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THERMONUCLEAR REACTION RATES IN A DEUTERIUM-TRITIUM PLASMA

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Abstract

In a deuterium-tritium plasma six thermonuclear reactions take place between the deuterons, tritons and the ^{3}He-particles formed in about half of the d-d-reactions. The rate constants for these six reactions have been calculated from the latest evaluations of the reaction cross sections which were available. In some cases, notably the reactions t+t, t+^{3}He and ^{3}He+^{3}He, the number of published cross section measurements is small, and the uncertainty in the calculated rate constants consequently large.

Analytical expressions for the rate constants as functions of the plasma temperature have been set up.

Sammanfattning

I ett deuterium-tritium plasma förekommer sex termonukleära reaktioner mellan deutronerna, tritonerna och ^{3}He-partiklarna som bildas i ungefär hälften av d-d-reaktionerna. Reaktionsraterna för dessa reaktioner har beräknats utgående från de senaste utvärderingarna av tvärsnitten som varit tillgängliga. I några fall, särskilt gäller detta reaktionerna t+t, t+^{3}He och ^{3}He+^{3}He, är antalet publicerade tvärsnittsmätningar litet, och följaktligen är osäkerheten i de beräknade reaktionsraterna stor.

Analytiska uttryck för reaktionsraterna som funktioner av plasmatemperaturen har satts upp.

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Contents

Introduction

In a deuterium-tritium plasma only the three thermonuclear reactions d + d, d + t and t + t are initially possible. Of the new particles formed in these reactions only ^{3}He will take part in the energy production, except of course for the tritium formed in about half of the d + d-reactions. Thus, there are three more thermonuclear reactions possible, d + ^{3}He, t + ^{3}He and ^{3}He + ^{3}He, see Table 1.

Rate constants for the most important of these thermonuclear reactions were published by Tuck (Tuck 61). However, in recent years new evaluations and new results of measurements of the cross sections for the reactions $T(d,n)^{4}He$ and $D(d,n)^{3}He$ have been published (Liskien 71 and 73, Stewart 75, Drosg 78). Also surveys of the cross section data for some of the other reactions have been published by Crocker et al (Crocker 70) and Stewart and Hale (Stewart 75, cited above). These are the reasons for a reevaluation of the rate constants. Based on the data mentioned and for the reactions t + ^{3}He and ^{3}He + ^{3}He on the only experimental results that have been published (Moak 53, Good 54) the rate constants for the six thermonuclear reactions have thus been calculated.

Table 1

Reacting particles	Final reaction products	Q-value MeV	Probability
d + t	n + ^{4}He	17.6	
d + d	n + ^{3}He	3.3	50%
d + d	p + t	4.0	50%
t + t	2n + ^{4}He	11.3	
d + ^{3}He	p + ^{4}He	18.3	
t + ^{3}He	d + ^{4}He	14.3	43%
t + ^{3}He	p + n + ^{4}He	12.1	57%
^{3}He + ^{3}He	2p + ^{4}He	12.8	

In a plasma with a Maxwell distribution the number of reactions per unit of volume and time between two kinds of particles A and B with the concentrations N_A and N_B is $C.N_A.N_B$ where the rate constant C is

$$C = \frac{1}{\sqrt{\pi m_A}} \left(\frac{2m_B}{(m_A+m_B)kT}\right)^{3/2} \int_0^\infty e^{-\frac{m_B E}{(m_A+m_B)kT}} \sigma(E).E.dE.$$

Here m_A and m_B are the masses of the particles, T is the temperature of the plasma, $\sigma(E)$ the cross section and E the energy of particle A in the coordinate frame where particle B is at rest. Thus the rate constant can be calculated by numerical integration over an energy range where the cross section is known.

At very low energies E where no published data exist, the cross sections have been assumed to vary with E according to the Gamow approximation. Thus

$$\sigma = \frac{c_1}{E} e^{-31.40\, Z_A Z_B \sqrt{M_A/E}}$$

where Z_A, Z_B are the charge numbers, M_A the mass number and E is measured in keV. By adjusting the constant c_1 the cross section has been fitted to the experimental data for the lowest energies.

At high energies, at least above 20 MeV, there are no experimental data and for most of the reactions in Table 1 the cross sections have been assumed to vary as

$$\sigma = c_2\, E^{-c_3}.$$

The constants c_2 and c_3 have been adjusted to fit both the measured cross section and its slope at the highest energies in a log E - log σ diagram.

The rate constants for the different reactions have then been calculated numerically and the values have been tabulated in Tables 2 and 3. The assumed values of the cross sections for energies above the measured data have negligible influence on the rate constant below a temperature of 500 keV for the first five reactions of Table 1.

For the reactions t + ^{3}He and ^{3}He + ^{3}He there seems to be no experimental data above 800 keV triton- or ^{3}He-energy. In these cases the rate constants were calculated by assuming a constant value of the cross section above 800 keV. This is a very poor approximation but it is easy to calculate the plasma temperature at which this part of the cross section will make a sizeable contribution to the rate constant.

When the rate constants are used in for instance fusion plasma calculations it is often convenient to employ analytical expressions. The only way to obtain a fairly simple expression valid over a large temperature region, say 0.5-500 keV, seems to be to express log C as a polynomial in log(kT). Such expressions have been set up for the different reaction rate constants. Brigg´s logarithms have been used here for greater convenience in plotting. The constants in the polynomials have been determined by minimizing the sum of the squares of the differences between the value of the analytical expression and the corresponding value in Table 2. In large computer calculations such expressions are probably not the most economical to use. Instead special algorithms adjusted to the problem in question should perhaps be preferred.

1 The reaction T(d,n)^{4}He

The reaction T(d,n)^{4}He is the most thoroughly investigated of all the thermonuclear and neutron-producing reactions and the cross section is probably known with an accuracy of about one percent except at very low and very high energies where the uncertainty is larger. The rate constant has been calculated by use of the results of the R-matrix-calculations of the cross section published by Stewart and Hale (Stewart 75) for the region 5 keV-1 MeV, "the LASL prediction". These data fit very well to the measured points. In the deuteron energy region 1-6 MeV the data published by Liskien and Paulsen (Liskien 73) have been used and above 6 MeV the data published by Drosg (Drosg 78). For deuteron energies below 5 keV the cross section has been assumed to vary as

$$\sigma = \frac{18160}{E} e^{-44.4/\sqrt{E}}, \sigma \text{ in barn, E in keV.}$$

Above 6 MeV the analytical expression

$$\sigma = 52\ E^{-0.75}, \sigma \text{ in barn, E in keV}$$

was found to fit very well to the data.

In figure 1 are shown the cross section data together with the low and high energy fits. In figure 2 are shown the calculated values of the rate constant together with the analytical approximation

$$^{10}\log C = -21.06+(x-x_o)^2(-1.57+0.1519x-0.00879x^2+0.08191x^3-0.017357x^4).$$

Here C is obtained in m^3s^{-1} and $x = {}^{10}\log(kT)$, kT in keV. $x_o = {}^{10}\log 66.3 =$ $= 1.8215$. The expression has been chosen to give the correct value and location of the maximum in C, which is $0.871 \times 10^{-21}\ m^3s^{-1}$ at 66.3 keV. The relative error in the analytical approximation is shown in figure 3. It is smaller than about 10 % in the temperature region 0.1 keV - 5 MeV.

A simpler but less accurate analytical expression usable in the region 1-100 keV is

$$C = 0.87 \cdot 10^{-21} \cdot e^{-0.546|\log y|^{2.15}} \qquad m^3s^{-1}$$

$$\text{where } y = \frac{kT}{66}, \text{ kT in keV.}$$

The deuteron energy range above 10 MeV and the assumed cross section in this region contributes 0.4 % to the value of the rate constant at 1 MeV temperature and 40% to its value at 5 MeV.

2 The reactions $D(d,n)^3He$ and $D(d,p)t$

An evaluation of the $D(d,n)^3He$ cross section based on different experimental investigations has been published by Liskien and Paulsen (Liskien 71). It covers the energy region 20 keV - 10 MeV. Recently

Drosg has published values for the region 3 - 25 MeV (Drosg 78). For deuteron energies below 20 keV the Gamow approximation

$$\sigma = \frac{100}{E} e^{-44.4/\sqrt{E}}, \quad \sigma \text{ in barn, } E \text{ in keV}$$

has been used and for deuteron energies above 6 MeV the analytical expression

$$\sigma = 0.113e^{-0.0000316E}, \quad \sigma \text{ in barn, } E \text{ in keV.}$$

The cross section data together with the low and high energy fits are shown in figure 4. The rate constant has the analytical approximation

$$^{10}\log C = -28.032+5.6885x-2.4010x^2+0.61048x^3-0.082645x^4+0.003993x^5$$
$$C \text{ in } m^3s^{-1}, \; x = {}^{10}\log(kT), \; kT \text{ in keV.}$$

The relative error in the analytical approximation of C is smaller than about 5 %.
The range above 10 MeV deuteron energy contributes 3 % to the value of the rate constant at 1 MeV temperature and 70% to its value at 5 MeV.

Data for the cross section of the proton branch D(d,p)T have been put together by Crocker et al (Crocker 70). By making a "conservative" choice of the cross section, e.g. choosing the smallest experimental data, one obtains values which are somewhat smaller than for the neutron branch in the region 100 keV - 5 MeV deuteron energy, see figure 5. However, both below 20 keV and above 6 MeV the same approximations of the cross section as for the neutron branch will fit the data.

The analytical approximation for the rate constant for the proton branch is

$$^{10}\log C = -28.058+5.6127-2.3956x^2+0.64776x^3-0.10058x^4+0.006459x^5$$
$$C \text{ in } m^3s^{-1}, \; x = {}^{10}\log(kT), \; kT \text{ in keV.}$$

The relative error in the analytical approximation is smaller than 3%. C is at most 16 % lower than for the neutron branch and the maximum deviation occurs at about 300 keV temperature.

3 The reaction $T(t,2n)^4He$

Experimental data for the reaction $T(t,2n)^4He$ have been put together by Stewart and Hale (Stewart 75). The agreement between the results of different investigators is not very good. In order to obtain a "conservative" estimate of the cross section and the rate constant the data obtained by Strelnikov et al up to 400 keV triton energy have been used. These data fit well to the low energy Gamow approximation

$$\sigma = \frac{326}{E} e^{-54.5/\sqrt{E}} , \quad \sigma \text{ in barn, E in keV.}$$

Above 400 keV the data obtained by Govorov and above 2.5 MeV Duane's fit were used, see Stewart 75. Above 10 MeV triton energy the cross section is assumed to vary as

$$\sigma = 0.001 \left(\frac{E}{10000}\right)^{-3.6} , \quad \sigma \text{ in barn, E in keV,}$$

though the extremely rapid decrease in the cross section with increasing triton energy looks rather unnatural. The cross section data together with the low and high energy fits are shown in figure 6.

The analytical approximation of the rate constant is

$$^{10}\log C = -28.781 + 6.5386x - 2.8399x^2 + 0.70854x^3 - 0.08140x^4$$

$$C \text{ in } m^3 s^{-1}, \quad x = {}^{10}\log(kT), \text{ kT in keV.}$$

The range above 10 MeV triton energy makes a negligible contribution to the value of the rate constant at 1 MeV temperature and contributes 2 % at 5 MeV.

The value of the cross section especially at high triton energies is very uncertain, which produces a corresponding uncertainty in C for temperatures above about 500 keV.

4 The reaction $^{3}He(d,p)^{4}He$

Cross section data for this reaction have been put together by Crocker et al (Crocker 70). The data show a fairly large spread. The most recent of these data obtained by Bonner et al and Kunz (Bonner 52, Kunz 55) are in reasonably good agreement and will also give a "conservative" estimate of the cross section. The data in the region 200 keV - 1 MeV have been fitted to the following expression for σ

$$\sigma = \frac{24300}{E} e^{-88.8/\sqrt{E}} \frac{1}{1+0.0000154(E-328)^2}, \quad \sigma \text{ in barn, E in keV.}$$

Here the product of the Gamow penetrability and the Lorentzian was used because the data points cover the region around the resonance.

The data obtained by Stewart et al (Stewart 60) have been used to extend the estimate of the cross section over the region above 10 MeV. Thus the high energy approximation

$$\sigma = 0.0507 \left(\frac{E}{10000}\right)^{-0.65}, \quad \sigma \text{ in barn, E in keV,}$$

has been used for $E > 10$ MeV. The cross section data and the low and high energy fits are shown in figure 7.

The analytical approximation of the rate constant is

$$^{10}\log C = -31.655 + 9.8306x - 3.03598x^2 + 0.25848x^3 + 0.010397x^4$$

$$C \text{ in } m^3s^{-1}, \quad x = {}^{10}\log(kT), \text{ kT in keV.}$$

The range above 10 MeV deuteron energy contributes 0.6 % to the value of the rate constant at 1 MeV temperature and 45 % to its value at 5 MeV.

5 The reactions $^{3}He(t,d)^{4}He$ and $^{3}He(t,p+n)^{4}He$

The only data for the cross sections of these reactions that have been published seems to be those by Moak (Moak 53). They cover the triton energy region 100-800 keV and over the whole region the reaction $^{3}He(t,d)^{4}He$ occurs with 43 % probability. The other possibilities are the three-body break-up of the compound nucleus ^{6}Li in the reaction $^{3}He(t,p+n)^{4}He$ or the formation of ^{5}He in the reaction $^{3}He(t,p)^{5}He$ followed instantaneously by the disintegration of ^{5}He into a neutron and ^{4}He.

The data for the total cross section including all three reactions were fitted to the low energy Gamow approximation

$$\sigma = \frac{5920}{E} e^{-108.8/\sqrt{E}} , \quad \sigma \text{ in barn, E in keV.}$$

For triton energies above 800 keV the cross section was assumed to remain at the constant value of 0.16 barn which is the measured value at 800 keV. The data together with the low energy fit is shown in figure 8.

The analytical approximation of the rate constant for the sum of all three reactions is

$$^{10}\log C = -32.9737 + 10.8825x - 4.53521x^2 + 1.1243x^3 - 0.141042x^4$$

$$C \text{ in } m^3 s^{-1}, \quad x = {}^{10}\log(kT), \text{ kT in keV.}$$

The triton energy range above 800 keV with the assumed constant cross section has a negligible influence on the rate constant at 20 keV temperature, contributes 2.4 % at 50 keV and 23 % at 100 keV.

6 The reaction $^{3}He(^{3}He, 2p)^{4}He$

The only data for the cross section of this reaction that exist seem to be those published by Good et al (Good 54). They cover the same energy range as the data for the ^{3}He+t-reactions, 100-800 keV. The data have here been fitted to the low energy Gamow approximation

$$\sigma = \frac{2930}{E} e^{-217.5/\sqrt{E}} , \quad \sigma \text{ in barn, E in keV.}$$

For energies above 800 keV a constant value of the cross section was used in the calculations of the rate constant, 0.0018 barn. The data together with the low energy fit are shown in figure 9.

The analytical approximation of the rate constant is

$$^{10}\log C = -41.5734 + 16.0485x - 4.78245x^2 + 0.270038x^3 + 0.128987x^4$$

$$C \text{ in } m^3s^{-1},\ x = {}^{10}\log(kT),\ kT \text{ in keV.}$$

At 20 keV temperature the contribution to the rate constant from the energy range above 800 keV is negligible. At 50 keV temperature this contribution amounts to 8 %

7 Conclusions

The rate constants for the reactions d+d, d+t and t+t as functions of temperature are shown in figure 10 and for the reactions involving ^{3}He in figure 11.

The accuracy of the calculated values of the rate constants is difficult to estimate. The d+t-reaction is the best known and the probable error in C is in this case of the order of 1% in the temperature region 100 keV - 1 MeV but larger below 10 keV temperature. The second best known reaction is probably the neutron branch of the d+d-reaction and the probable error in C is of the same order of magnitude. The probable error for the proton branch is larger.

The values of the rate constants for the reactions t+t and d+^{3}He are more uncertain. The probable error in C is estimated to be of the order of tens of percent below about 1 MeV. For these reactions the calculated values of C should be "conservative", e.g. the correct value is probably larger.

The values of the rate constants for the last reactions, t+^{3}He and ^{3}He+^{3}He, are still more uncertain and the temperature region within which they are fairly reliable is more narrow; it extends up to 50-100 keV only.

References:

Bonner 52 — T W Bonner, J P Conner, A B Lillie, Cross Section and Angular Distribution of the $He^3(d,p)He^4$ Nuclear Reaction, Phys Rev vol 88 p 473, 1952

Crocker 70 — V S Crocker, S Blow, C J H Watson, Nuclear Cross-section Requirements for Fusion Reactors, UKAEA, Culham Lab, CLM-P 240, 1970

D-osg 78 — M Drosg, Unified Absolute Differential Cross Sections for Neutron Production by the Hydrogen Isotopes for Charged-Particle Energies between 6 and 17 MeV, Nucl Sci Eng vol 67, p 190, 1978

Good 54 — W M Good, W E Kunz, C D Moak, The $He^3 + He^3$ Reactions, Phys Rev vol 94, p 87, 1954

Kunz 55 — W E Kunz, Deuterium He^3 Reaction, Phys Rev vol 97, p 456, 1955

Liskien 71 — H Liskien, A Paulsen, An Evaluation for Cross Sections of the Reaction $D(d,n)^3He$, EANDC(E)-143 "L", 1971

Liskien 73 — H Liskien, A Paulsen, Nucl Data Tables vol 11, p 569, 1973

Moak 53 — C D Moak, A Study of the $H^3 + He^3$ Reactions, Phys Rev vol 92, p 383, 1953

Stewart 60 — L Stewart, J E Brolley Jr, L Rosen, Interaction of 6- to 14-MeV Deuterons with Helium Three and Tritium, Phys Rev vol 119, p 1649, 1960

Stewart 75 — L Stewart, G M Hale, The $T(d,n)^4He$ and T(t,2n) Cross Sections at Low Energies, Los Alamos, LA-5828-MS (USNDC-CTR-2), 1975

Table 2. Calculated rate constant in $m^{+3}s^{-1}$. The number .148-30 means 0.148×10^{-30}.

Temperature	$T(d,n)^4He$	$D(d,n)^3He$	$D(d,p)T$	$^3He(d,p)^4He$	$T(t,2n)^4He$
keV					
.1	.241-35	.150-36	.150-36		
.2	.110-31	.403-33	.403-33		.103-34
.4	.735-29	.194-30	.194-30	.624-36	.131-31
.8	.142-26	.238-28	.238-28	.289-32	.348-29
1	.590-26	.881-28	.876-28	.295-31	.159-28
2	.260-24	.293-26	.268-26	.136-28	.861-27
3	.164-23	.160-25	.134-25	.263-27	.577-26
4	.530-23	.456-25	.372-25	.169-26	.188-25
5	.122-22	.944-25	.773-25	.632-26	.431-25
6	.231-22	.163-24	.135-24	.173-25	.803-25
7	.383-22	.251-24	.210-24	.386-25	.131-24
8	.575-22	.357-24	.301-24	.752-25	.196-24
9	.804-22	.481-24	.407-24	.132-24	.275-24
10	.106-21	.620-24	.526-24	.214-24	.366-24
15	.262-21	.150-23	.128-23	.117-23	.985-24
20	.419-21	.260-23	.223-23	.339-23	.181-23
30	.652-21	.520-23	.451-23	.127-22	.379-23
40	.782-21	.811-23	.708-23	.284-22	.596-23
50	.844-21	.112-22	.976-23	.482-22	.817-23
60	.868-21	.144-22	.125-22	.696-22	.102-22
70	.870-21	.176-22	.153-22	.908-22	.124-22
80	.860-21	.208-22	.180-22	.111-21	.146-22
90	.843-21	.239-22	.208-22	.129-21	.167-22
100	.822-21	.271-22	.232-22	.145-21	.188-22
150	.711-21	.418-22	.353-22	.199-21	.287-22
200	.619-21	.548-22	.460-22	.224-21	.380-22
300	.493-21	.761-22	.637-22	.238-21	.530-22
400	.415-21	.928-22	.788-22	.236-21	.626-22
500	.364-21	.106-21	.912-22	.229-21	.678-22
600	.328-21	.118-21	.102-21	.223-21	.699-22
700	.300-21	.127-21	.111-21	.217-21	.699-22
800	.280-21	.136-21	.121-21	.211-21	.688-22
900	.273-21	.144-21	.128-21	.208-21	.669-22
1000	.260-21	.150-21	.135-21	.203-21	.646-22
1500	.219-21	.176-21	.163-21	.188-21	.523-22
2000	.199-21	.193-21	.182-21	.179-21	.422-22
3000	.179-21	.213-21	.206-21	.172-21	.290-22
4000	.167-21	.223-21	.217-21	.165-21	.214-22
5000	.161-21	.226-21	.221-21	.159-21	.165-22

Table 3. Calculated rate constants in m^3s^{-1}. The number .105-32 means 0.105×10^{-32}.

Temperature keV	$^3He(t,d)^4He$ + $^3He(t,p+n)^4He$	$^3He(^3He,2p)^4He$
1	.105-32	
2	.639-30	.646-37
3	.199-28	.114-34
4	.147-27	.291-33
5	.593-27	.265-32
6	.171-26	.149-31
7	.387-26	.625-31
8	.764-26	.199-30
9	.138-25	.531-30
10	.226-25	.123-29
15	.129-24	.235-28
20	.379-24	.149-27
30	.144-23	.156-26
40	.328-23	.687-26
50	.583-23	.187-25
60	.895-23	
70	.125-22	
80	.163-22	
90	.202-22	
100	.242-22	

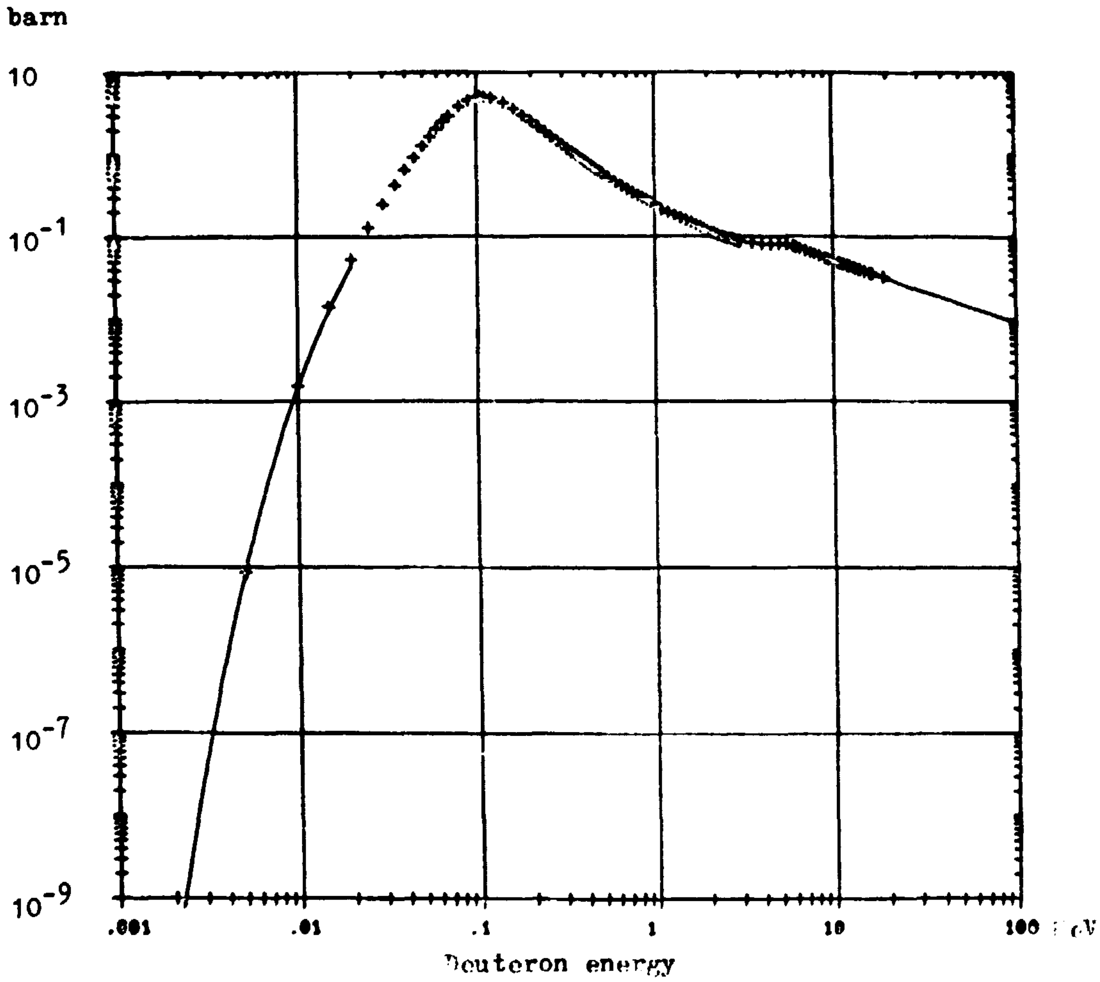

Figure 1. The cross section for the reaction $T(d,n)^4He$ as a function of deuteron energy. + mark the data published in Stewart 75, Liskien 73 and Drosg 78. The solid lines show the low energy fit

$$\frac{18160}{E} e^{-44.4/\sqrt{E}}$$ and the high energy fit $52.E^{-0.75}$

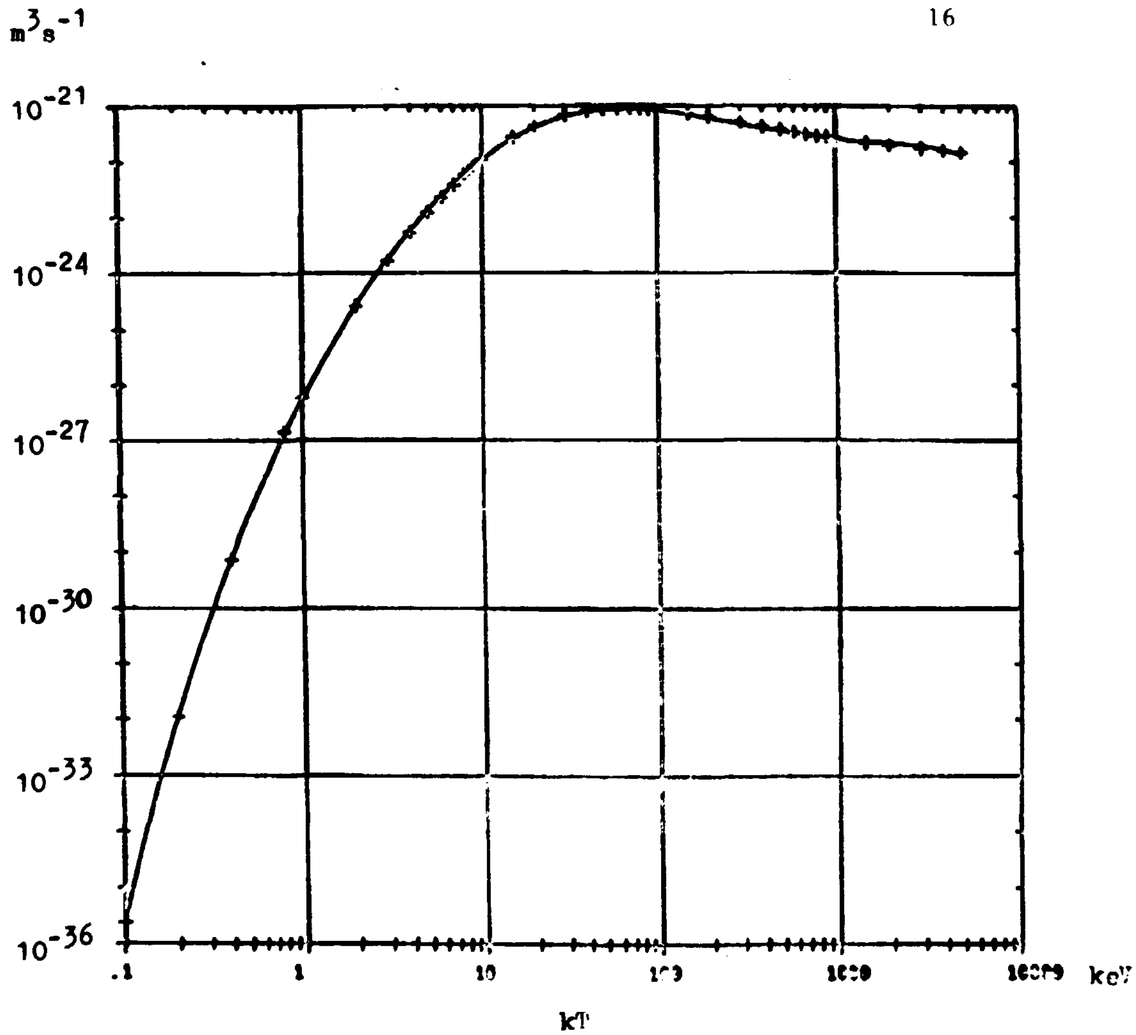

Figure 2. The rate constant for the reaction $T(d,n)^4He$ as a function of temperature. + mark the calculated values, the solid line shows the analytical approximation.

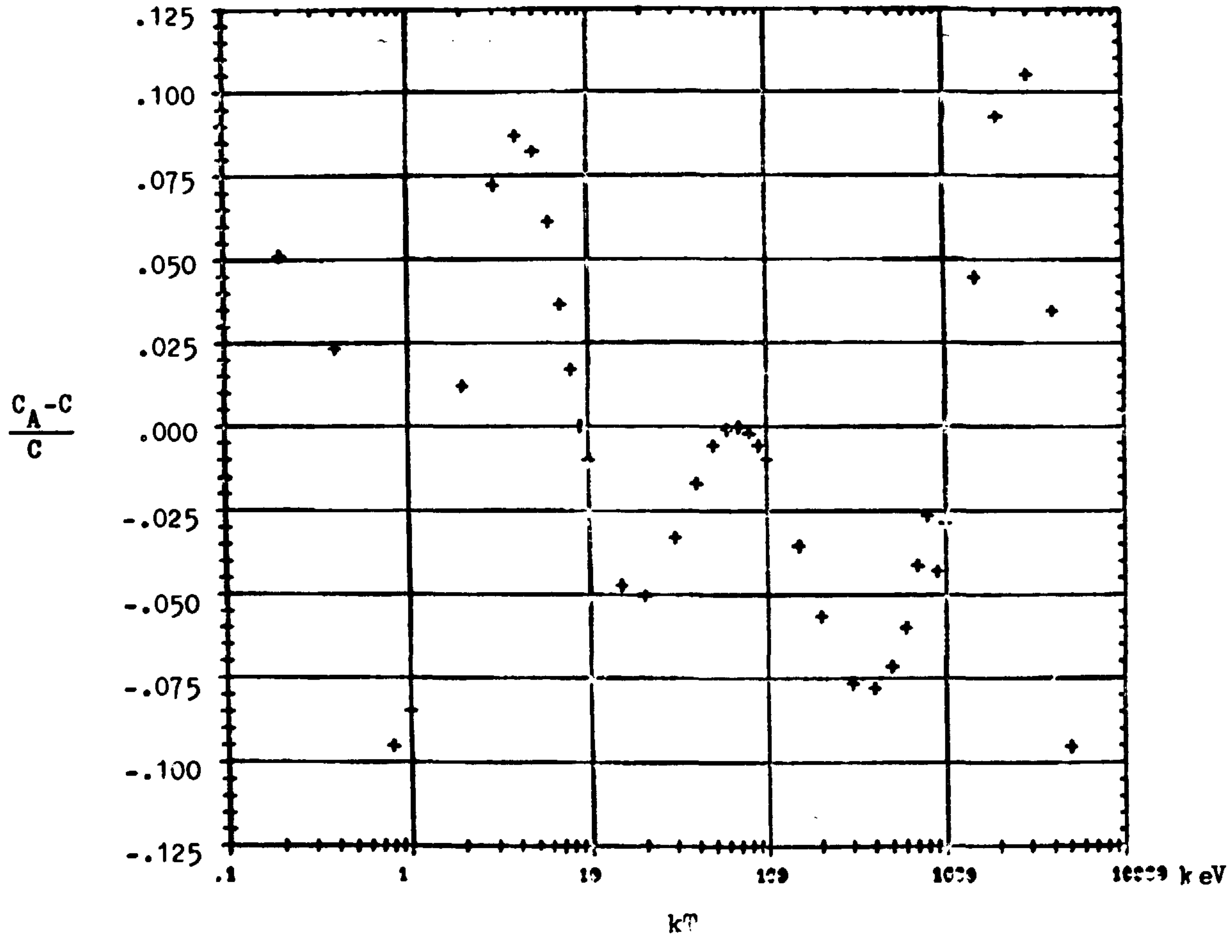

Figure 3. The relative error in the analytical approximation of the rate constant for the reaction $T(d,n)^4He$, C_A, when compared to the calculated values, C, as a function of temperature.

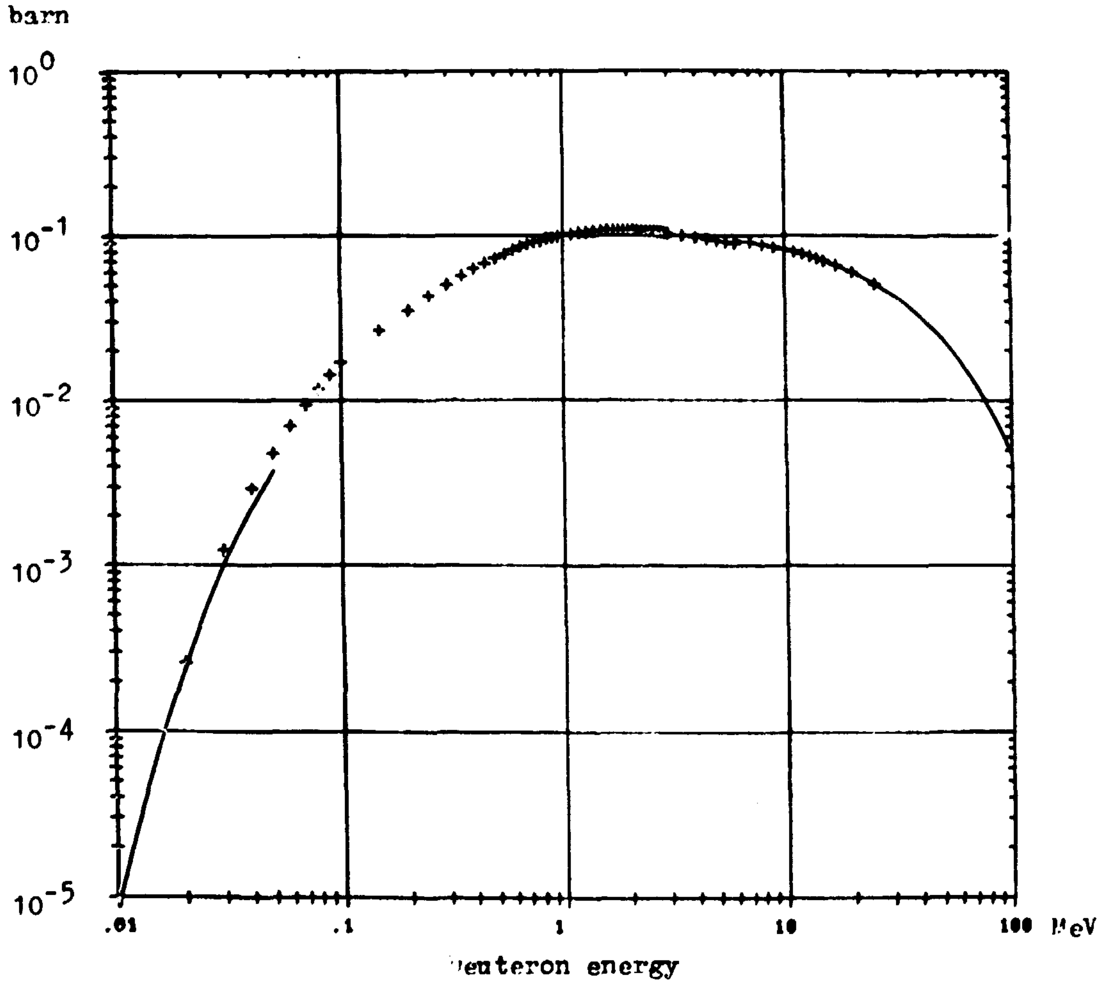

Figure 4. The cross section for the reaction $D(d,n)^3He$ as a function of deuteron energy. + mark the data published in Liskien 71 and Drosg 78. The solid lines show the low energy fit

$\frac{100}{E} e^{-44.4/\sqrt{E}}$ and the high energy fit $0.113e^{-0.0000316E}$

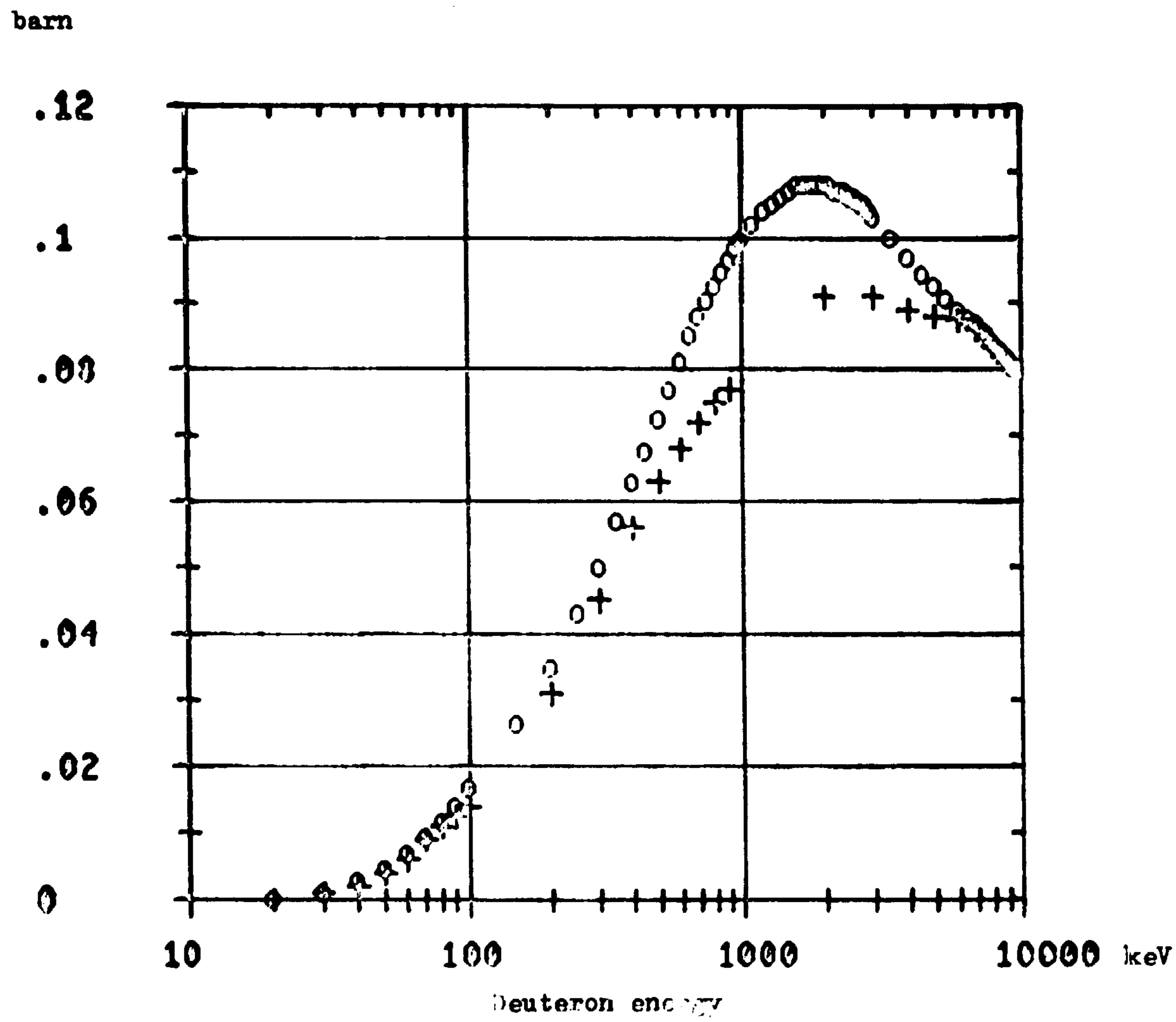

Figure 5. The cross sections for the reactions D(d,n)^{3}He (o) and D(d,p)T (+) as functions of deuteron energy.

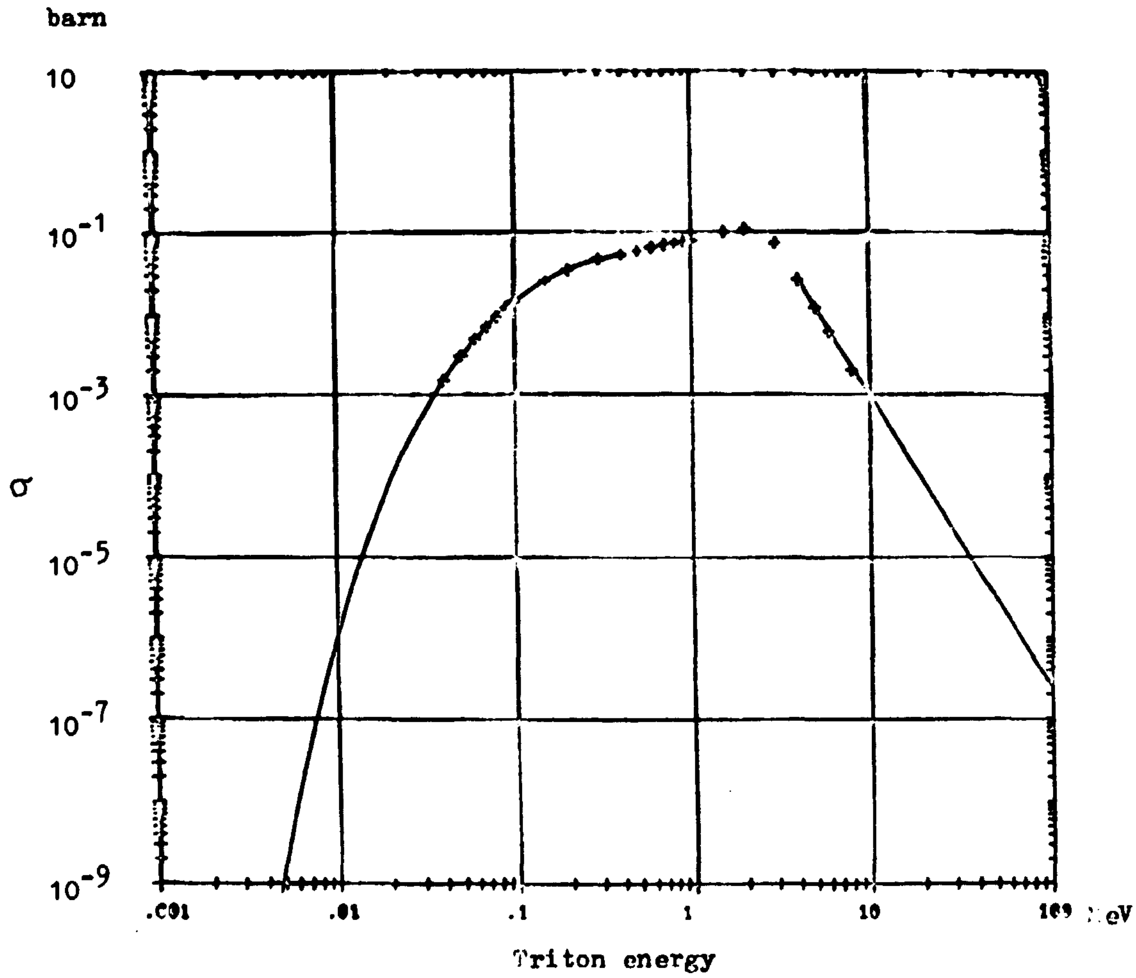

Figure 6 The cross section data that have been used for the reaction $T(t,2n)^4He$. The solid lines show the low energy fit

$$\frac{326}{E} e^{-54.5/\sqrt{E}}$$

and the high energy fit

$$0.001\left(\frac{E}{10000}\right)^{-3.61}$$

, σ in barn, E in keV.

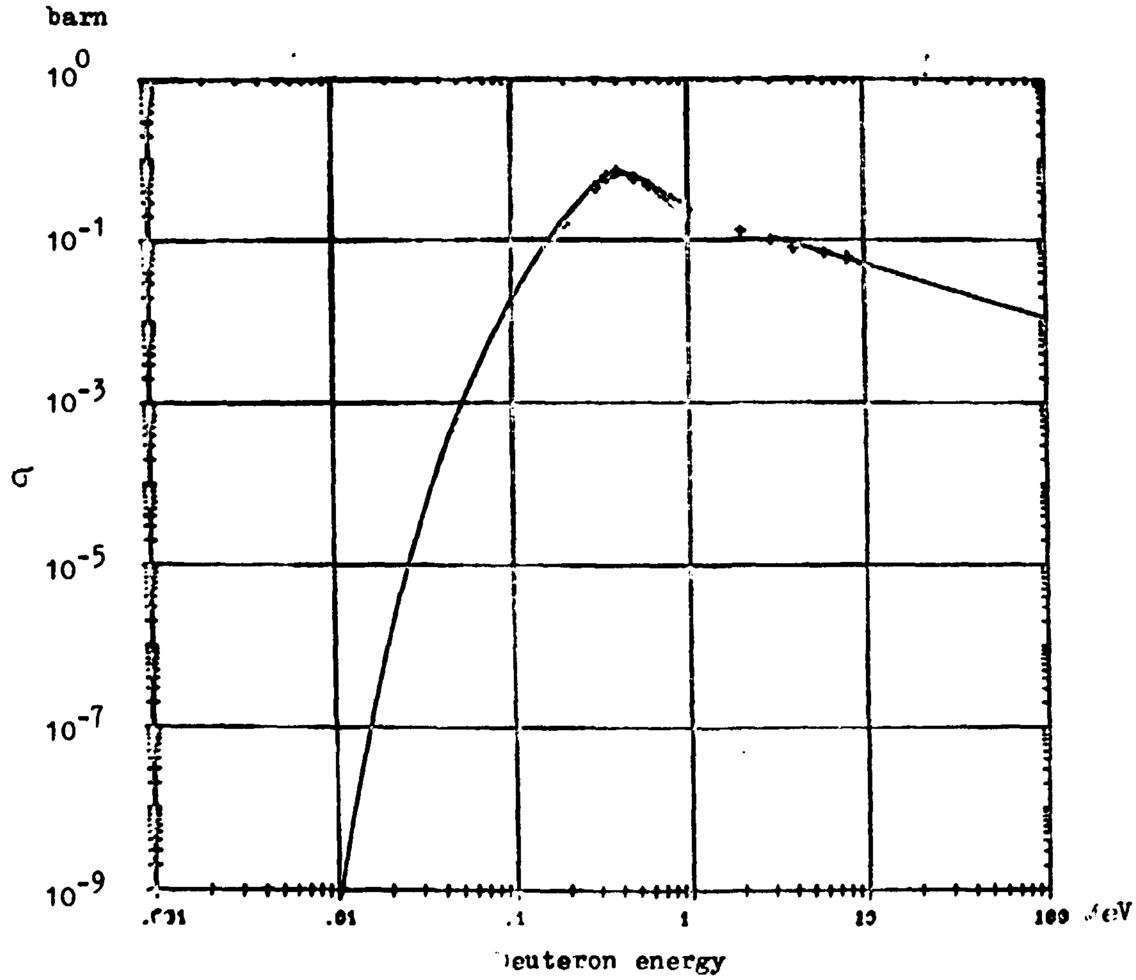

Figure 7 The cross section data that have been used for the reaction $^3He(d,p)^4He$. The solid lines show the low energy fit

$$\frac{24300}{E} e^{-88.8/\sqrt{E}} \frac{1}{1 + 0.0000154(E-328)^2}$$ and the high energy fit

$$0.0507\left(\frac{E}{10000}\right)^{-0.65}$$, σ in barn, E in keV.

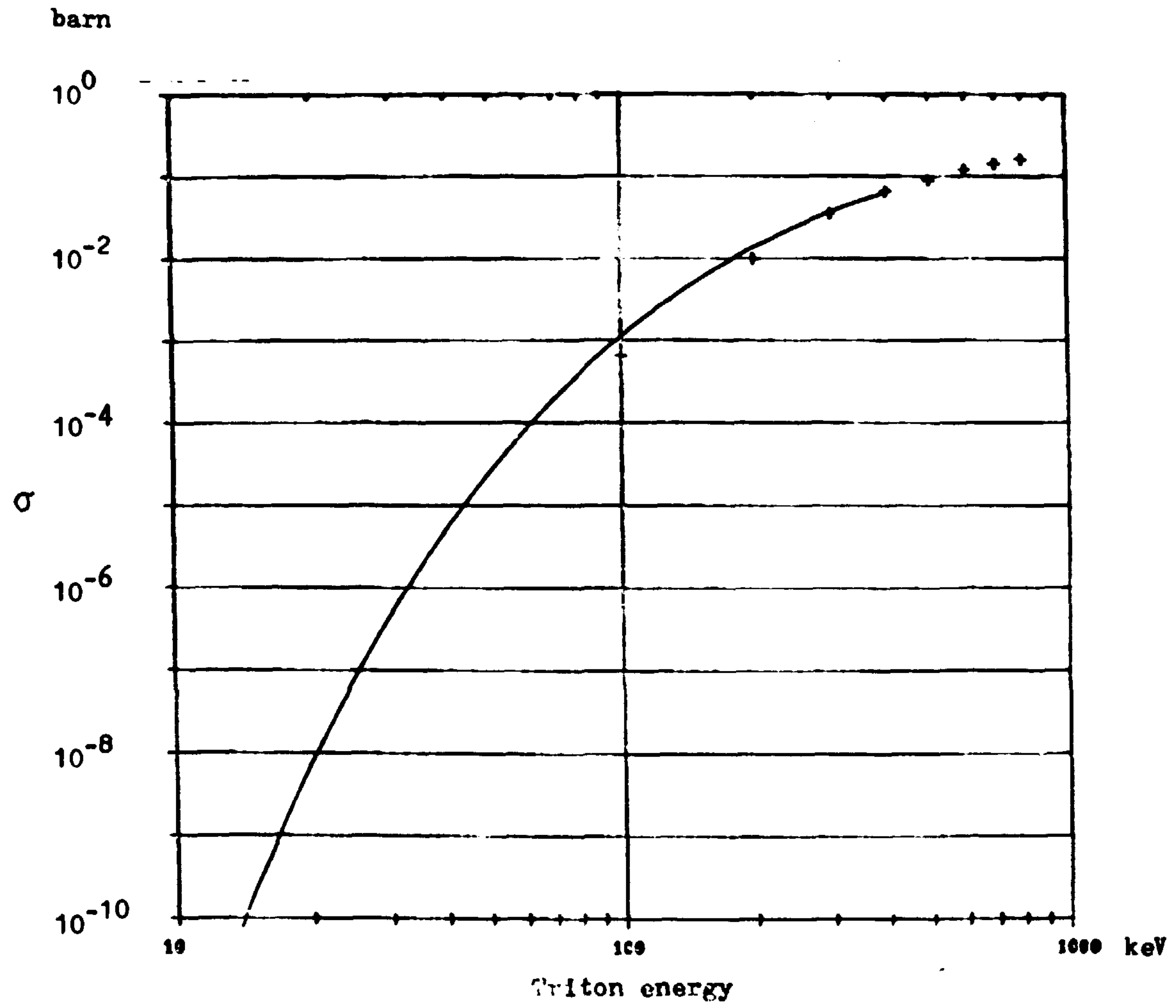

Figure 8. The total cross section for the reactions $^3He(t,\alpha)^4He$ + $^3He(t,p+n)^4He$. The crosses mark the measured values, the solid line shows the low energy fit

$$\frac{5920}{E} e^{-108.8/\sqrt{E}}, \quad \sigma \text{ in barn, } E \text{ in keV.}$$

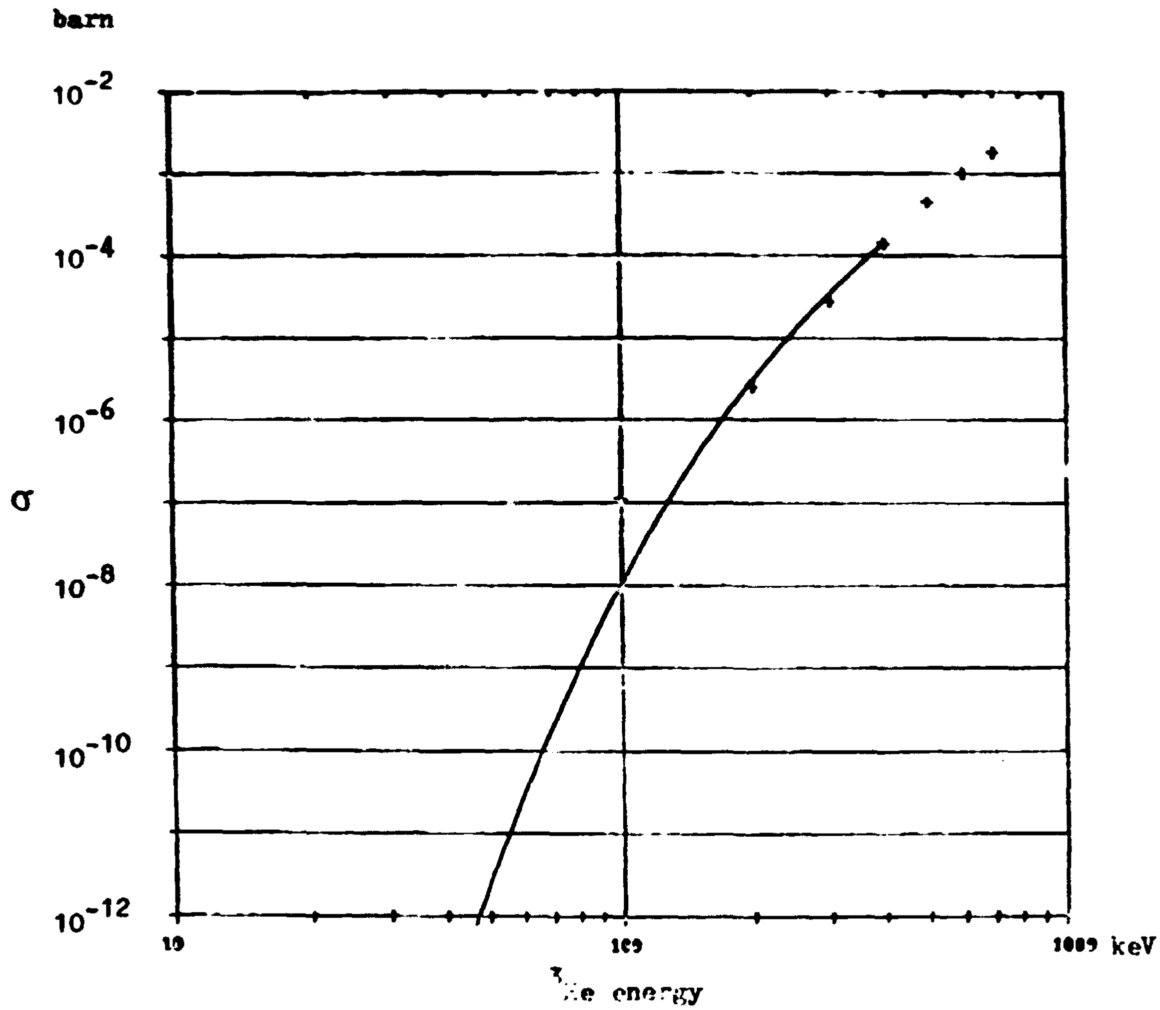

Figure 9. The cross section for the reaction $^3He(^3He,2p)^4He$. The crosses mark the measured values, the solid line shows the low energy fit

$$\frac{2930}{E}\, e^{-217.5/\sqrt{E}}, \quad \sigma \text{ in barn, } E \text{ in keV.}$$

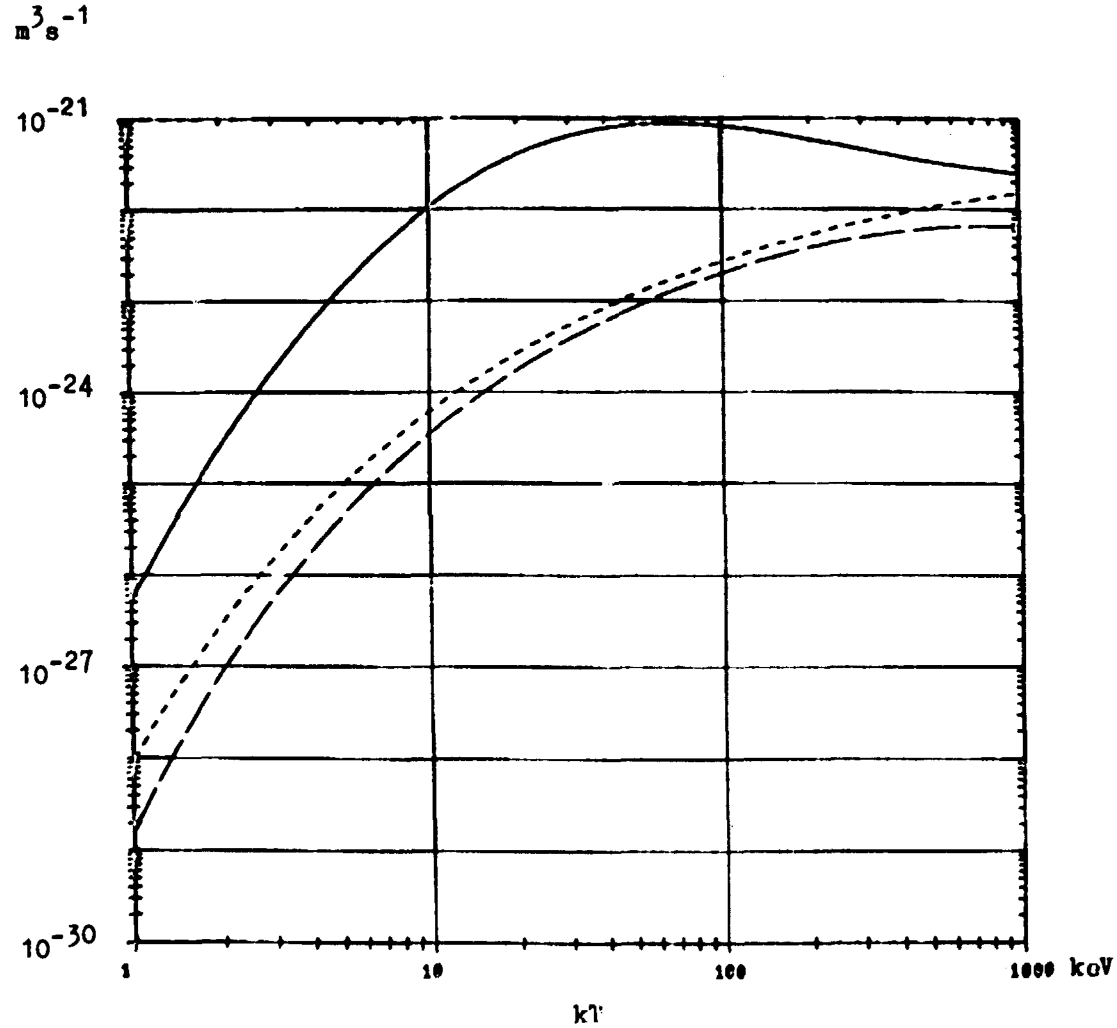

Figure 10. The rate constants for the reactions d+t (——), d+d neutron branch (----) and t+t (— —) as functions of temperature.

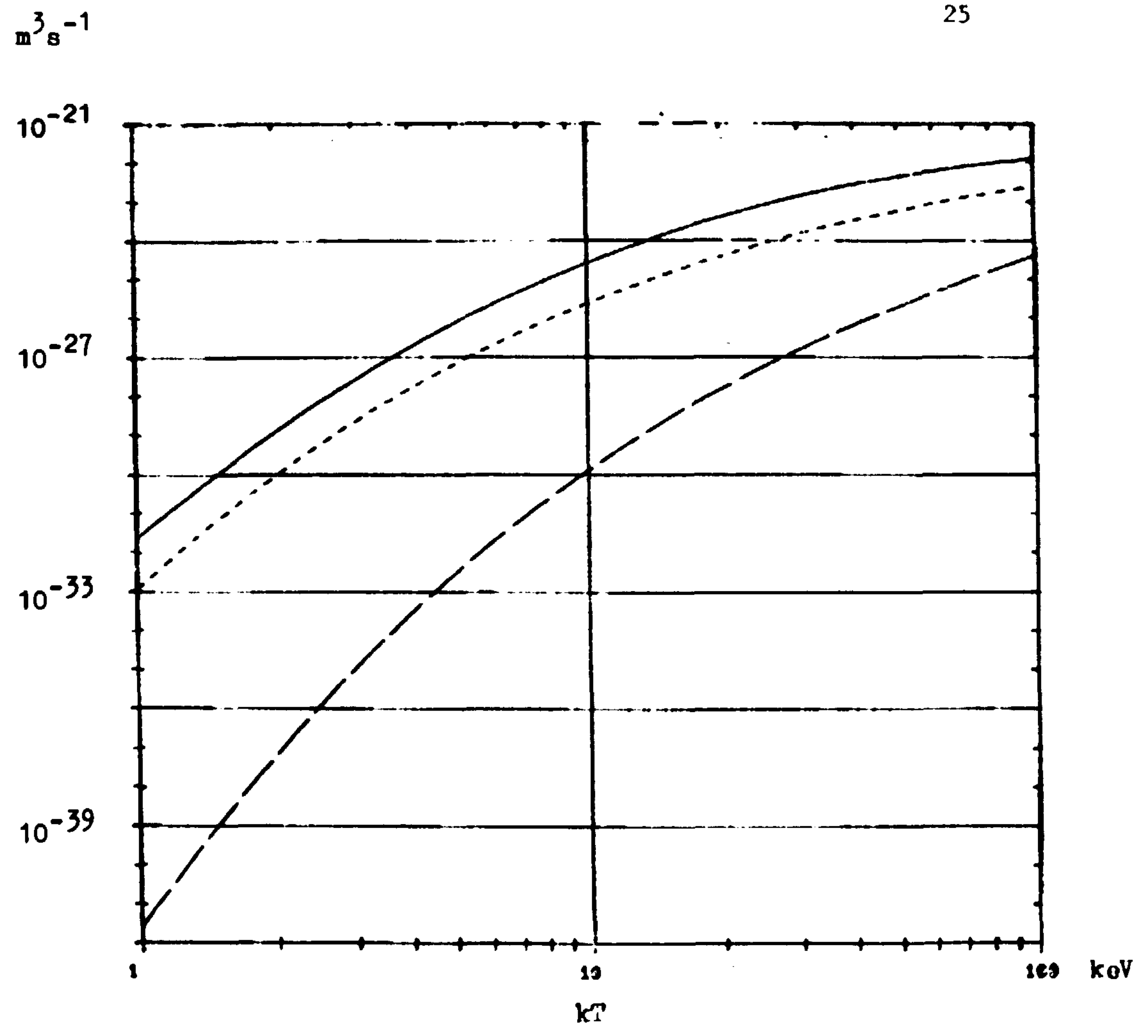

Figure 11. The rate constants for the reactions d+^{3}He (———), t+^{3}He (- - - - -) and ^{3}He+^{3}He (— — —) as functions of temperature.