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Electron Impact Ionization Cross Sections and Ionization Rate Coefficients for Atoms and Ions.

Wolfgang Lotz

IPP 1/47 April 1966

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IPP 1/47 W. Lotz Electron Impact Ionization Cross Sections and Ionization Rate Coefficients for Atoms and Ions.

Abstract: All available experimental data on cross sections for single ionization of atoms and ions from the ground state by electron impact in the low energy range ($\leq$ 1o keV) have been collected. For each species a best fit curve has been drawn. The experimental results can be approximated by the following formulae:

$$\sigma = \zeta_1 \frac{a \ln(E/\chi)}{\chi \cdot E} \quad [cm^2] , \qquad \text{if } \chi \leq E \leq \chi' ,$$

$$\sigma = \zeta_1 \frac{a \ln(E/\chi)}{\chi \cdot E} + \zeta_2 \frac{a \ln(E/\chi')}{\chi' \cdot E} = \zeta_3 \frac{a \ln(E/\bar{\chi})}{\bar{\chi} \cdot E} , \quad \text{if } E \geq \chi' ,$$

where χ is the ionization potential for electrons in the outermost shell in eV, χ' is the ionization potential for electrons in the next inner (sub)-shell, $\bar{\chi}$ is a weighted mean of χ and χ', E is the electron energy in eV, $a = 3.6 \times 10^{-14}$ for atoms, $a = 4.0 \times 10^{-14}$ for ions. $\zeta \geq 0.5$ is a slowly varying function and asymptotically equal to the number of equivalent electrons. By comparison of isoelectronic species as well as of equally charged species it is possible to make predictions for yet unknown cross sections. Ionization rate coefficients for all species in the triangle H I - Na I - Na XI are given with an estimated error of $^{+40}_{-30}$ %.

Introduction

For many problems in plasma physics knowledge of ionization cross sections or ionization rates is important, as has been demonstrated in recent years by Post 1961/121/, Goldman, Kilb 1964/122/, Hinnov 1964/123/, Kolb, McWhirter 1964/124/, House 1964/125/, and Seaton 1964/126/.

Until recently knowledge about these cross sections has been rather poor both experimentally and theoretically. There has been a theoretical calculation as early as 1912 by Thomson /127/, and in the course of time there have been many publications in this field, for example by Bethe 1930/72/, Seaton 1959/128/, Gryzinski 1959/129/, Trefftz 1963/130/, Burgess, Rudge 1963/131/, and Kolb, Griem et al. 1965/132/ But as far as comparison between theory and experiment is concerned, the agreement was more or less poor, or the comparison was impossible because there were no experiments.

It was not until 1965 that Rudge and Schwartz /133/ presented theoretical calculations which agreed excellently with measured values for the ionization cross section of He^+. In the meantime Rudge 1966/134/ calculated cross sections for hydrogen and a hydrogen-like ion with Z=128.

There have been several attempts to express the functional dependence of the cross section versus electron energy by an empirical formula, for example by Elwert 1952/135/, Knorr 1958/136/ and Drawin 1961/137/. With the exception of values near threshold the formula of Drawin gave astonishingly good results - as long as the two free parameters were chosen "correctly". Unfortunately the values near threshold are the most important in plasma physics.

Up to 1958 measurements of ionization cross sections were not too frequent and mostly relative. Since then more and more cross sections are known, so that it should be possible now to make reasonable estimates by inter- and extrapolation for cross sections not measured yet, at least for the light elements up to sodium. Therefore a program was started to collect all available data on ionization cross sections, curves of best fit were drawn, and the relevant data tabulated.

Recently Kieffer and Dunn 1966/120/published a survey on experimental ionization cross sections, which proved to be (of great help.) Our references /1/ to /119/ are identical with those given in /120/.

The experimental material

Figs. 1 to 38 are ordered by Z-number of the element irrespective of experimental or empirical origin of the cross section. The experimental curves are hand-drawn best fits to the data given by the respective authors and are derived as follows:

Atomic Hydrogen - H I:

The curve generally follows the data given by Boksenberg 1961/31/, near maximum the higher values of Fite, Brackmann 1958/24/ are slightly taken into account. From 400 to

75o eV the data of Fite, Brackmann 1958 and of Rothe, Marino, Neynaber, Trujillo 1962/29/ are followed, while for energies higher than 75o eV the experimental values are extrapolated by the indicated formula.

Helium - He I:

The curve follows the data given by Rapp, Englander-Golden 1965/7/ up to 3oo eV, the data of P.T. Smith 193o/3/ and Harrison 1956/62/ between 3oo eV and 1 keV, and the data of P.T. Smith 193o, Liska 1934/61/, and Schram, de Heer, van der Wiel, Kistemaker 1964/8/ above 1 keV.

He II:

The curve follows the data given by Dolder, Harrison, Thonemann 1961/25/ up to 1 keV and is extrapolated by the indicated formula.

Lithium - Li I:

The relative measurements of Brink 1962/117/ have been normalized using the absolute values given by McFarland, Kinney 1965/33/. Above 5oo eV, the curve has been extrapolated.

Li II:

The curve follows the data given by Lineberger, Hooper, McDaniel 1966/27/. Above 8oo eV the curve has been extrapolated by the formula indicated.

Atomic Nitrogen - N I:

The curve follows the data given by A.C.H. Smith, Caplinger, Neynaber, Rothe, Trujillo 1962/3o/ and has been extrapolated above 5oo eV by the formula indicated. The values given by Peterson 1963/26/ were rejected, as they are probably too large.

N II:

The curve follows the data given by Harrison, Dolder, Thonemann 1963/64/ and has been extrapolated above 5oo eV by the formula indicated.

Atomic Oxygen - O I:

The curve follows the data given by Fite, Brackmann 1959/28/ and Rothe, Marino, Neynaber, Trujillo 1962/29/ and has been extrapolated above 5oo eV by the formula indicated. The values of Boksenberg 1961/31/ were rejected, as they are probably too large.

Neon - Ne I:

The curve follows the mean value of the data given by Asundi, Kurepa 1963/5/, P.T. Smith 193o/3/, Rapp, Englander-Golden 1965/7/. Above 1 keV the data given by Schram, de Heer, van der Wiel, Kistemaker 1964/8/ are taken into account. The data are essentially total ionization cross sections; corrections for multiple ionization have not been applied.

Ne II:

The curve follows the data given by Dolder, Harrison, Thonemann, 1963/63/ and has been extrapolated above 1 keV by the formula indicated.

Sodium - Na I:

The relative measurements of Tate, P.T. Smith 1934/19/ and of Brink 1962/117/ have been normalized using the absolute values given by McFarland, Kinney 1965/33/. The absolute values of Brink 1964/32/ have been rejected as they are inconsistent with the relative measurements .

Na II:

The curve follows the data given by Hooper, Lineberger, Bacon 1966/27/.

Argon - A I:

The curve follows the mean value of the data given by P.T. Smith 1930/3/, Tozer, Craggs 1960/65/, Asundi, Kurepa 1963/5/, and Rapp, Englander-Golden 1965/7/. Above 1 keV the data given by Schram, de Heer, van der Wiel, Kistemaker 1964/8/ are taken into account. The data are total ionization cross sections and have been corrected for multiple ionization by the relative cross sections given by Bleakney 1930/70/ and by Schram, Boerboom, van der Wiel, de Heer 1964/71/.

Potassium - K I:

The same comments are valid as for Na I.

K II:

The same comments are valid as for Na II.

Krypton - Kr I:

The curve follows the mean value of the data given by Asundi, Kurepa 1963/5/, Tozer, Craggs 1960/65/, Rapp, Englander-Golden 1965/7/ and Schram, de Heer, van der Wiel, Kistemaker 1964/8/. These total ionization cross section data have been corrected for multiple ionization by the relative cross sections given by Tate, P.T. Smith 1934/19/ and Schram, Boerboom, van der Wiel, de Heer 1964/71/.

Rubidium - Rb I:

The relative measurements of Tate, P.T. Smith 1934/19/ have been normalized using the absolute values given by McFarland, Kinney 1965/33/.

Xenon - Xe I:

The same comments are valid as for Kr I.For correction the relative cross sections of Tate, P.T. Smith 1934/19/ have been used.

Cesium - Cs I:

The same comments are valid as for Rb I.

Mercury - Hg I:

The curve follows the data given by Harrison 1956/62/, which accidentally coincide with the mean value of the data given by Jones 1927/2/, P.T. Smith 1931/60/, Bleakney 1930/59/, Liska 1934/61/. For correction the relative cross sections of Bleakney 1930 and Harrison 1956 have been used.

Discussion

In Table I all species under consideration have been tabulated. In column 2 the electron configuration of the ground state is given. Columns 3 and 4 give the ionization potential χ for outer shell electrons and the ionization potential χ' for electrons of the next inner (sub)-shell, which were derived from Moore 1958/138/ or from calculations along isoelectronic sequences. The ionization potential $\bar{\chi}$ is a weighted mean of χ and χ' (see below!).

Columns 6 and 7 give the positions of the maximum cross sections in units of the ionization potential: $U(\chi) = E/\chi$, $U(\bar{\chi}) = E/\bar{\chi}$.

The shapes of the different cross section curves are very similar and resemble the function (ln U)/U, which was predicted by Bethe 193o/72/ for $U \gg 1$. Burgess, Rudge 1963/131/ and more precisely Rudge 1966/134/ predicted a functional dependence of the form (ln U)/U for hydrogen-like ions of high Z-number.

We tried therefore to approximate the experimental cross sections by the formula

$$\sigma = \zeta \frac{a \ln (E/\chi)}{\chi \cdot E} \quad (1)$$

where ζ should be the number of equivalent electrons in the outer shell. As for large U the electrons of the next inner (sub)-shell also contribute appreciably to the cross section, Equation (1) was extended in the following manner:

$$\sigma = \zeta_1 \frac{a \ln (E/\chi)}{\chi \cdot E} + \zeta_2 \frac{a \ln (E/\chi')}{\chi' \cdot E} = \zeta_3 \frac{a \ln (E/\bar{\chi})}{\bar{\chi} \cdot E} . \quad (2)$$

$\bar{\chi}$ is a weighted mean of χ and χ' and is derived as follows:

$$\ln \bar{\chi} = \frac{\zeta_1 \chi' \ln \chi + \zeta_2 \chi \ln \chi'}{\zeta_1 \chi' + \zeta_2 \chi} ,$$

while

$$\zeta_3 = \frac{\bar{\chi}}{\chi} \zeta_1 + \frac{\bar{\chi}}{\chi'} \zeta_2 \approx \zeta_1 + \zeta_2 .$$

By comparison with the experimental values, setting ζ_1 and ζ_2 equal to the number of equivalent electrons in the respective (sub)-shells, it turned out that "a" is a constant (within experimental error) in the range 5oo eV $\leq$ E $\leq$ 1o keV, but is slightly different for atoms and ions:

$a = 3.6 \times 10^{-14}$ for atoms,

$a = 4.0 \times 10^{-14}$ for ions,

if E and χ are measured in eV and σ in cm^2.

Theory for hydrogen-like ions predicts /131, 134/ that "a" will be approximately the same for multiply charged ions, namely $a \approx 4.0 \times 10^{-14}$ for multiply charged ions.

The function (1) has its maximum at $U_{max} = e = 2.72$. Experimental values for atoms and singly charged ions however generally lie between 2.7 and 8, thus Equations (1) or (2) are only asymptotically correct for these species. In other words: the product $\zeta \cdot a$ is a slowly varying function of the electron energy E. We chose to set "a" equal to the above values over the hole energy range, thus only ζ remains a slowly varying function of the electron energy E. We will name ζ the "effective" number of electrons in the outer shell(s).

Columns 8 to 13 of Table I give effective numbers ζ for the region near threshold, for the maximum, and for the high energy tail in comparison with the case that ζ_1 and ζ_2 were the number of equivalent electrons.

From Table I the following conclusions can be drawn:

1. Depending on the configuration, $U_{max} = U(\sigma_{max})$ is increasing in the following sequence: 3 s, 2 s, 1 s, 1 s^2, 2 p^2, 2 $p^3/p^4/p^5$, 2 p^6.

2. U_{max} is larger for atoms than for ions. U_{max} = 2.7 could be a lower limit for H through Na.

3. ζ is $\geqslant$ o.5 and is approaching the theoretical predictions for large U within experimental error (exception: Ne I?).

4. The ratio of ζ_{exp} to ζ_{theor} is the smaller the larger U_{max} is. Generally ζ_{exp} is larger for ions than for atoms, but it never exceeds the theoretical predictions (exception: Na I?).

With these experimental facts it was possible to predict the data that are given in brackets in Table I. U_{max} is chosen in such a way that there is an experimental curve that can be scaled up in order to facilitate drawing of the predicted cross section curves that are given in Figs. 6 through 3o. Cross sections of the three times and higher ionized species as for example Be IV are assumed to follow Equation (2) closely, so that corrections become unnecessary.

Table II gives the complete formulae for species in the triangle Be IV - Na IV - Na XI, which are self-explanatory.

Table III gives the ionization rate coefficients for ionization from the ground state by electron impact to the next higher ion. The rates have been derived using the cross sections given by Figs. 1 to 3o or by Table II. The error is estimated to be not higher than $^{+40\%}_{-30\%}$, while in some cases it is as low as 1o%.

While this paper was being prepared, data for the ionization of Na^+ (= Na II) became available. The then predicted values agreed with the experimental values within 5% up to the maximum, and within 1o% at larger electron energies; this close agreement might of course be accidental.

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Table I: Relevant data for the elements H through Na, and A I; K I + II; Kr I; Rb I; Cs I; Hg I. Brackets indicate predicted values. (* = second maximum!)

1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Configura-tion	Ionization-Potential			U_{max}		Effective Number ζ						exp. Error
							$U \approx 1{,}25$		$U = U_{max}$		$E \gg \chi'$		
		χ	χ'	$\bar{\chi}$	$U(\chi)$	$U(\bar{\chi})$	exp.	theor.	exp.	theor.	exp.	theor.	%
HI	1s	13,6	-	-	4.0	-	0.54	1	1.00	1	1.04	1	10
HeI	$1s^2$	24.6	-	-	4.9	-	0.78	2	1.94	2	2.0	2	10
LiI	2s	5.39	64,5	7.71	3.0	-	0.72	1	1.15	1	2.1	1.7	+40 -30
BeI	$2s^2$	9.32	-	-	(4.0)	-	(1.0)	2	(1.8)	2	(2.0)	2	-
BI	$2s^2p$	8.30	12.9	10.7	(5.9)	(4.6)	(0.6)	1	(2.3)	2.9	(2.9)	2.9	-
CI	$2s^2p^2$	11.3	16.6	13.2	(5.9)	(5.0)	(0.8)	2	(3.1)	3.9	(3.9)	3.9	-
NI	$2s^2p^3$	14.5	20.4	16.2	6,9	6.2	0.64	3	3.7	4.9	4.7	4.9	20
OI	$2s^2p^4$	13.6	28.5	15.8	5.9	5.1	0.92	4	3.3	5.8	4.9	5.8	20
FI	$2s^2p^5$	17.4	37.8	19.2	(6.9)	(6.3)	(0.7)	5	(4.3)	6.6	(5.5)	6.6	-
NeI	$2s^2p^6$	21.6	48.5	24.0	8.1	7.3	0.58	6	4.7	7.7	6.0	7.7	20
NaI	3s	5.14	38.0	12.7	2.7	-	1.0	1	1.5	1	4.5	4.5	+40 -30
AI	$3s^2p^6$	15.8	29.2	17.4	4.4	4.0	2.9	6	7.4	7.8	9.3	7.8	20
KI	$3s^2p^64s$	4.34	18.7	10.0	2.2	3.2*	1.1	1	5.8*	5.5	6.4	5.5	+40 -30
KrI	$4s^2p^6$	14.0	27.5	15.2	5.0	4.6	2.4	6	8.8	7.6	10.3	7.6	20
RbI	$4s^2p^65s$	4.18	15.3	9.6	2.4	2.3*	1.0	1	6.2*	6.0	6.7	6.0	+40 -30
XeI	$5s^2p^6$	12.1	23.4	13.3	3.5	3.2	3.1	6	8.0	7.7	9.2	7.7	20
CsI	$5s^2p^66s$	3.89	12.3	8.3	2.6	1.8*	0.52	1	5.1*	6.2	7.8	6.2	+40 -30
HgI	$5s^2p^6d^{10}6s^2$	10.4	14.8	13.8	5.3	4.0	1.80	2	8.4	11.6	12.4	11.6	20
HeII	1s	54.4	-	-	3.2	-	0.77	1	1.00	1	1.10	1	10
LiII	$1s^2$	75.6	-	-	3.7	-	1.22	2	1.82	2	1.91	2	10
BeII	2s	18.2	139	27.8	(2.7)	-	(1)	1	(1.0)	1	(1.9)	1.9	-
BII	$2s^2$	25.1	-	-	(3.2)	-	(1.5)	2	(1.85)	2	(2)	2	-
CII	$2s^2p$	24.4	30.9	28.2	(3.7)	(3.2)	(1)	1	(2.8)	3	(3)	3	-
NII	$2s^2p^2$	29.6	36.7	32.6	3.7	3.4	1.77	2	3.8	4	4.1	4	10
OII	$2s^2p^3$	35.1	42.6	37.6	(3.7)	(3.4)	(2)	3	(4.5)	5	(5)	5	-
FII	$2s^2p^4$	35.0	53.8	38.9	(3.7)	(3.3)	(2)	4	(4.6)	6	(5.5)	6	-
NeII	$2s^2p^5$	41.1	66.4	45.2	4.9	4.4	0.96	5	4.8	6.9	6.0	6.9	10
NaII	$2s^2p^6$	47.3	80.1	51.5	5.7	5.2	1.23	6	5.7	7.9	7.4	7.9	10
KII	$3s^2p^6$	31.8	48.0	34.1	3.2	2.9	6.2	6	6.9	7.9	7.5	7.9	10
LiIII	1s	122	-	-	(2.7)	-	(1)	1	(1)	1	(1)	1	-
BeIII	$1s^2$	154	-	-	(3.2)	-	(1.6)	2	(2)	2	(2)	2	-
BIII	2s	37.9	236	59.0	(2.7)	-	(1)	1	(1)	1	(2.05)	2.05	-
CIII	$2s^2$	47.9	-	-	(2.7)	-	(2)	2	(2)	2	(2)	2	-
NIII	$2s^2p$	47.4	55.7	52.5	(3.2)	(2.9)	(1)	1	(2.9)	3	(3)	3	-
OIII	$2s^2p^2$	54.9	63.8	58.9	(3.2)	(3.0)	(1.9)	2	(3.8)	4	(4)	4	-
FIII	$2s^2p^3$	62.9	71.9	66.0	(3.2)	(3.1)	(2.8)	3	(4.7)	5	(5)	5	-
NeIII	$2s^2p^4$	63.5	86.3	69.0	(3.5)	(3.2)	(3)	4	(5.5)	6	(6)	6	-
NaIII	$2s^2p^5$	71.6	102	77.3	(3.7)	(3.4)	(2)	5	(6)	7	(7)	7	-

<u>Table I:</u> continued.

1	2	3	4	5	6
	Configuration	Ionization Potential χ	χ'	$\bar{\chi}$	Effective Number ξ_3
BeIV	1s	218	-	-	1
BIV	$1s^2$	259	-	-	2
CIV	2s	64.5	363	101	2.14
NIV	$2s^2$	77.4	-	-	2
OIV	$2s^2p$	77.4	87.6	83.6	3
FIV	$2s^2p^2$	87.1	97.8	91.9	4
NeIV	$2s^2p^3$	97.0	108	101	5
NaIV	$2s^2p^4$	98.9	126	107	6
BV	1s	340	-	-	1
CV	$1s^2$	392	-	-	2
NV	2s	97.9	517	155	2.18
OV	$2s^2$	114	-	-	2
FV	$2s^2p$	114	126	122	3
NeV	$2s^2p^2$	126	139	130	4
NaV	$2s^2p^3$	138	150	142	5
CVI	1s	490	-	-	1
NVI	$1s^2$	552	-	-	2
OVI	2s	138	699	218	2.20
FVI	$2s^2$	157	-	-	2
NeVI	$2s^2p$	158	172	167	3
NaVI	$2s^2p^2$	172	187	179	4
NVII	1s	667	-	-	1
OVII	$1s^2$	739	-	-	2
FVII	2s	185	908	293	2.22
NeVII	$2s^2$	207	-	-	2
NaVII	$2s^2p$	208	224	218	3
OVIII	1s	871	-	-	1
FVIII	$1s^2$	954	-	-	2
NeVIII	2s	239	1142	379	2.24
NaVIII	$2s^2$	264	-	-	2
FIX	1s	1103	-	-	1
NeIX	$1s^2$	1195	-	-	2
NaIX	2s	300	1406	477	2.26
NeX	1s	1362	-	-	1
NaX	$1s^2$	1465	-	-	2
NaXI	1s	1648	-	-	1

Table II: Empirical formulae for the functional dependence of the electron impact ionization cross sections for single ionization from the ground state. σ in cm^2, E in eV.

Specie	Energy Range	Cross Section
Be IV		$\sigma = 1.84 \times 10^{-16} \ln(E/218)/E$
B IV		$\sigma = 3.09 \times 10^{-16} \ln(E/259)/E$
B V		$\sigma = 1.18 \times 10^{-16} \ln(E/340)/E$
C IV	$64,5 \leq E \leq 363$	$\sigma = 6.20 \times 10^{-16} \ln(E/64.5)/E$
	$E > 363$	$\sigma = 8.40 \times 10^{-16} \ln(E/101)/E$
C V		$\sigma = 2.04 \times 10^{-16} \ln(E/392)/E$
C VI		$\sigma = 8.17 \times 10^{-17} \ln(E/490)/E$
N IV		$\sigma = 1.03 \times 10^{-15} \ln(E/77.4)/E$
N V	$97.9 \leq E \leq 517$	$\sigma = 4.08 \times 10^{-16} \ln(E/97.9)/E$
	$E > 517$	$\sigma = 5.63 \times 10^{-16} \ln(E/155)/E$
N VI		$\sigma = 1.45 \times 10^{-16} \ln(E/552)/E$
N VII		$\sigma = 6.00 \times 10^{-17} \ln(E/667)/E$
O IV	$77.4 \leq E \leq 87.6$	$\sigma = 5.17 \times 10^{-16} \ln(E/77.4)/E$
	$E > 87.6$	$\sigma = 1.43 \times 10^{-15} \ln(E/83.6)/E$
O V		$\sigma = 7.02 \times 10^{-16} \ln(E/114)/E$
O VI	$138 \leq E \leq 699$	$\sigma = 2.90 \times 10^{-16} \ln(E/138)/E$
	$E > 699$	$\sigma = 4.04 \times 10^{-16} \ln(E/218)/E$
O VII		$\sigma = 1.08 \times 10^{-16} \ln(E/739)/E$
O VIII		$\sigma = 4.59 \times 10^{-17} \ln(E/871)/E$
F IV	$87.1 \leq E \leq 97.8$	$\sigma = 9.18 \times 10^{-16} \ln(E/87.1)/E$
	$E > 97.8$	$\sigma = 1.74 \times 10^{-15} \ln(E/92.0)/E$
F V	$114 \leq E \leq 126$	$\sigma = 3.51 \times 10^{-16} \ln(E/114)/E$
	$E > 126$	$\sigma = 9.86 \times 10^{-16} \ln(E/122)/E$
F VI		$\sigma = 5.10 \times 10^{-16} \ln(E/157)/E$

Table II: continued.

Specie	Energy Range	Cross Section
F VII	$185 \leq E \leq 908$	$\sigma = 2.16 \times 10^{-16} \ln (E/185)/E$
	$E > 908$	$\sigma = 3.04 \times 10^{-16} \ln (E/293)/E$
F VIII		$\sigma = 8.38 \times 10^{-17} \ln (E/954)/E$
F IX		$\sigma = 3.63 \times 10^{-17} \ln (E/1103)/E$
Ne IV	$97.0 \leq E \leq 108$	$\sigma = 1.24 \times 10^{-15} \ln (E/97.0)/E$
	$E > 108$	$\sigma = 1.98 \times 10^{-15} \ln (E/101)/E$
Ne V	$126 \leq E \leq 139$	$\sigma = 6.35 \times 10^{-16} \ln (E/126)/E$
	$E > 139$	$\sigma = 1.21 \times 10^{-15} \ln (E/130)/E$
Ne VI	$158 \leq E \leq 172$	$\sigma = 2.53 \times 10^{-16} \ln (E/158)/E$
	$E > 172$	$\sigma = 7.18 \times 10^{-16} \ln (E/167)/E$
Ne VII		$\sigma = 3.87 \times 10^{-16} \ln (E/207)/E$
Ne VIII	$239 \leq E \leq 1142$	$\sigma = 1.67 \times 10^{-16} \ln (E/239)/E$
	$E > 1142$	$\sigma = 2.37 \times 10^{-16} \ln (E/379)/E$
Ne IX		$\sigma = 6.69 \times 10^{-17} \ln (E/1195)/E$
Ne X		$\sigma = 2.94 \times 10^{-17} \ln (E/1362)/E$
Na IV	$98.9 \leq E \leq 126$	$\sigma = 1.62 \times 10^{-15} \ln (E/98.9)/E$
	$E > 126$	$\sigma = 2.25 \times 10^{-15} \ln (E/107)/E$
Na V	$138 \leq E \leq 150$	$\sigma = 8.63 \times 10^{-16} \ln (E/138)/E$
	$E > 150$	$\sigma = 1.39 \times 10^{-15} \ln (E/142)/E$
Na VI	$172 \leq E \leq 187$	$\sigma = 4.65 \times 10^{-16} \ln (E/172)/E$
	$E > 187$	$\sigma = 8.93 \times 10^{-16} \ln (E/179)/E$
Na VII	$208 \leq E \leq 224$	$\sigma = 1.92 \times 10^{-16} \ln (E/208)/E$
	$E > 224$	$\sigma = 5.49 \times 10^{-16} \ln (E/218)/E$
Na VIII		$\sigma = 3.03 \times 10^{-16} \ln (E/264)/E$
Na IX	$300 \leq E \leq 1406$	$\sigma = 1.33 \times 10^{-16} \ln (E/300)/E$
	$E > 1406$	$\sigma = 1.90 \times 10^{-16} \ln (E/477)/E$
Na X		$\sigma = 5.46 \times 10^{-17} \ln (E/1465)/E$
Na XI		$\sigma = 2.43 \times 10^{-17} \ln (E/1648)/E$

Table III: Ionization rate coefficients for single ionization from the ground state by electron impact (Maxwellian distribution).
E-08 = 10^{-8} etc., T_e in eV, S = $\langle \sigma v \rangle$ in cm^3/s; error $^{+40}_{-30}$ % unless stated otherwise.

Hydrogen, Helium, Lithium, Beryllium, Boron.

T_e	H I, 10%	He I, 10%	He II, 10%	Li I	Li II, 10%	Li III
1.0	7.80E-15	5.13E-20	0.	2.52E-10	0.	0.
1.4	4.49E-13	6.65E-17	9.59E-27	1.42E-09	0.	0.
2.0	9.92E-12	1.56E-14	1.32E-21	5.43E-09	3.24E-26	8.04E-37
2.8	8.24E-11	6.34E-13	3.73E-18	1.38E-08	1.77E-21	3.51E-29
4.0	4.25E-10	1.10E-11	1.52E-15	2.83E-08	6.70E-18	1.97E-23
5.0	9.41E-10	4.31E-11	2.58E-14	3.98E-08	3.23E-16	9.77E-21
7.0	2.42E-09	2.17E-10	6.79E-13	5.90E-08	2.83E-14	1.21E-17
10	5.13E-09	7.77E-10	8.24E-12	7.90E-08	8.52E-13	2.65E-15
14	8.74E-09	1.92E-09	4.53E-11	9.51E-08	8.65E-12	9.98E-14
20	1.34E-08	3.95E-09	1.69E-10	1.08E-07	5.15E-11	1.57E-12
28	1.81E-08	6.65E-09	4.21E-10	1.16E-07	1.76E-10	1.02E-11
40	2.28E-08	1.01E-08	8.57E-10	1.21E-07	4.62E-10	4.24E-11
50	2.54E-08	1.24E-08	1.21E-09	1.23E-07	7.37E-10	8.35E-11
70	2.86E-08	1.59E-08	1.81E-09	1.23E-07	1.28E-09	1.84E-10
100	3.07E-08	1.93E-08	2.46E-09	1.22E-07	1.98E-09	3.36E-10
140	3.14E-08	2.17E-08	3.02E-09	1.19E-07	2.66E-09	5.06E-10
200	3.10E-08	2.35E-08	3.51E-09	1.15E-07	3.33E-09	6.89E-10
280	2.98E-08	2.43E-08	3.85E-09	1.10E-07	3.83E-09	8.45E-10
400	2.80E-08	2.44E-08	4.06E-09	1.05E-07	4.20E-09	9.78E-10
500	2.67E-08	2.40E-08	4.12E-09	1.01E-07	4.34E-09	1.04E-09
700	2.47E-08	2.31E-08	4.12E-09	9.52E-08	4.43E-09	1.11E-09
1000	2.28E-08	2.18E-08	4.02E-09	8.86E-08	4.41E-09	1.14E-09

T_e	Be I	Be II	Be III	Be IV
1.0	2.56E-12	8.98E-17	0.	0.
1.4	4.19E-11	1.90E-14	0.	0.
2.0	3.58E-10	1.10E-12	0.	0.
2.8	1.57E-09	1.72E-11	4.81E-34	0.
4.0	4.99E-09	1.41E-10	8.36E-27	2.36E-34
5.0	8.78E-09	3.81E-10	2.05E-23	1.43E-29
7.0	1.73E-08	1.21E-09	1.59E-19	4.30E-24
10	2.98E-08	2.94E-09	1.38E-16	5.80E-20
14	4.40E-08	5.37E-09	1.30E-14	3.42E-17
20	5.98E-08	8.48E-09	4.08E-13	4.27E-15
28	7.40E-08	1.15E-08	4.20E-12	1.11E-13
40	8.65E-08	1.45E-08	2.49E-11	1.32E-12
50	9.24E-08	1.61E-08	5.78E-11	4.24E-12
70	9.82E-08	1.81E-08	1.54E-10	1.65E-11
100	1.00E-07	1.96E-08	3.27E-10	4.68E-11
140	9.91E-08	2.05E-08	5.45E-10	9.51E-11
200	9.54E-08	2.09E-08	8.04E-10	1.64E-10
280	9.03E-08	2.08E-08	1.04E-09	2.36E-10
400	8.42E-08	2.04E-08	1.26E-09	3.11E-10
500	8.02E-08	1.99E-08	1.37E-09	3.54E-10
700	7.42E-08	1.92E-08	1.50E-09	4.07E-10
1000	6.80E-08	1.82E-08	1.58E-09	4.46E-10

T_e	B I	B II	B III	B IV	B V
1.0	4.79E-12	8.78E-20	6.29E-26	0.	0.
1.4	5.94E-11	1.21E-16	3.72E-21	0.	0.
2.0	4.17E-10	2.92E-14	1.47E-17	0.	0.
2.8	1.62E-09	1.19E-12	3.85E-15	0.	0.
4.0	4.75E-09	2.02E-11	2.60E-13	1.19E-38	0.
5.0	8.12E-09	7.80E-11	1.90E-12	5.57E-33	0.
7.0	1.56E-08	3.79E-10	1.89E-11	1.75E-26	4.82E-32
10	2.69E-08	1.29E-09	1.09E-10	1.37E-21	1.22E-25
14	4.01E-08	3.02E-09	3.58E-10	2.62E-18	2.36E-21
20	5.57E-08	5.84E-09	8.92E-10	7.89E-16	4.05E-18
28	7.07E-08	9.21E-09	1.66E-09	3.68E-14	6.05E-16
40	8.55E-08	1.31E-08	2.67E-09	6.82E-13	2.68E-14
50	9.36E-08	1.54E-08	3.35E-09	2.71E-12	1.61E-13
70	1.04E-07	1.86E-08	4.34E-09	1.34E-11	1.27E-12
100.	1.11E-07	2.13E-08	5.27E-09	4.56E-11	6.20E-12
140.	1.14E-07	2.30E-08	6.30E-09	1.05E-10	1.82E-11
200.	1.14E-07	2.40E-08	6.57E-09	1.99E-10	4.15E-11
280.	1.11E-07	2.42E-08	6.93E-09	3.07E-10	7.27E-11
400.	1.06E-07	2.37E-08	7.12E-09	4.26E-10	1.12E-10
500.	1.02E-07	2.32E-08	7.15E-09	4.97E-10	1.36E-10
700.	9.51E-08	2.21E-08	7.07E-09	5.89E-10	1.71E-10
1000.	8.81E-08	2.09E-08	6.87E-09	6.63E-10	2.02E-10

<u>Table III:</u> continued.
Carbon, Nitrogen,

T_e	C I	C II	C III	C IV	
1.0	1.93E-13	1.19E-19	3.59E-30	6.15E-38	
1.4	5.50E-12	1.39E-16	3.70E-24	7.29E-30	
2.0	7.37E-11	2.99E-14	1.26E-19	8.69E-24	
2.8	4.47E-10	1.16E-12	1.37E-16	1.02E-19	
4.0	1.85E-09	1.93E-11	2.72E-14	1.20E-16	
5.0	3.70E-09	7.46E-11	3.28E-13	3.34E-15	
7.0	8.57E-09	3.64E-10	5.81E-12	1.54E-13	
10	1.70E-08	1.26E-09	5.18E-11	2.82E-12	
14	2.79E-08	3.00E-09	2.29E-10	2.02E-11	
20	4.21E-08	6.02E-09	7.14E-10	9.09E-11	
28	5.70E-08	9.86E-09	1.55E-09	2.53E-10	
40	7.29E-08	1.46E-08	2.80E-09	5.55E-10	
50	8.23E-08	1.76E-08	3.71E-09	8.06E-10	
70	9.50E-08	2.19E-08	5.13E-09	1.24E-09	
100	1.05E-07	2.57E-08	6.53E-09	1.73E-09	
140	1.12E-07	2.82E-08	7.63E-09	2.16E-09	
200	1.14E-07	2.98E-08	8.50E-09	2.56E-09	
280	1.13E-07	3.02E-08	9.01E-09	2.86E-09	
400	1.09E-07	2.99E-08	9.26E-09	3.09E-09	
500	1.05E-07	2.94E-08	9.28E-09	3.19E-09	
700	9.85E-08	2.83E-08	9.15E-09	3.27E-09	
1000	9.09E-08	2.70E-08	8.84E-09	3.27E-09	

T_e	N I, 20%	N II, 10%	N III	N IV	N V
1.0	3.46E-15	6.60E-22	3.02E-30	0.	0.
1.4	2.55E-13	3.59E-18	2.71E-24	1.01E-33	0.
2.0	6.86E-12	2.44E-15	8.42E-20	1.92E-26	2.13E-31
2.8	6.62E-11	2.00E-13	9.00E-17	1.42E-21	2.96E-25
4.0	3.92E-10	5.81E-12	1.86E-14	6.71E-18	1.26E-20
5.0	9.41E-10	2.88E-11	2.37E-13	3.56E-16	1.86E-18
7.0	2.73E-09	1.87E-10	4.61E-12	3.43E-14	5.83E-16
10	6.59E-09	8.03E-10	4.57E-11	1.10E-12	4.51E-14
14	1.27E-08	2.22E-09	2.20E-10	1.14E-11	8.49E-13
20	2.22E-08	4.97E-09	7.41E-10	6.83E-11	7.92E-12
28	3.36E-08	8.78E-09	1.70E-09	2.30E-10	3.61E-11
40	4.73E-08	1.38E-08	3.23E-09	5.84E-10	1.15E-10
50	5.60E-08	1.71E-08	4.37E-09	9.09E-10	2.00E-10
70	6.83E-08	2.20E-08	6.22E-09	1.52E-09	3.80E-10
100	7.90E-08	2.66E-08	8.09E-09	2.25E-09	6.21E-10
140	8.60E-08	2.98E-08	9.61E-09	2.92E-09	8.67E-10
200	8.99E-08	3.20E-08	1.08E-08	3.54E-09	1.12E-09
280	9.03E-08	3.30E-08	1.16E-08	3.99E-09	1.33E-09
400	8.81E-08	3.28E-08	1.20E-08	4.31E-09	1.52E-09
500	8.56E-08	3.23E-08	1.21E-08	4.44E-09	1.61E-09
700	8.10E-08	3.11E-08	1.20E-08	4.52E-09	1.71E-09
1000	7.53E-08	2.95E-08	1.17E-08	4.49E-09	1.77E-09

T_e	C V	C VI	N VI	N VII	
10	1.01E-27	1.81E-32	5.79E-35	0.	
14	8.69E-23	2.55E-26	4.81E-28	4.48E-32	
20	4.56E-19	1.10E-21	7.81E-23	8.56E-26	
28	1.43E-16	1.40E-18	2.43E-19	1.38E-21	
40	1.11E-14	3.13E-16	1.05E-16	2.06E-18	
50	8.67E-14	3.99E-15	1.83E-15	6.38E-17	
70	9.29E-13	7.52E-14	4.95E-14	3.33E-15	
100	5.67E-12	7.04E-13	6.06E-13	6.71E-14	
140	1.94E-11	3.21E-12	3.31E-12	5.13E-13	
200	4.98E-11	1.03E-11	1.21E-11	2.42E-12	
280	9.46E-11	2.26E-11	2.94E-11	6.97E-12	
400	1.55E-10	4.15E-11	5.79E-11	1.57E-11	
500	1.95E-10	5.53E-11	7.99E-11	2.30E-11	
700	2.54E-10	7.70E-11	1.16E-10	3.59E-11	
1000	3.08E-10	9.86E-11	1.53E-10	5.04E-11	
1400	3.49E-10	1.16E-10	1.84E-10	6.31E-11	
2000	3.77E-10	1.29E-10	2.09E-10	7.42E-11	
2800	3.92E-10	1.37E-10	2.26E-10	8.19E-11	
4000	3.97E-10	1.41E-10	2.35E-10	8.70E-11	
5000	3.94E-10	1.42E-10	2.37E-10	8.87E-11	
7000	3.84E-10	1.40E-10	2.36E-10	8.93E-11	
10000	3.68E-10	1.36E-10	2.37E-10	8.79E-11	

Table III: continued.

Oxygen, Fluorine.

T_e	O I, 20%	O II	O III	O IV	O V	O VI
1.0	1.33E-14	2.50E-24	0.	0.	0.	0.
1.4	7.67E-13	6.17E-20	3.29E-26	5.37E-34	0.	0.
2.0	1.72E-11	1.32E-16	3.99E-21	9.68E-27	1.00E-34	0.
2.8	1.46E-10	2.35E-14	1.04E-17	7.41E-22	1.40E-27	9.06E-32
4.0	7.70E-10	1.23E-12	4.13E-15	3.76E-18	3.33E-22	2.83E-25
5.0	1.73E-09	8.06E-12	7.04E-14	2.14E-16	1.11E-19	3.12E-22
7.0	4.57E-09	7.27E-11	1.91E-12	2.35E-14	8.69E-17	9.70E-19
10	1.00E-08	4.01E-10	2.40E-11	8.62E-13	1.35E-14	4.22E-16
14	1.77E-08	1.32E-09	1.37E-10	1.01E-11	4.02E-13	2.51E-14
20	2.82E-08	3.36E-09	5.26E-10	6.68E-11	5.33E-12	5.59E-13
28	3.98E-08	6.49E-09	1.33E-09	2.43E-10	3.07E-11	4.57E-12
40	5.28E-08	1.09E-08	2.75E-09	6.55E-10	1.17E-10	2.27E-11
50	6.08E-08	1.41E-08	3.89E-09	1.05E-09	2.21E-10	4.86E-11
70	7.20E-08	1.89E-08	5.83E-09	1.82E-09	4.63E-10	1.18E-10
100	8.20E-08	2.37E-08	7.95E-09	2.78E-09	8.17E-10	2.32E-10
140	8.89E-08	2.75E-08	9.79E-09	3.68E-09	1.20E-09	3.68E-10
200	9.32E-08	3.03E-08	1.14E-08	4.54E-09	1.60E-09	5.25E-10
280	9.44E-08	3.19E-08	1.25E-08	5.18E-09	1.93E-09	6.69E-10
400	9.30E-08	3.25E-08	1.32E-08	5.66E-09	2.21E-09	8.05E-10
500	9.09E-08	3.24E-08	1.34E-08	5.85E-09	2.34E-09	8.78E-10
700	8.67E-08	3.17E-08	1.34E-08	6.00E-09	2.47E-09	9.66E-10
1000	8.12E-08	3.03E-08	1.32E-08	5.99E-09	2.53E-09	1.03E-09

T_e	F I	F II	F III	F IV	F V	F VI
1.0	1.59E-16	2.95E-24	0.	0.	0.	0.
1.4	2.55E-14	7.02E-20	9.18E-29	7.28E-37	0.	0.
2.0	1.24E-12	1.45E-16	6.92E-23	1.13E-28	5.04E-35	0.
2.8	1.78E-11	2.50E-14	6.16E-19	3.46E-23	7.14E-28	1.59E-34
4.0	1.42E-10	1.27E-12	5.99E-16	4.84E-19	1.80E-22	3.80E-27
5.0	3.93E-10	8.23E-12	1.53E-14	4.34E-17	6.35E-20	1.08E-23
7.0	1.35E-09	7.35E-11	6.46E-13	7.89E-15	5.63E-17	9.99E-20
10	3.69E-09	4.05E-10	1.12E-11	4.18E-13	1.01E-14	9.82E-17
14	7.80E-09	1.34E-09	7.89E-11	6.23E-12	3.42E-13	1.01E-14
20	1.47E-08	3.43E-09	3.55E-10	4.94E-11	5.08E-12	3.39E-13
28	2.36E-08	6.67E-09	10.00E-10	2.03E-10	3.19E-11	3.64E-12
40	3.50E-08	1.13E-08	2.24E-09	6.00E-10	1.31E-10	2.23E-11
50	4.27E-08	1.46E-08	3.31E-09	1.01E-09	2.56E-10	5.26E-11
70	5.42E-08	1.96E-08	5.24E-09	1.84E-09	5.60E-10	1.43E-10
100	6.52E-08	2.46E-08	7.45E-09	2.91E-09	1.02E-09	3.07E-10
140	7.31E-08	2.85E-08	9.46E-09	3.97E-09	1.53E-09	5.16E-10
200	7.84E-08	3.13E-08	1.13E-08	5.00E-09	2.08E-09	7.68E-10
280	8.03E-08	3.28E-08	1.26E-08	5.80E-09	2.55E-09	1.00E-09
400	7.95E-08	3.32E-08	1.35E-08	6.42E-09	2.95E-09	1.22E-09
500	7.79E-08	3.29E-08	1.39E-08	6.68E-09	3.14E-09	1.33E-09
700	7.44E-08	3.20E-08	1.40E-08	6.91E-09	3.33E-09	1.45E-09
1000	7.01E-08	3.06E-08	1.39E-08	6.95E-09	3.43E-09	1.53E-09

T_e	O VII	O VIII	F VII	F VIII	F IX
10	0.	0.	2.17E-18	0.	0.
14	4.27E-34	1.24E-38	4.97E-16	0.	0.
20	3.82E-27	1.88E-30	3.35E-14	4.95E-32	1.14E-35
28	1.72E-22	5.59E-25	4.91E-13	4.82E-26	9.17E-29
40	5.57E-19	7.45E-21	4.08E-12	1.56E-21	1.46E-23
50	2.48E-17	6.42E-19	1.11E-11	2.04E-19	3.99E-21
70	1.96E-15	1.08E-16	3.56E-11	5.54E-17	2.53E-18
100	5.38E-14	5.25E-15	8.73E-11	3.85E-15	3.32E-16
140	5.06E-13	7.24E-14	1.69E-10	6.74E-14	8.90E-15
200	2.80E-12	5.34E-13	2.55E-10	5.96E-13	1.09E-13
280	8.96E-12	2.08E-12	3.51E-10	2.62E-12	5.92E-13
400	2.19E-11	5.88E-12	4.49E-10	8.12E-12	2.16E-12
500	3.34E-11	9.64E-12	5.04E-10	1.39E-11	4.01E-12
700	5.46E-11	1.71E-11	5.76E-10	2.60E-11	8.21E-12
1000	7.94E-11	2.65E-11	6.35E-10	4.20E-11	1.42E-11
1400	1.02E-10	3.56E-11	6.72E-10	5.79E-11	2.06E-11
2000	1.22E-10	4.43E-11	6.93E-10	7.37E-11	2.72E-11
2800	1.37E-10	5.09E-11	6.96E-10	8.60E-11	3.27E-11
4000	1.47E-10	5.59E-11	6.84E-10	9.57E-11	3.71E-11
5000	1.51E-10	5.80E-11	6.71E-10	9.99E-11	3.92E-11
7000	1.53E-10	5.96E-11	6.44E-10	1.04E-10	4.12E-11
10000	1.52E-10	5.97E-11	6.[illegible]8E-10	1.[illegible]4E-10	4.2[illegible]E-11

Table III: continued.
Neon, Sodium.

T_e	Ne I, 20%	Ne II, 10%	Ne III	Ne IV	Ne V	Ne VI	Ne VII
1.0	1.15E-18	3.25E-27	0.	0.	0.	0.	0.
1.4	6.32E-16	3.87E-22	5.97E-29	0.	0.	0.	0.
2.0	7.78E-14	2.66E-18	5.08E-23	9.21E-31	2.04E-37	0.	0.
2.8	2.07E-12	1.04E-15	4.83E-19	1.17E-24	1.59E-29	5.54E-35	0.
4.0	2.64E-11	1.01E-13	4.91E-16	4.73E-20	1.41E-23	1.54E-27	8.20E-33
5.0	9.05E-11	8.99E-13	1.28E-14	6.93E-18	8.74E-21	4.83E-24	2.85E-28
7.0	3.97E-10	1.18E-11	5.51E-13	2.19E-15	1.45E-17	5.26E-20	4.59E-23
10	1.32E-09	9.01E-11	9.84E-12	1.74E-13	4.09E-15	6.22E-17	3.86E-19
14	3.21E-09	3.81E-10	7.10E-11	3.40E-12	1.87E-13	7.54E-15	1.66E-16
20	6.79E-09	1.22E-09	3.29E-10	3.29E-11	3.47E-12	2.93E-13	1.64E-14
28	1.20E-08	2.81E-09	9.56E-10	1.54E-10	2.53E-11	3.53E-12	3.62E-13
40	1.94E-08	5.51E-09	2.20E-09	5.06E-10	1.16E-10	2.37E-11	3.82E-12
50	2.49E-08	7.69E-09	3.31E-09	8.91E-10	2.39E-10	5.84E-11	1.16E-11
70	3.39E-08	1.15E-08	5.35E-09	1.72E-09	5.57E-10	1.67E-10	4.25E-11
100	4.34E-08	1.57E-08	7.77E-09	2.85E-09	1.06E-09	3.75E-10	1.15E-10
140	5.13E-08	1.95E-08	1.00E-08	4.00E-09	1.65E-09	6.51E-10	2.25E-10
200	5.78E-08	2.29E-08	1.21E-08	5.16E-09	2.31E-09	9.91E-10	3.77E-10
280	6.18E-08	2.54E-08	1.37E-08	6.09E-09	2.88E-09	1.31E-09	5.35E-10
400	6.35E-08	2.71E-08	1.48E-08	6.83E-09	3.38E-09	1.62E-09	6.95E-10
500	6.35E-08	2.78E-08	1.53E-08	7.16E-09	3.62E-09	1.78E-09	7.84E-10
700	6.22E-08	2.81E-08	1.56E-08	7.46E-09	3.88E-09	1.96E-09	8.93E-10
1000	5.93E-08	2.77E-08	1.56E-08	7.56E-09	4.03E-09	2.08E-09	9.75E-10

T_e	Na I	Na II, 10%	Na III	Na IV	Na V	Na VI	Na VII
1.0	4.82E-10	5.75E-30	0.	0.	0.	0.	0.
1.4	2.52E-09	4.47E-24	0.	0.	0.	0.	0.
2.0	9.07E-09	1.24E-19	4.31E-25	5.06E-31	0.	0.	0.
2.8	2.19E-08	1.19E-16	1.25E-20	8.13E-25	1.89E-31	6.26E-37	0.
4.0	4.31E-08	2.19E-14	3.02E-17	3.84E-20	6.71E-25	7.61E-29	3.26E-33
5.0	5.95E-08	2.58E-13	1.19E-15	5.99E-18	7.95E-22	4.70E-25	1.24E-28
7.0	8.59E-08	4.61E-12	8.42E-14	1.99E-15	2.74E-18	1.08E-20	2.32E-23
10	1.13E-07	4.33E-11	2.26E-12	1.63E-13	1.32E-15	2.18E-17	2.33E-19
14	1.34E-07	2.09E-10	2.23E-11	3.24E-12	8.59E-14	3.74E-15	1.19E-16
20	1.52E-07	7.35E-10	1.36E-10	3.20E-11	2.07E-12	1.88E-13	1.37E-14
28	1.63E-07	1.82E-09	4.85E-10	1.53E-10	1.79E-11	2.69E-12	3.43E-13
40	1.69E-07	3.84E-09	1.32E-09	5.13E-10	9.33E-11	2.05E-11	4.00E-12
50	1.71E-07	5.58E-09	2.16E-09	9.15E-10	2.05E-10	5.39E-11	1.28E-11
70	1.71E-07	8.82E-09	3.84E-09	1.80E-09	5.10E-10	1.66E-10	4.96E-11
100	1.69E-07	1.28E-08	6.03E-09	3.02E-09	1.03E-09	3.93E-10	1.40E-10
140	1.63E-07	1.66E-08	8.22E-09	4.30E-09	1.66E-09	7.07E-10	2.85E-10
200	1.56E-07	2.04E-08	1.04E-08	5.61E-09	2.38E-09	1.11E-09	4.90E-10
280	1.47E-07	2.34E-08	1.21E-08	6.67E-09	3.03E-09	1.50E-09	7.07E-10
400	1.37E-07	2.57E-08	1.35E-08	7.53E-09	3.61E-09	1.87E-09	9.32E-10
500	1.31E-07	2.67E-08	1.41E-08	7.92E-09	3.91E-09	2.07E-09	1.06E-09
700	1.20E-07	2.76E-08	1.47E-08	8.29E-09	4.23E-09	2.31E-09	1.22E-09
1000	1.10E-07	2.76E-08	1.49E-08	8.43E-09	4.42E-09	2.48E-09	1.34E-09

T_e	Ne VIII	Ne IX	Ne X	Na VIII	Na IX	Na X	Na XI
10	5.93E-21	0.	0.	8.00E-22	8.50E-24	0.	0.
14	6.39E-18	0.	0.	1.76E-18	5.25E-20	0.	0.
20	1.25E-15	1.85E-37	0.	5.92E-16	3.82E-17	0.	0.
28	4.39E-14	5.64E-30	5.59E-33	2.97E-14	3.21E-15	2.45E-34	1.40E-37
40	6.55E-13	2.43E-24	1.44E-26	5.81E-13	9.26E-14	1.90E-27	7.77E-30
50	2.35E-12	1.06E-21	1.45E-23	2.37E-12	4.53E-13	3.21E-24	3.27E-26
70	1.04E-11	1.14E-18	4.07E-20	1.21E-11	2.85E-12	1.62E-20	4.71E-22
100	3.22E-11	2.24E-16	1.64E-17	4.19E-11	1.16E-11	1.01E-17	6.47E-19
140	6.98E-11	7.85E-15	9.27E-16	9.80E-11	3.02E-11	7.72E-16	8.32E-17
200	1.26E-10	1.17E-13	1.98E-14	1.88E-10	6.30E-11	2.36E-14	3.30E-15
280	1.89E-10	7.31E-13	1.58E-13	2.92E-10	1.04E-10	1.91E-13	3.98E-14
400	2.59E-10	2.96E-12	7.69E-13	4.38E-10	1.53E-10	1.04E-12	2.65E-13
500	3.00E-10	5.76E-12	1.63E-12	4.77E-10	1.84E-10	2.33E-12	6.51E-13
700	3.57E-10	1.25E-11	3.91E-12	5.67E-10	2.28E-10	5.93E-12	1.85E-12
1000	4.07E-10	2.26E-11	7.63E-12	6.41E-10	2.69E-10	1.21E-11	4.12E-12
1400	4.42E-10	3.37E-11	1.20E-11	6.87E-10	3.00E-10	1.98E-11	7.11E-12
2000	4.66E-10	4.56E-11	1.70E-11	7.13E-10	3.23E-10	2.87E-11	1.38E-11
2800	4.76E-10	5.57E-11	2.14E-11	7.17E-10	3.36E-10	3.67E-11	1.42E-11
4000	4.76E-10	6.42E-11	2.52E-11	7.05E-10	3.41E-10	4.39E-11	1.75E-11
5000	4.70E-10	6.82E-11	2.71E-11	6.91E-10	3.40E-10	4.76E-11	1.92E-11
7000	4.56E-10	7.23E-11	2.92E-11	6.62E-10	3.34E-10	5.17E-11	2.11E-11
10000	4.35E-10	7.43E-11	3.03E-11	6.24E-10	3.21E-10	5.41E-11	2.24E-11

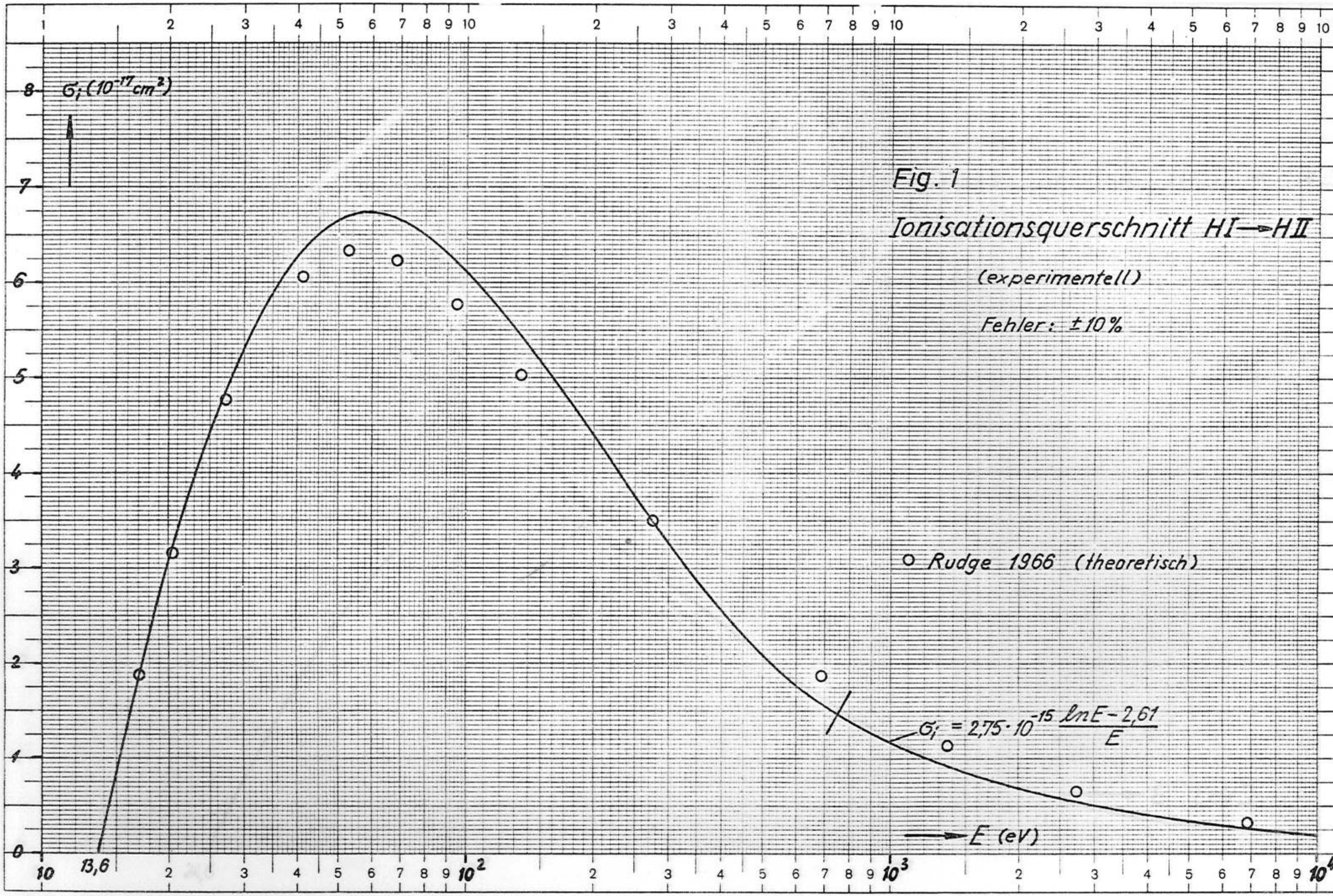


Fig. 1
Ionisationsquerschnitt HI → HII
(experimentell)
Fehler: ±10%
○ Rudge 1966 (theoretisch)
$\sigma_i = 2{,}75 \cdot 10^{-15} \frac{\ln E - 2{,}61}{E}$
σ_i (10^{-17} cm^2)
E (eV)
13,6
10
10^2
10^3
10^4
0
1
2
3
4
5
6
7
8
MADE IN GERMANY

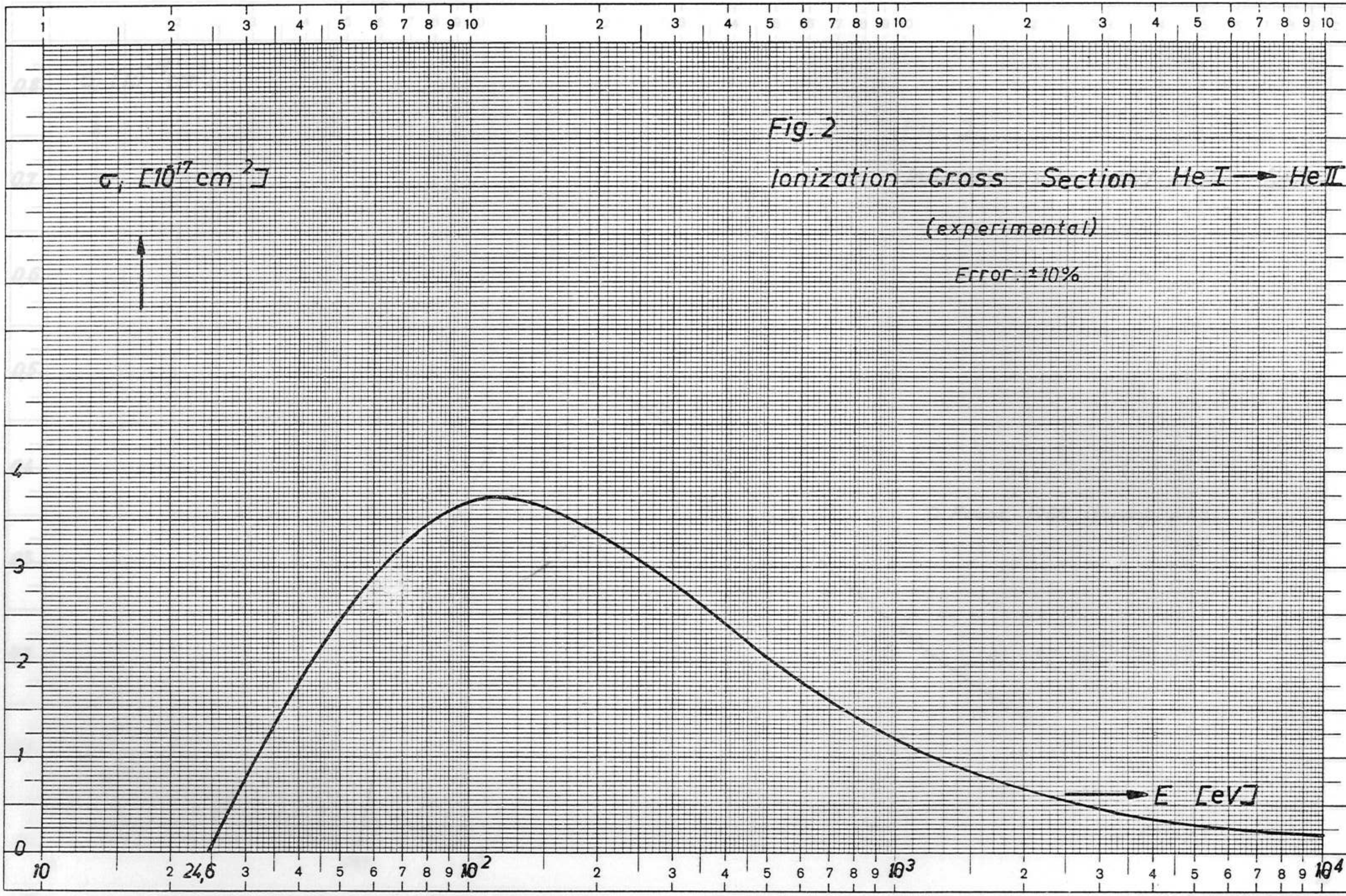
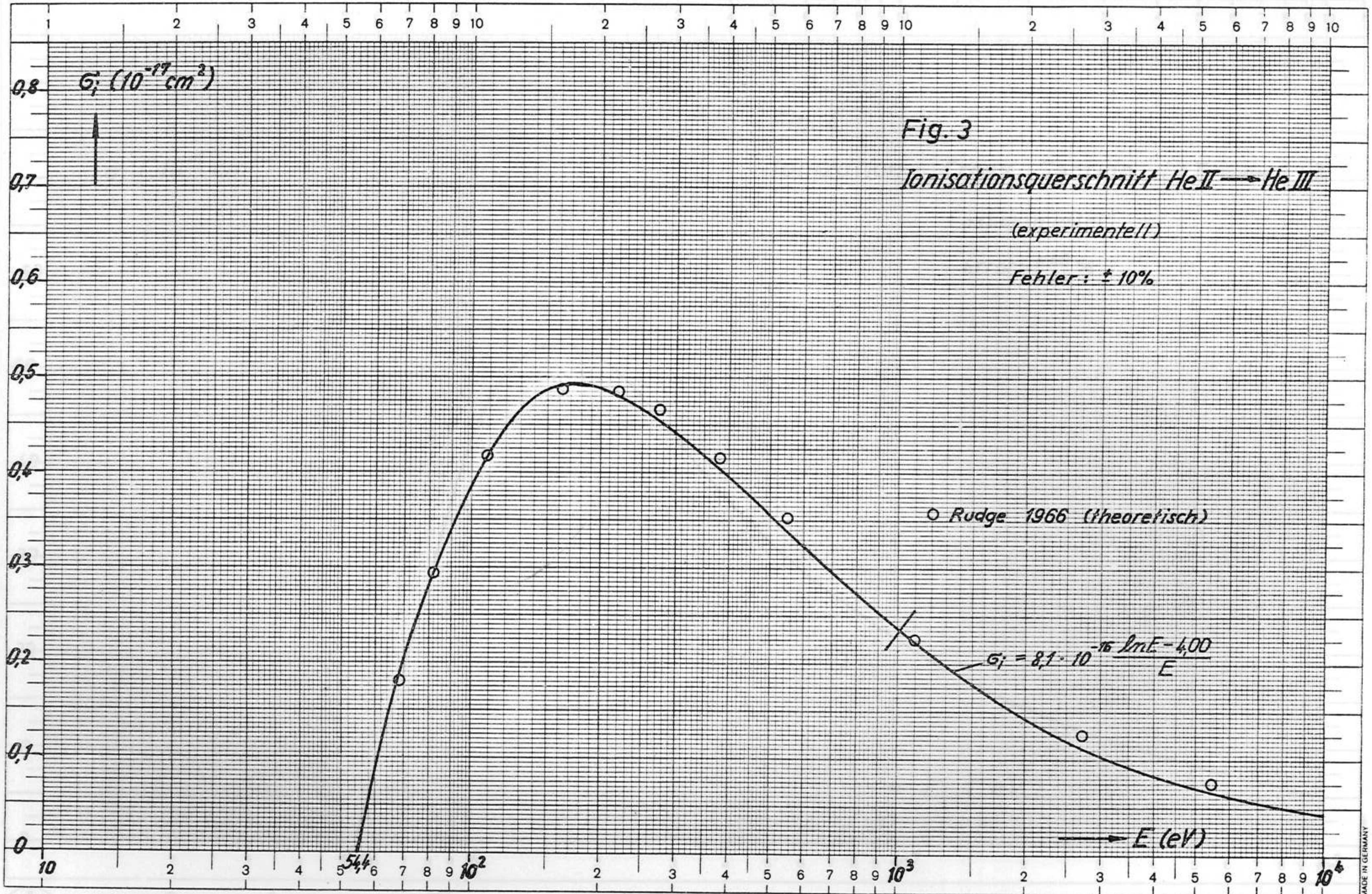


Fig. 2
Ionization Cross Section He I → He II
(experimental)
Error: ±10%
σ_i [10^-17 cm^2]
E [eV]
24,6
10
10^2
10^3
10^4
0
1
2
3
4
MADE IN GERMANY



σi (10^-17 cm²)
Fig. 3
Ionisationsquerschnitt He II → He III
(experimentell)
Fehler: ± 10%
○ Rudge 1966 (theoretisch)
σi = 8,1 · 10^-16 (ln E − 4,00)/E
E (eV)
54,4
10
10²
10³
10⁴
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8

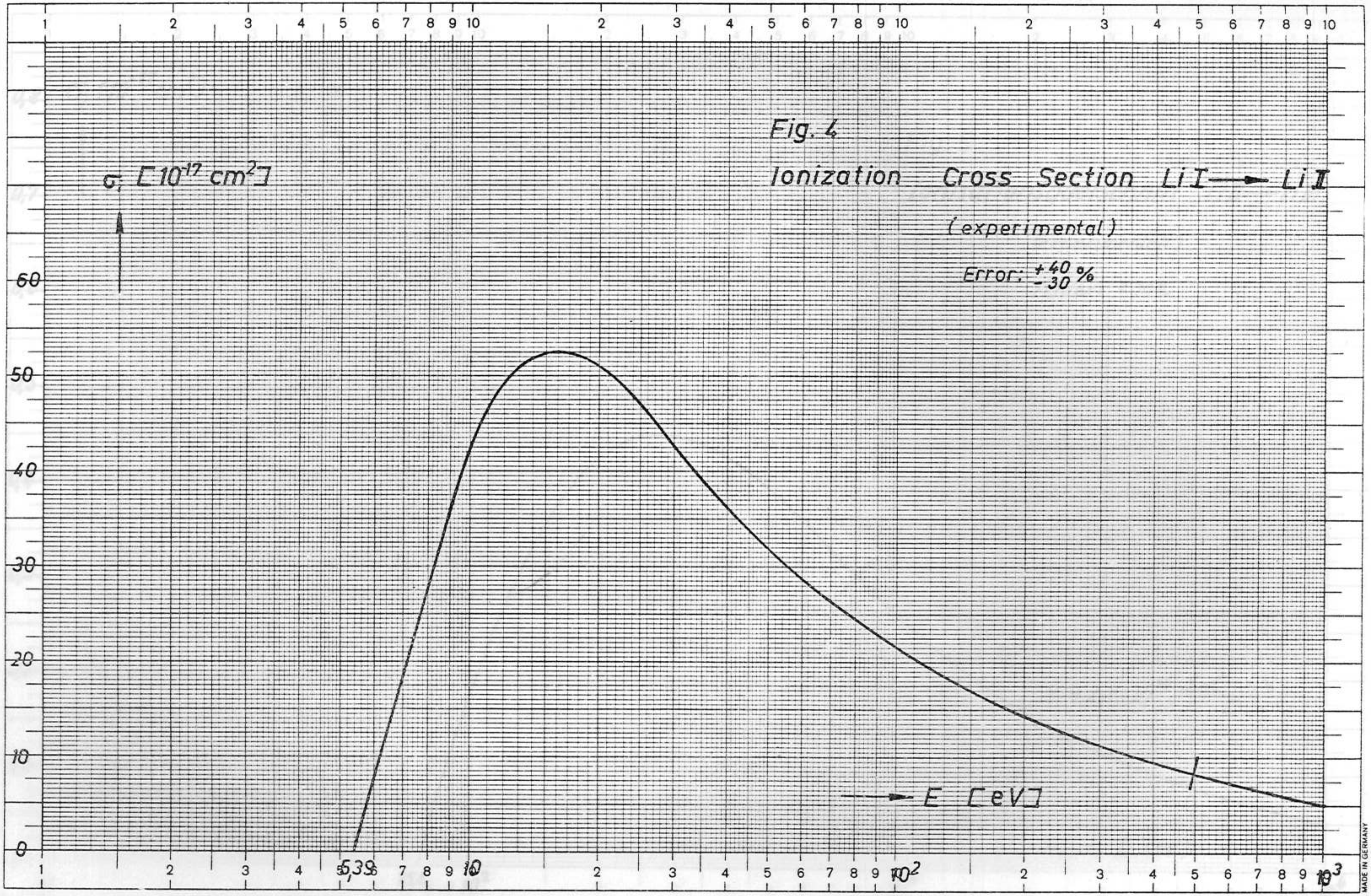


Fig. 4
Ionization Cross Section Li I ⟶ Li II
(experimental)
Error: +40 % -30 %
σ; [10^17 cm^2]
E [eV]
5,39
0
10
20
30
40
50
60
10
10^2
10^3

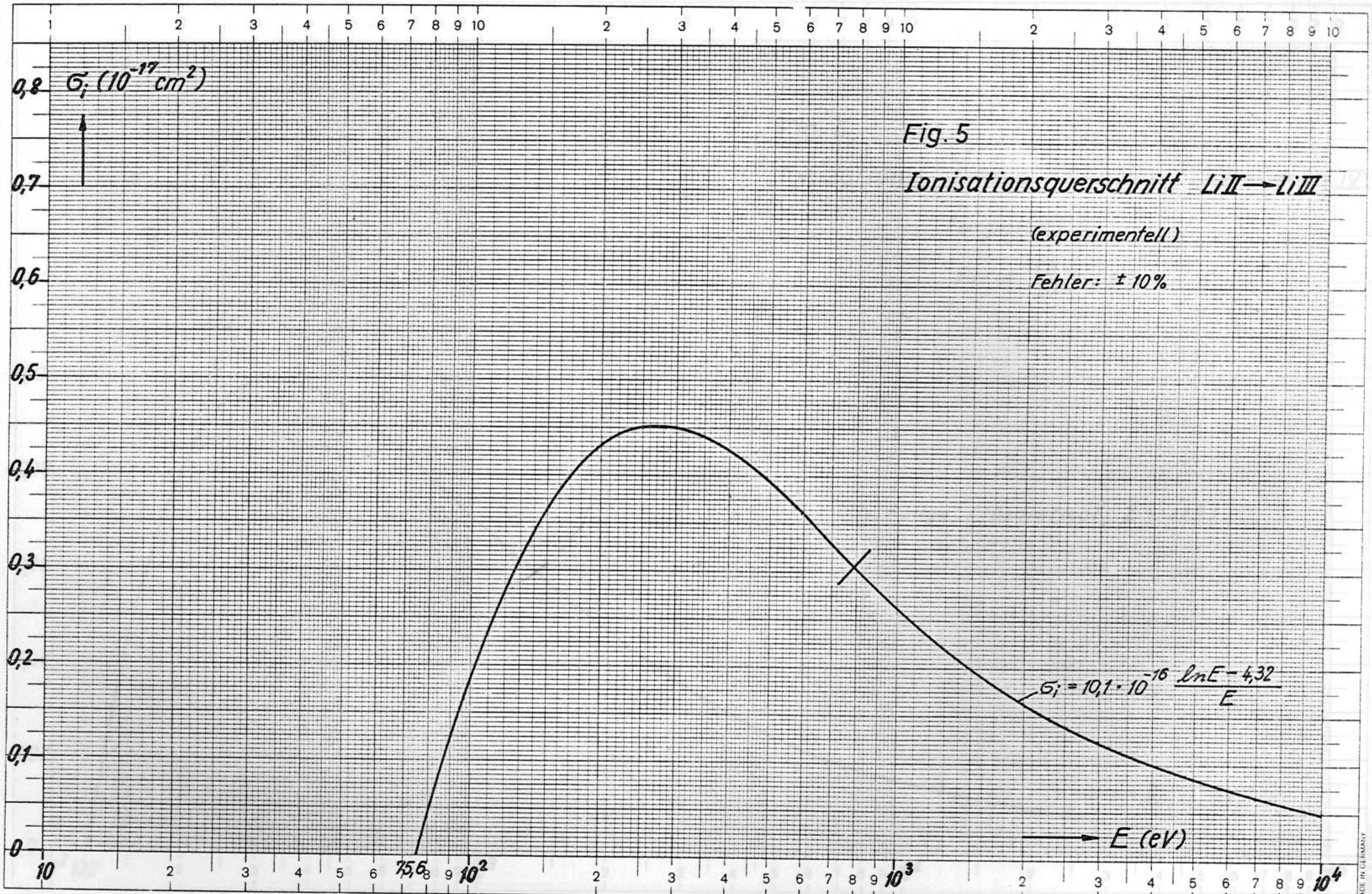


Fig. 5
Ionisationsquerschnitt LiII ⟶ LiIII
(experimentell)
Fehler: ± 10%
σᵢ (10⁻¹⁷ cm²)
E (eV)
σᵢ = 10,1 · 10⁻¹⁶ (ln E − 4,32)/E
75,6
10
10²
10³
10⁴
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8

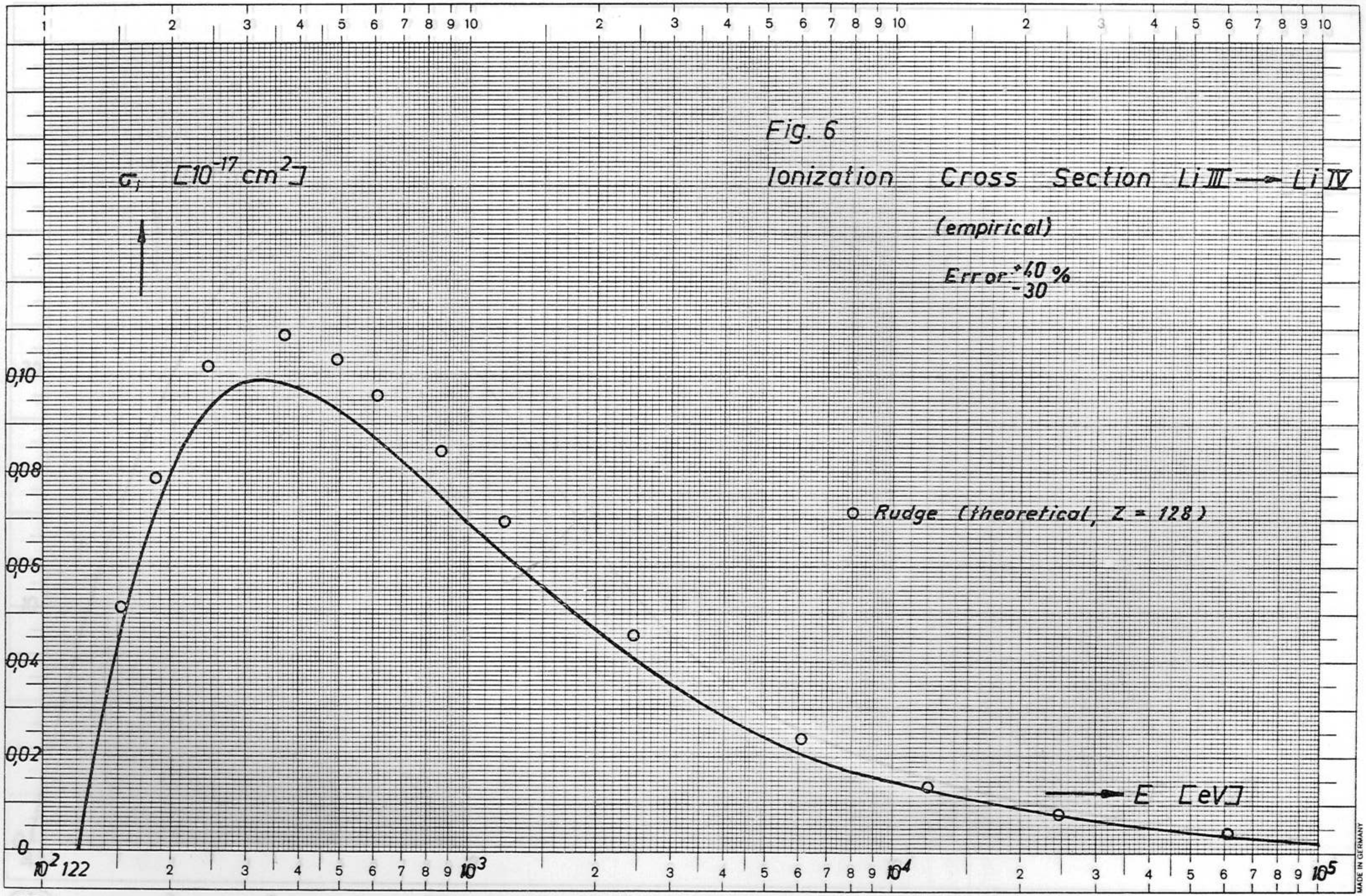


Fig. 6
Ionization Cross Section Li III → Li IV
(empirical)
Error: +40 % -30
σᵢ [10⁻¹⁷ cm²]
○ Rudge (theoretical, Z = 128)
E [eV]
0,10
0,08
0,06
0,04
0,02
0
10²
122
10³
10⁴
10⁵

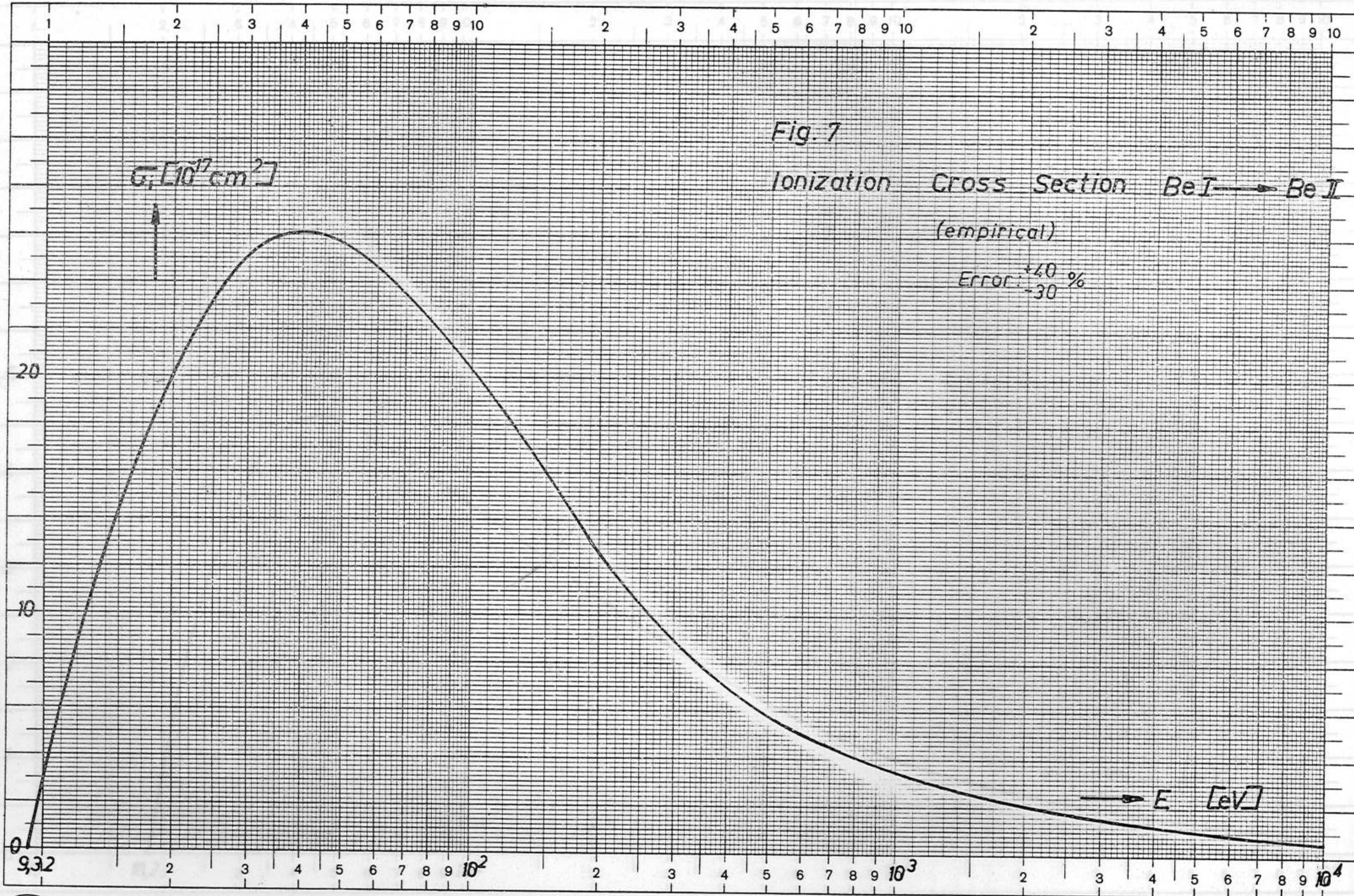


Fig. 7
Ionization Cross Section Be I → Be II
(empirical)
Error: +40 -30 %
σᵢ [10⁻¹⁷ cm²]
E [eV]
0
10
20
9,32
10²
10³
10⁴

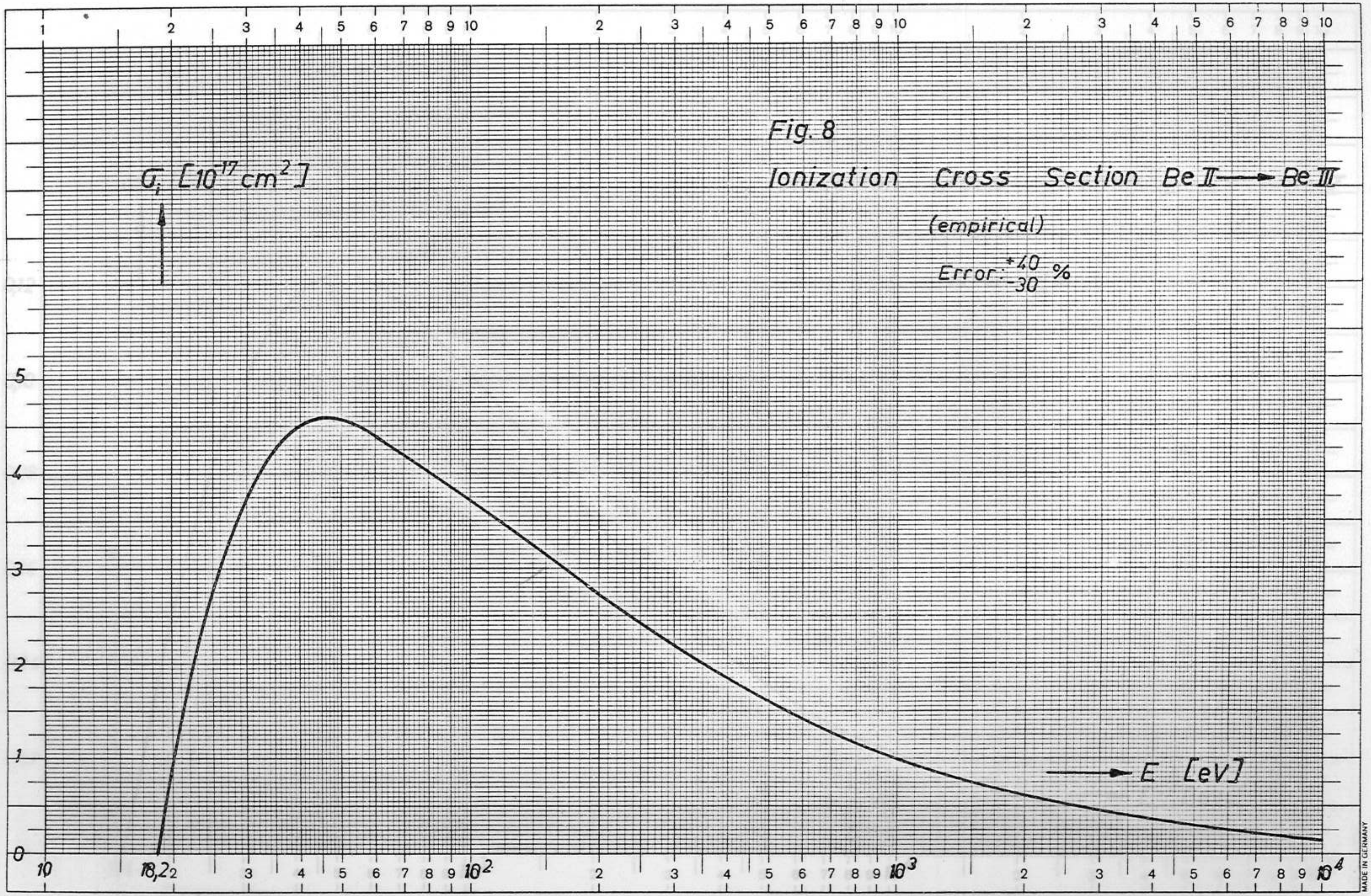


Fig. 8
Ionization Cross Section Be II → Be III
(empirical)
Error: +40 -30 %
σ_i [10^-17 cm^2]
E [eV]
10
18,2
10^2
10^3
10^4
0
1
2
3
4
5

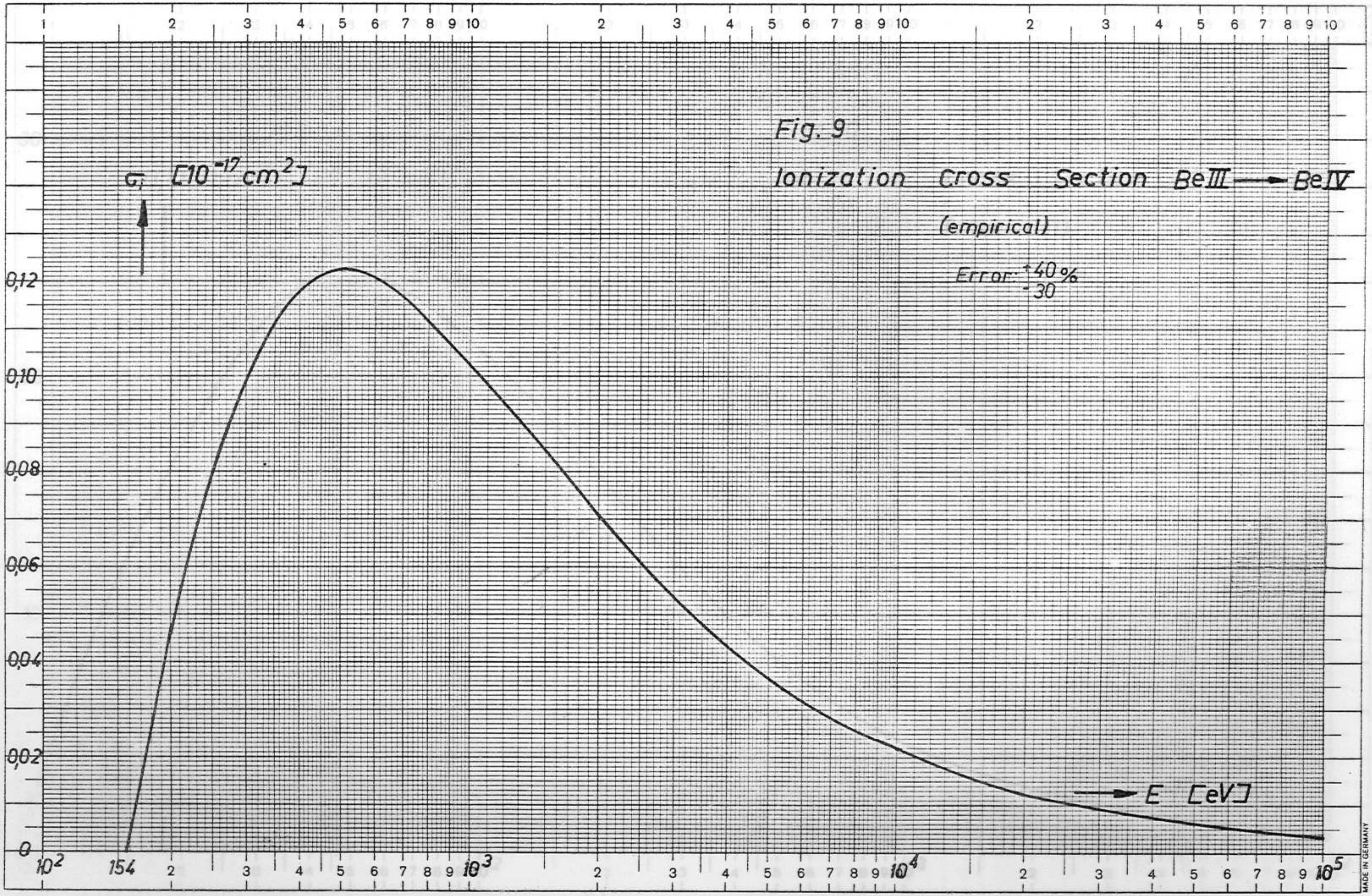


Fig. 9
Ionization Cross Section BeIII → BeIV
(empirical)
Error: +40 % -30
σ_i [10^-17 cm^2]
E [eV]
0,12
0,10
0,08
0,06
0,04
0,02
0
10^2
154
10^3
10^4
10^5

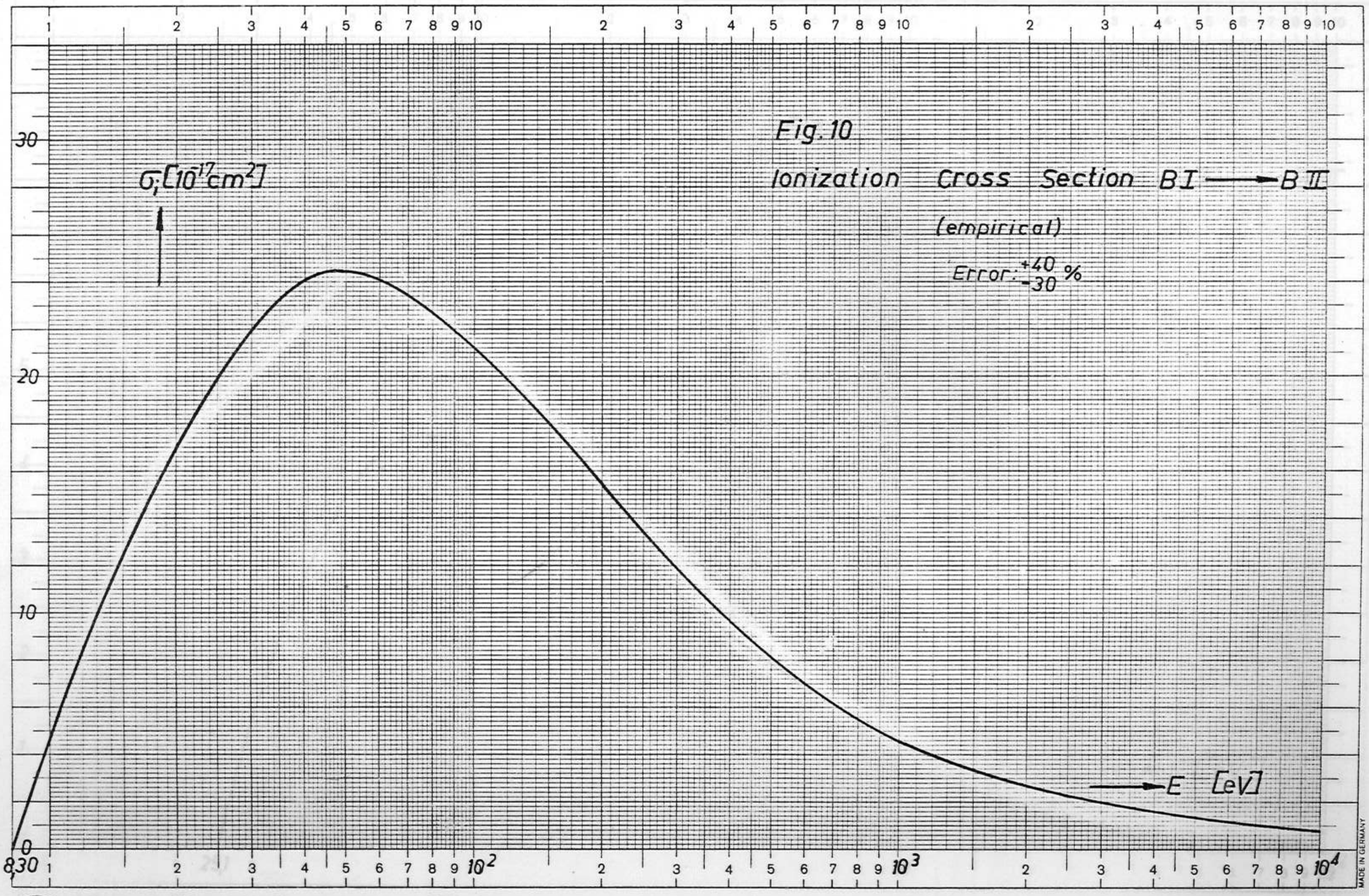


Fig. 10
Ionization Cross Section BI ——→ BII
(empirical)
Error: +40 -30 %
σ_i [10^-17 cm^2]
→ E [eV]
30
20
10
0
8,30
10^2
10^3
10^4

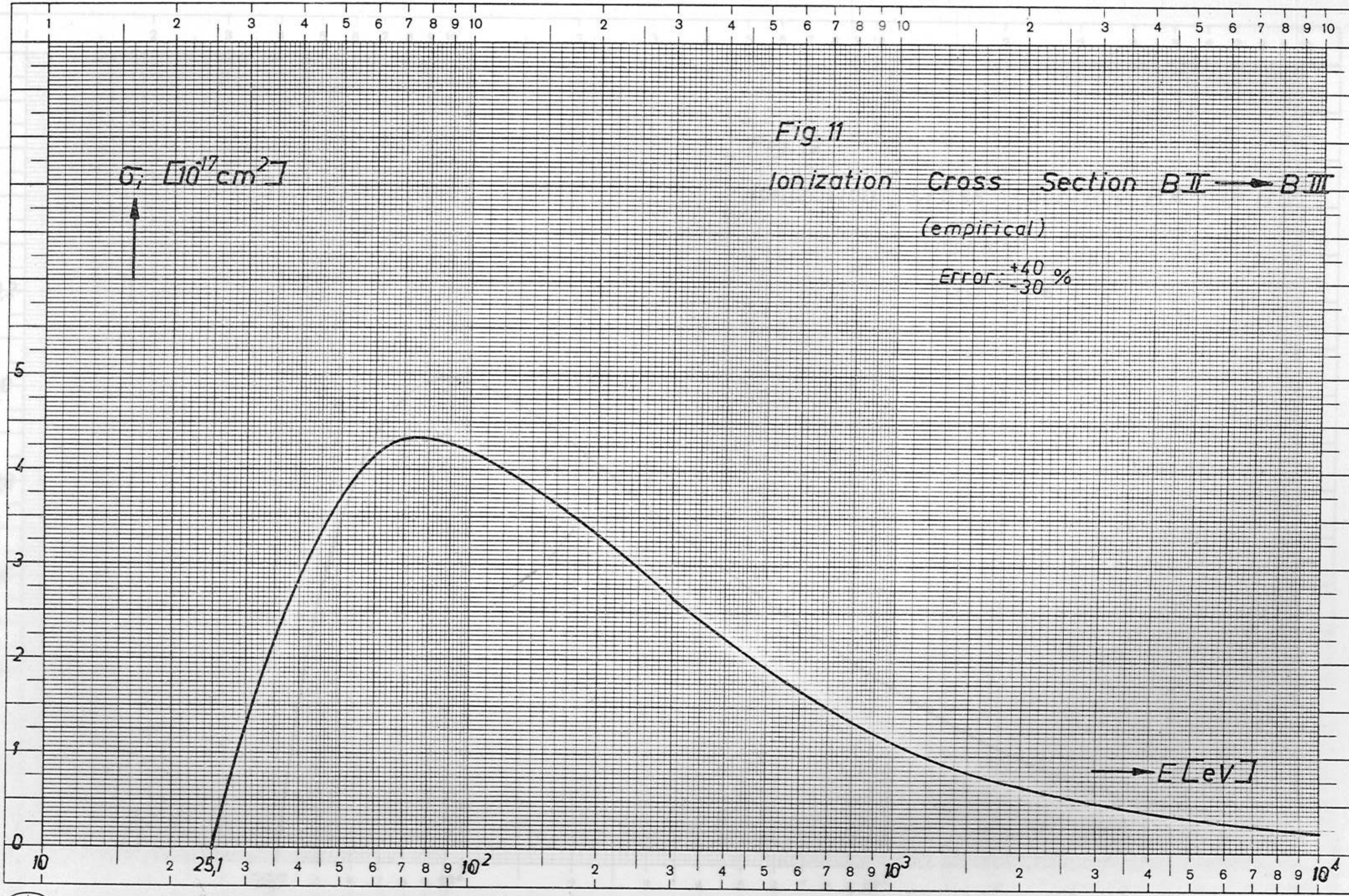


Fig. 11
Ionization Cross Section BII → BIII
(empirical)
Error: +40 / -30 %
σi [10⁻¹⁷ cm²]
E [eV]
25,1
0
1
2
3
4
5
10
10²
10³
10⁴

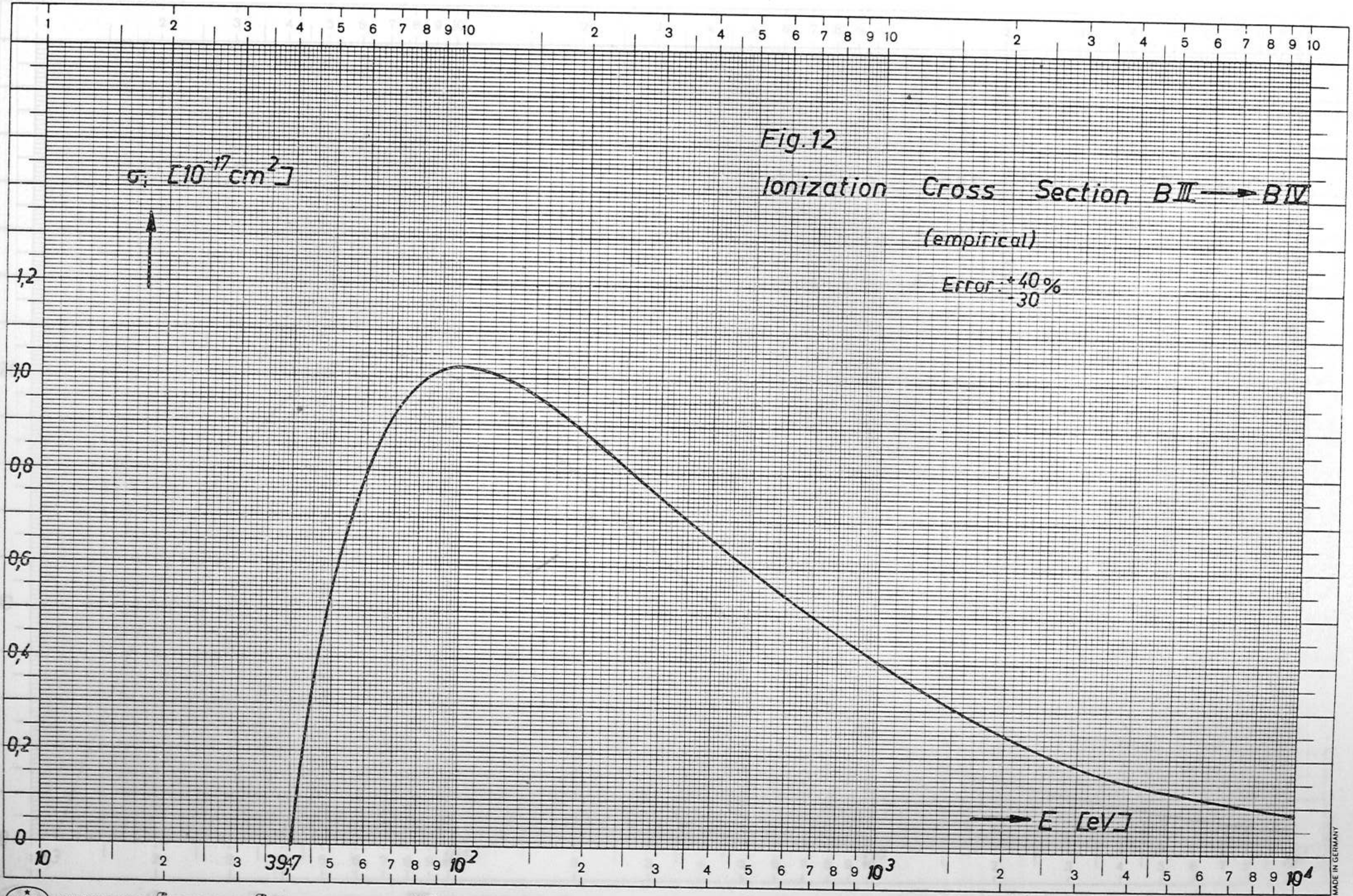


Fig.12
Ionization Cross Section BIII → BIV
(empirical)
Error: +40 % -30
σi [10^-17 cm^2]
E [eV]
39,7
10
10^2
10^3
10^4
0
0,2
0,4
0,6
0,8
1,0
1,2

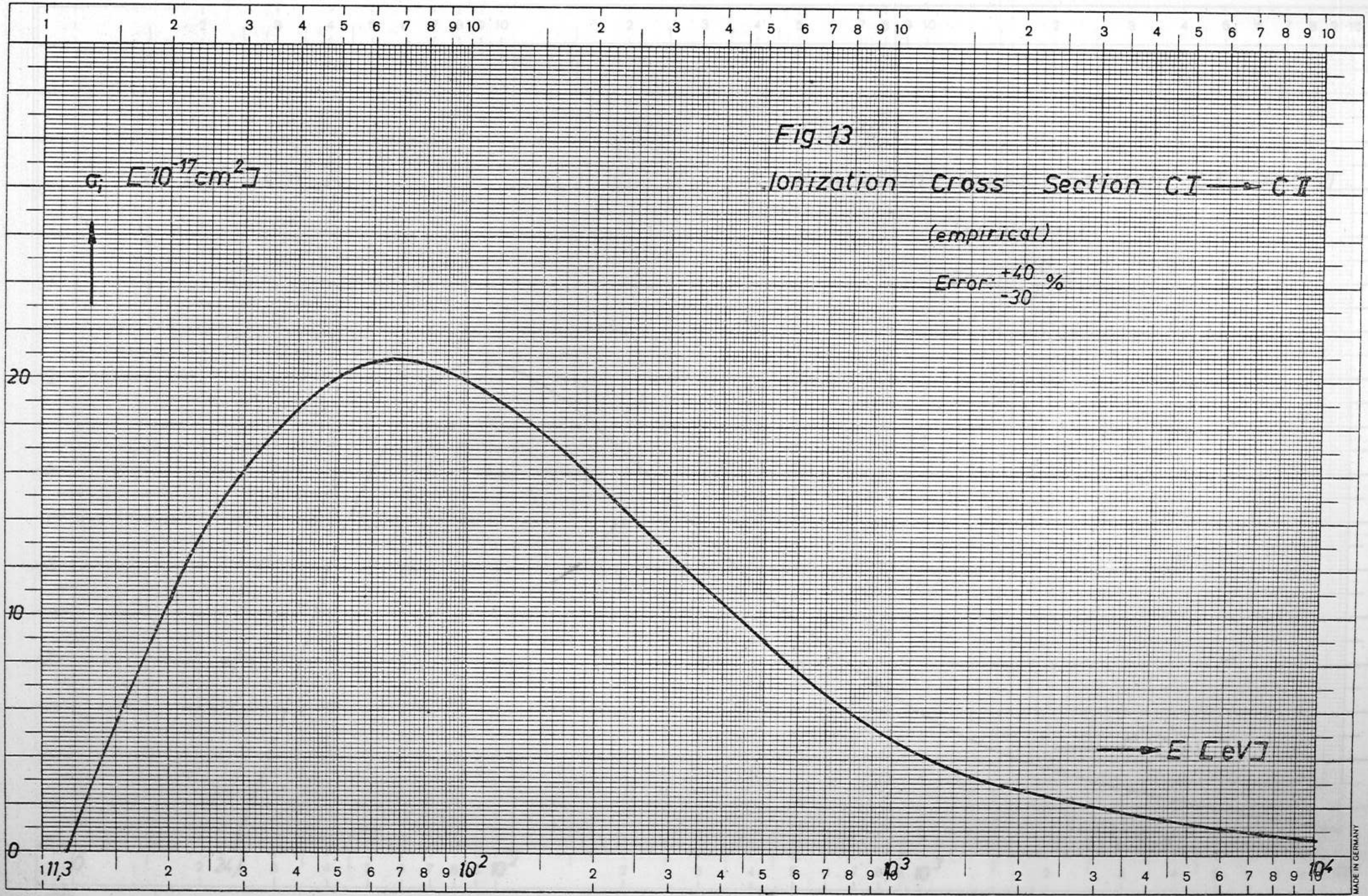


Fig. 13
Ionization Cross Section CI → CII
(empirical)
Error: +40 -30 %
σi [10^-17 cm^2]
E [eV]
20
10
0
11,3
10^2
10^3
10^4

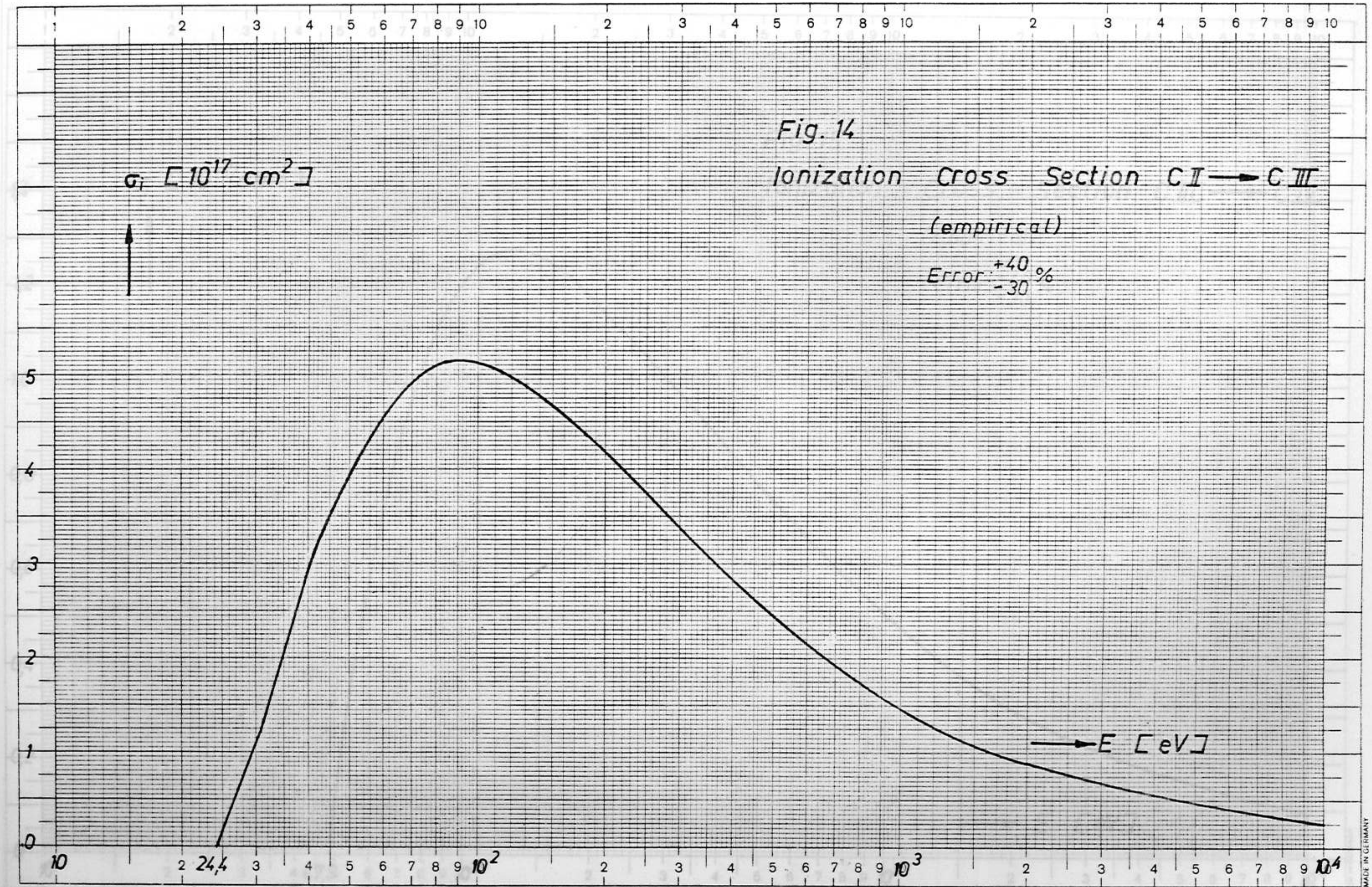


Fig. 14
Ionization Cross Section C II → C III
(empirical)
Error: +40 -30 %
σ_i [10^{-17} cm^2]
E [eV]
24,4
0
1
2
3
4
5
10
10^2
10^3
10^4

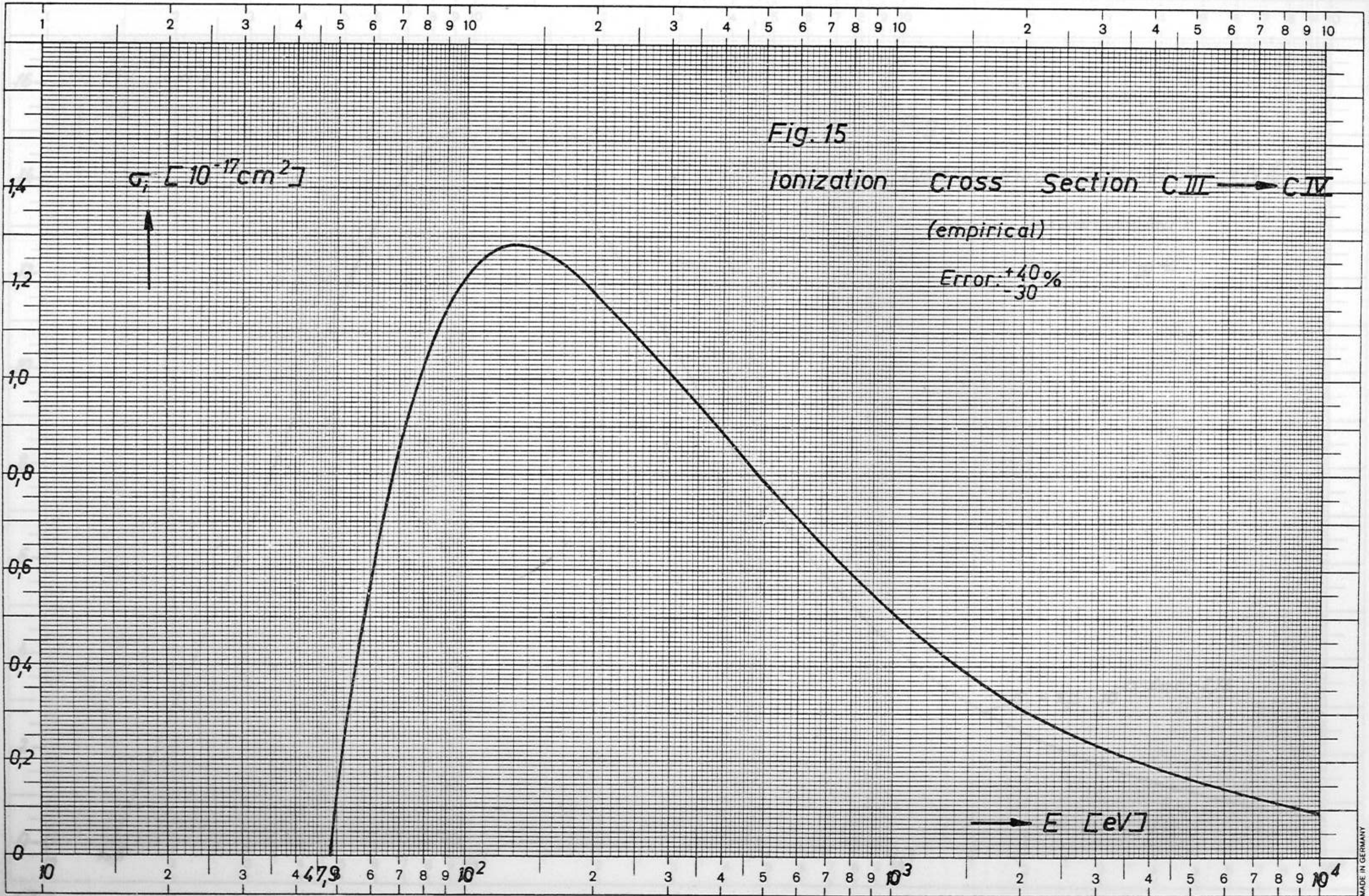
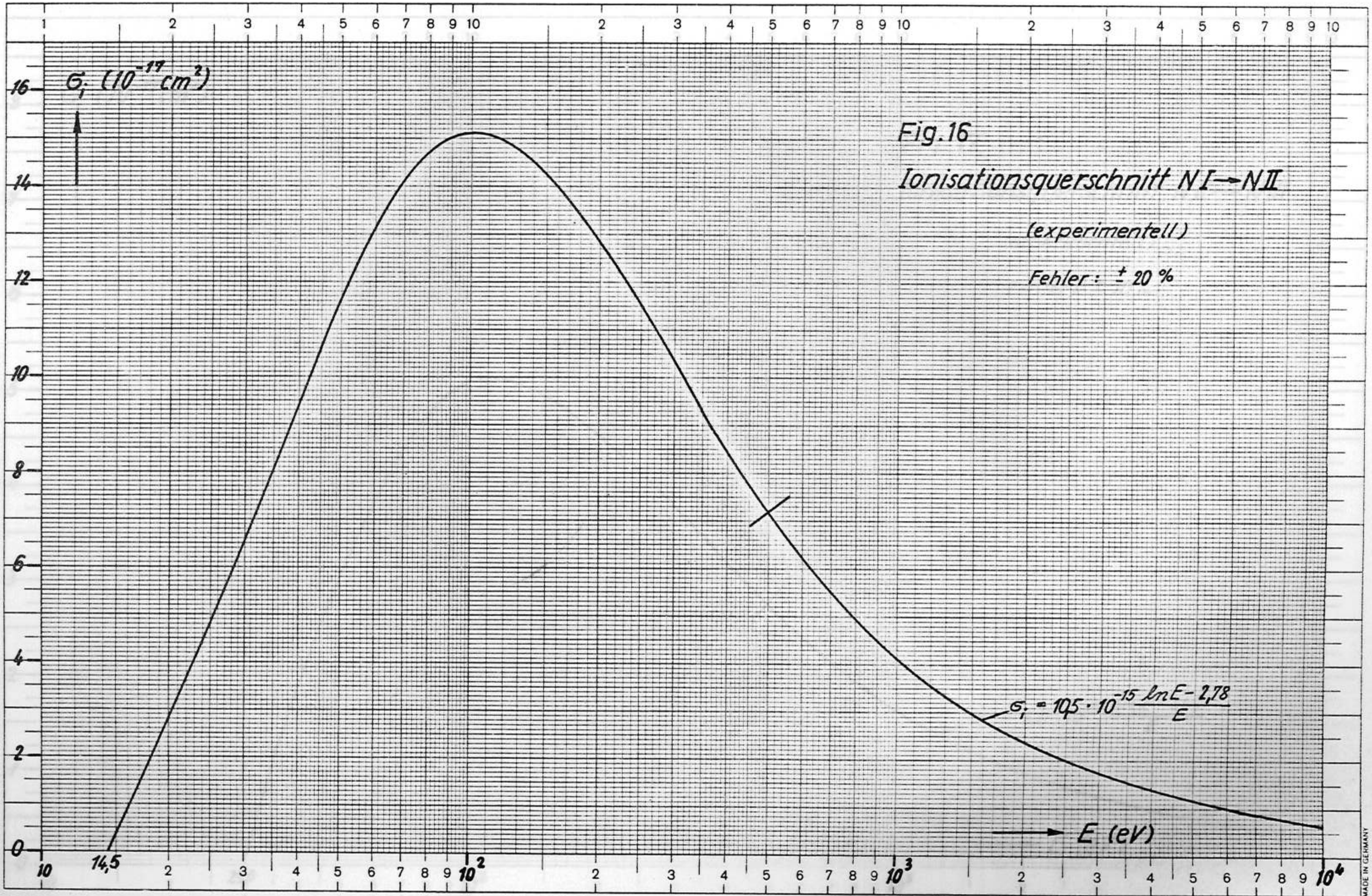


Fig. 15
Ionization Cross Section C III ⟶ C IV
(empirical)
Error: +40 % -30
σ_i [10^-17 cm^2]
E [eV]
1,4
1,2
1,0
0,8
0,6
0,4
0,2
0
10
47,9
10^2
10^3
10^4



σ_i (10^{-17} cm^2)
Fig. 16
Ionisationsquerschnitt NI → NII
(experimentell)
Fehler: ± 20 %
$\sigma_i = 10{,}5 \cdot 10^{-15} \frac{\ln E - 2{,}78}{E}$
E (eV)
14,5

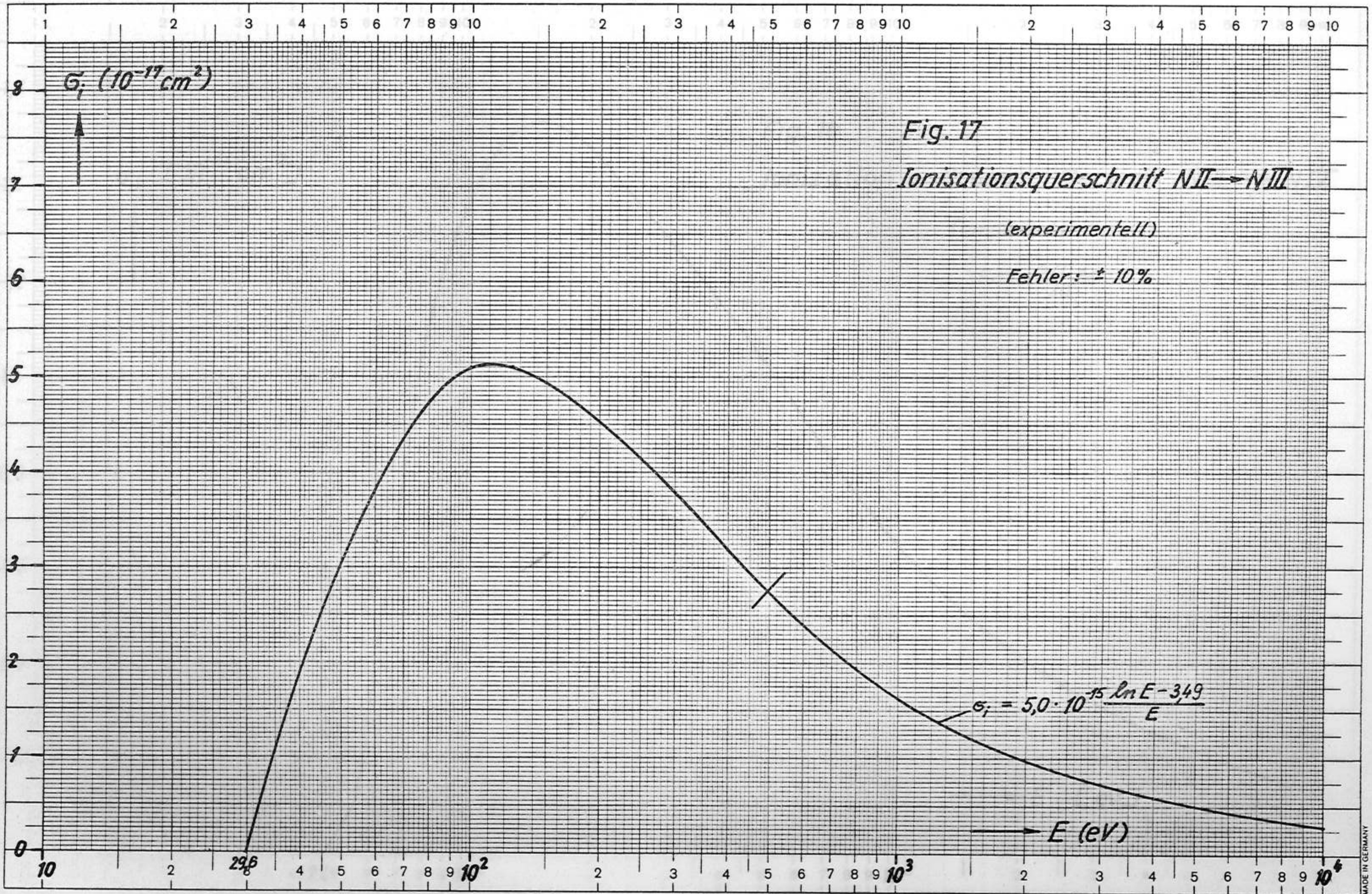


Fig. 17
Ionisationsquerschnitt NII → NIII
(experimentell)
Fehler: ± 10%
σi (10^-17 cm^2)
σi = 5,0·10^-15 (ln E − 3,49)/E
E (eV)
29,6
10
10^2
10^3
10^4

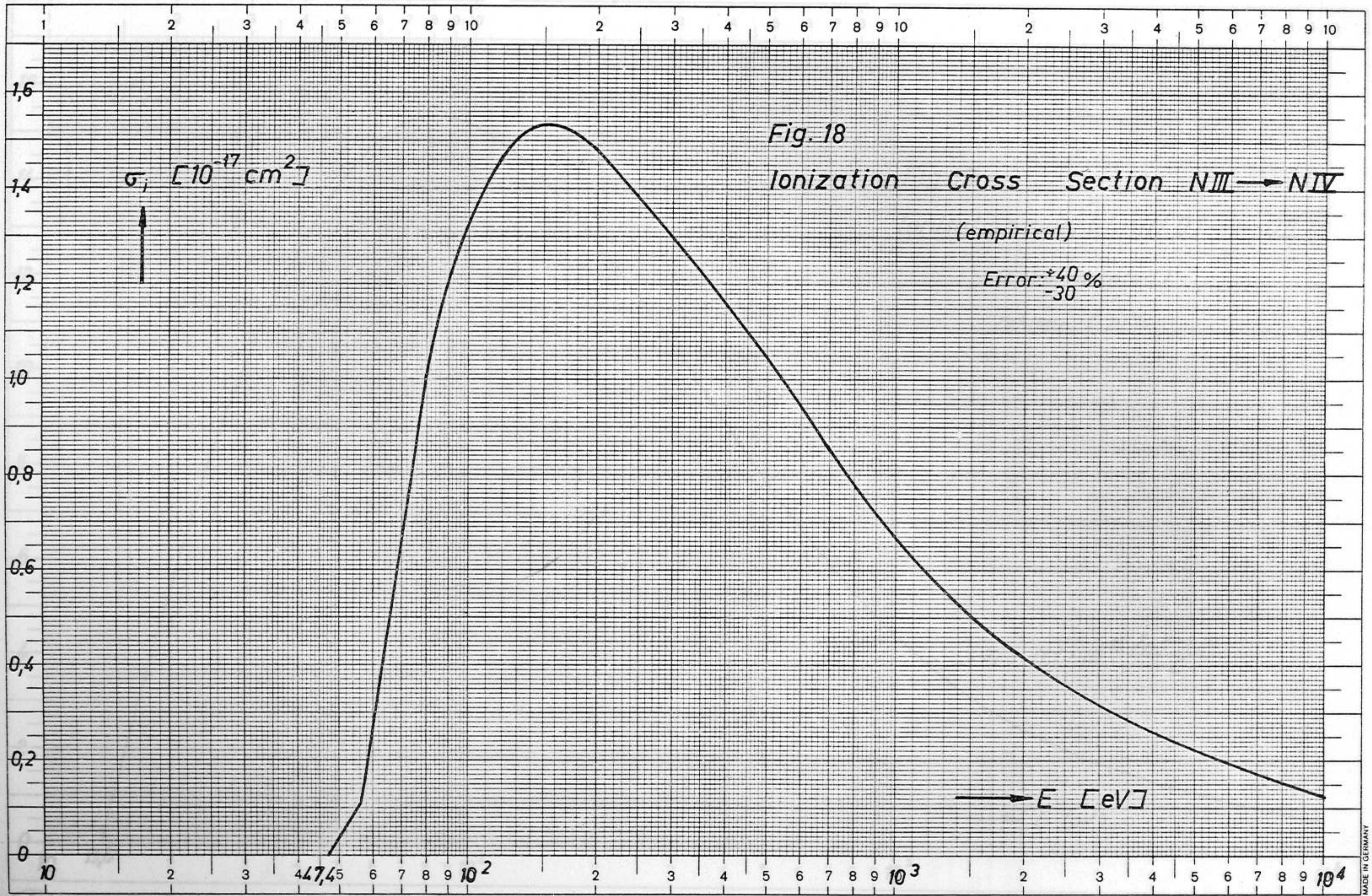
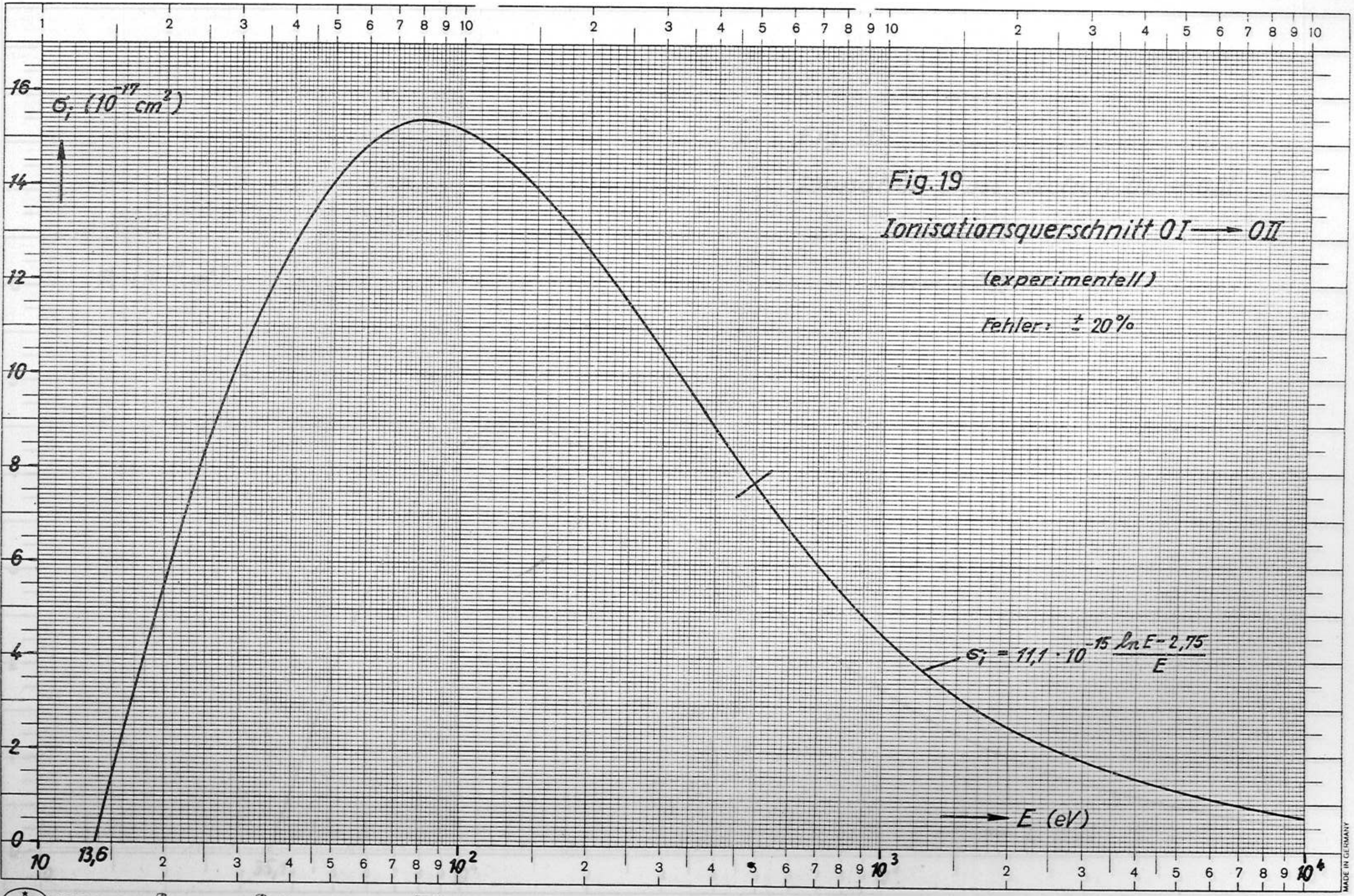


Fig. 18
Ionization Cross Section NIII → NIV
(empirical)
Error: +40 % / -30
σ_i [10^-17 cm^2]
1,6
1,4
1,2
1,0
0,8
0,6
0,4
0,2
0
10
47,45
10^2
10^3
10^4
E [eV]


σᵢ (10⁻¹⁷ cm²)
Fig. 19
Ionisationsquerschnitt OI → OII
(experimentell)
Fehler: ± 20%
σᵢ = 11,1 · 10⁻¹⁵ (ln E − 2,75)/E
E (eV)
13,6

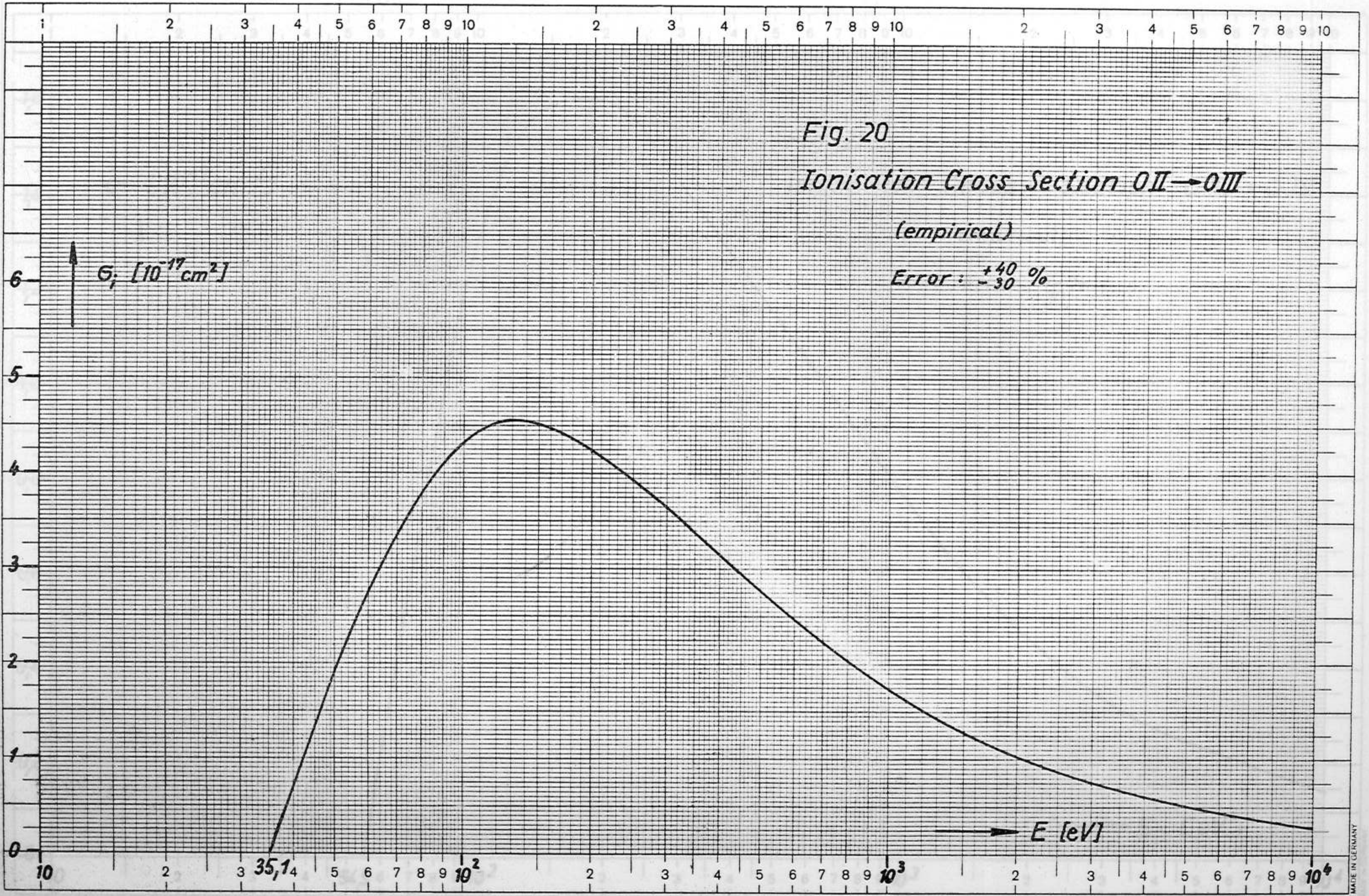


Fig. 20
Ionisation Cross Section OII → OIII
(empirical)
Error: +40 −30 %
σi [10⁻¹⁷ cm²]
E [eV]
35,1
10
10²
10³
10⁴
0
1
2
3
4
5
6
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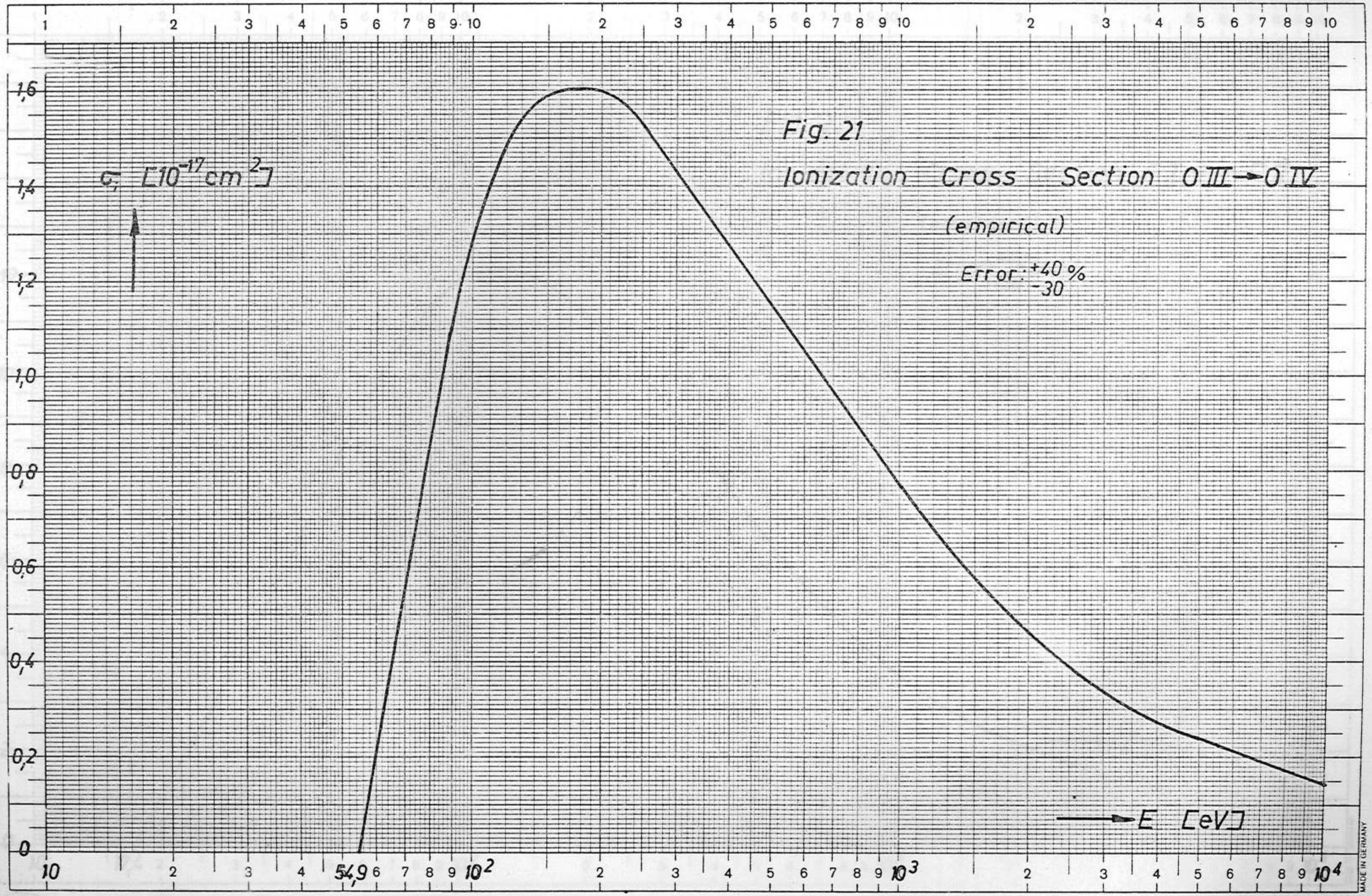


Fig. 21
Ionization Cross Section O III → O IV
(empirical)
Error: +40 % -30
σ_i [10^-17 cm^2]
E [eV]
1,6
1,4
1,2
1,0
0,8
0,6
0,4
0,2
0
10
54,9
10^2
10^3
10^4

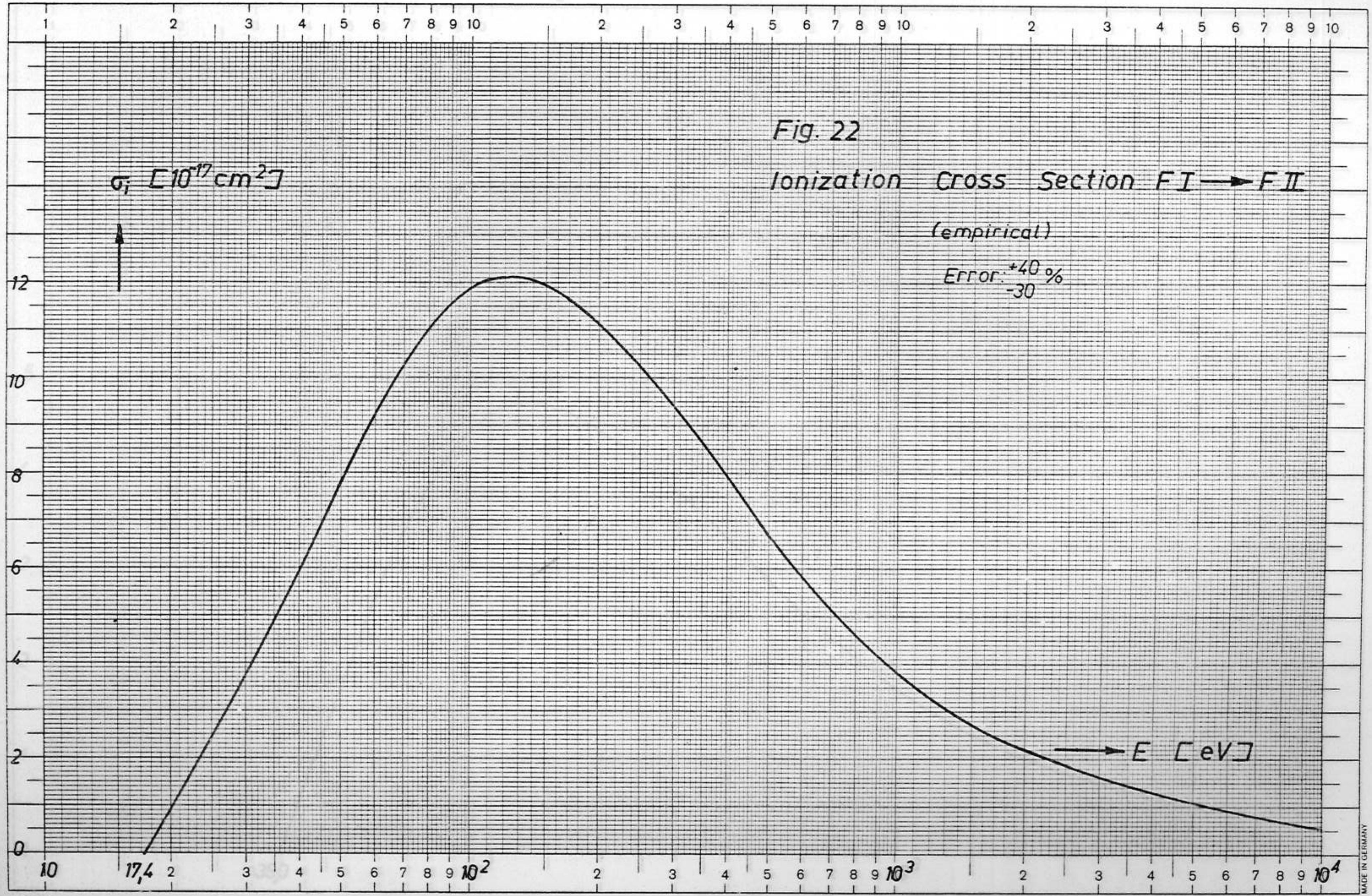


Fig. 22
Ionization Cross Section F I → F II
(empirical)
Error: +40 -30 %
σ_i [10^-17 cm^2]
E [eV]
17,4
10
10^2
10^3
10^4
0
2
4
6
8
10
12

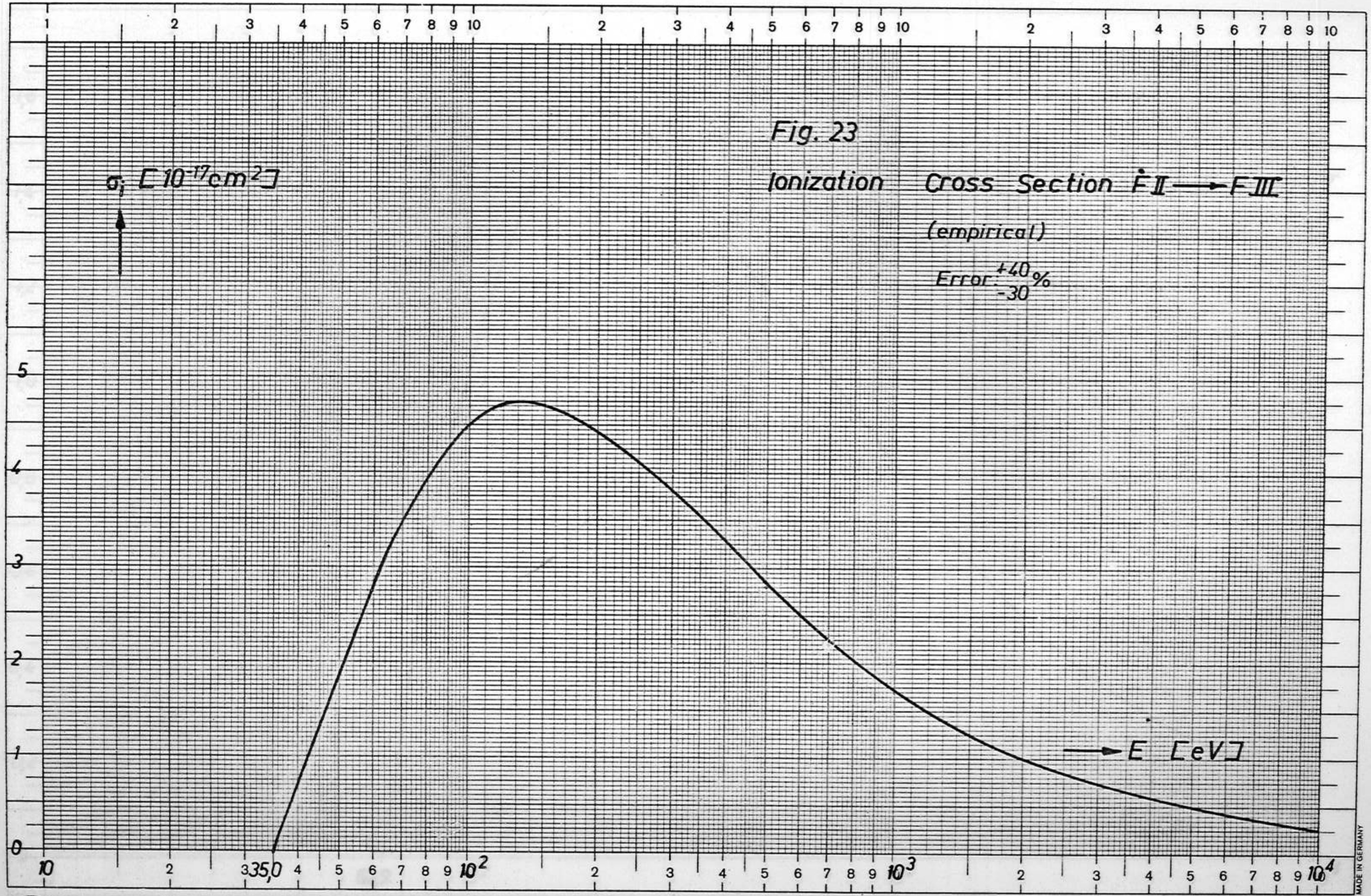


Fig. 23
Ionization Cross Section FII ⟶ FIII
(empirical)
Error: +40 / −30 %
σi [10^-17 cm^2]
⟶ E [eV]
35,0
10
10^2
10^3
10^4
0
1
2
3
4
5
MADE IN GERMANY

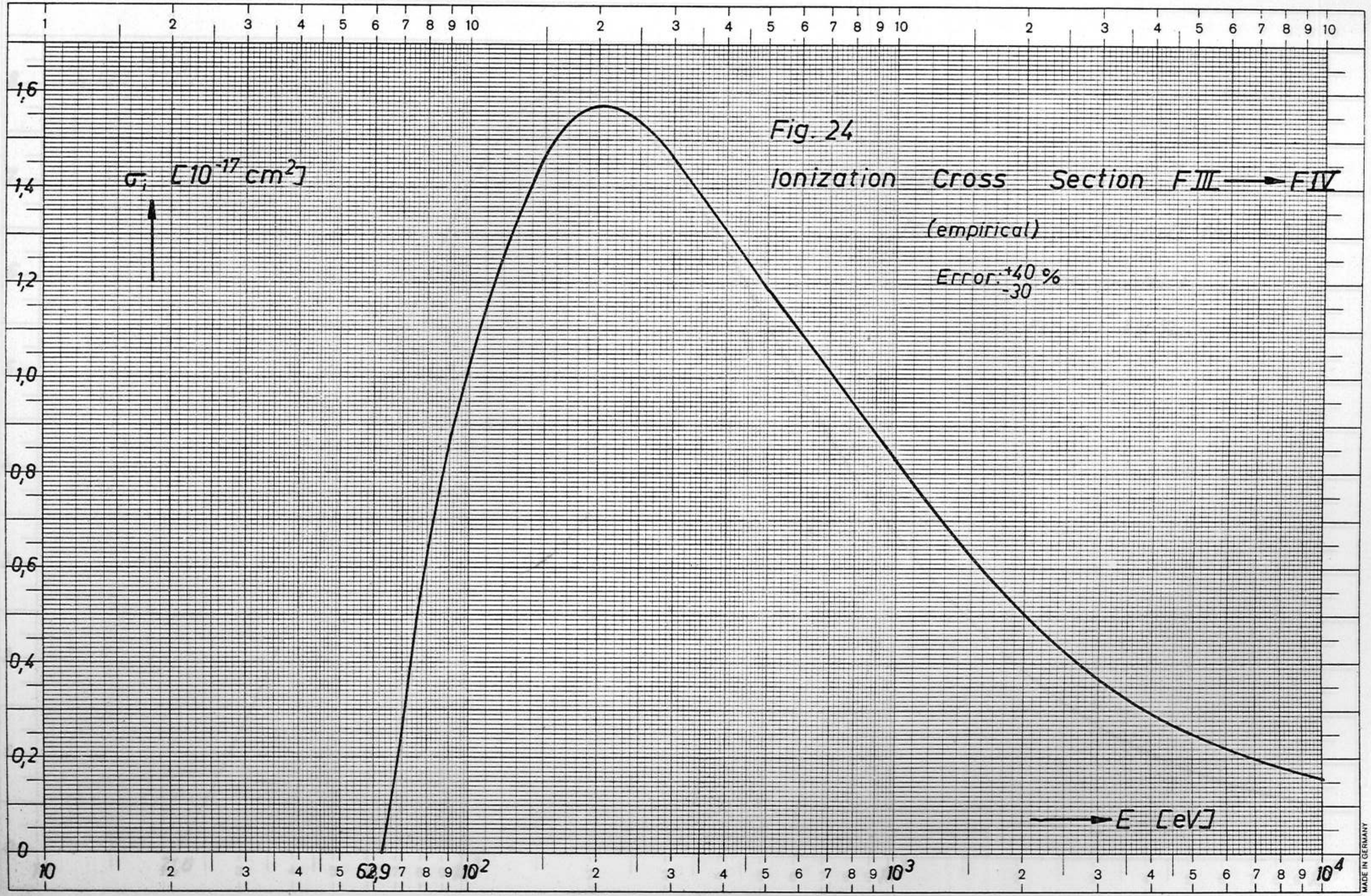


Fig. 24
Ionization Cross Section FIII → FIV
(empirical)
Error: +40 % -30
σ_i [10^-17 cm^2]
E [eV]
62,9
10
10^2
10^3
10^4
0
0,2
0,4
0,6
0,8
1,0
1,2
1,4
1,6

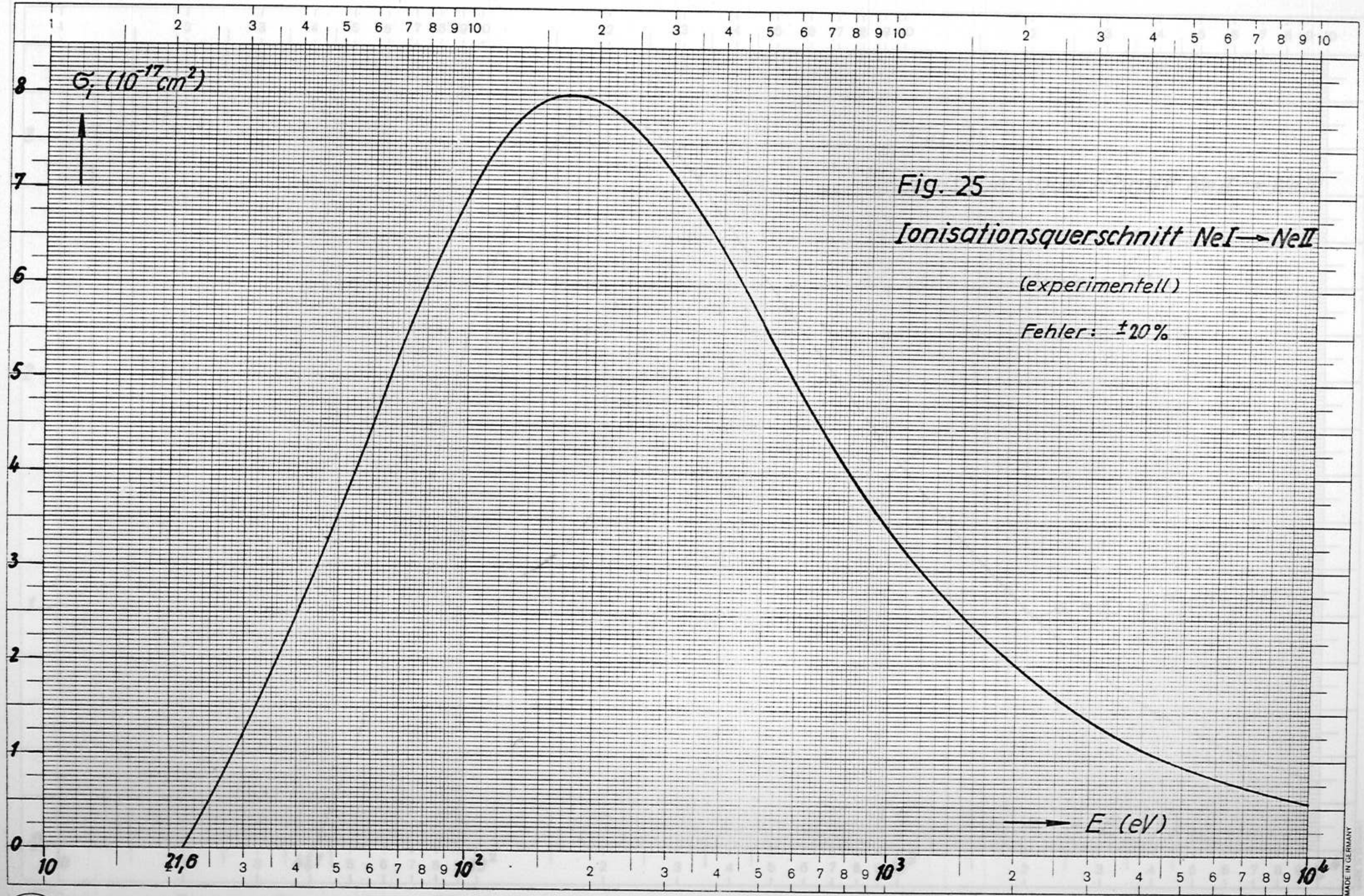
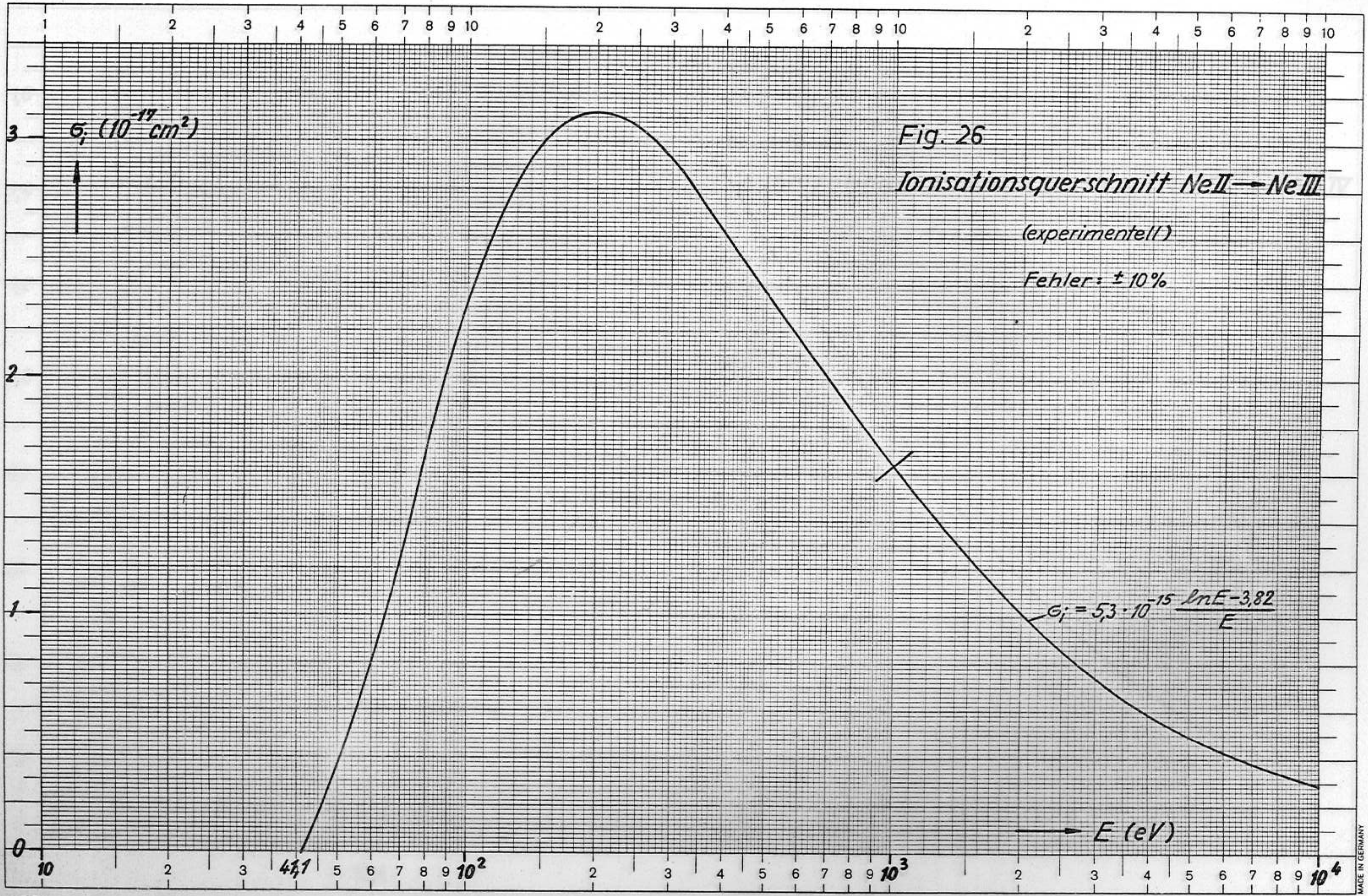


Fig. 25
Ionisationsquerschnitt NeI → NeII
(experimentell)
Fehler: ±20%
σ_i (10^-17 cm^2)
E (eV)
21,6
10
10^2
10^3
10^4
0
1
2
3
4
5
6
7
8



$\sigma_i\ (10^{-17}\ cm^2)$
Fig. 26
Ionisationsquerschnitt NeII → NeIII
(experimentell)
Fehler: ± 10%
$\sigma_i = 5{,}3 \cdot 10^{-15}\ \frac{\ln E - 3{,}82}{E}$
E (eV)
41,1

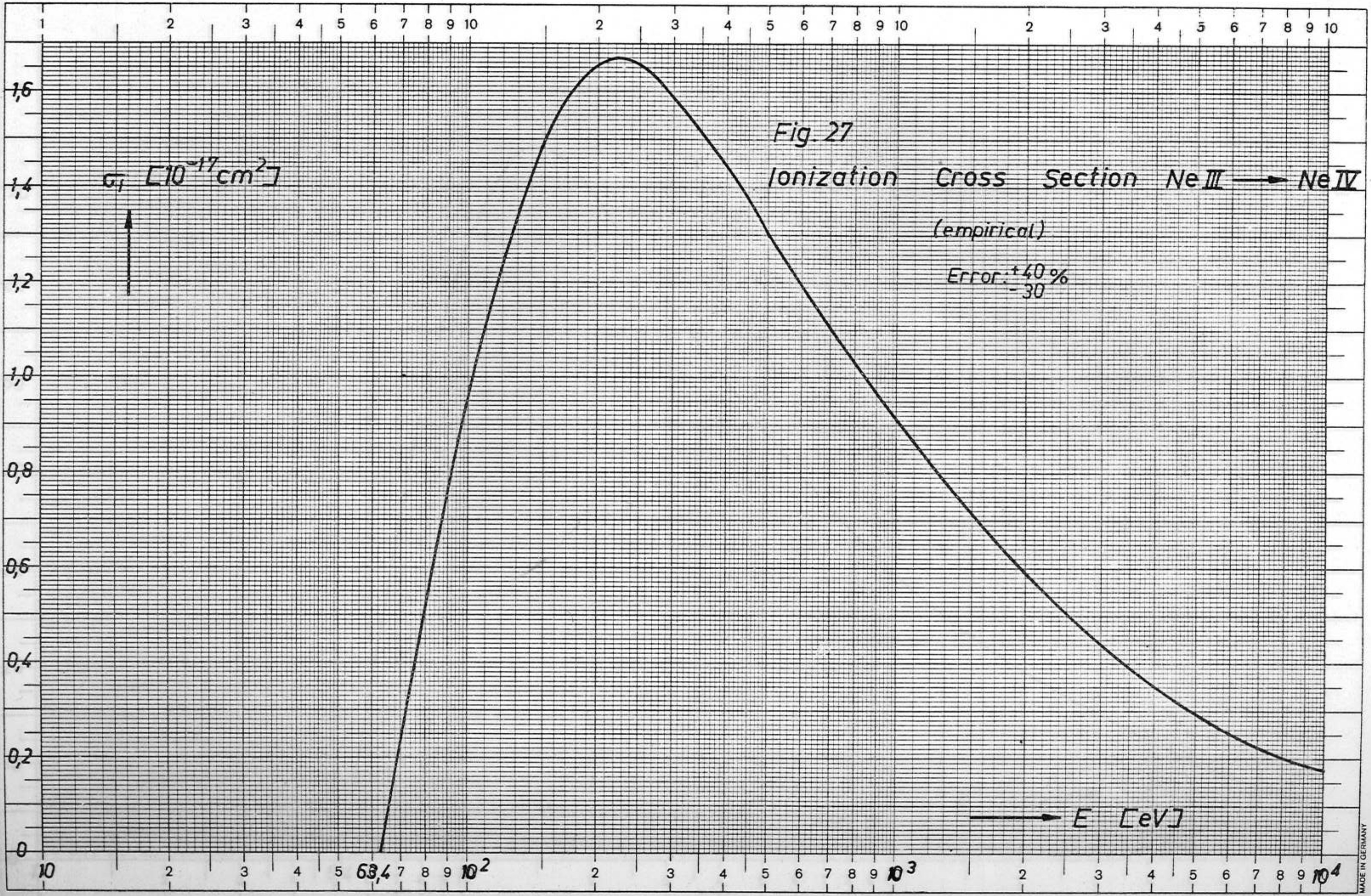


Fig. 27
Ionization Cross Section Ne III ⟶ Ne IV
(empirical)
Error: +40 % / -30
σ_I [10^-17 cm^2]
E [eV]
63,4
1,6
1,4
1,2
1,0
0,8
0,6
0,4
0,2
0
10
10^2
10^3
10^4

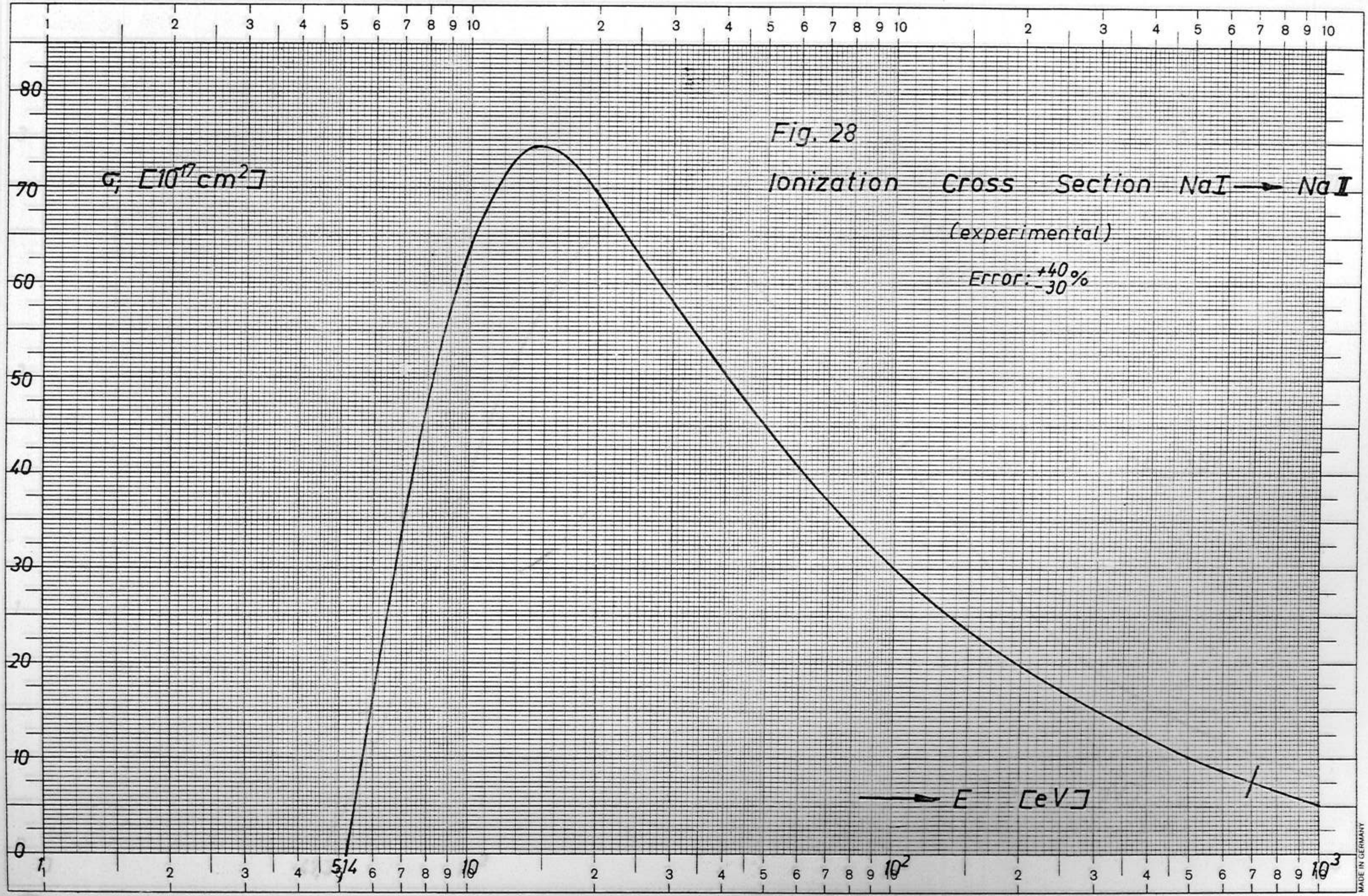


Fig. 28
Ionization Cross Section NaI → NaII
(experimental)
Error: +40% −30%
σ_i [10^-17 cm^2]
→ E [eV]
5.14
10
10^2
10^3
0
10
20
30
40
50
60
70
80

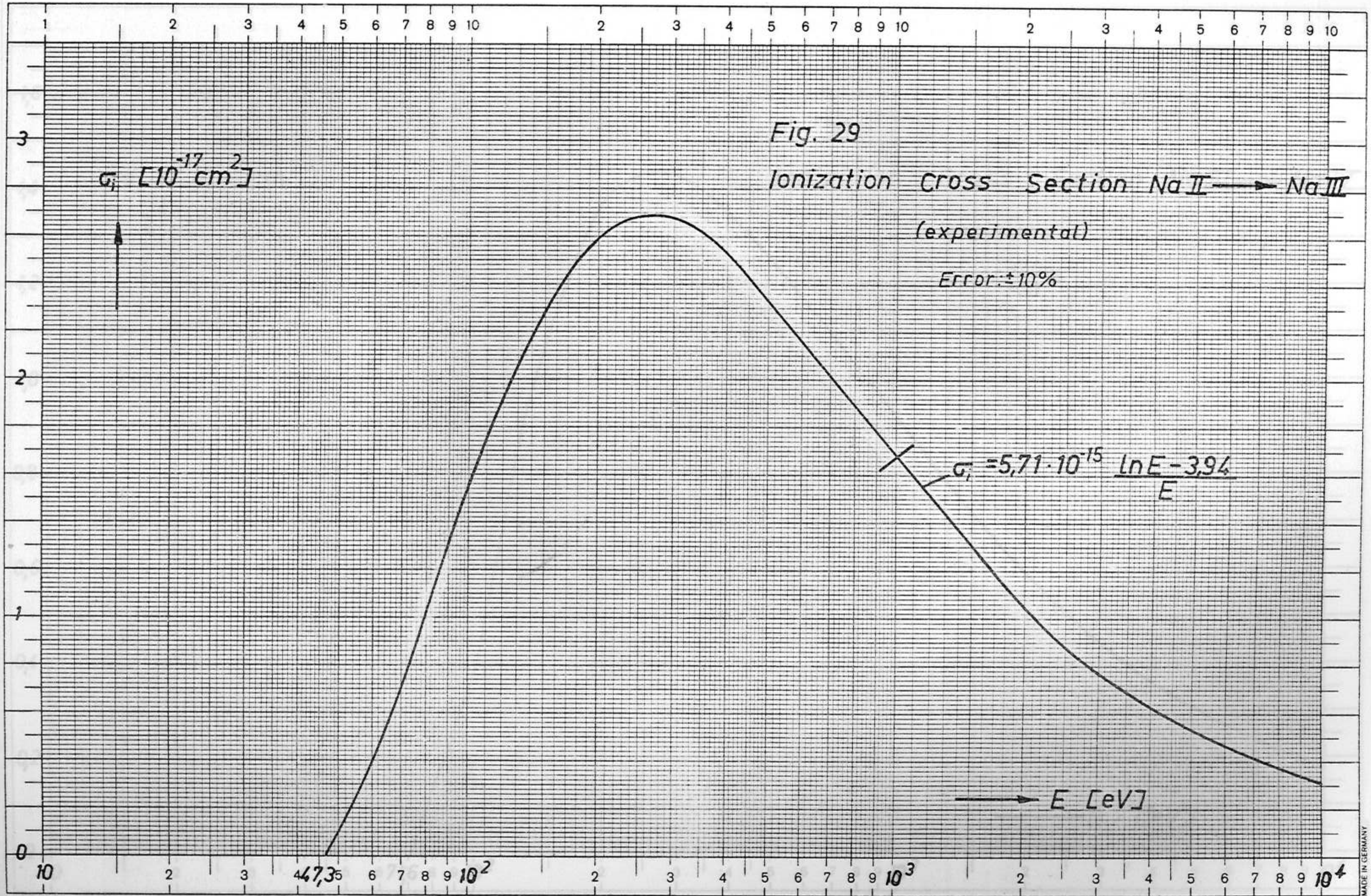


Fig. 29
Ionization Cross Section Na II ⟶ Na III
(experimental)
Error: ±10%
σ_i [10^-17 cm^2]
σ_i = 5,71·10^-15 (ln E − 3,94)/E
E [eV]
47,3
10
10^2
10^3
10^4
0
1
2
3

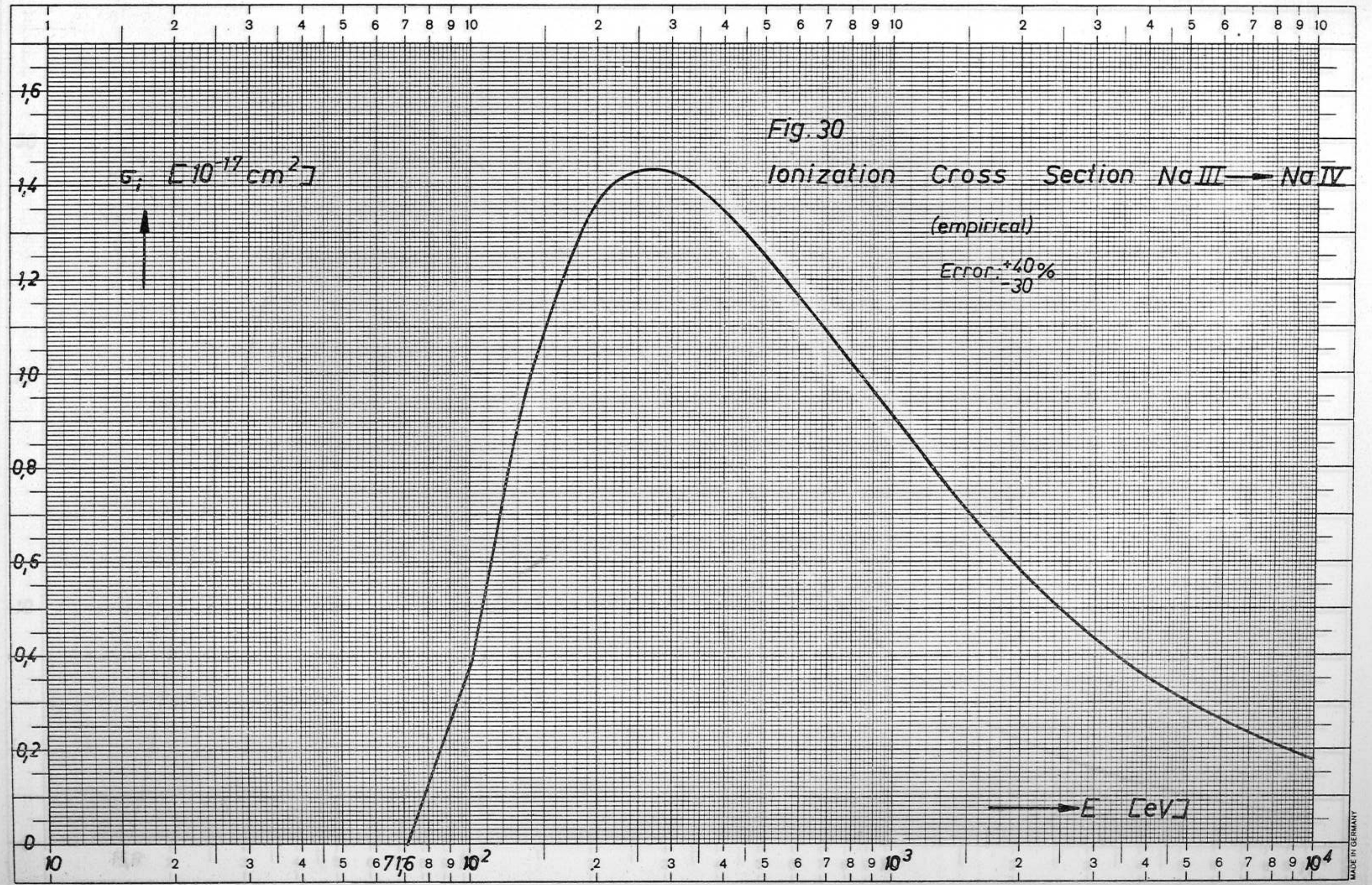


Fig. 30
Ionization Cross Section Na III → Na IV
(empirical)
Error: +40% −30
σ_i [10^-17 cm^2]
E [eV]
71,6
MADE IN GERMANY

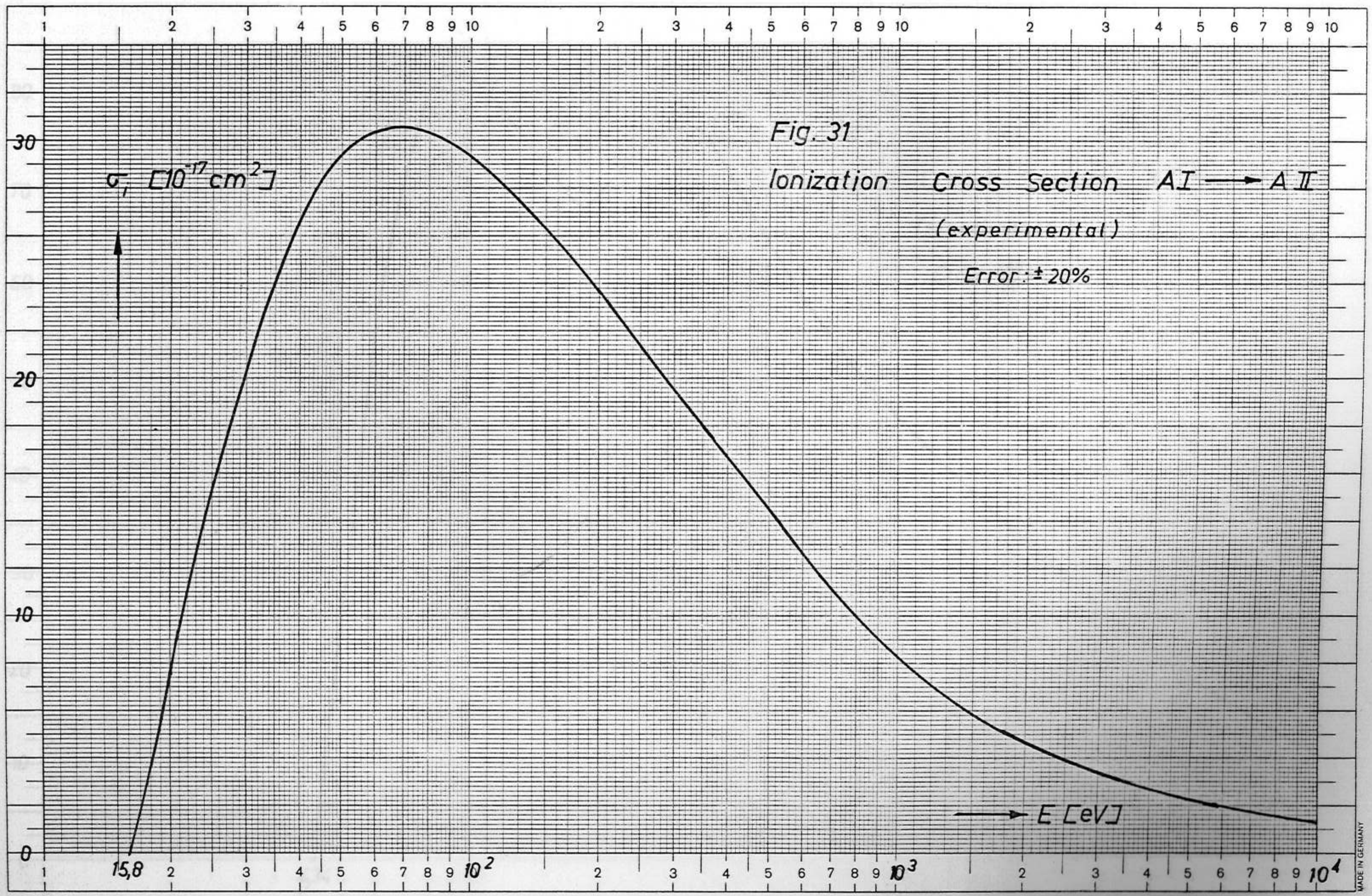


Fig. 31
Ionization Cross Section AI ⟶ AII
(experimental)
Error: ± 20%
σ_i [10^-17 cm^2]
E [eV]
15,8
10^2
10^3
10^4
0
10
20
30

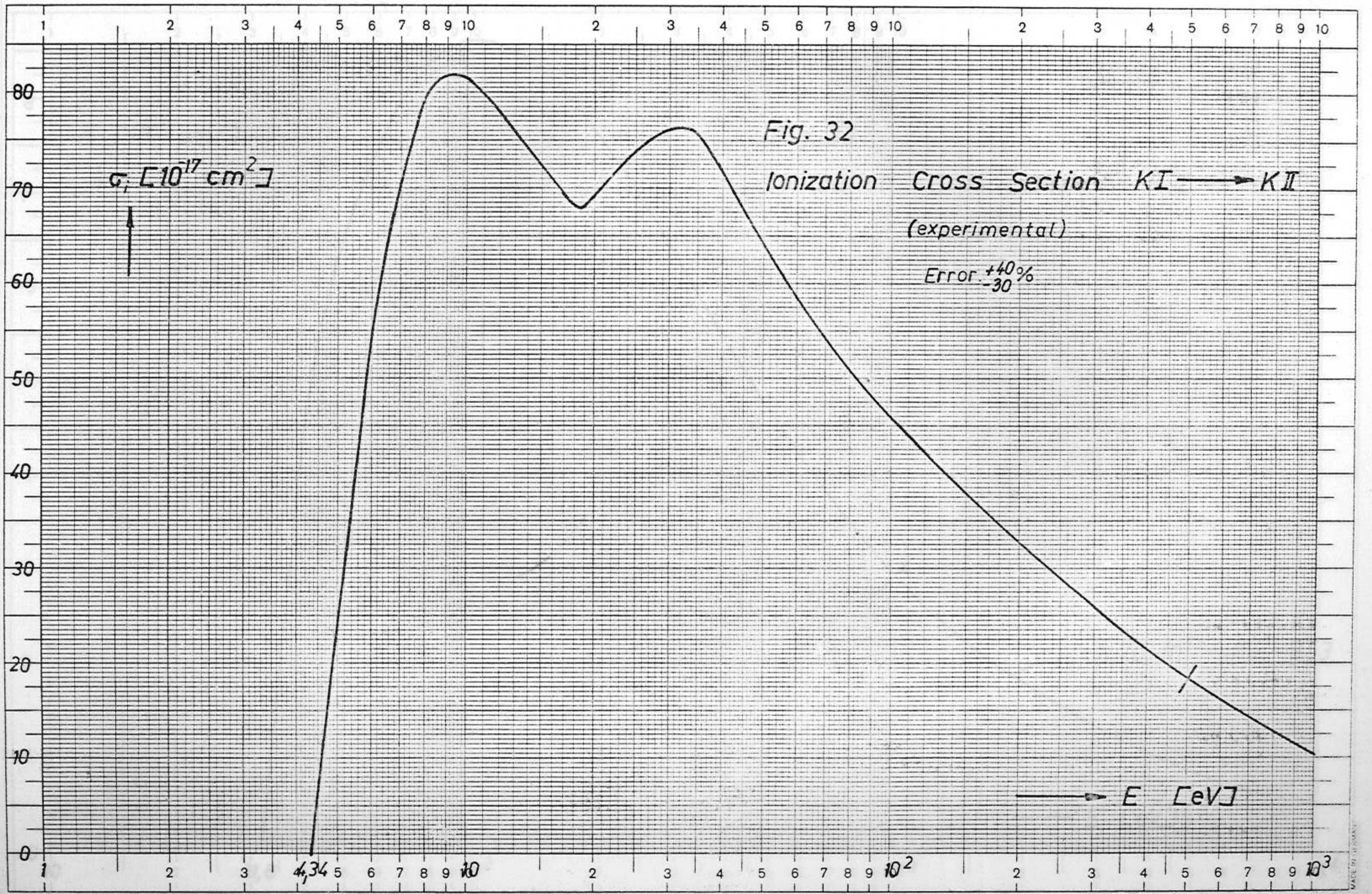


Fig. 32
Ionization Cross Section KI ⟶ KII
(experimental)
Error $^{+40}_{-30}$%
σ_i [10^{-17} cm^2]
E [eV]
4,34
10^2
10^3

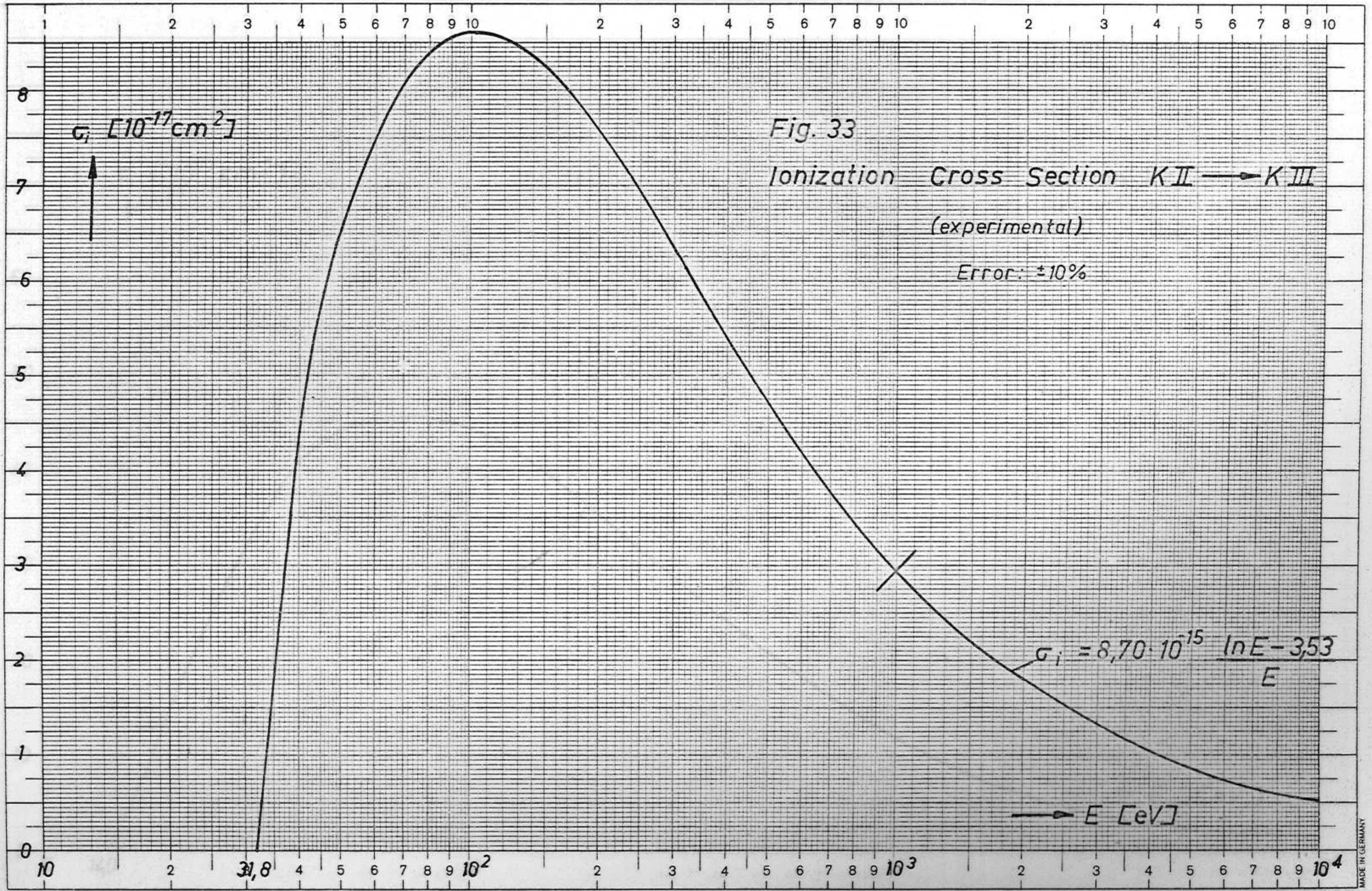


Fig. 33
Ionization Cross Section KII → KIII
(experimental)
Error: ±10%
σi [10^-17 cm^2]
σi = 8,70·10^-15 (ln E − 3,53)/E
E [eV]
31,8
10
10^2
10^3
10^4
0
1
2
3
4
5
6
7
8

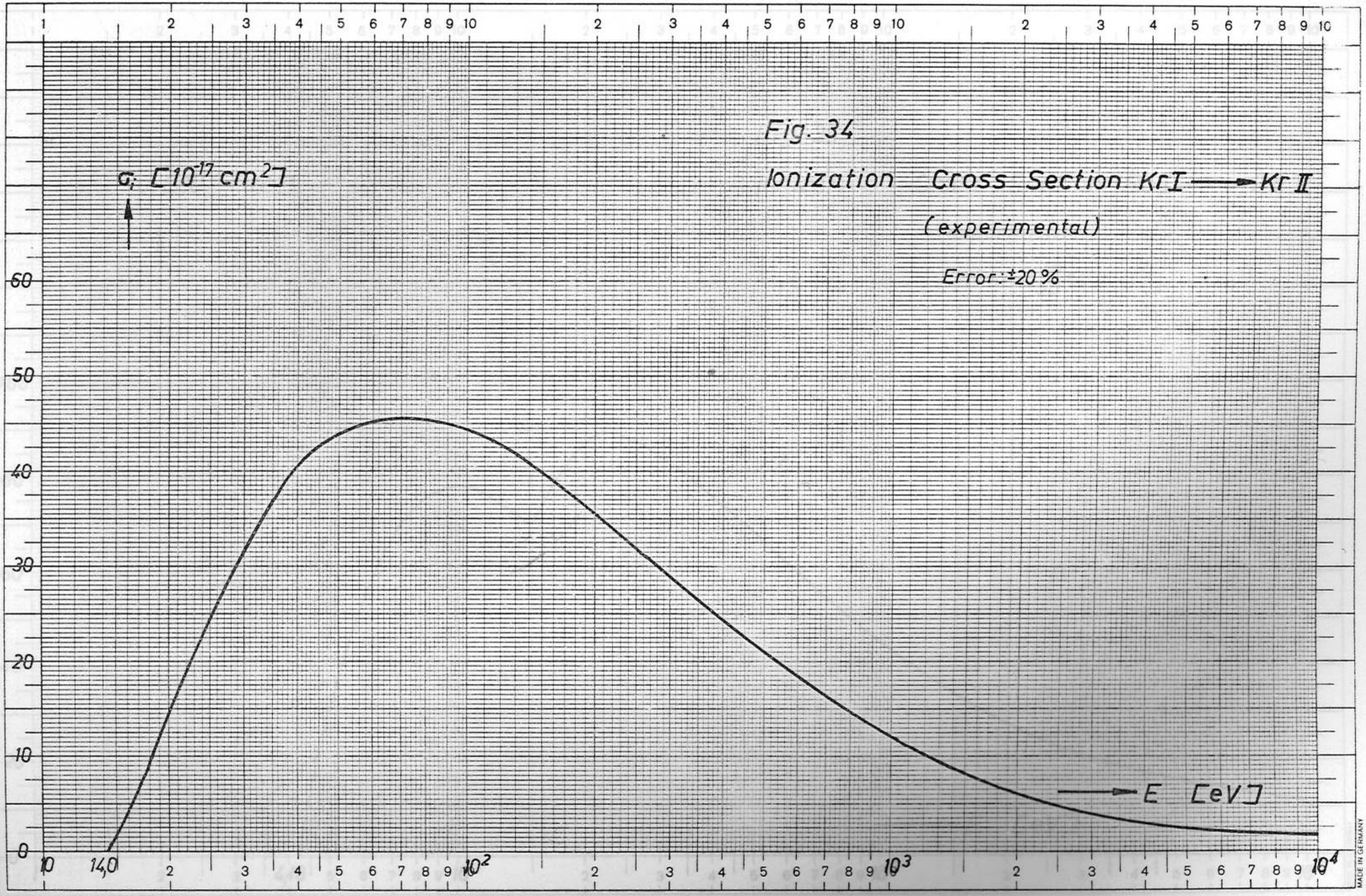


Fig. 34
Ionization Cross Section KrI ——► Kr II
(experimental)
Error: ±20 %
σᵢ [10⁻¹⁷ cm²]
E [eV]
60
50
40
30
20
10
0
10
14,0
10²
10³
10⁴
MADE IN GERMANY

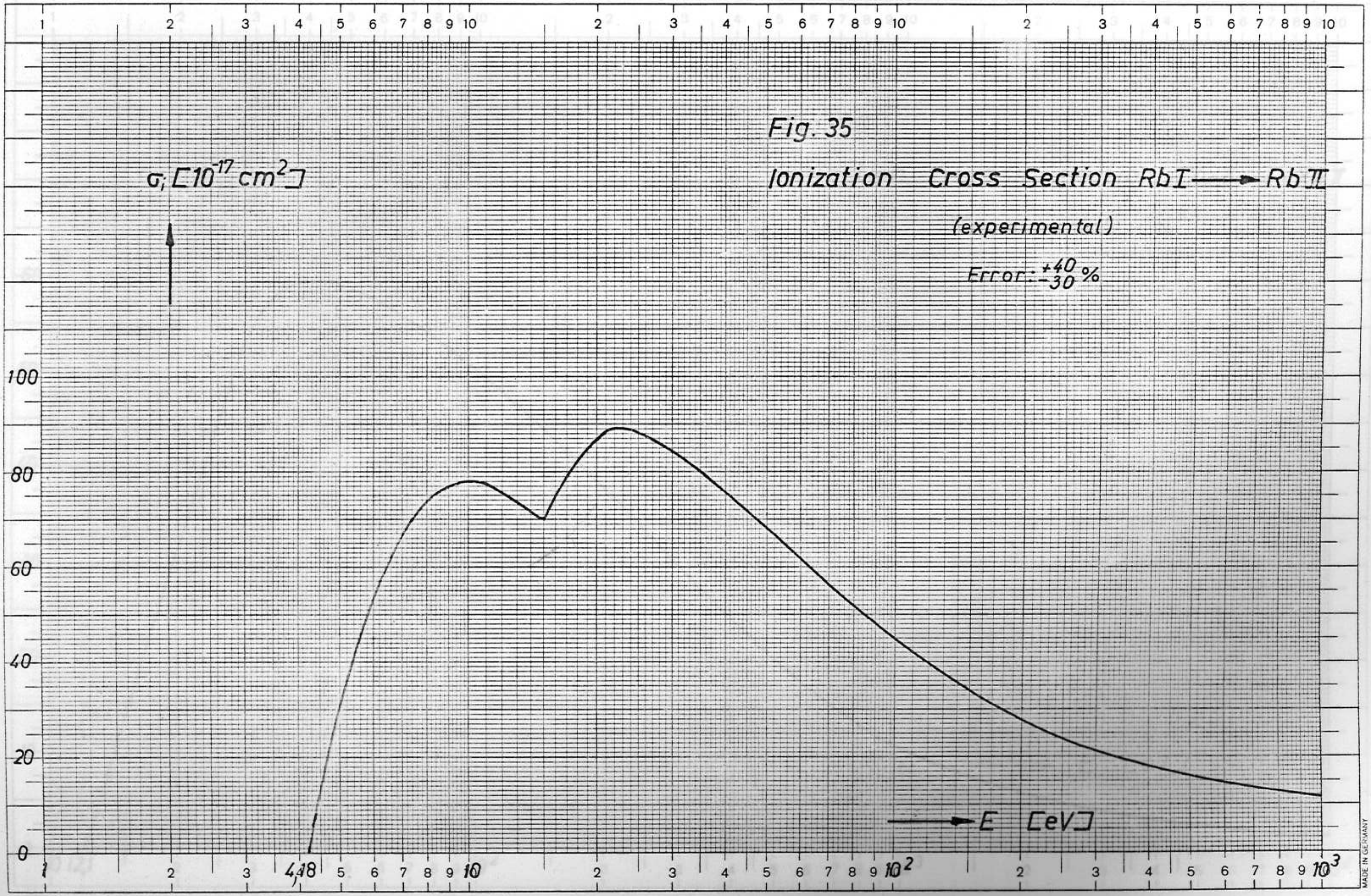


Fig. 35
Ionization Cross Section RbI ⟶ RbII
(experimental)
Error: +40 −30 %
σ_i [10^-17 cm^2]
E [eV]
4,18
100
80
60
40
20
0
1
10
10^2
10^3
MADE IN GERMANY

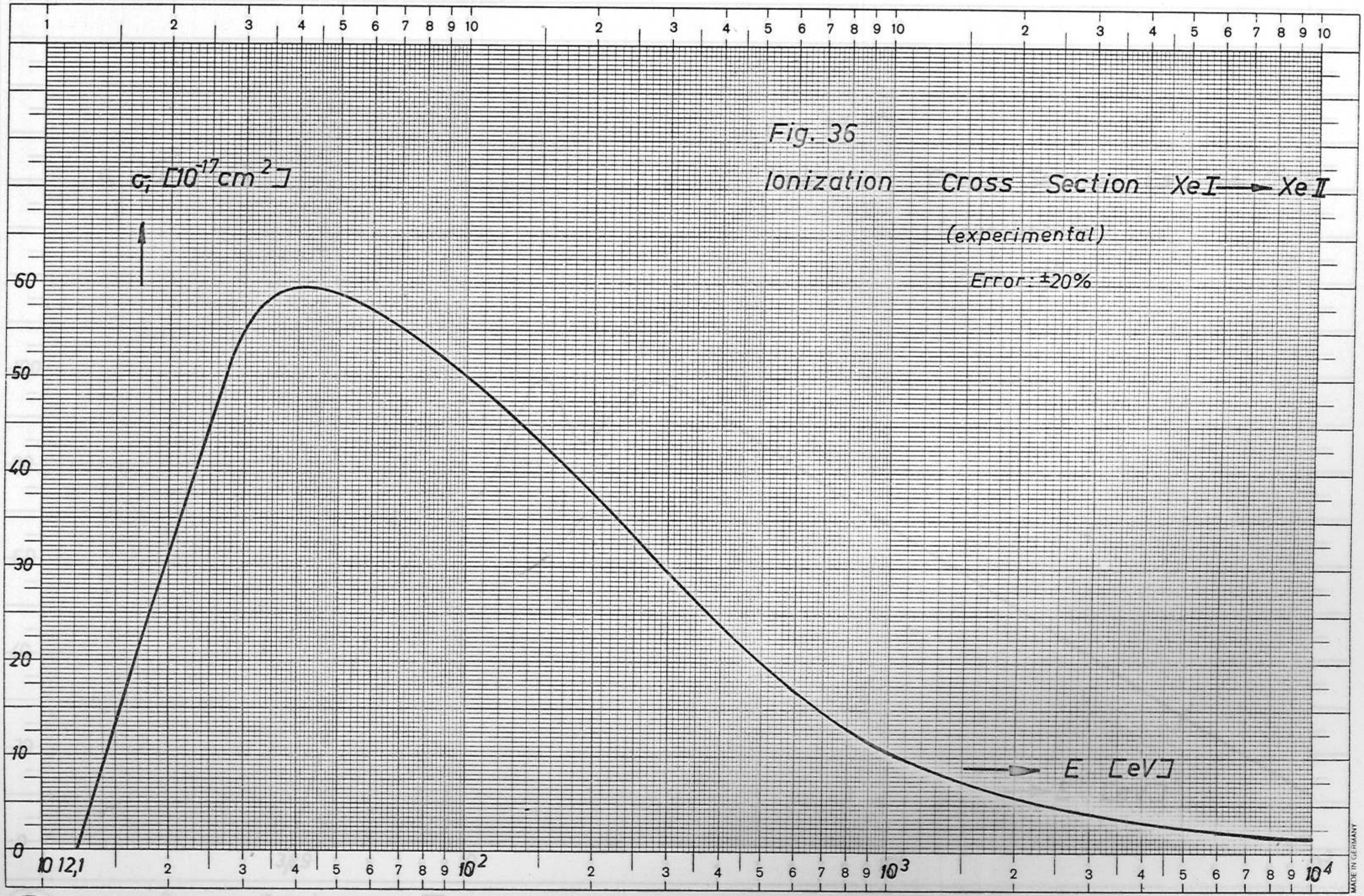


Fig. 36
Ionization Cross Section XeI ⟶ XeII
(experimental)
Error: ±20%
σ_i [$10^{-17} cm^2$]
E [eV]
0
10
20
30
40
50
60
10
12,1
10^2
10^3
10^4

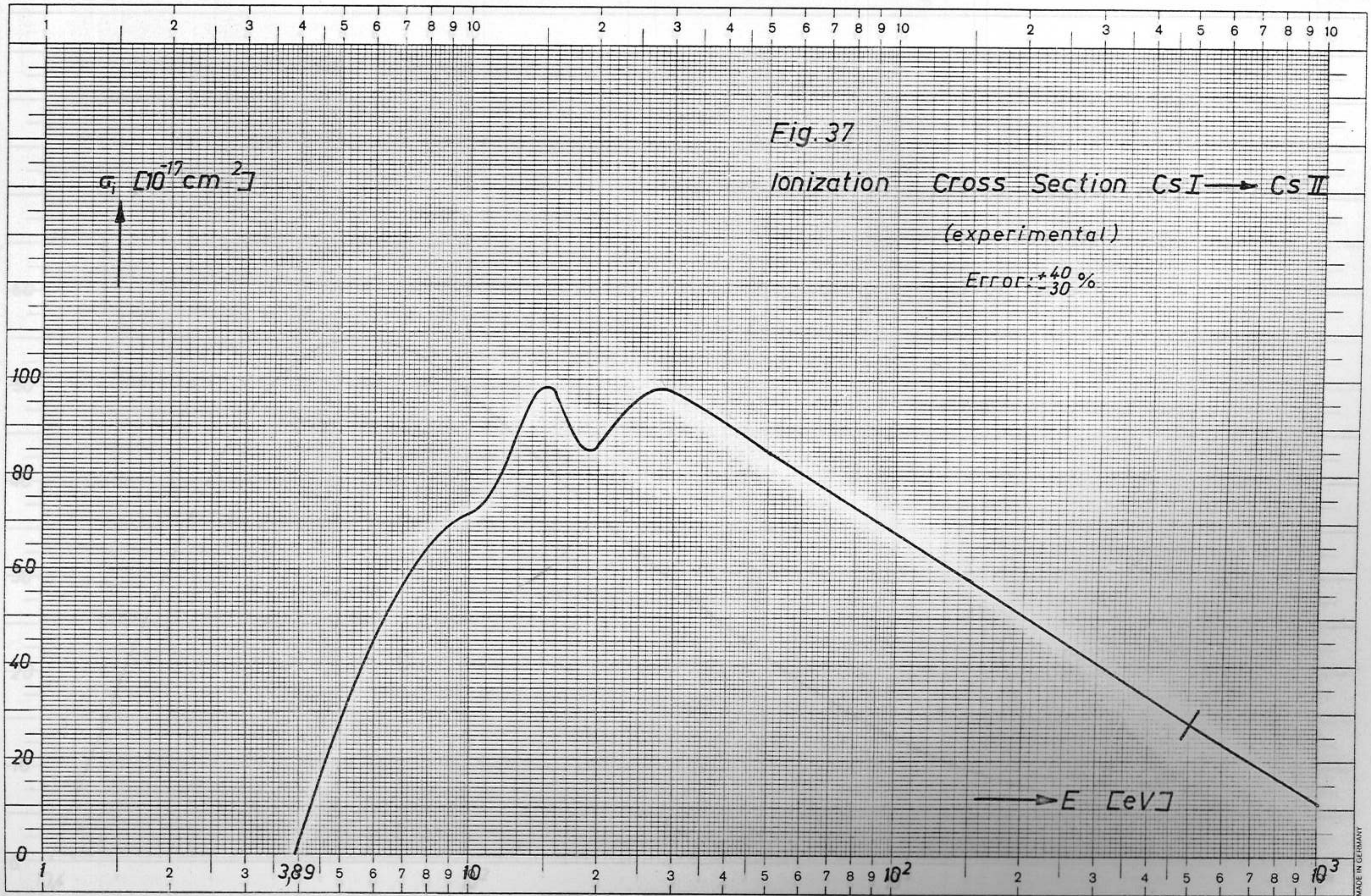


Fig. 37
Ionization Cross Section Cs I → Cs II
(experimental)
Error: +40 % −30 %
σ_i [10^-17 cm^2]
100
80
60
40
20
0
3,89
10
10^2
10^3
E [eV]

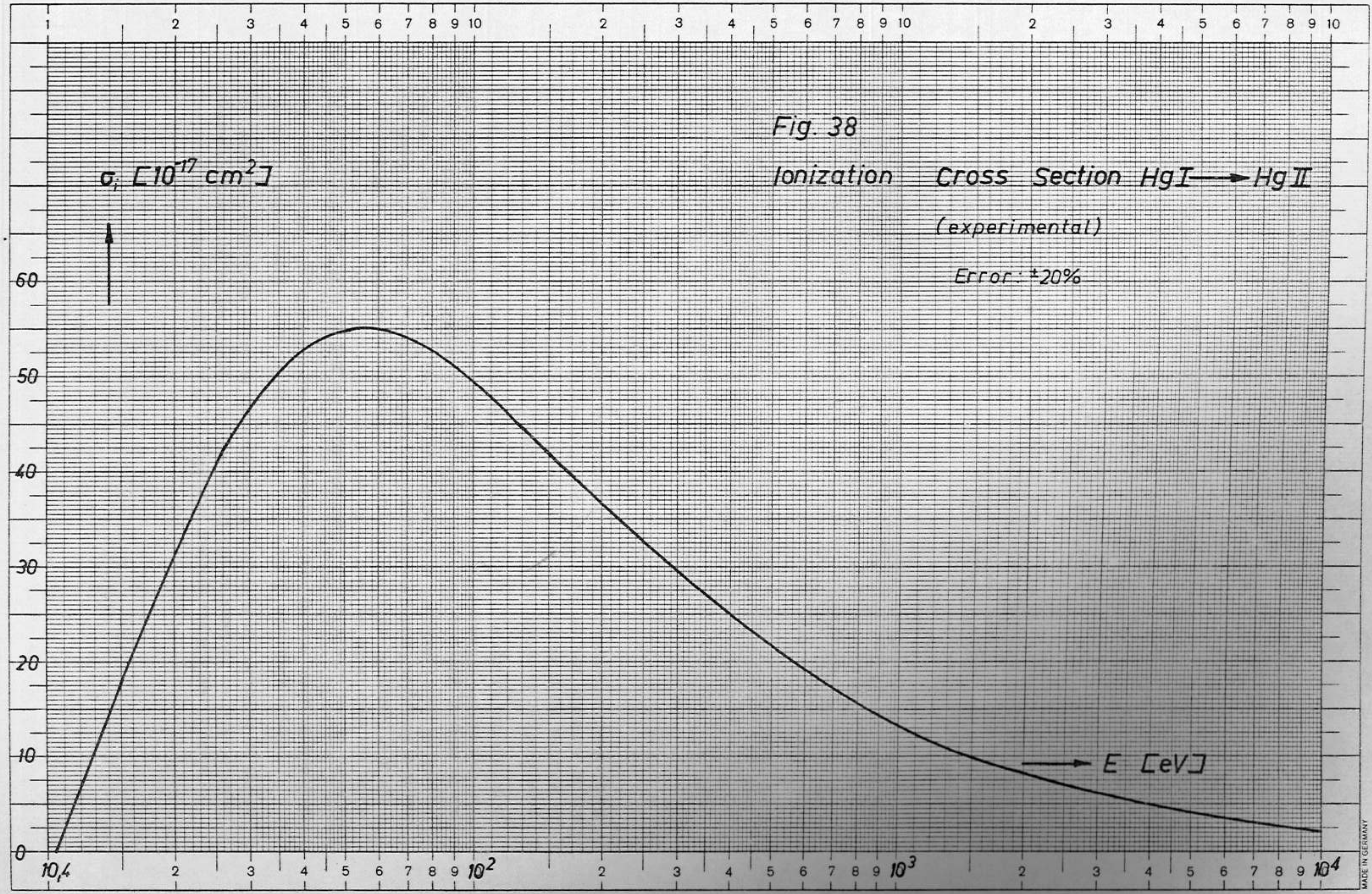


Fig. 38
Ionization Cross Section HgI ⟶ HgII
(experimental)
Error: ±20%
σᵢ [10⁻¹⁷ cm²]
E [eV]
0
10
20
30
40
50
60
10,4
10²
10³
10⁴