Table 1. Helium isotopic data. Data are for the 2050°C fractions of samples 1-A through 5. The 900°C fractions were negligibly small. Total fusion at 2050°C was used for samples 82401 through 82406. Errors in ^{3}He and ^{4}He for the diamond samples are sums of the standard deviations of the peak height measurements and 50 percent of the hot blank. Errors in ^{3}He/^{4}He are estimated as the sum of the errors in ^{3}He and ^{4}He. The ^{4}He peak height determination was reproducible within about 10 percent. Hot-blank corrections were applied to all abundances.

Sample		Hot blank (2050°C)		Diamond		
Number	Weight (g)	^{3}He (10^{-13} cm^3 STP/g)	^{4}He (10^{-7} cm^3 STP/g)	^{3}He (10^{-13} cm^3 STP/g)	^{4}He (10^{-7} cm^3 STP/g)	R/R_a
1-A	0.2115	0.2	0.11	1.9 ± 0.1	1.51 ± 0.07	0.91 ± 0.10
2-A	0.1473	0.2	0.15	2.2 ± 0.1	0.99 ± 0.08	1.57 ± 0.17
3-A	0.1828	2.4	0.12	87 ± 4.6	0.37 ± 0.06	168 ± 38
1	0.3299	1.0	0.08	3.0 ± 0.6	1.93 ± 0.05	1.1 ± 0.02
2	0.3124	6.2	0.11	< 1.8	21.2 ± 0.3	< 0.06
3	0.3324	1.3	0.14	2.5 ± 0.9	58.8 ± 0.7	0.03 ± 0.01
4	0.3466	0.8	0.15	0.6 ± 0.4	14.7 ± 6.2	0.03 ± 0.02
5	0.2976	0.8	0.18	2.4 ± 1.3	4.73 ± 0.12	0.36 ± 0.3
82401	0.1788	1.6	0.20	424 ± 4	1.34 ± 0.10	226 ± 18
82402	0.2671	1.4	0.13	121 ± 5	3.75 ± 0.05	23.1 ± 1.6
82403	0.1383	3.0	0.25	4.1 ± 2.1	5.85 ± 0.23	0.5 ± 0.3
82405	0.1170	2.8	0.30	150 ± 7.0	4.42 ± 0.16	24.2 ± 2.0
82406	0.1466	2.3	0.21	31.7 ± 3.2	1.23 ± 0.11	18.4 ± 4.0

monds; iso-^{3}He lines are drawn corresponding to the same ^{3}He content. Addition of radiogenic ^{4}He would move the isotopic ratio downward along an iso-^{3}He line. Since ^{3}He production in the mantle (*8*) and the diamonds is probably insignificant, we consider the large spread in ^{3}He/^{4}He values in Fig. 1 to be primarily due to addition of radiogenic ^{4}He, either in the diamonds or in the mantle source region where the diamonds trapped the helium. It is interesting that most of the diamonds with small ^{3}He/^{4}He values ($\lesssim 5 \times 10^{-6}$) lie approximately on a single iso-^{3}He line, suggesting that they evolved from a single component of helium with similar ^{3}He/^{4}He values. Diamonds with higher ^{3}He/^{4}He values ($> 10^{-4}$) may represent very primitive helium that evolved little since the formation of the earth. Preservation of such primitive helium throughout a geological age would be possible only in an environment where uranium and thorium were highly depleted or the U/He ratio was extremely small. Possible candidates for such an environment would be a deeper part of the mantle which has remained decoupled from the outer part of the earth, or diamonds whose uranium and thorium contents are generally extremely small ($\lesssim$ 0.1 ppb) (*4*). We prefer the latter interpretation, because we know of no geological evidence supporting the existence of such a primitive mantle.

We propose that the very high ^{3}He/^{4}He values found in some diamonds represent helium trapped by the diamonds soon after the formation of the earth. The lower ^{3}He/^{4}He values found in other samples then reflect either relatively high uranium and thorium contents or a relatively younger age of the diamonds, which trapped highly radiogenic "aged helium" in the mantle. Of further interest is the fact that the diamonds with smaller ^{3}He/^{4}He values have a much lower ^{3}He content than diamonds with higher ^{3}He/^{4}He values. This may indicate that the diamonds with smaller values formed in the mantle after it had degassed and had less ^{3}He, while the diamonds with primitive helium crystallized before the mantle degassed. The existence of nearly solar-type helium in the earth implies that the accretion of the earth may be different from that of meteorite parent bodies with respect to the time or the process involved. For example, this may indicate that the dust grains from which the earth accreted were subjected to intense solar wind radiation after the deuterium burning stage in the sun, while those from which the meteorite parent bodies accreted may have trapped only the planetary helium (He-A) in the surrounding solar nebula.

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Carbon-13 and Carbon-14 Abundances in Alaskan Aquatic Organisms: Delayed Production from Peat in Arctic Food Webs

Abstract. *Inputs of terrestrial peat carbon to the nearshore Alaskan Beaufort Sea from erosion and fluvial transport are of the same magnitude as in situ primary production within 10 kilometers of shore. Nevertheless, carbon-13/carbon-12 ratios and carbon-14 abundances in marine organisms show that only small amounts of the terrestrial carbon are transferred beyond the microbial level. Freshwater organisms, however, are heavily dependent on peat, as shown by pronounced seasonal radiocarbon depressions in resident fish and ducks. Tundra ponds and lakes are areas where accumulated terrestrial peat carbon is apparently transferred to aquatic insect larvae and passed on to higher organisms. The lack of functionally analogous abundant marine prey organisms may explain why peat carbon is not efficiently transferred to apical food web species in the marine environment.*

The intricacies of nearshore and estuarine marine food webs present formidable obstacles to assigning significance to various energy source materials supporting resident fauna. Primary production from phytoplankton, benthic microalgae, macrophytes, and allochthonous (originating outside the system) terrigenous vegetation can all contribute, and quantification of inputs is often difficult or impossible. Recent studies have sought to identify the carbon source and the consumer of interest by using natural ^{13}C/^{12}C isotope ratios (*1–4*). The marked difference in δ^{13}C resulting from C-3 and C-4 photosynthetic pathways yields a natural signal easily traced in herbivores that graze on these plants (*5*). As long as

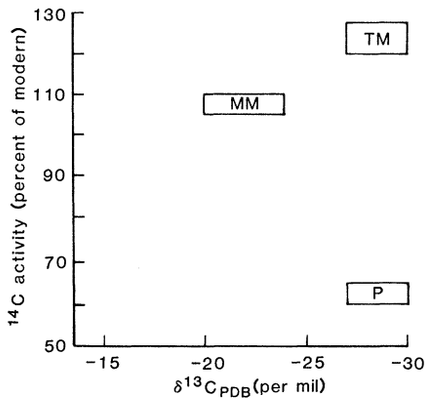

Fig. 1. Values of $\delta^{13}C$ and radiocarbon activities of terrestrial modern vascular plants (*TM*), marine coastal phytoplankton (*MM*), and "average" peat (*P*). Stable carbon isotope ratios serve to differentiate terrestrial from marine carbon, while radiocarbon activity distinguishes modern terrestrial carbon from peat.

the source materials have a large separation in isotopic signature and are limited to two or three in number, their allocation can often be accomplished. In estuarine situations (*1–4, 6*), flora are varied in species and isotopic composition. Contributions by heterogeneous populations of benthic algae, photosynthetic bacteria, and less abundant species of vascular plants lead to overlapping $^{13}C/^{12}C$ abundances. Chemosynthetic fixation has also been proposed as a pathway of carbon input by Peterson *et al.* (*7*) to account for the data obtained by Haines (*6*) regarding the role of *Spartina*-derived detritus in Georgian estuaries. Ambiguous conclusions result when there is an overlap in $\delta^{13}C$ values and a single isotopic label is used to trace food web pathways.

I present here a study on Beaufort Sea estuarine food webs in arctic Alaska based on natural abundances of ^{13}C and ^{14}C and describe an ecosystem dependent on allochthonous carbon with delays of several thousand years between primary production and use by consumers. Nearshore carbon inputs consist of primary production by ice algae and phytoplankton, supplemented by peat and vegetative detritus transported by rivers or added directly by shoreline erosion. Within the shallow nearshore zone (< 10 m in depth, extending to about 10 km offshore), allochthonous carbon inputs were found to be approximately the same as annual primary production, 30 g m^{-2} $year^{-1}$ from peat versus 20 g m^{-2} $year^{-1}$ from phytoplankton (*8*). Dating of soil sections showed peat accumulation for 8,000 to 12,000 years before present, and large depletions in ^{14}C abundances were anticipated in food webs based on peat carbon. Abundance ratios of ^{13}C to ^{12}C typical of subarctic marine algae were found in pelagic organisms offshore (*9*), and a C-3 isotopic signature represented the terrigenous organic matter. The typically short food chains of the Arctic also indicated that there should be minimal interference with biochemical fractionation effects (*5*). Organisms that consume these sources directly or indirectly should yield an isotopic distribution based on source materials as shown in Fig. 1.

Sampling of particulate organic matter transported by the Colville River during spring breakup flood season indicated that most particulate carbon was peat with a ^{14}C activity of 71 to 74 percent modern and not modern vegetative detritus carried by surficial runoff. However, the large mysid and gammarid amphipod populations in the receiving marine waters showed only minor depressions in ^{14}C content and had $\delta^{13}C$ values of predominantly marine carbon (Table 1). Radiotracer experiments with ^{14}C-labeled cellulose indicated active microbial degradation of the peat when exposed to marine waters, but the food web linkages necessary for efficient transfer to higher trophic levels are apparently lacking. Pelagic marine organisms, such as fourhorn sculpins (*Myoxocephalus quadricornis*) and arctic cod (*Boreogadus saida*), contained stable and radioactive carbon isotope abundances typical of a phytoplankton carbon source. This confirms their dependence on marine carbon fixation. In contrast, the tundra grazers, lemmings and caribou, have carbon isotopic compositions that indicate complete dependence on living terrestrial plants.

Seasonal residents of the nearshore Beaufort Sea are typified by migratory oldsquaw ducks (*Clangula hyemalis*) and several species of anadromous fish, principally ciscoes and whitefish (*Coregonus* spp.). The coregonids enter the marine environment after overwintering in the rivers. Oldsquaw ducks migrate north to the tundra lakes and ponds, where pairs nest and females raise broods and molt, while feeding on freshwater invertebrates. Some nonbreeding females and most of the postbreeding males, however, summer on the nearshore marine lagoons and feed on marine invertebrates, splitting the species into segments dependent on either freshwater or marine food webs (*10, 11*). Similarly, the ciscoes do not reenter the rivers until freeze-up, when they ascend the rivers to overwinter in deep pools along with the obligate freshwater fish species. Since these rivers freeze to the bottom in

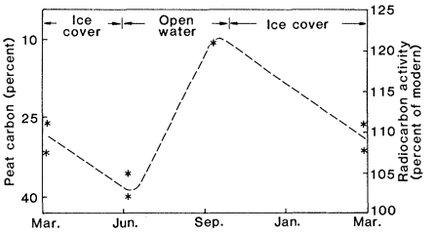

Fig. 2. Seasonal radiocarbon activity in *Thymallus arcticus* from the Colville River and equivalent peat carbon content.

shallow areas by late winter and essentially cease flowing (*12*), movement within the river system is very restricted for overwintering fish.

Fish were collected before they entered the Colville River in autumn, beneath the river ice in March, and in the Colville delta as they were reentering the marine waters in June. The isotopic composition of the fish and oldsquaw ducks from freshwater and marine environments are listed with energy source materials in Table 1. The marine fish are grouped near a $\delta^{13}C$ of −21 ppt and a ^{14}C content of 104 to 110 percent modern (*13*). Anadromous fish captured after feeding in the marine environment for the summer were isotopically indistinguishable from obligate marine species. The principal prey species found in stomach contents were mysids (^{14}C = 106 percent modern) and gammarid amphipods (^{14}C = 104 percent modern), indicating that very little of the peat carbon reaches the larger marine invertebrate populations. Only one species of amphipod, *Gammarus setosus*, was low in ^{14}C abundance (96.6 percent modern); it has been shown by Schneider (*14*) to be an avid consumer of peat detritus and to readily metabolize ^{14}C-labeled cellulose. It does not, however, constitute a large fraction of the prey invertebrates consumed by anadromous fish or oldsquaws (*10, 15*).

The freshwater organisms sampled contrast markedly with marine organisms in ^{14}C content. Although modern aquatic primary producers center around 123 percent modern, as evidenced by both submerged algal mats (122 percent modern) and emergent macrophytes (123.9 percent modern, N = 3), the ^{14}C contents of the fauna range from 93.5 to 120.9 percent modern. The seasonal variation of ^{14}C content in Colville River grayling (*Thymallus arcticus*) suggests a major alteration of food dependences over the hydrologic year (Fig. 2). During the runoff season, grayling ascend the tributaries and feed heavily on insect drift in headwaters. Here benthic primary production is rapid (*16*) and the fish

acquire a high ^{14}C content (120.9 percent modern). With the onset of freezing and cessation of runoff, the fish descend to deep pools in the main channels to overwinter. Specimens sampled in March had ^{14}C contents of 108 and 111 percent modern. By breakup of the 2-m ice cover in June, values dropped to 102 and 106 percent modern. Since under-ice primary production is very low during arctic winter darkness, this change in ^{14}C content must represent an increasing dependence on peat carbon by grayling prey organisms. If average peat is 63 percent modern, the peat carbon content of these fish increases from less than 4 percent in late summer to a maximum of about 32 percent by the end of the winter season.

The anadromous fish follow a similar pattern. The least cisco (*Coregonus sardinella*), entering the Colville River delta in early October, was isotopically a marine modern fish ($\delta^{13}C = -21.2$, 109.2 percent modern); by November ($\delta^{13}C = -22.9$, 103.1 percent modern) it was 20 percent peat carbon. By June (during breakup flooding and out-migration), the stable carbon isotope ratios were typical of freshwater fish ($\delta^{13}C = -29.1$) with a large depression in ^{14}C (91.8 percent modern) equivalent to 52 percent peat carbon. The only other anadromous fish sampled in both fall and spring was the broad whitefish, *C. nasus*, which showed a similar isotopic shift but did not lose its entire marine carbon content over the winter (as indicated by $\delta^{13}C$ values). This may reflect wintering on the high fat content acquired by the fish during summer feeding in the marine environment.

The samples of oldsquaw, *C. hyemalis*, represent a wide spectrum of food web dependences and isotopic variation as functions of season and age. The 28 August 1979 sample (Table 1) was a nonbreeding female captured after summering in marine waters. It is isotopically similar to obligate marine fish and reflects a diet of marine invertebrates. The 2 August 1980 sample is a molting adult male taken very shortly (1 to 2 weeks) after leaving tundra breeding lakes. The oriented thaw lakes of the coastal plain also receive large erosional inputs of peat and two carbon samples from surface sediments were 72 and 77 percent modern. This bird (2 August 1980) had a $\delta^{13}C$ value near that of freshwater organisms and a ^{14}C depression equivalent to 63 percent peat carbon. At 85 percent modern (radiocarbon "age" = 1300 years before present), it contains the lowest ^{14}C content of any organism sampled to date. Its prey organisms must have had the same cumulative ^{14}C depression. I have not yet been able to acquire enough insect larvae (especially chironomids, a favored prey organism in tundra lakes) to perform precise radiocarbon content determinations. The availability of accelerator carbon-dating instruments in the near future will permit the analysis of these small samples.

Three oldsquaw samples acquired in 1980 from lakes (70°42′N, 152°40′W) included a migrant newly arrived to the tundra (26 June 1980), a juvenile tundra bird (28 August 1980), and a postmolt male (24 August 1980). The bird taken on 26 June was marine-modern, and the two birds from the tundra were isotopically terrestrial and ^{14}C-depressed to a maximum peat equivalent of 31 percent peat carbon in the male. The higher ^{14}C content of the juvenile, which favored shallow areas of feeding, reflects a higher percentage of modern primary production supporting prey organisms. The considerable difference in peat content between the bird of 2 August 1980 (60 percent) and that of 24 August 1980 (30 percent) may indicate considerable variation in energy source dependences among the lakes on the coastal plain.

The carbon isotope compositions of arctic freshwater and marine biota indicate a major separation in the trophic energetics of the coastal zone. Although large amounts of peat carbon are available in the marine environment, utilization at higher trophic levels is limited. Strictly marine organisms rely on the more variable supply of primary production by marine microalgae. Apical organisms of the pelagic food webs (seals, whales, and polar bears) typically have large energy storage capacities, which may help smooth out pronounced seasonal and perhaps annual variations in food supply. Freshwater and anadromous arctic fish and oldsquaw ducks,

Table 1. Radiocarbon activities and $\delta^{13}C$ values of common coastal Beaufort Sea and tundra flora and fauna [from a comprehensive listing in (*8*)].

Sample	$\delta^{13}C$ (ppt)	^{14}C activity (percent modern)
Vegetative		
Basal peat, Milne Point	−28.7	32.4
Basal peat, Pingok Island	−28.3	35.0
Emergent grass, *Arctophila fulva*	−26.8	121.1
Sedge, *Carex aquatilis*	−30.5	127.1
Willow, *Salix* spp.	−28.1	138.1
Kelp (marine), *Laminaria solidungula*	−15.4	105.7
Particulate carbon, Colville River (12 to 14 June 1979)	−27.0	74.4
Algal mat (freshwater), *Nostoc* spp. (27 June 1981)	−20.2	122.2
Surface sediments, Gooseneck Lake	−27.1	77.3
Surface sediments, lake C-2	−30.7	71.6
Invertebrates (marine)		
Mysids, *Mysis* spp. (August 1978)	−23.6	105.9
Amphipods, *Onisimus* spp. (August 1978)	−18.3	103.7
Amphipod, *Gammarus setosus* (July 1980)	−19.9	96.6
Fish		
Humpback, whitefish, *Coregonus pidschian* (October 1977)	−20.4	109.5
Least cisco, *C. sardinella* (October 1977)	−21.2	109.2
Least cisco, *C. sardinella* (June 1980)	−29.1	91.8
Least cisco, *C. sardinella* (November 1980)	−22.9	103.1
Arctic cisco, *C. autumnalis* (October 1977)	−21.8	109.6
Broad whitefish, *C. nasus* (5 November 1980)	−22.3	102.0
Broad whitefish, *C. nasus* (16 June 1980)	−24.9	94.8
Fourhorn sculpin, *Myoxocephalus quadricornis* (August 1978)	−20.5	105.3
Arctic cod, *Boreogadus saida* (August 1978)	−21.5	107.3
Arctic grayling, *Thymallus arcticus* (September 1979)	−26.4	120.9
Arctic grayling, *T. arcticus* (22 March 1980)	−29.8	111.1
Arctic grayling, *T. arcticus* (22 March 1980)	−28.2	107.5
Arctic grayling, *T. arcticus* (June 1980)	−26.7	105.5
Arctic grayling, *T. arcticus* (June 1980)	−26.9	102.1
Birds		
Oldsquaw, *Clangula hyemalis* (28 August 1979), adult female	−20.7	104.9
Oldsquaw, *C. hyemalis* (2 August 1980), adult male	−26.1	85.0
Oldsquaw, *C. hyemalis* (26 June 1980), adult male	−21.0	114.7
Oldsquaw, *C. hyemalis* (28 August 1980), juvenile	−27.8	109.6
Oldsquaw, *C. hyemalis* (24 August 1980), adult male	−28.5	104.6
Mammals		
Lemming, *Lemmus sibericus* (27 June 1981)	−26.1	127.4
Caribou, *Rangifer tarandus* (August 1981)	−28.7	130.6

however, rely on the trophic transfer of peat carbon through the critical link of insect larvae and attain partial independence from the seasonal variation in primary production. This "fossil fuel subsidy" is important in an environment where primary production is essentially nil for about 7 months of the year.

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13. Ratios of ^{13}C to ^{12}C are expressed as $\delta^{13}C_{PDB}$, where $\delta^{13}C_{PDB} = [(R_{sample} - R_{std})/R_{std}] \times 1000$ and R is the ratio $^{13}C/^{12}C$; $\delta^{13}C$ is reported in parts per thousand (ppt) relative to the Pee Dee belemnite (PDB) standard. The ^{14}C activity of an A.D. 1950 sample is expressed as 100 percent modern, normalized to $\delta^{13}C$ of −25 ppt to correct for fractionation effects. Modern tundra vegetation is 122 to 140 percent, with lower values in annual grasses, leaves, and aquatic algae. Higher values are found in woody plants, standing dead grasses, and sedges. Marine macroalgae samples (*Laminaria* spp.) are 103 to 107 percent (N = 4). "Average peat" was taken to be the mean activity of a uniform layer of peat accumulating at constant rate for 8142 years. Actual basal peats along shorelines and rivers ranged from 3,400 to 12,600 years before present. The mean was 36.3 percent modern (N = 6, standard deviation = ±15.3 percent modern), yielding an average activity of 62.9 + 10.2, −11.3 percent modern. This average peat activity is probably lower than the overall activity of peat entering the aquatic systems. An actual particulate sample from the Colville River was 74.4 percent modern. Since no quantitation of modern material in these samples was attempted, the more conservative value of 62.9 percent was used to determine peat carbon content in organisms.
Organisms collected for isotopic analyses were frozen until processed in the laboratory. Small organisms such as mysids, amphipods, lemmings, and *Daphnia* were dried whole in vacuo at 70°C. For larger animals muscle tissue was used. Vegetation samples from aquatic and terrestrial sites were dried after any foreign matter was manually removed. Riverborne detritus was collected by suspending a 120-μm mesh plankton net in the Colville River until sufficient material had been collected to provide 5 g of carbon.
Isotopic analyses were performed by Beta Analytic, Inc. (BAI), Geochron Division (GD) of Krueger Industries, and Teledyne Isotopes. Precision in ^{14}C analyses was typically ±1 percent and ^{13}C analyses were ±0.05 to 0.1 ppt. Costs of analyses limited replication of samples. *Laminaria* from one collection site were sent to each laboratory and yielded the following activities: 105.7 (GD); 105.0, 107.1 (BAI); and 102.8 (Teledyne).
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Lithium, Compression and High-Pressure Structure

Abstract. *Lithium is found to transform from a body-centered cubic (bcc) to a face-centered cubic (fcc) structure at 6.9 gigapascals (69 kilobars) and 296 kelvin. The relative volume of the bcc structured lithium at 6.9 gigapascals is 0.718, and the fcc structure is 0.25 percent denser. The bulk modulus and its pressure derivative for the bcc structure are 11.57 gigapascals and 3.4, and for the fcc structure are 13.1 gigapascals and 2.8. Extrapolation of the bcc-fcc phase boundary and the melting curve indicate a triple point around 15 gigapascals and 500 kelvin.*

Lithium has three electrons per atom and is thus the most elementary metal available for study. The nature of the forces generated by the electrons in bonding lithium into a solid is partially revealed by studying the structure and density of the metal in response to temperature and pressure changes. In the study described here the structure and density of lithium were measured to 10 GPa (100 kbar, 10×10^{10} dyne/cm^2) at an ambient temperature of 296 K.

The technique used in this study has been described (*1*). Briefly, an annulus of beryllium 2.5 mm in diameter and 0.25 mm thick with a 0.33-mm hole in the center is pressed between two tungsten-carbide Bridgman anvils. The hole is filled with a mixture of Li and LiF powder (pressure indicator). A Cu$K\alpha$ x-ray beam is directed through the annulus, and the diffraction is recorded on a 114.6-mm-diameter cylindrical film surrounding the annulus. Diamond anvils were not used for three experiments because of the very low scattering power of Li.

The diffraction patterns of the Li-LiF mixture exhibited the 110, 200, and 211 diffraction lines of the body-centered cubic (bcc) structure of Li, the 111 and 220 lines of the high-pressure face-centered cubic (fcc) structure of Li, and the 111 and 220 lines of LiF. The pressure is deduced from the LiF volume calculated from the diffraction patterns and correlated with values calculated from a shock compression study of LiF (*2*).

A preliminary study was made with Li alone to avoid confusing diffraction lines of new structures with those of LiF. Lithium was compressed to a minimum relative volume of $V/V_0 = 0.654$. The ambient bcc structure transformed to a fcc structure at $V/V_0 = 0.712$ (bcc) as the pressure was being increased and trans-

Table 1. Lithium compression data. The ambient (V_0) volume of lithium is 1.876 cm^3/g; a is the cubic cell parameter.

Film number	a (LiF) (Å)	a (Li) (Å)	P (GPa)	V/V_0
		bcc structure		
2-3	3.968(1)*	3.285(5)*	3.3(1)*	0.820(3)*
4-4	3.965(−)	3.272(0)	3.5(−)	0.811(0)
4-5	3.946(−)	3.216(2)	4.7(−)	0.770(2)
2-4	3.945(2)	3.217(5)	4.7(1)	0.771(3)
2-5	3.919(−)	3.161(−)	6.6(−)	0.731(−)
		fcc structure		
4-7	3.900(3)	3.900(3)	8.0(2)	0.687(1)
2-8	3.880(−)	3.855(−)	9.6(−)	0.663(−)
4-9	3.877(3)	3.843(3)	9.8(3)	0.657(1)
4-10	3.876(0)	3.832(2)	9.9(0)	0.651(1)
4-11	3.874(−)	3.828(1)	10.1(−)	0.649(0)

*The standard deviations are listed after each number. They are the uncertainty of the final figure in each number. A dash in parentheses signifies that only one value could be determined because of diffraction line interference.