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Angular distribution of electrons elastically scattered from CH_4

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Abstract. Differential elastic (vibrationally) scattering cross sections of CH_4 by electron impact have been measured using a modulated crossed-beam method. The energy and angular range covered were from 5 to 50 eV and from 12 to 156°, respectively. The integrated and momentum transfer cross sections were obtained from the differential cross sections. The present results are compared with the earlier data of Tanaka *et al* and with theoretical results of Lima *et al* and Jain and Thompson. Some discrepancies were found in the measurements and theoretical results.

1. Introduction

Methane is an important constituent of the atmospheres of the outer planets and comets. Electron interaction with CH_4 or other gases plays a role in determining temperatures, electron densities and airglow or auroral emissions in these atmospheres. Understanding these atmospheric processes requires a knowledge of electron impact cross sections for CH_4. Infrared emission (CH_4 bands) observed from Jupiter provides evidence that energetic auroral electrons are precipitating deep enough into atmosphere to reach the Jovian hydrocarbon layer (Kim 1988). Also, the upper atmosphere of Neptune might contain a few per cent of CH_4 (Romani and Atreya 1988), in which case interaction of auroral electrons or photoelectrons with this gas will be important. Titan's upper atmosphere is known to be composed mainly of molecular nitrogen and methane (Hunten *et al* 1985), and electrons from the Saturnian magnetosphere can then collide with these gases, generating ionisation and airglow (Neubauer *et al* 1984). Some comets also contain significant amounts of methane, with which solar wind and atmospheric electrons can interact (cf Mendis *et al* 1985, Cravens *et al* 1987).

Electron impact cross section measurements for methane are required in order to understand the behaviour of both high- and low-energy electrons in many atmospheres. Vuskovic and Trajmar (1983) summarised the previous measurements on methane very well. In this paper, the discussion is restricted to the present energy range of total and elastic scattering cross sections. Total cross sections have been measured by Bruche (1927) from 0.85 to 49 eV and by Barbarito *et al* (1979) from 0 to 16 eV. Three experimental determinations of absolute elastic cross sections have been made in the present energy region (5-50 eV). Rohr (1980) measured differential cross sections (DCS) in the energy range below 10 eV, over the angular range of 20-120°. Recently,

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Tanaka *et al* (1982) measured DCS in the energy range of 3 to 20 eV for scattering angles from 30 to 140°. Vuskovic and Trajmar (1983) have measured relative DCS at 20, 30 and 200 eV and normalised their results to those of Tanaka *et al* at 100° for 20 and 30 eV impact.

There are more theoretical than experimental studies on electron impact collision with CH_4. Gianturco and Thompson (1980) calculated total and momentum transfer cross sections below 1.5 eV and DCS for 10 eV by using a simple model in which electrons are scattered from a rigid molecule with exchange and polarisation effects. They compared their results of elastic scattering cross sections at 10 eV with the relative DCS measured by Hughes and McMillen (1933) after being normalised at 90°, and found that the agreement is not so good. Jain and Thompson (1982) recently calculated the DCS by using a parameter-free polarisation potential for polyatomic molecules. The results of total cross sections are in relatively good agreement with the integrated cross sections of Tanaka *et al.* Also the DCS at 5 eV is in good agreement with the measurements made by Tanaka *et al*, except for forward scatterings. Recently, Lima *et al* (1985) applied the Schwinger multichannel formulation with the static-plus-exchange interaction to calculate integrated and differential cross sections in the energy range from 3 to 20 eV. Their calculated values of DCS are in good agreement with the measurements only at 7 eV, however, their integrated cross sections agree well with the data of Tanaka below 8 eV. More recently, Jain (1986) calculated total and DCS using a spherical model in the energy range of 0.1 to 500 eV. His results are in good agreement, in general, in forward scattering with the measurements but not in backward scattering.

As shown above, the existing measurements and theoretical calculations are not in good agreement and are quite fragmentary; thus, more extensive cross section information is still required. In this paper, we present the results of measurements of absolute differential elastic (vibrationally) cross sections for electron impact on methane for energies between 5 eV and 50 eV, and scattering angles between 12 and 156°.

2. Apparatus and procedure

The schematic diagram of the apparatus used is shown in figure 1. A detailed description of the apparatus can be found elsewhere (Shyn *et al* 1972, 1988, Shyn 1980, Shyn and Sharp 1986). Briefly, the apparatus consists of an upper and a lower chamber. The two chambers are pumped differentially in order to maintain a low background pressure for the measurements in the lower chamber. The apparatus consists of three subsystems: (1) a methane source in the upper chamber, (2) a rotatable electron beam source, and (3) a fixed electron detector system on the vacuum chamber wall in the lower chamber.

The electron beam source, which is rotatable from −90° to 160° continuously, consists of an electron gun, a 127° electrostatic energy selector, two electron lens systems and two beam deflectors. The electron beam source can produce a current exceeding 10^{-8} A at energies above 10 eV with 80 meV full width at half maximum (FWHM). The half-angle spread of the elctron beam is less than ±3°.

The detector system has two electron lens systems, two electrostatic energy analysers in series and a channeltron electron multiplier. The energy resolution of the detector system is beter than 80 meV at FWHM.

The collimated CH_4 beam from the upper chamber enters the lower chamber through a double skimmer located between the two chambers. The beam was modulated

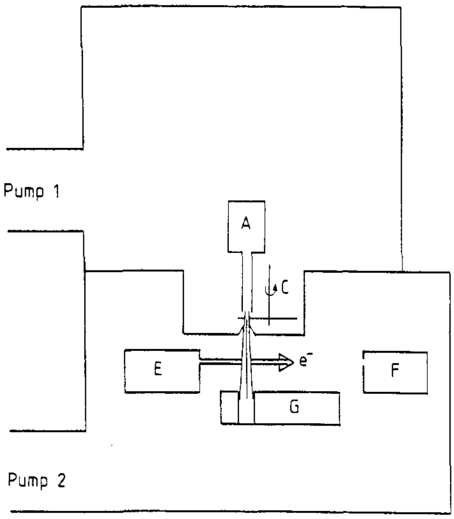

Figure 1. Schematic diagram of the apparatus. A, CH_4 beam source; C, chopper; E, electron beam source; F, electron detector; G, mass spectrometer.

at an audio frequency ($\simeq$150 Hz) by a toothed chopper wheel so that the pure beam signal can be separated from the background by using a phase-sensitive detector. Since the time constant of the present vacuum system for methane is estimated to be longer than 0.3 s; therefore, it is believed there is negligible contribution to the beam signal from the background pressure, because the chopping period ($\simeq$7 ms) is shorter than the time constant of the vacuum system by more than 40 times.

The incident electron beam of a given energy in the horizontal plane intersects with the vertically collimated and modulated neutral beam in an interaction region. The electrons elastically scattered from the modulated beam at a given angle are detected by the electron channeltron multiplier after energy analysis. The signals due to electrons scattered with the chopper open and closed are recorded by two counters, and the difference of these two signals gives the true scattered signal from the pure beam. This procedure is repeated for different angles and incident energies in order to obtain relative angular distributions. The impact energy scale is calibrated against the 19.3 eV resonance in He. It should be noted that, before the final cross section data of CH_4 were taken, the angular distributions of electrons elastically scattered from helium for each incident energy were measured carefully and confirmed previous measurements. This was done in order to eliminate all systematic errors, including stray magnetic field effects and interaction volume effects. Three sets of Helmholtz coils reduce stray magnetic fields down to less than 20 mG in all directions near the interaction region.

The relative angular distributions measured at each energy were put on absolute scale by normalisation with the elastic differential cross section of He reported by Shyn (1980) utilising a volume experiment (static gas background). The relative densities of the two gases (He and CH_4) were determined by measuring the corresponding pressures with an ion gauge, which was calibrated against an MKS Baratron pressure gauge.

The statistical uncertainty of each data point is 3%. The uncertainty in the normalisation procedure is estimated to be 10%. Therefore, the overall uncertainty of the present results is about 14% including the uncertainty of the He cross sections (10%).

3. Experimental results and discussion

Absolute differential elastic cross sections have been measured at the following incident energies: 5.0, 10, 15, 20, 30 and 50 eV. The results are summarised in table 1, including the integrated and momentum transfer cross sections.

Figure 2 shows DCS at 5.0 eV impact energy along with the results of Tanaka *et al* and Rohr. The theoretical results of Jain are also included. The DCS indicates a dominant D-wave character. The previous measurements are in good agreement with the present results except that their minima are shifted toward smaller angles (45° and

Table 1. Differential elastic cross sections, integrated and momentum transfer cross sections of methane. The numbers in parentheses are extrapolated data points. σ_i and σ_{mt} are given in units of 10^{-16} cm^2.

	$d\sigma/d\Omega$ 10^{-17} cm^2 sr^{-1}														
ϕ(deg) = 12 E (eV)		24	36	48	60	72	74	96	108	120	132	144	156	168	σ_i	σ_{mt}
5.0	44.2	27.5	16.1	13.3	12.3	13.5	15.0	13.3	9.2	3.6	2.3	4.2	6.7	(10.5)	14.8	10.7
10	115.2	66.7	38.1	25.4	14.6	9.4	7.3	5.2	2.9	2.1	3.5	8.0	14.0	(29.5)	19.8	10.5
15	154.8	74.3	30.4	19.9	10.3	6.0	3.4	2.9	1.9	2.3	4.5	6.9	9.2	(12.4)	17.6	7.5
20	169.1	73.3	24.6	13.2	6.7	4.2	2.8	1.8	1.6	2.2	3.3	4.9	5.7	(7.2)	15.3	5.4
30	165.0	52.3	13.4	6.7	3.8	2.5	1.7	1.1	1.2	1.7	2.5	3.2	3.7	(4.8)	11.3	3.5
50	82.3	18.0	4.4	3.0	1.6	0.85	0.49	0.48	0.62	1.2	1.8	1.9	2.1	(2.3)	5.0	1.8

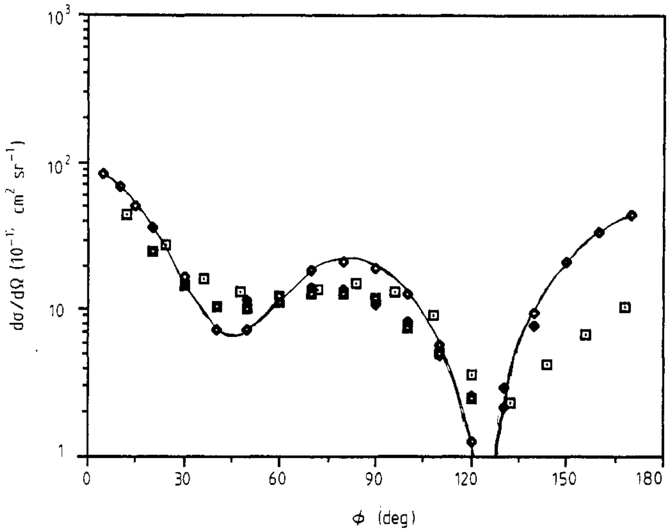

Figure 2. Measured angular distribution of elastic cross sections at 5.0 eV (⊡). The measurements of Tanaka *et al* (1982) (◆) and Rohr (1980) (■) and the theoretical results of Jain (1986) (–◇–) are also shown.

120°) compared with the present results at 60 and 135°. The theoretical results of Jain agree with the present results in general shape but his results have larger values near 90° and backward scattering than the present results by more than a factor of two except near 120°. The present results show a shallower distribution than those of Jain around 110–120°. This may be due to the contributions from the rotational excitations ($\Delta J = 0$) as Jain mentioned. The present DCS at 10 and 15 eV exhibit strong forward and backward scattering with a small inflection near 90° and with the minimum at 120° and 105°, respectively.

Figure 3 is the same as figure 2 but for 20 eV impact. The results of Tanaka *et al* agree with the present results except near 90°. Both results show a typical P-wave shape. Jain's results have the same tendencies as at 5.0 eV.

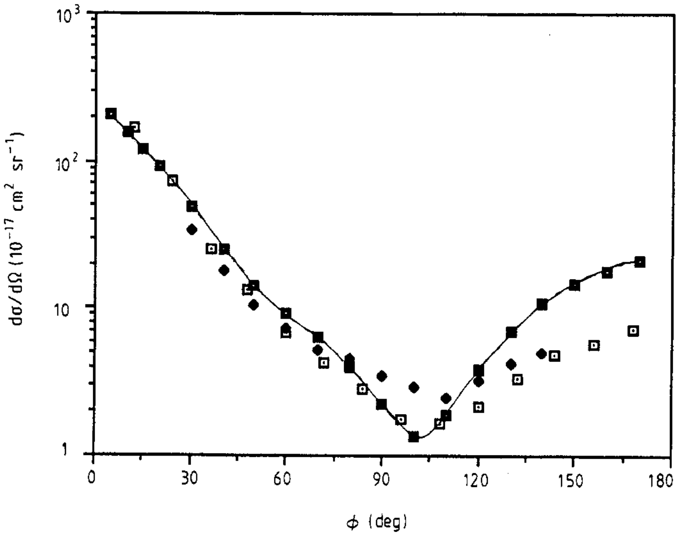

Figure 3. Measured angular distribution of elastic cross section at 20 eV (□). The measurements of Tanaka *et al* (1982) (◆) and the theoretical results of Jain (1986) (—■—) are also shown.

Figure 4 shows DCS of 50 eV along with the results of Jain. Very strong forward scattering and a mild backward peak with a minimum near 90° are evident. The theoretical results of Jain agree very well in shape with the present results but their absolute values are larger than the present results by approximately a factor of two. Generally, the minimum in the DCS moves to smaller scattering angles as the incident energy increases.

Figure 5 shows integrated cross sections along with those of Tanaka *et al* and the theoretical values of Lima *et al.* The total cross sections of Bruche (1927) and Barbarito *et al* (1979) are also shown. The integrated cross sections were obtained by integrating DCS over scattering angles after exponentially extrapolating to 180°. Since there is a sin ϕ factor in the integration over solid angles, the expected uncertainty due to the extrapolations to extreme angles is less than a few per cent. Agreement is relatively good between the two sets of measured integrated cross sections. Both measurements show a broad maximum between 5 and 10 eV. It is noted that Tanaka *et al* used the relative flow technique for the normalisation of relative cross sections and an effective range theory expansion in a phaseshift analysis was used to extrapolate the data to

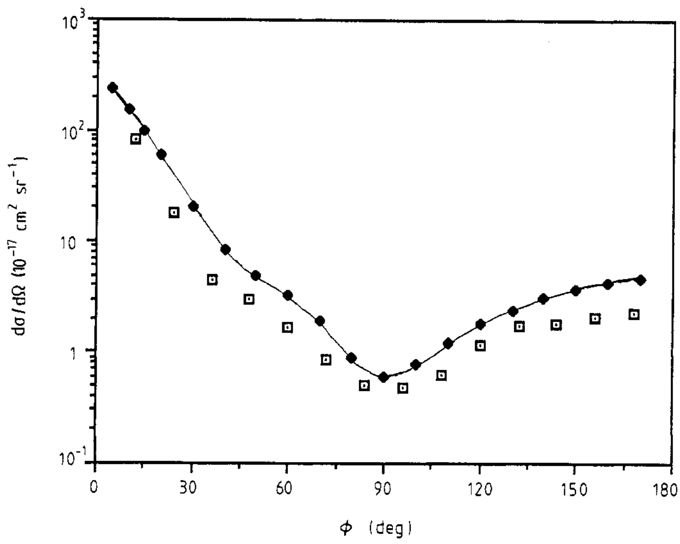

Figure 4. Measured angular distribution of elastic cross section at 50 eV impact energy (□). The theoretical results of Jain (1986) (-◆-) are also shown.

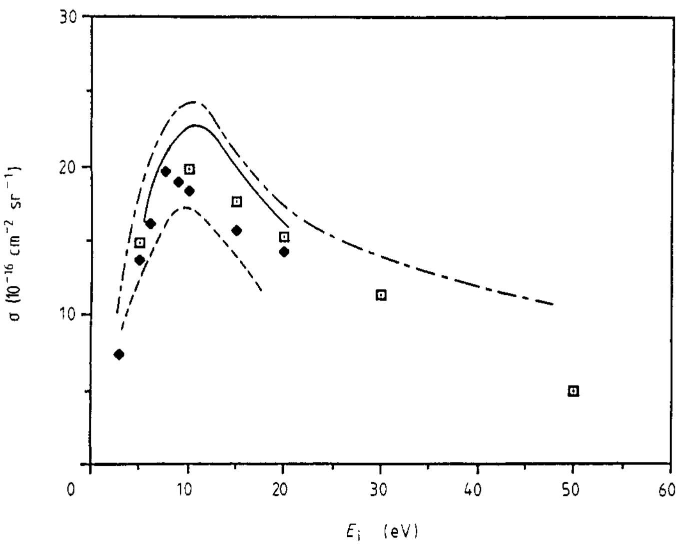

Figure 5. Total and integrated cross sections of methane from this paper (□) and the results of Tanaka *et al* (1982) (◆). Also shown are the total cross sections measured by Bruche (1927) (— · —) and Barbarito *et al* (1979) (– – –) and the theoretical results of Lima *et al* (1985) (——) (integrated).

the extreme angles. The difference between the total cross sections of Bruche and the present integrated cross sections is the sum of inelastic cross sections. However, the results of Barbarito *et al* are smaller than the present integrated cross sections for all incident energies and, therefore, something must be wrong with their measurements. The theoretical results of Lima *et al* are in agreement with the present results at 5 and 20 eV impact energy but they have larger values between these two energies. The theoretical values of Jain indicate the same trend as Lima *et al* and his values are almost the same as the values of Bruche's total cross sections.

Finally, momentum transfer cross sections have been calculated from the present DCS and are shown in figure 6 along with the results of Tanaka *et al.* The results of Tanaka *et al* are larger than the present results by about 20% except at 15 eV, even though their DCS are smaller than present results by about 10%. Perhaps something is wrong with their extrapolations of the DCS to 0° and 180°.

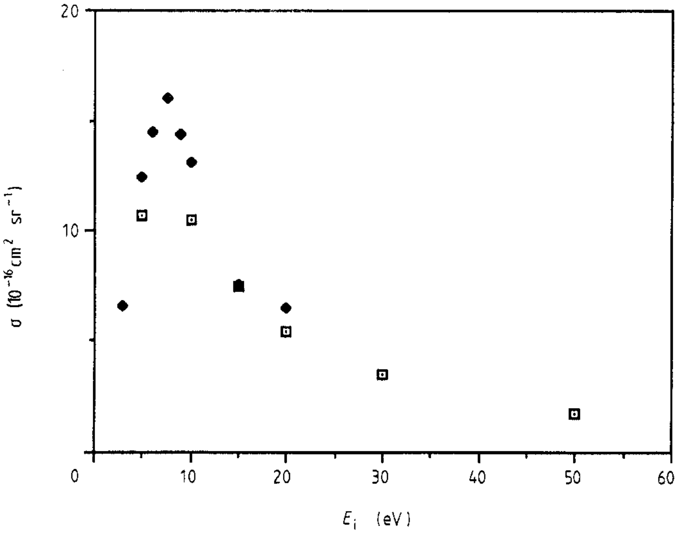

Figure 6. Momentum transfer cross sections from this paper (□) and the results of Tanaka *et al* (1982) (◆).

Measured electron impact cross sections, such as those presented in this paper, are needed in order to calculate electron fluxes in planetary atmospheres, such as that of Titan, which contain significant amounts of methane (Hunten *et al* 1985). For example, the two-stream method of calculating atmospheric superthermal electron fluxes (as a function of energy) requires elastic backscattering probabilities (cf Banks and Kockarts 1973). Backscattering probabilities for elastic scattering for CH_4 can easily be calculated from the measured differential cross sections presented in this paper.

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References

Banks P M and Kockards G 1973 *Aeronomy* (New York: Academic)
Barbarito E, Basta M and Calicchio M 1979 *J. Chem. Phys.* **71** 54
Bruche E 1927 *Ann. Phys., Lpz.* **83** 1065
Cravens T E, Kozyra J U, Nagy A F, Combosi T I and Kurtz M 1987 *J. Geophys. Res.* **92** 7341
Gianturco F A and Thompson D G 1980 *J. Phys. B: At. Mol. Phys.* **13** 613

Hughes and McMillen 1933 *Phys. Rev.* **44** 876
Hunten D M, Tomasko M G, Flasar F M, Samuelson R E, Strobel D F and Stevens D J 1984 *Saturn* ed T Gehrels and M S Matthews (Tucson: University of Arizona Press) pp 671–760
Jain A 1986 *Phys. Rev.* A **34** 3707
Jain A and Thompson D G 1982 *J. Phys. B: At. Mol. Phys.* **15** L631
Kim S J 1988 *Icarus* **75** 399
Lima M A, Gibson T L, Huo W M and McKoy V 1985 *Phys. Rev.* A **32** 2696
Mendis D A, Houpis H L F and Marconi M L 1985 *Fund. Cosmic Phys.* **10** 1
Neubauer F M, Gurnett D A, Schudder J D and Hartle R E 1984 *Saturn* ed T Gehrels and M S Matthews (Tucson: University of Arizona Press) pp 671–760
Rohr K 1980 *J. Phys. B: At. Mol. Phys.* **13** 4897
Romani P N and Atreya S K 1988 *Icarus* **74** 424
Shyn T W, Stolarski R S and Carignan G R 1972 *Phys. Rev.* A **6** 1002
Shyn T W 1980 *Phys. Rev.* A **22** 916
Shyn T W, Cho S Y and Cravens T E 1988 *Phys. Rev.* A **38** 678
Shyn T W and Sharp W E 1986 *J. of Geophys. Res.* **91** 1691
Tanaka H, Okada T, Boesten L, Suzuki T, Yamamoto T and Kubo M 1982 *J. Phys. B: At. Mol. Phys.* **15** 3305
Vuskovic L and Trajmar S 1983 *J. Chem. Phys.* **78** 4947