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BUDAPEST

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K X-RAY PRODUCTION CROSS-SECTIONS INDUCED BY 1.6 TO 4.0 MeV DEUTERONS

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ABSTRACT

Thin P,S,Cl,K,Ni,Cu and Ga targets were bombarded by deuterons of 1.6 to 4.0 MeV energy. From the measured K Y-ray intensities the X-ray production cross sections were determined. The results were compared with proton induced cross-sections.

АННОТАЦИЯ

Тонкие мишени сделанные из P, S, Cl, K, Ni, Cu и Ga были облучены пучком дейтеронов, энергия которых менялась от 1,6 МэВ до 4.0 МэВ. Была измерена интенсивность К-линий возникщихся рентгеновских лучей. Из полученных данных была определена величина сечения образования рентгеновского излучения. Приведено сравнение значений сечений возникновения рентгеновских лучей при бомбардировке мишени протонами и дейтеронами.

KIVONAT

Vékony P,S,Cl,K,Ni,Cu és Ga céltárgyakat bombáztunk deuteronokkal, melyek energiáját 1.6 és 4.0 MeV között változtattuk. Megmértük a keletkezett K röntgensugárzások erősségét és ezekből meghatároztuk a röntgensugárzás keltésének hatáskeresztmetszetét. A hatáskeresztmetszetek értékeit protonbombázással kapott hatáskeresztmetszet értékekkel vetettük egybe.

1. Introduction

Particle induced X-ray emission /PIXE/ is important for both basic and applied research. The comparison of cross--sections, relative line intensities and other characteristic features of X-rays induced by different bombarding ions offers an experimental basis for understanding the ion-atom collision mechanism and inner-shell ionization processes. On the other hand, the knowledge of accurate cross-section data makes PIXE very suitable for quantitative elemental analysis. The overwhelming majority of published cross-sections were obtained by proton bombardment, but after all data referring to alpha particles are also fairly frequent [1] . By way of contrast deuteron induced cross-sections have been measured in one or two cases only [2,3] and the main aim of these measurements was to test the "scaling" property of cross-section values. According to this "scaling", projectiles of the same velocity and electric charge have the same ionization cross-sections[4]. Since for analytical purposes low energy protons are preferable [5], deuteron induced X-ray cross-sections were previously irrelevant from all practical points of view but, as realized recently[6], deuteron beams can play an important role in the case of biological samples. Although X-rays of C, N, O /the major constituents of biological samples/ can not be detected using standard Si/Li/ detectors, this is not true of deuteron induced nuclear reactions producing high energy charged particles or photons which are very suitable for measuring the concentration of the low Z-elements [4]. If these two methods were to be combined light and heavier elements could simultaneously be determined.

This paper presents experimental cross-section data of deuteron bombardment together with those of proton bombardments on thin P,S,Cl,K,Ni,Cu and Ga targets. Whereas a good many proton cross-sections are available for Ni and Cu, no cross--sections for P,S,Cl and K were published before our present results.

2. Experimental

The CRIP 5 MeV Van de Graaff accelerator was used to produce deuteron beams from 1.6-4.0 MeV and proton beams from 1.4-2.0 MeV energy. The target chamber was a stainless steel block with circular holes in all its sides and two other holes for additional particle detectors at angles $\pm 160^{\circ}$ with respect to the incident beam direction. A special vacuum lock-system enabled the samples to be changed quickly. The chamber was insulated from the beam tube so it behaved as a Faraday cup. The incoming charges were integrated by an ORTEC digital current integrator. To avoid serious dead-time difficulties beam currents were limited to a few nA. The X-rays produced passed through the 4 μm thick mylar window of the chamber and 17.5 mm air before entering the 30 mm^2 Canberra Si/Li/ X-ray detector positioned at 90° to the beam. The entrance window of the detector was 25 μm Be foil, and about 100 μm thick external polypropylene absorber was always used to prevent the scattered particles reaching the detector. The detector pulses were processed by the special Canberra X-ray amplifier system and stored in a Canberra 8100 multichannel analyser. For dead-time corrections signals from a pulse-generator were fed into the test input of the preamplifier. The energy resolution of the system was 180 eV for the 5.89 keV Mn K_α -line. The detector efficiency was calculated using the mass-absorption coefficients of Storm and Israel [7] ; the transmission of the chamber window and the external absorber were experimentally determined by a series of measurements with a proton beam of 2 MeV energy. The peak areas of the spectra were extracted by an off-line small computer and several test evaluations were also performed by graphical method. For the elements P,S,Cl and K only the total X-ray intensities were calculated; in the case of Ni, Cu and Ga the K_α and K_β lines were separately determined. The four targets in this measurement were supplied by the International Atomic Energy Agency for intercomparison. The Agency's specification indicated that 43 $\mu g/cm^2$ GaP, 45 $\mu g/cm^2$ KCl, 45 $\mu g/cm^2$ Ni and CuS containing 54 $\mu g/cm^2$ Cu and 14 $\mu g/cm^2$ S were evaporated onto 6.35 μm mylar foils. The given thicknesses were checked by separate backscattering measurements using 3 and 4 MeV α beams. These measurements confirmed the nominal values to within a few percent except in the case of the GaP target, where only the half amount of phosphorus was found. For the evaluation of the X-ray measurements the measured thicknesses were used.

3. Results and Discussion

K X-ray production cross-sections were measured by changing the deuteron energy from 1.6-4.0 MeV in 0.2 MeV steps, and the proton energy from 1.4-2.0 MeV in 0.1 MeV steps. The cross-sections were calculated from the thin target formula:

$$\sigma_{prod} = 2.407\cdot 10^{-6} \frac{N_x A}{Q \varrho t \eta} ,$$

where N_x is the X-ray yield, Q denotes the incoming charge measured in 10^{-10}C, ϱt is the thickness of the element with atomic weight A expressed in $\mu g/cm^2$, η means the energy dependent efficiency of the detector for the radiation of interest. The solid angle of the detector is absorbed into the constant factor. The numerical results are displayed in Tables 1 and 2. In the first four columns of these tables the total σ^K_{prod} cross-sections are indicated, the last three columns show K_α production cross-sections. The numbers under each column indicates the estimated errors of the cross-section values as percentages. For the sake of easier comparison the deuteron and proton induced cross-sections are plotted together in Fig.1a-c. The proton data are indicated at those deuteron energies where, according to the "scaling" rule, they must be equal to the deuteron cross-sections. It can be seen that the measured values confirm this rule rather well within the quoted experimental errors.

As far as the absolute values of the cross-sections are concerned for lack of other measurements they are compared with the empirical expression of Johansson and Johansson [5] calculated at the "scaled" proton energies. The solid lines in the figures correspond to these calculations. For Ni, Cu and Ga the agreement is very good. In the case of the lighter elements the agreement becomes worse, the measured values are significantly too low.

Tables 1 and 2 also contain measured K_β/K_α ratios. The intensity ratios did not show significant variation as a function of the bombarding energy, therefore the given values are averages of all the measurements on a certain element. Furthermore the K_β/K_α ratios are the same for deuteron and proton bombardment and within the experimental error they agree with the values measured by photon excitation [8]. This agreement shows that no significant multiple ionization takes place in our bombarding conditions.

Summarizing the cross-section results presented here the following conclusions can be drawn. For analytical purposes the expected X-ray yields induced by deuteron beam can be fairly well estimated from proton induced ones with the help of the "scaling" rule. Although the relatively large background in the high energy part of the X-ray spectra caused by the energetic reaction products from deuteron induced nuclear reactions limits the sensitivity to heavier elements, subsequent runs using proton bombardment could complement the deuteron measurements. If the X-ray spectra are normalized with the help of the doubly measured concentrations of light elements complete analyses can be performed including also the light major components of biological samples.

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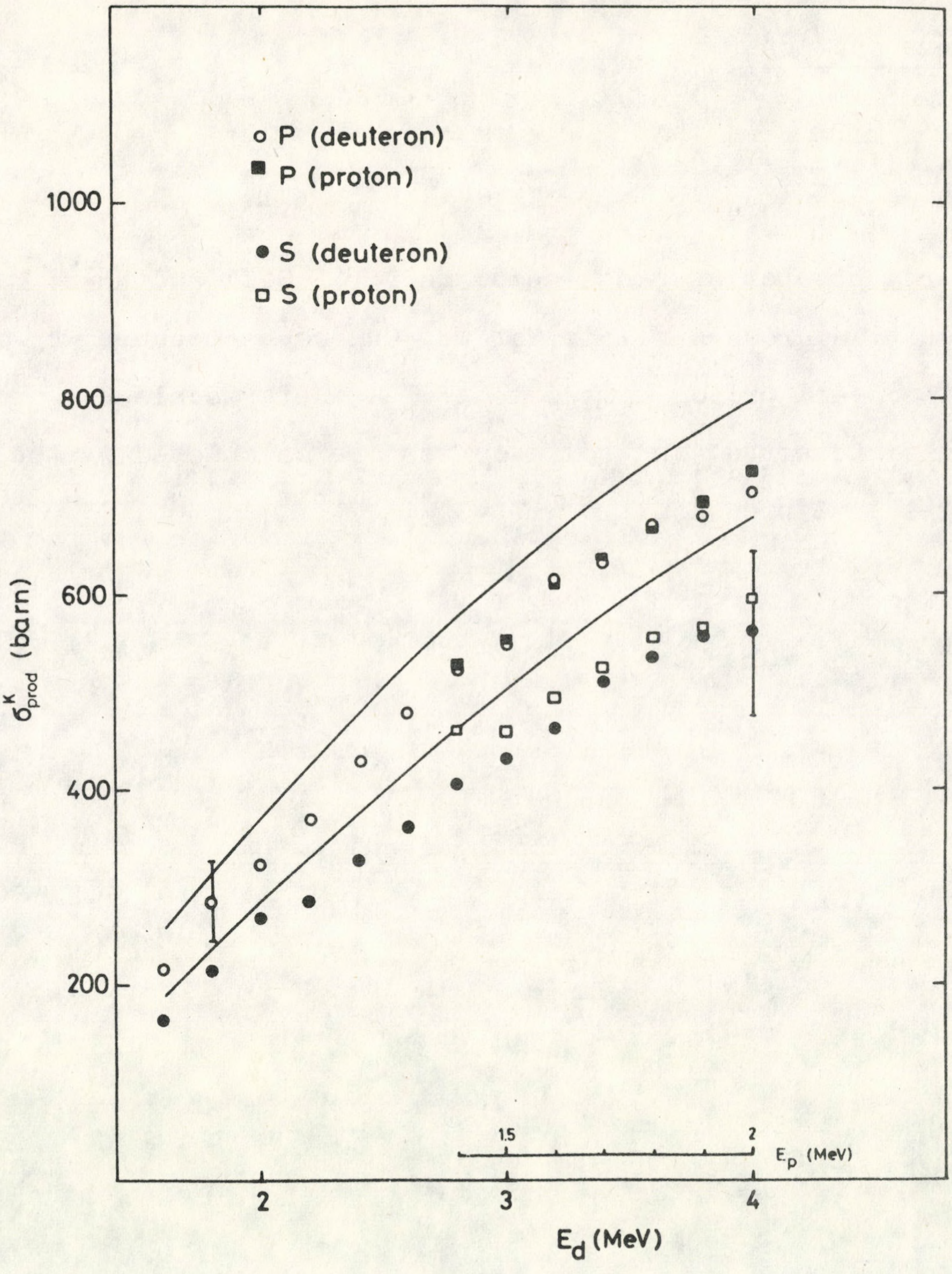
Figure caption

Figure 1a-c.

K X-ray production cross-sections for P,S,Ci and K and K_{α} production cross-sections for Ni, Cu and Ga measured by deuteron and proton bombardment. The energy scale for protons is also inserted. The solid curves are calculated by the empirical expression from ref.5.



○ P (deuteron)
■ P (proton)
● S (deuteron)
□ S (proton)
1000
800
600
400
200
σ^K_prod (barn)
1.5
2
E_p (MeV)
2
3
4
E_d (MeV)

Fig. 1/a

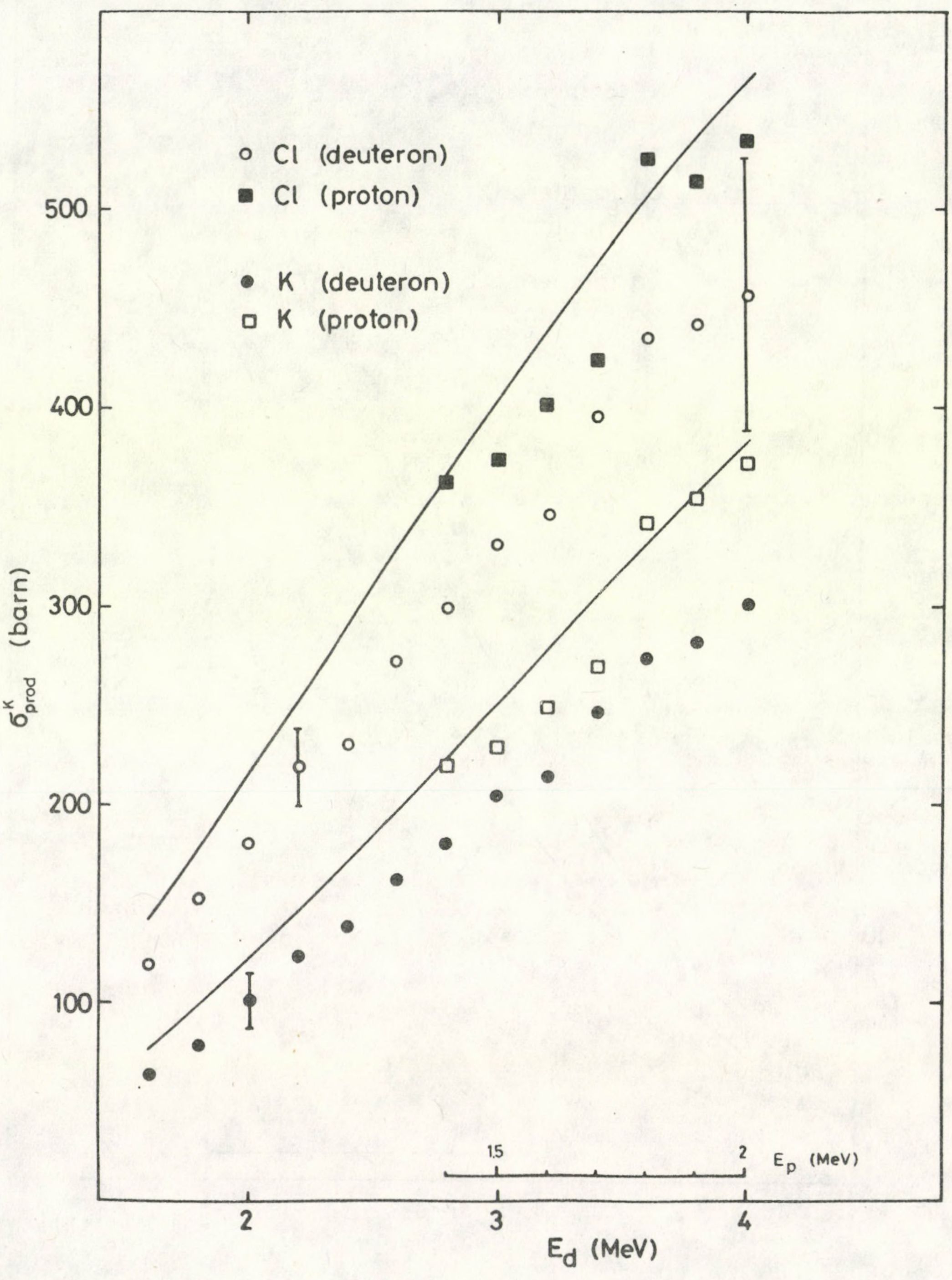
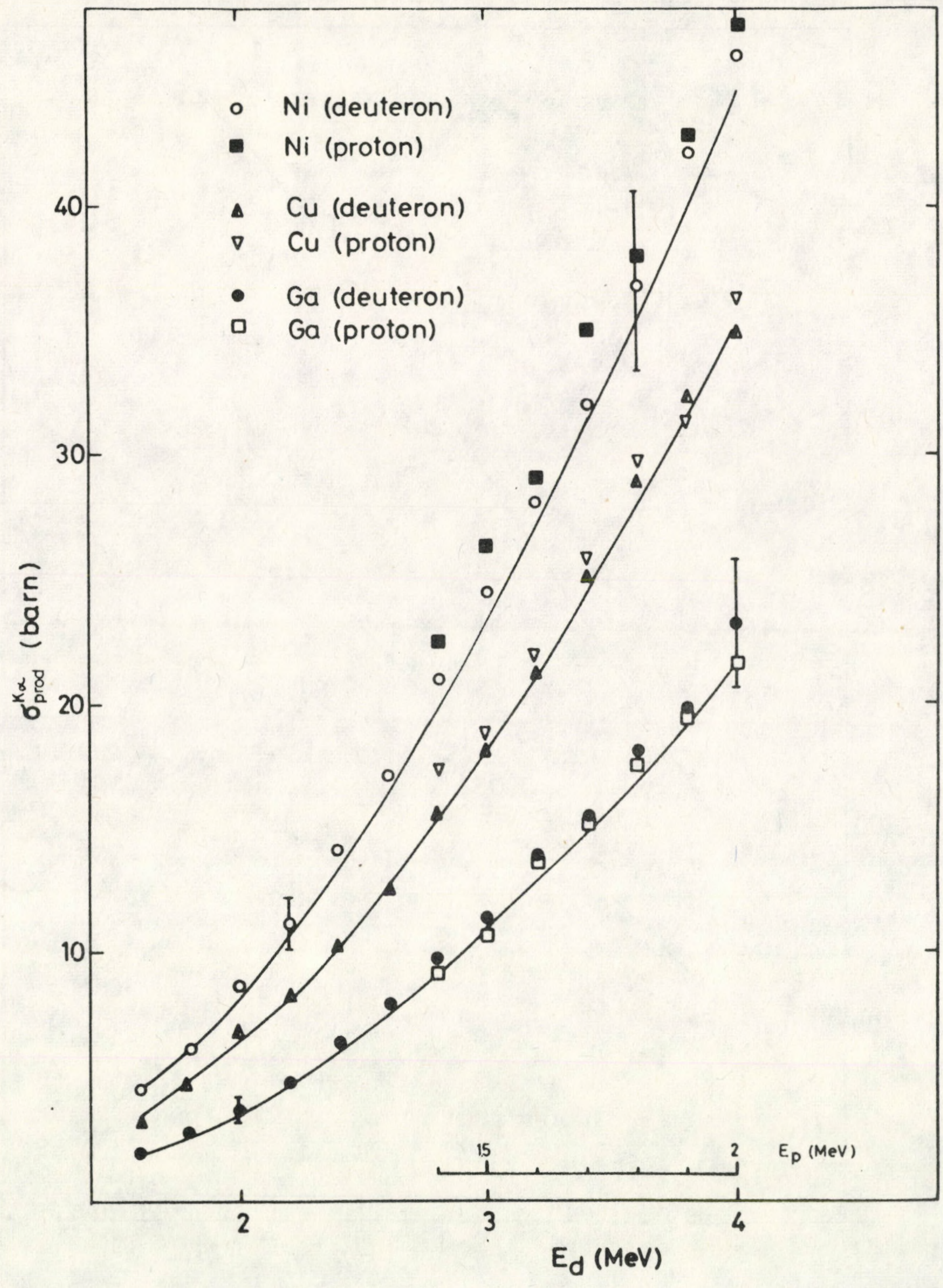

Cl (deuteron)
Cl (proton)
K (deuteron)
K (proton)
500
400
300
200
100
σ^K_{prod} (barn)
1.5
2
E_p (MeV)
2
3
4
E_d (MeV)

Fig. 1/b



Ni (deuteron)
Ni (proton)
Cu (deuteron)
Cu (proton)
Ga (deuteron)
Ga (proton)
40
30
20
10
$\sigma_{prod}^{K\alpha}$ (barn)
1.5
2
E_p (MeV)
2
3
4
E_d (MeV)

Fig. 1/c

Table 1.

Experimental K X-ray production cross-sections and K_β / K_α intensity ratios obtained by deuteron bombardment.

E_d (MeV)	σ^K_{prod}(barn)				σ^K_{prod}(barn)		
	P	S	Cl	K	Ni	Cu	Ga
1.6	232	164	119	61.3	4.51	3.18	1.86
1.8	283	215	151	80.5	5.95	4.75	2.70
2.0	322	268	181	101	8.48	6.74	3.62
2.2	368	284	218	123	11.1	8.23	4.76
2.4	429	325	228	132	14.0	10.3	6.23
2.6	477	359	272	162	17.0	12.6	7.84
2.8	520	404	299	180	20.9	15.7	9.68
3.0	546	429	331	204	24.4	18.1	11.3
3.2	613	462	341	213	28.0	21.3	13.8
3.4	631	510	396	247	32.0	25.1	15.5
3.6	670	534	434	274	36.8	28.9	18.1
3.8	677	555	439	282	42.2	32.3	19.8
4.0	704	559	457	301	46.2	34.9	23.2
Error(%)	20	20	15	15	10	10	10
K_β / K_α					0.1385(19)	0.1412(13)	0.1480(20)

Table 2.

Experimental K X-ray production cross-sections and K_β/K_α intensity ratios obtained by proton bombardment.

E_d (MeV)	σ^K_{prod} (barn)				σ^K_{prod} (barn)		
	P	S	Cl	K	Ni	Cu	Ga
1.4	527	462	363	220	22.3	17.4	9.00
1.5	551	456	374	227	26.3	18.9	10.6
1.6	612	491	402	248	29.0	22.0	13.1
1.7	633	526	423	270	35.0	25.8	15.2
1.8	670	558	525	343	38.0	29.8	17.5
1.9	695	565	515	355	42.8	31.4	19.4
2.0	725	597	534	372	47.4	36.4	21.6
Error(%)	20	20	15	15	10	10	10
K_β/K_α					0.1396(19)	0.1408 (18)	0.1471(17)

63.049

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