess ^{129}Xe and ^{131}Xe may be interpreted as the products of neutron capture [13] by ^{128}Te and ^{130}Te respectively. But the ratio is 1.58 on the average, while the ratio, expected from cross sections of thermal neutron capture for ^{128}Te and ^{130}Te and from their abundance ratio, is 0.6 [27]. To check whether the excessive ^{129}Xe and ^{131}Xe are really due to neutron capture by ^{128} Te and ^{130}Te respectively, or not, the xenon extracted from the tellurium ore and tellurium metal irradiated by thermal and fast neutrons, is being studied.

As for the excessive ^{128}Xe, it is very interesting that ^{128}Te can disintegrate into ^{128}Xe by double β-decay. There was an excess in ^{128}Xe as shown in

	$\frac{^{128}\text{Xe (excess)}}{^{130}\text{Xe (excess)}}$	$\frac{^{129}\text{Xe (excess)}}{^{131}\text{Xe (excess)}}$	$\frac{^{130}\text{Xe (excess)}}{^{129}\text{Xe (excess)}}$
Sample III	—	1.73 ± 0.10	1.94 ± 0.07
Sample IV	—	1.58 ± 0.36	1.93 ± 0.21
Sample V	—	1.52 ± 0.12	2.08 ± 0.11
Sample VI	0.09 ± 0.01	1.52 ± 0.21	2.55 ± 0.26
Sample VII	0.01 ± 0.004	1.52 ± 0.09	2.23 ± 0.13
Sample VIII	− 0.007 ± 0.004	1.60 ± 0.06	1.89 ± 0.08
Average	0.03 ± 0.03	1.58 ± 0.03	2.10 ± 0.09

Table 3. Abundance ratios of excess xenon isotopes extracted from tellurium ores.

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[25] J. H. REYNOLDS, Geochim. Cosmochim. Acta **12**, 177 [1957].
[26] H. FECHTIG, W. GENTNER, and J. ZÄHRINGER, Geochim. Cosmochim. Acta **19**, 70 [1960].
[27] W. H. SULLIVAN, Trilinear Chart of Nuclides 1957. Atomic Energy Commission, USA.

Tab. 1, but it is difficult to assign it entirely to ^{128}Te double β-decay, since a small, persistent background in the mass spectrometer disturbed exact measurements at ^{128}Xe. However, if all the excess ^{128}Xe should come from the double β-decay of ^{128}Te, a lower limit of the half-life is estimated to be 3×10^{22} years by comparing the excess ^{128}Xe with the excess ^{130}Xe, and using the half-life of the ^{130}Te double β-decay. It is shorter by about three orders of magnitude than the half-life predicted from the decay energy of 0.85 MeV [1].

The excesses in other isotopes of xenon are shown in Fig. 3 in terms of δ_{m}, the ratio of the excessive xenon to the contaminating atmospheric xenon, where δ_{m} is defined by the following expression;

$$\delta_{\mathrm{m}} = 1000 \left\{ ({}^{\mathrm{m}}\mathrm{Xe}/{}^{132}\mathrm{Xe}) / ({}^{\mathrm{m}}\mathrm{Xe}/{}^{132}\mathrm{Xe})_{\mathrm{atm}} - 1 \right\} .$$

It is to be noted that the values of δ_{m} for light isotopes seem to be slightly larger than for heavy ones, and that the values for ^{130}Xe are remarkably larger. The tendency is similar to that of the well-known general anomalies in meteoritic [28] xenon where the values of δ_{m} increase with decreasing mass number.

Further experiments are in preparation to confirm the results on the half-life of ^{130}Te and, if possible, on that of ^{128}Te also, and to ascertain such tendency of δ_{m} as shown in Fig. 3 and Fig. 4.

Acknowledgements

The authors wish to express their heartfelt thankfulness to Prof. Dr. H. HINTENBERGER for his kind suggestions on the construction of the mass spectrometer. We are greatly indebted to Prof. G. KAWANO and Dr. Y. UEDA of Tohoku University for supplying us with the tellurium ores and for their valuable guidance in the geological problems. We also wish to thank Prof. T. HAYAKAWA, Dr. S. YAMASHITA and Dr. M. UEDA of Osaka Prefecture University for the chemical analysis of the tellurium ores.

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Zur Theorie der Entstehung der Atomkerne unseres Sonnensystems

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(Z. Naturforschg. **21 a**, 90—92 [1966]; eingegangen am 30. September 1965)

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Im allgemeinen hält man die Schwierigkeiten, die den Theorien der Elemententstehung anhaften, durch die Annahme für überwunden, daß die Elemente unseres Sonnensystems Mischungen darstellen von Kernsorten, die auf verschiedene Weise, zu verschiedenen Zeiten und an verschiedenen Orten entstanden sind. Gegen diese Vorstellung läßt sich jedoch u. a. ein grundlegender Einwand erheben: Durch Wahl einer geeigneten Klassifizierung der Kernsorten läßt sich zeigen, daß in bestimmten Massengebieten die Kernhäufigkeiten mit dem Gang der Kernbindungsenergien nach MATTAUCH et al. [1], zum Beispiel mit den Bindungsenergien der letzten α-Teilchen, in einem, wenn auch derzeit nicht quantitativ deutbaren, augenfälligen Zusammenhang stehen.

Nachdem bereits vor langem gezeigt werden konnte [2], daß die naheliegende Deutung der Häufigkeitsverteilung der Atomkernsorten in der Natur, und zwar die Vorstellung eines eingefrorenen kernchemischen Gleichgewichts [3], keine befriedigende Näherung ergibt, haben zahlreiche Autoren eine Antwort auf die Frage der Elemententstehung entweder in der Kinetik von Kernaufbaureaktionen [4] oder in der von Abbaureaktionen massiver Kerne [5] gesucht. Wenn auch manche dieser Versuche zu recht plausiblen Bildern führten, so gelang es doch nicht, die empirisch vorliegenden Häufigkeitsdaten quantitativ zu deuten. Die vergeblichen Bemühungen um ein einheitlich geschlossenes, kosmologisch und kernphysikalisch einwandfreies Bild einer Elementsynthese im Zuge eines bestimmten kosmologischen Ereignisses führten schließlich zu der Annahme, daß die uns umgebende Materie eine Mischung darstelle von Produkten, die auf verschiedene Weise in verschiedenen Quellen, und zwar im Innern von Sternen, ent-

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* Die Arbeiten des Autors über „Häufigkeiten der Elemente" werden von der National Aeronautics and Space Administration, Washington, D.C. finanziell unterstützt.

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