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Electron scattering by magnesium: excitation of the 3s4s $^1S_0$, 3s3d $^1D_2$ and 3s4p $^1P_1$ states

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Abstract
Differential cross sections (DCSs) for electron impact excitation of the 3s4s $^1S_0$, 3s3d $^1D_2$ and 3s4p $^1P_1$ states in magnesium at incident electron energies of 10, 20, 40, 60 eV have been measured. The energy-loss spectra within the energy range of the 3s4s $^1S_0$, 3s3d $^1D_2$, 3s4p $^1P_1$ and 3s3p $^1P_1$ states have been recorded up to 150°. The absolute DCSs were determined by using inelastic (3s4s $^1S_0$, 3s3d $^1D_2$, 3s4p $^1P_1$)-to-inelastic (3s3p $^1P_1$ resonance state) intensity ratios and DCSs for the resonance state (Filipović *et al* 2006b *J. Phys. B: At. Mol. Opt. Phys.* **39** 2583). The absolute DCSs were extrapolated to 0° and 180° and then integrated to yield integral, momentum transfer and viscosity cross sections. The results have been analysed and compared with available experimental data and theoretical calculations.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

During the last few years the interest for experimental and theoretical investigation of the excitation of the magnesium atom has been increased. Besides the papers from our laboratory (Filipović *et al* 2006a, 2006b, Predojević *et al* 2007), there are other recent works that refer different aspects in excitation of Mg (Brown *et al* 2003, 2005, Rafiq *et al* 2007a, 2007b, Wehlitz *et al* 2007, Bartschat *et al* 2007). In order to complete earlier investigations of Mg, we extended our studies to the electron impact excitation of the 3s4s $^1S_0$, 3s3d $^1D_2$ and 3s4p $^1P_1$ states. As in our previous articles, incident electron energies belong to low and intermediate energy ranges.

There are relatively few articles concerning the electron impact excitation of the 3s4s $^1S_0$, 3s3d $^1D_2$ and 3s4p $^1P_1$ states in magnesium. Williams and Trajmar (1978) published experimentally obtained differential cross section (DCSs), integral (Q_I) and momentum transfer (Q_M) cross sections for these three states. They measured the DCSs for the 3s4s $^1S_0$ and 3s4p $^1P_1$ sates at 20 and 40 eV and for the 3s3d $^1D_2$ at 10, 20 and 40 eV incident electron energies. All measurements were performed at scattering angles from 10° to 130°.

Mitroy and McCarthy (1989) calculated DCSs and Q_I for the electron impact excitation of Mg from the ground $(3s)^2\,^1S_1$ state to the 3s4s $^1S_0$, 3s3d $^1D_2$ and 3s4p $^1P_1$ states. They exploited five-state close-coupling (CC5) approximation and obtained results for electron impact energies (E_o) of 10, 20, 40 and 100 eV. Srivastava *et al* (2001) applied the relativistic distorted-wave (RDW) method to calculate the DCSs for excitation of the 3 ^{1,3}D states for the electron impact energies of 20 and 40 eV. In order to investigate effects of configuration interaction they carried out calculations with two different sets of wavefunctions, SCGS (single-configuration ground state) and MCGS (multi-configuration ground state).

Clark *et al* (1991) used the distorted-wave approximation (DWA) and first-order many-body theory (FOMBT) for the calculations of the Q_I for electron impact excitation of the 3s4s $^1S_0$ and 3s3d $^1D_2$ states at 10, 20, 40 and 100 eV. Gedeon *et al* (1999) reported results of Q_I in 19-state close-coupling (19CC) and plane-wave Born–Ochkur (PWBOA) approximation for the excitation from the ground state to the 3s4s $^1S_0$, 3s3d $^1D_2$ and 3s4p $^1P_1$ states from the threshold to 30 eV.

In this paper, we present experimentally obtained absolute differential cross sections for electron impact excitation of the 3s4s $^1S_0$, 3s3d $^1D_2$ and 3s4p $^1P_1$ states at 10, 20, 40, 60, eV electron impact energies. We used inelastic (3s4s $^1S_0$, 3s3d $^1D_2$, 3s4p $^1P_1$)-to-inelastic (3s3p $^1P_1$ resonance state) ratio and our experimental absolute DCSs for the resonance (3s3p $^1P_1$) state (Filipović *et al* 2006b) to yield DCSs at an absolute scale. In this way obtained absolute DCS values were extrapolated to 0° and 180° and utilized as a base for the determination of the integral, momentum transfer and viscosity cross sections.

In section 2, the apparatus is described and the experimental procedure is given. In section 3, the present absolute DCS values and integral cross sections are tabulated, and presented graphically together with other measurements and calculations for mutual comparison. Finally, in section 4, our results are discussed and conclusion is given.

2. Apparatus and experimental procedure

Experimental arrangement used for the measurements is a conventional cross-beam electron spectrometer described in our earlier papers of Mg (Filipović *et al* 2006a, 2006b, Predojević *et al* 2007). The spectrometer has been used in the energy-loss mode to record energy-loss spectra in the energy range from 3.9 to 6.4 eV, which includes all the four excited states. The spectra have been recorded in the angular range from 2° to 150°. Only a brief description of the apparatus is given here with more details relating to the energy-loss spectra.

A channel electron multiplier is utilized for single-electron counting. The overall system energy resolution (as FWHM) of 120 meV was maintained for these measurements. Before actual DCSs measurements, calibration of the impact energy scale and calibration of the scattering angle were done. The impact energy was calibrated against the known excitation threshold energy (4.346 eV) of the 3s3p $^1P_1$ state in Mg. Influence of the contact potential difference on the energy scale is assumed to be low (Filipović *et al* 2006b). The uncertainty in the energy was estimated to be less than 0.1 eV. The real zero scattering angles were determined on the basis of symmetry of the scattered electron intensity with respect to the mechanical zero, within 0.2° uncertainty.

Construction of a resistively heated oven used as the magnesium source and the vapour beam characteristics are the same as previously reported (Predojević *et al* 2007). The measurements were performed at a temperature of 780 K for magnesium of 99.9% purity. The working temperature mentioned above corresponds to the metal-vapour pressure of approximately 9.5 Pa. The beam of magnesium effuses through a cylindrical channel, aspect ratio $\gamma = 0.075$. Water cooling of the oven shield together with the thermal insulation by ceramics protected the channel electron multiplier and other components from a rise in temperature.

Measurements of the DCSs for excitation of the 3s4s $^1S_0$, 3s3d $^1D_2$, 3s4p $^1P_1$ states included the following steps. The energy-loss spectra were accumulated at impact energies 10, 20, 40 and 60 eV for scattering angles from 2° (10° at 10 eV) to 150°. The energy range of interest was adjusted to include completely resolved features that correspond to the 3s3p $^1P_1$, 3s4s $^1S_0$, 3s3d $^1D_2$, and 3s4p $^1P_1$ excitations. For a given spectrum, feature intensities of the 3s4s $^1S_0$, 3s3d $^1D_2$, 3s4p $^1P_1$ relative to the 3s3p $^1P_1$ feature intensity were measured by subtracting the background signal. The relative 3s4s $^1S_0$, 3s3d $^1D_2$, 3s4p $^1P_1$ to 3s3p $^1P_1$ DCS ratios obtained by this method were normalized using the absolute DCSs for 3s3p $^1P_1$ states measured by Filipović *et al* (2006b).

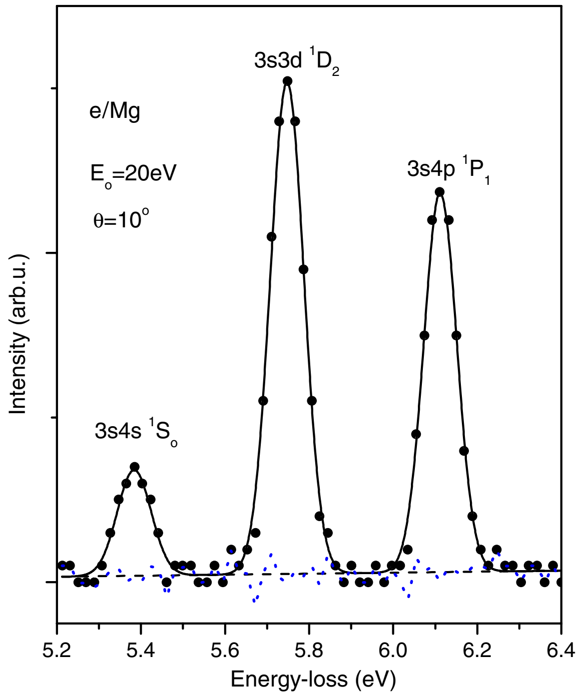

Figure 1. Electron energy-loss spectrum of magnesium at $E_0 =$ 20 eV impact energy and scattering angle $\theta = 10°$. ●, raw data; ——, the fit of raw data with a line profile obtained from three Gaussians; – – –, baseline; · · · · · ·, the difference between raw data and fit.

Contributions to the total error of the absolute DCSs come from: (a) uncertainties in our experimental values and (b) uncertainty in the normalization procedure. The errors in our experimental values arise from statistical errors in the measurements of the inelastic-to-inelastic intensity ratios. Uncertainties in the normalization procedure were determined taking into account errors of the reference DCSs. Total errors of absolute DCSs are obtained as the square root of the sum of squared particular errors. The total errors of the integral cross sections arise from the DCS errors mentioned above and errors of the extrapolation of DCSs to 0° and to 180° and numerical integration (0.1 and 0.15 for 10 eV).

3. Results

An energy-loss (ΔE from 5.2 to 6.4 eV) spectrum of magnesium at incident electron energy of 20 eV and a scattering angle of 10° is shown in figure 1. The spectrum contains completely resolved features corresponding to the

Table 1. Differential cross sections for electron impact excitation of the 3s4s $^1S_0$ state of magnesium. The last three rows present integral (Q_I), momentum transfer (Q_M) and viscosity (Q_V) cross sections in units of 10^{-20} m^2. The absolute errors are indicated in parentheses, while the extrapolated values are given in square brackets.

Scattering angle (°)	DCS ($\times 10^{-20}$ m^2 sr^{-1}) 10 eV	20 eV	40 eV	60 eV
0	[0.495]	[3.20]	[3.70]	[5.12]
2	[0.488]	2.35(0.64)	2.71(0.57)	3.68(0.64)
4	[0.4600]	1.60(0.44)	2.20(0.43)	2.32(0.32)
6	[0.409]	1.22(0.34)	1.41(0.28)	1.75(0.49)
8	[0.347]	1.06(0.31)	0.768(0.152)	0.926(0.187)
10	0.291(0.059)	0.658(0.187)	0.478(0.093)	0.397(0.120)
20	0.0995(0.0223)	0.178(0.042)	0.0545(0.0129)	0.0184(0.0062)
30	0.0698(0.0198)	0.0908(0.0280)	0.0188(0.0071)	0.006 60(0.002 40)
40	0.106(0.026)	0.0509(0.0199)	0.0181(0.0081)	0.004 00(0.001 30)
50	0.0597(0.0177)	0.0326(0.0136)	0.0098(0.0029)	0.002 40(0.000 91)
60	0.0529(0.0197)	0.0230(0.0117)	0.008 60(0.002 58)	$4.30 \times 10^{-4}(2.19 \times 10^{-4})$
70	0.0133(0.0061)	0.008 13(0.004 38)	0.0079(0.0022)	0.001 80(0.000 66)
80	0.005 75(0.003 10)	0.0117(0.0051)	0.007 23(0.001 98)	0.001 50(0.000 59)
90	0.0112(0.0052)	0.0225(0.0093)	0.007 26(0.001 33)	$5.41 \times 10^{-4}(2.50 \times 10^{-4})$
100	0.0122(0.0055)	0.0221(0.0087)	0.004 77(0.001 55)	$5.41 \times 10^{-4}(2.51 \times 10^{-4})$
110	0.0192(0.0059)	0.0173(0.0087)	0.002 56(0.000 93)	$1.79 \times 10^{-4}(1.06 \times 10^{-4})$
120	0.0108(0.0043)	0.007 03(0.003 98)	0.001 78(0.001 15)	$2.03 \times 10^{-4}(1.09 \times 10^{-4})$
130	0.007 08(0.003 93)	0.007 21(0.004 31)	0.001 86(0.000 87)	$4.68 \times 10^{-4}(3.56 \times 10^{-4})$
140	0.009 73(0.003 44)	0.0114(0.0078)	0.004 86(0.002 42)	$6.57 \times 10^{-4}(2.65 \times 10^{-4})$
150	0.0127(0.0078)	0.0132(0.0073)	0.0122(0.0048)	0.003 20(0.000 87)
160	[0.0161]	[0.0137]	[0.0211]	[0.00540]
170	[0.0202]	[0.0143]	[0.0273]	[0.00726]
180	[0.0249]	[0.0158]	[0.0300]	[0.00888]
Q_I	0.398(0.146)	0.495(0.188)	0.277(0.077)	0.198(0.056)
Q_M	0.264(0.108)	0.241(0.110)	0.106(0.033)	0.0286(0.0095)
Q_V	0.298(0.112)	0.257(0.105)	0.0899(0.0262)	0.0306(0.0099)

3s4s $^1S_0$ (5.39 eV), 3s3d $^1D_2$ (5.75 eV) and 3s4p $^1P_1$ (6.12 eV) states.

The absolute DCS values for the 3s4s $^1S_0$, 3s3d $^1D_2$ and 3s4p $^1P_1$ states are given in tables 1–3 (with total errors in parentheses). Also, absolute DCSs for these states with corresponding total errors are presented graphically in figures 2–4. In the same figures DCSs measured by Williams and Trajmar (1978), as well as calculated DCSs in CC5 (Mitroy and McCarthy 1989) and RDW (Srivastava *et al* 2001) approximations are included.

The integrated-integral Q_I, momentum transfer Q_M and viscosity cross sections Q_V (with total errors in parentheses) are given in the last three rows in tables 1–3. In figure 5(a) the present integral cross sections for the electron impact excitation of the 3s4s $^1S_0$, 3s3d $^1D_2$ and 3s4p $^1P_1$ states are shown from 10 to 60 eV. In figures 5(b)–(d) the present Q_I together with other relevant experimental and theoretical results are presented.

In order to analyse n independence of the $3\,^1S_0 \rightarrow n\,^1P_1$ (n = 3, 4) transitions the ratios of DCS(E_0, θ)$_{3P}$ to DCS(E_0, θ)$_{4P}$ with corresponding total errors are plotted in figures 6(a)–(d).

4. Discussion and conclusion

As one can see in figure 1, the energy resolution of 120 mV is sufficient to resolve all the three states (3^1S_0, 3^1D_2, 4^1P_1) in the energy loss-spectra. For the electron impact energy of 20 eV Williams and Trajmar (1988) measured DCSs for the unresolved 3s4p $^3P_{0,1,2}$ and 3s3d $^3D_{1,2,3}$ states (5.932 eV and 5.946 eV respectively). Our measurements of the energy-loss spectra do not show any intense structures at these energies. Also, we have not observed any significant or systematic asymmetry in the direction of these states in the line profiles for the 3s3d $^1D_2$ (5.75 eV) and 3s4p $^1P_1$ (6.12 eV) states.

For the 3s4s $^1S_0$ state and at impact energies of 20 eV and 40 eV the agreement between our results and the measurements made by Williams and Trajmar (1978) is poor both in shape and in intensity. At higher scattering angles (over 40°) the ratio of the intensities of their and our DCS is similar to that for the resonant state 3s3p $^1P_1$. Also, while the measured DCS values of Trajmar and Williams have in general monotone decrease with the increase of the angle our DCSs at the high scattering angles predict the existence of minima and maxima (figures 2(b), (c)). Our measured DCS, when compared with theory (CC5 Mitroy and McCarthy) at 10 eV, decrease rapidly for the angles between 60° and 80°. The CC5 theory fails to correctly reproduce the absolute values for the larger scattering angles at this energy. On the other hand, for larger angles the positions of the maxima match the experiment (figure 2(a)). Overlap with the theory is much better for the impact energy of 20 eV. The first minimum coincides very well both in magnitude and in position with CC5 calculations, but we obtained the second minimum at the smaller scattering angle (between 120° and 130°) than predicted by the theory (140°). At energy of 40 eV our DSC is smaller than that

Table 2. Differential cross sections for electron-impact excitation of the 3s3d $^1D_2$ state of magnesium. The last three rows present integral (Q_I), momentum transfer (Q_M) and viscosity (Q_V) cross sections in units of 10^{-20} m^2. The absolute errors are indicated in parentheses, while the extrapolated values are given in square brackets.

Scattering angle (°)	DCS ($\times 10^{-20}$ m^2 sr^{-1}) 10 eV	20 eV	40 eV	60 eV
0	[5.23]	[13.2]	[11.5]	[9.00]
2	[4.38]	10.7(2.6)	9.35(1.63)	8.06(1.20)
4	[3.75]	8.44(2.02)	5.13(0.93)	6.73(1.04)
6	[3.24]	6.84(1.71)	4.34(0.76)	3.77(0.58)
8	[2.80]	5.44(1.42)	3.47(0.63)	2.78(0.43)
10	2.43(0.39)	3.72(0.97)	3.02(0.55)	2.04(0.40)
20	1.17(0.19)	1.14(0.22)	0.399(0.067)	0.0965(0.0204)
30	0.512(0.093)	0.271(0.069)	0.0870(0.0250)	0.0139(0.0039)
40	0.222(0.046)	0.112(0.038)	0.0365(0.0079)	0.002 47(0.000 95)
50	0.197(0.043)	0.0521(0.0195)	0.0165(0.0043)	0.004 20(0.001 39)
60	0.122(0.035)	0.0308(0.0125)	0.009 90(0.002 81)	0.001 89(0.000 62)
70	0.0733(0.0197)	0.0207(0.0086)	0.007 82(0.002 19)	0.002 01(0.000 70)
80	0.0388(0.0109)	0.0113(0.0044)	0.008 66(0.002 28)	0.001 78(0.000 67)
90	0.0354(0.0114)	0.0182(0.0069)	0.006 69(0.001 25)	$7.73 \times 10^{-4}(3.18 \times 10^{-4})$
100	0.0262(0.0092)	0.0190(0.0072)	0.004 67(0.001 40)	$7.57 \times 10^{-4}(3.27 \times 10^{-4})$
110	0.0213(0.0064)	0.0240(0.0105)	0.004 15(0.001 30)	$3.57 \times 10^{-4}(1.97 \times 10^{-4})$
120	0.0217(0.0069)	0.0229(0.0095)	0.003 51(0.001 57)	$1.58 \times 10^{-4}(0.90 \times 10^{-4})$
130	0.007 08(0.003 93)	0.0260(0.0114)	0.003 36(0.001 50)	0.001 17(0.000 62)
140	0.0195(0.0056)	0.0302(0.0140)	0.006 73(0.002 71)	0.001 39(0.000 45)
150	0.0272(0.0087)	0.0283(0.0129)	0.0133(0.0051)	0.003 15(0.000 87)
160	[0.0393]	[0.0278]	[0.0219]	[0.00581]
170	[0.0549]	[0.0281]	[0.0317]	[0.00813]
180	[0.0733]	[0.0290]	[0.0422]	[0.00900]
Q_I	1.99(0.50)	1.89(0.55)	1.04(0.23)	0.586(0.137)
Q_M	1.05(0.29)	0.609(0.216)	0.203(0.054)	0.0592(0.0168)
Q_V	1.38(0.36)	0.774(0.251)	0.251(0.061)	0.0839(0.0221)

Table 3. Differential cross sections for electron-impact excitation of the 3s4p $^1P_1$ state of magnesium. The last three rows present integral (Q_I), momentum transfer (Q_M) and viscosity (Q_V) cross sections in units of 10^{-20} m^2. The absolute errors are indicated in parentheses, while the extrapolated values are given in square brackets.

Scattering angle (°)	DCS ($\times 10^{-20}$ m^2 sr^{-1}) 10 eV	20 eV	40 eV	60 eV
0	[1.31]	[7.80]	[13.0]	[20.0]
2	[1.28]	7.34(1.79)	9.79(1.72)	13.4(1.8)
4	[1.23]	6.03(1.47)	8.61(1.50)	7.52(1.14)
6	[1.17]	5.06(1.28)	5.18(0.92)	3.57(0.56)
8	[1.10]	3.55(0.95)	3.05(0.54)	2.64(0.41)
10	1.01(0.17)	2.53(0.67)	1.89(0.33)	1.16(0.25)
20	0.492(0.084)	0.649(0.132)	0.197(0.039)	0.0505(0.0123)
30	0.287(0.057)	0.187(0.054)	0.0489(0.0144)	0.0169(0.0045)
40	0.161(0.036)	0.137(0.047)	0.0256(0.0101)	0.003 96(0.001 30)
50	0.126(0.030)	0.0917(0.0369)	0.0104(0.0030)	0.002 40(0.000 91)
60	0.0953(0.0291)	0.0421(0.0169)	0.006 55(0.002 03)	0.001 55(0.000 53)
70	0.0378(0.0120)	0.0220(0.0122)	0.006 28(0.001 82)	0.001 53(0.000 56)
80	0.0302(0.0090)	0.009 08(0.004 08)	0.007 68(0.002 06)	0.001 33(0.000 55)
90	0.0187(0.0073)	0.0158(0.0065)	0.006 31(0.001 15)	$7.75 \times 10^{-4}(5.12 \times 10^{-4})$
100	0.0140(0.0059)	0.0155(0.0059)	0.005 41(0.001 69)	$5.95 \times 10^{-4}(4.41 \times 10^{-4})$
110	0.0132(0.0045)	0.0354(0.0145)	0.003 89(0.001 29)	$4.17 \times 10^{-4}(2.23 \times 10^{-4})$
120	0.0102(0.0047)	0.0289(0.0131)	0.002 29(0.001 19)	$2.80 \times 10^{-4}(1.40 \times 10^{-4})$
130	0.0124(0.0056)	0.0213(0.0098)	0.003 32(0.001 39)	0.001 17(0.000 97)
140	0.0187(0.0054)	0.0228(0.0115)	0.007 43(0.002 80)	0.001 17(0.000 39)
150	0.0177(0.0063)	0.0173(0.0091)	0.0126(0.0041)	0.002 64(0.000 76)
160	[0.0136]	[0.0128]	[0.0183]	[0.00375]
170	[0.0123]	[0.00911]	[0.0241]	[0.00483]
180	[0.0120]	[0.00600]	[0.0300]	[0.00600]
Q_I	1.02(0.28)	1.39(0.45)	0.805(0.189)	0.541(0.121)
Q_M	0.593(0.182)	0.527(0.203)	0.164(0.046)	0.0512(0.0144)
Q_V	0.766(0.221)	0.635(0.227)	0.194(0.051)	0.0754(0.0192)

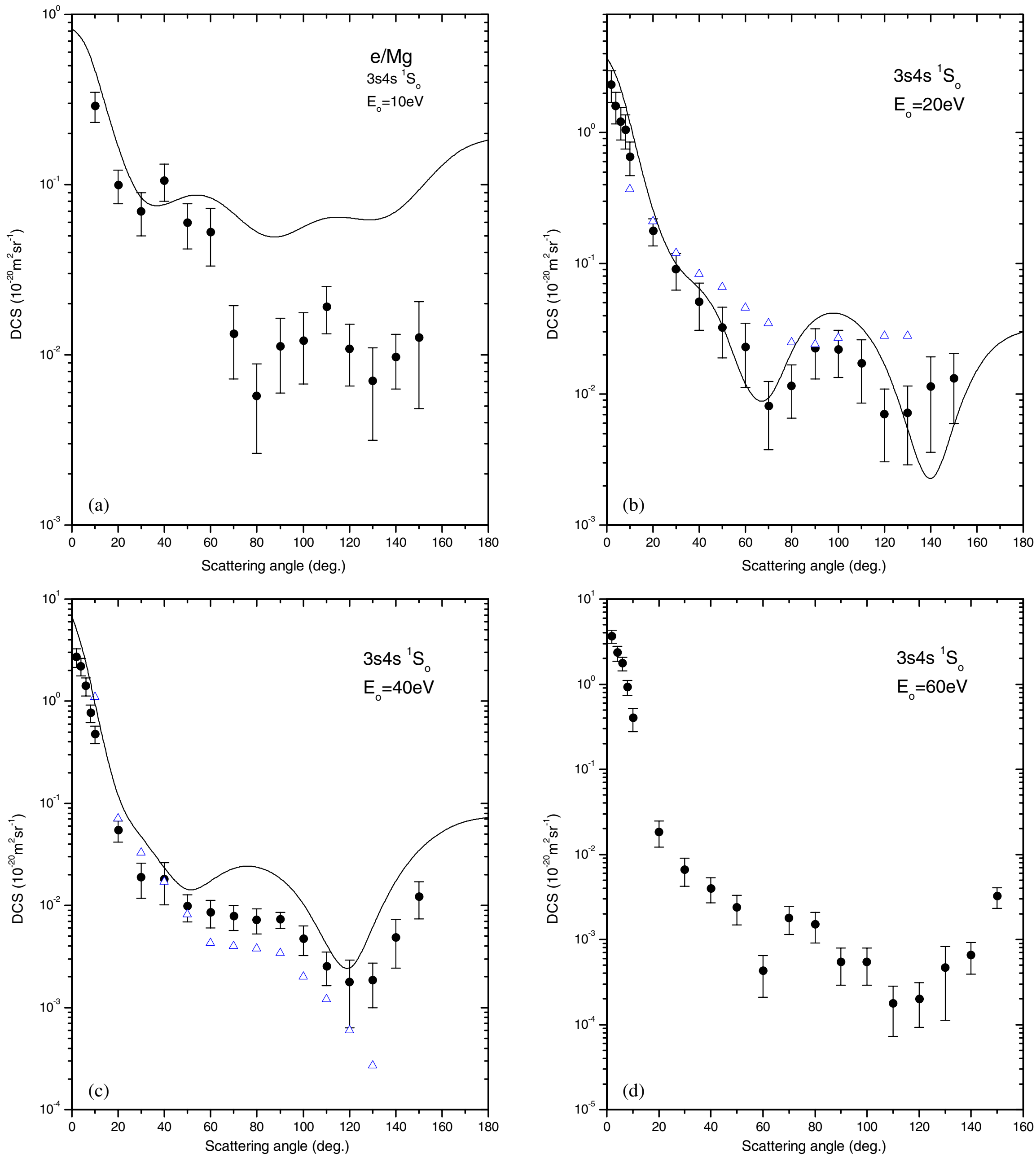

Figure 2. Differential cross sections (DCS) for the electron impact excitation of the 3s4s $^1S_0$ state of Mg at 10, 20, 40 and 60 eV impact energies. ●, present experiment (total error bars are indicated); △, Williams and Trajmar (1978); ——, CC5 (Mitroy and McCarthy 1989).

predicted by the theory but the matching in shape is very good. There are no results for the electron impact energy of 60 eV (figure 2(d)) to compare with.

Our DCS for the transition to the 3s3d $^1D_2$ and the impact energy of 10 eV agree very well with the measurements of Williams and Trajmar (1978) at the angles larger than 60°, except for the angle of 130°. For the angles smaller than 60° our DCS are systematically larger. On the other hand, our results fit very well with the CC5 theory for all scattering angles smaller than 110° (figure 3(a)). At 20 eV our DCSs for the small angles are very forward-peaked, and they are larger than those obtained by the experiment (Williams and Trajmar 1978) or by theoretical calculations CC5 (Mitroy and McCarthy 1989), SCGS-RDWA and MCGS-RDWA (Srivastava *et al* 2001). In the angle interval 20° to 80° the best overlap is achieved with the SCGS-RDWA (Srivastava *et al* 2001). At larger angles agreement between two experimental DCSs (the present one and that of Williams and Trajmar) is good, but they differ from all calculated values (figure 3(b)). At 40 eV and small angles ($\theta < 10°$) our measurements give smaller DCSs than those from Williams and Trajmar (1978), but at the higher angles our DCSs are systematically larger. We have the best match with the CC5 theory (figure 3(c)). As in the case of the 3s4s $^1S_0$ for the electron impact energy of 60 eV there are no results we can compare with. Our results show that from 2° to 40° the DSC decrease for about four orders of magnitude; also

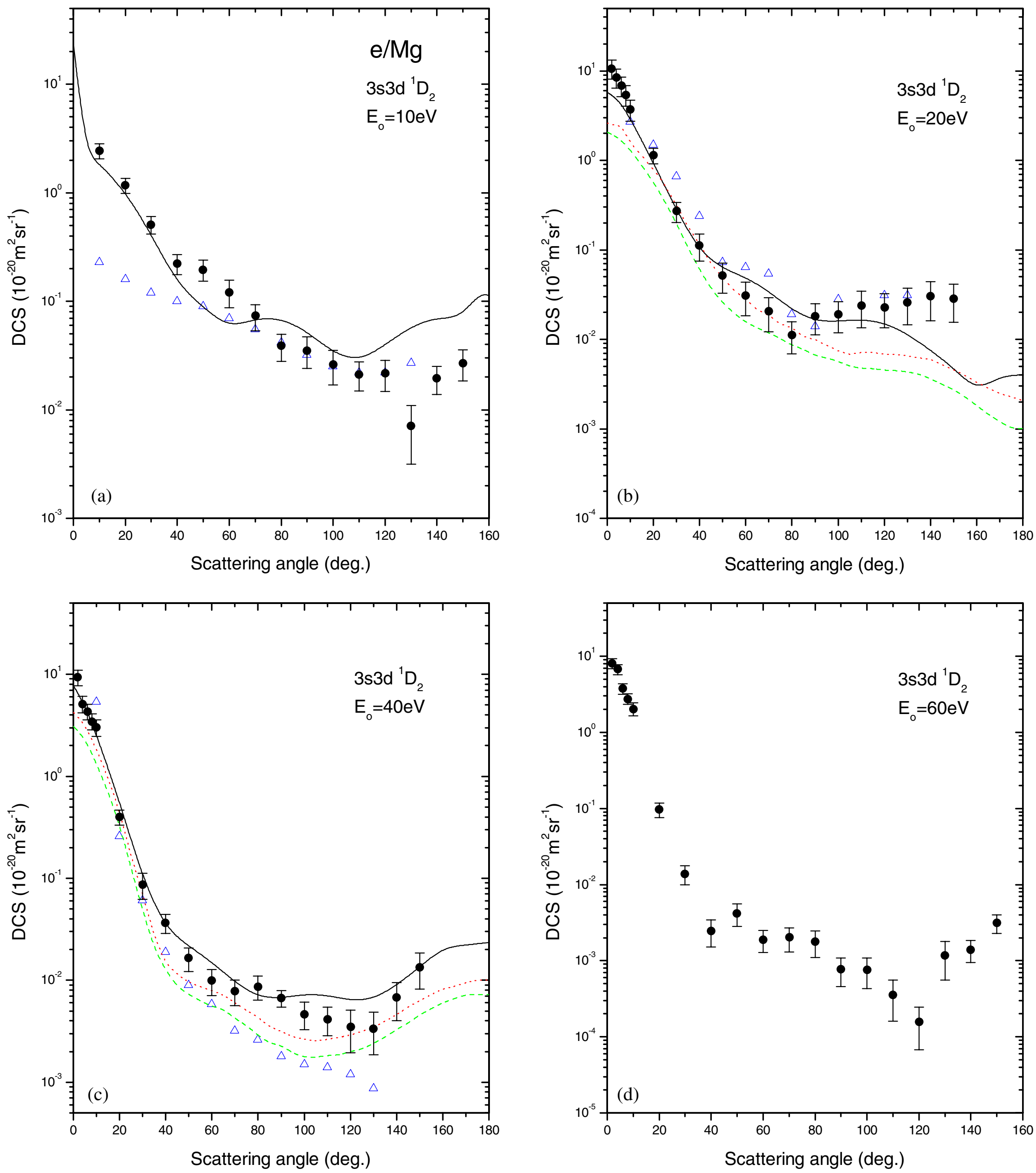

Figure 3. Differential cross section (DCS) for the electron impact excitation of the 3s3d $^1D_2$ state of Mg at 10, 20, 40 and 60 eV impact energies. ●, present experiment (total error bars are indicated); △, Williams and Trajmar (1978); ——, CC5 (Mitroy and McCarthy 1989); ······, RDW-MCGS (Srivastava *et al* 2001); – – –, RDW-SCGS (Srivastava *et al* 2001).

there are two minima—one at 40° and the other deeper at 120° (figure 3(d)). The minimum at 40° (as well as the minimum for the 3s4s $^1S_0$ state at 10 eV and 30°) could be viewed as a cusp-like feature suggested by Khakoo *et al* (2007).

As shown in figure 4(a), our results for the 3s4p $^1P_1$ state at energy 10 eV disagree with CC5 DCS values at larger scattering angles. The matching better concerns the shape; both the theory and the measurements show a rather simple DCS structure, with only one minimum present at around 120°. This is similar to the case of the $^1S_0$ excitation, but contrary to the $^1D_2$ excitation. Since the experimental values have been derived from the energy loss spectra where these three states are close to each other and fully resolved, we can conclude that the changes in the transmission function in the experiment could be ruled out as the reason of disagreement with the CC5 theory. For the electron impact energy of 20 eV and the angles larger than 30° we obtained the results similar to those of Williams and Trajmar (1978). Our results also agree very well with the CC5 calculations for angles larger than 10° (figure 4(b)). For angles smaller than 10° our experimental values overestimate the CC5 calculated values. In order to inspect small angle behaviour of the forward scattering at this energy, we have converted DCS values into generalized oscillator strengths (GOS) and have plotted them versus squared momentum transfer (K^2). The present GOS values show steady decrease over K^2, which is an expected

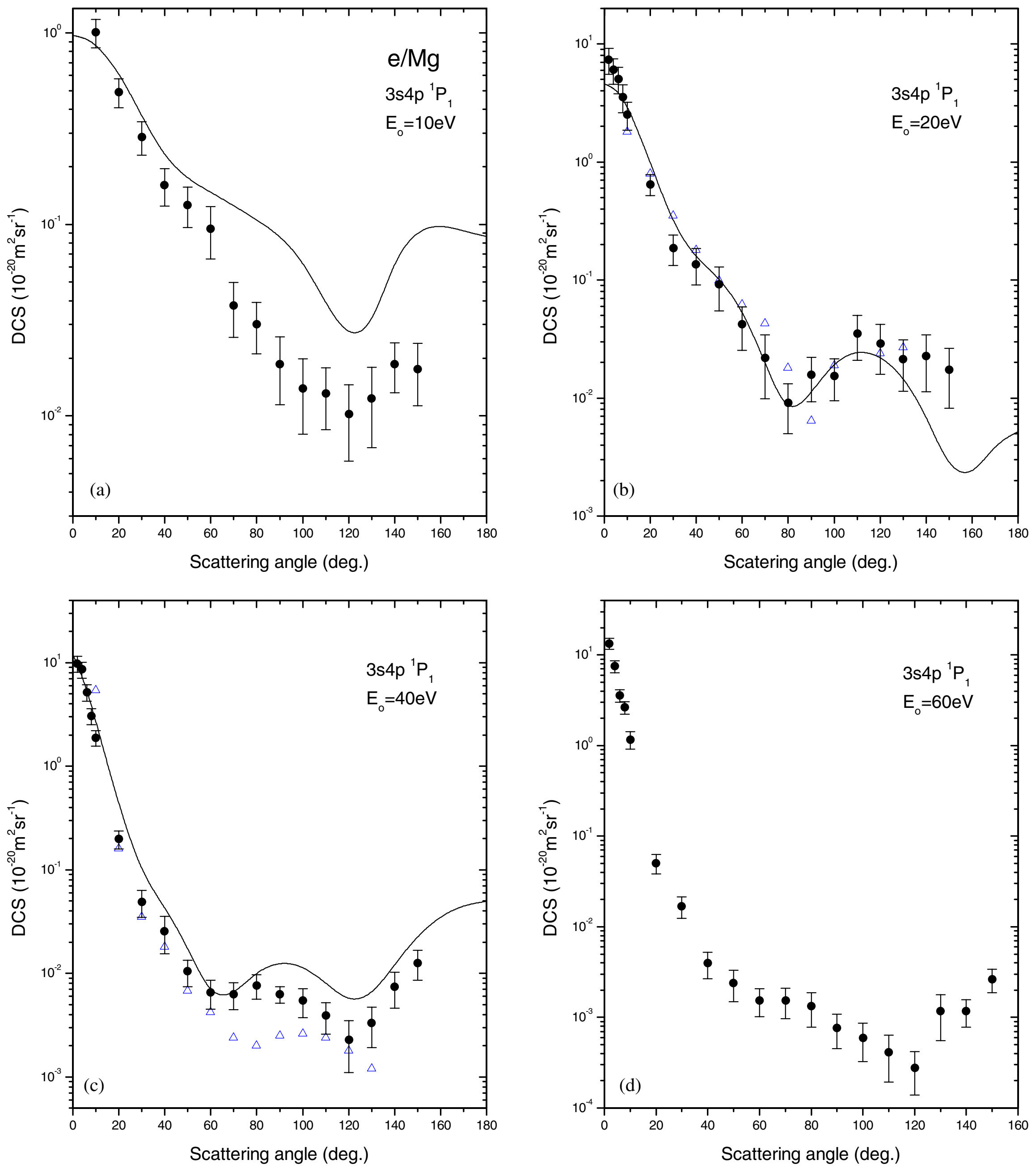

Figure 4. Differential cross sections (DCS) for the electron impact excitation of the 3s4p ^{1}P$_1$ state of Mg at 10, 20, 40 and 60 eV impact energies. ●, present experiment (total error bars are indicated); △, Williams and Trajmar (1978); ——, CC5 (Mitroy and McCarthy 1989).

behaviour. Contrarily, the CC5 GOS values rise with the increase of K^2. It would be interesting to carefully assess the reason why the theory underestimates the measurements. At 40 eV the correspondence of our results with the results of Williams and Trajmar (1978) is good for the angles smaller than 60°. At this energy we have good agreement with the CC5 theory; both give two minima at around 60° and 120° (figure 4(c)). As in the case of the 3s4s ^{1}S$_0$ and 3s3d ^{1}D$_2$ states there are no results with which we can compare ours. The measured DCS show one minimum at 120° and the drop in the interval from 2° to 120° of approximately five orders of magnitude.

As mentioned in section 2 the integrated cross sections are obtained by polynomial extrapolation of the DCSs to $\theta = 0°$ and 180°. The extrapolated values are given in square brackets in tables 1, 2 and 3. The contributions of the extrapolated values in integrated cross sections depend on ranges of extrapolations, electron impact energies and transitions. The largest contributions in Q_I are at an electron impact energy of 10 eV with 13%, 16% and 12% for the 3s4s ^{1}S$_0$, 3s3d ^{1}D$_2$ and 3s4p ^{1}P$_1$ states, respectively. For other impact energies the contributions are between 3% and 10%. The extrapolated values give larger contributions in Q_M. The largest contributions are for the 3s4s ^{1}S$_0$ state at electron impact energies of 40 eV and 60 eV (30.8% and 32%). For other energies and states the contributions are smaller than 20%.

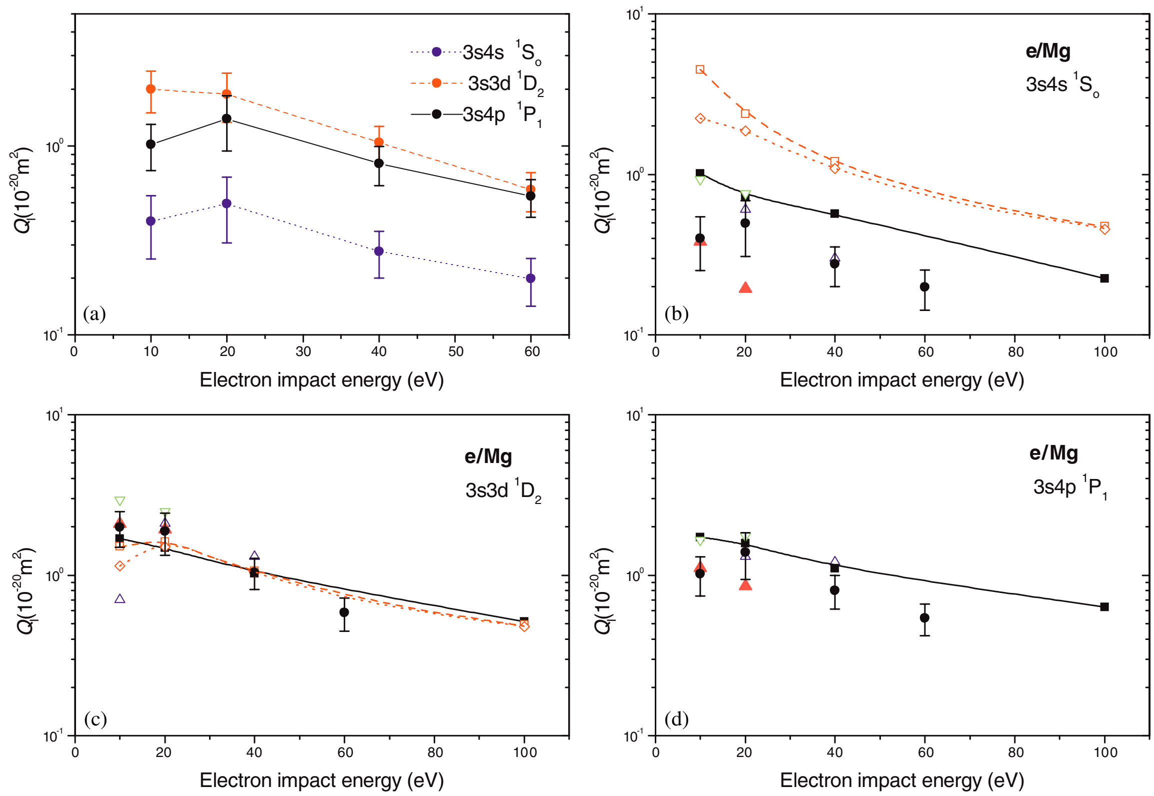

Figure 5. (a) Integral cross sections (Q_I) for the electron impact excitation of the 3s4s $^1S_0$, 3s3d $^1D_2$ and 3s4p $^1P_1$ states of Mg. The data points have been connected by a spline line for the ease of viewing. (b), (c), (d) Comparison between the present and other available data; ●, present experiment (total error bars are indicated); △, Williams and Trajmar (1978); ■, CC5 (Mitroy and McCarthy 1989); □, DWA (Clark *et al* 1991); ◇, FOMBT (Clark *et al* 1991); ▲, 19CC (Gedeon *et al* 1999); ∇, PWDOA (Gedeon *et al* 1999). The connecting lines between CC5, DWA and FOMBT are the best fit drawn for the ease of viewing.

As one can see in figure 5(a) integral cross sections show the relation $Q_I(3s3d\,^1D_2) > Q_I(3s4p\,^1P_1) > Q_I(3s4s\,^1S_0)$ for all measured electron impact energies. It is worth noting that the integral cross sections for the optically forbidden transition $(3s)^2\,^1S_0 \rightarrow (3s3d)\,^1D_2$ are larger than those for the optically allowed one $(3s)^2\,^1S_0 \rightarrow (3s4p)\,^1P_1$. In the case of the 3s4s $^1S_0$ state, our results are consistent with the results of Williams and Trajmar (1978). On the other hand, CC5 (Mitroy and McCarthy 1989), DWA and FOMBT (Clark *et al* 1991), and PWDOA (Gedeon *et al* 1999) calculations predict larger integral cross sections than the measured ones (figure 5(b)). Contrarily, the 19CC (Gedeon *et al* 1999) calculated value at 10 eV agrees perfectly with ours, while the value at 20 eV is much smaller. As shown in figure 5(c), for the 3s3d $^1D_2$ state we have very good agreement among the experimental results and the different theories for energies 20 eV and 40 eV. Williams and Trajmar (1978) obtained the integral cross section at an energy of 10 eV smaller than any other relevant result. Our Q_I for the 3s4p $^1P_1$ sate at 20 eV is consistent with the other results (figure 5(d)). At different energies our measured integral cross sections are smaller than those predicted by CC5 (Mitroy and McCarthy 1989) and PWDOA (Gedeon *et al* 1999) theories. At 10 eV our result agrees very well with the 19CC (Clark *et al* 1991) calculations.

In addition, we have analysed the n independence of the DCSs for the $3\,^1S_0 \rightarrow n\,^1P_1$ (n = 3, 4) transitions. We have used a similar manner as applied for $1\,^1S_0 \rightarrow n\,^1P_1$ (n = 3, 4) transitions in helium (Khakoo *et al* 1996). The effective quantum numbers (n^*) for the excited 3s3p and 3s4p states of Mg were calculated by using the simple Rydberg formula. We obtained the effective quantum numbers of 2.03 and 2.98 for $n = 3$ and $n = 4$, respectively. Using these effective quantum numbers the DCSs scaling law $(n_n^*)^{-3}$, at a given impact energy (E_0) and a scattering angle (θ), predicts for the ratio

$$r = \frac{\mathrm{DCS}(E_0, \theta)_{4P}}{\mathrm{DCS}(E_0, \theta)_{3P}}$$

a value of 0.31.

From figures 6(a)–(d), one can see that n independence is not reached for all energies measured. The experimental values of r clearly show a very complicated shape which indicates that this ratio does not follow the scaling law. Also, the average values of r over scattering angles are considerably different, 0.19 (E_0 = 10 and 20 eV), 0.13 (E_0 = 40 and 60 eV) from the theoretical 0.31 value. We point out that these ratios provide a very sensitive test of theoretical models. At small angles ($\theta < 10°$) agreements among present r and theoretical ratios are very good at all energies considered. At E_0 = 10 eV and $\theta > 70°$ agreement between experiment and theory (CC5) is unsatisfactory. At E_0 = 20 eV the CC5 (Mitroy and McCarthy 1989) calculations are in very good agreement with our r values (figure 6(b)). At E_0 = 40 eV and $\theta > 10°$ we find that the experimentally obtained values of r are

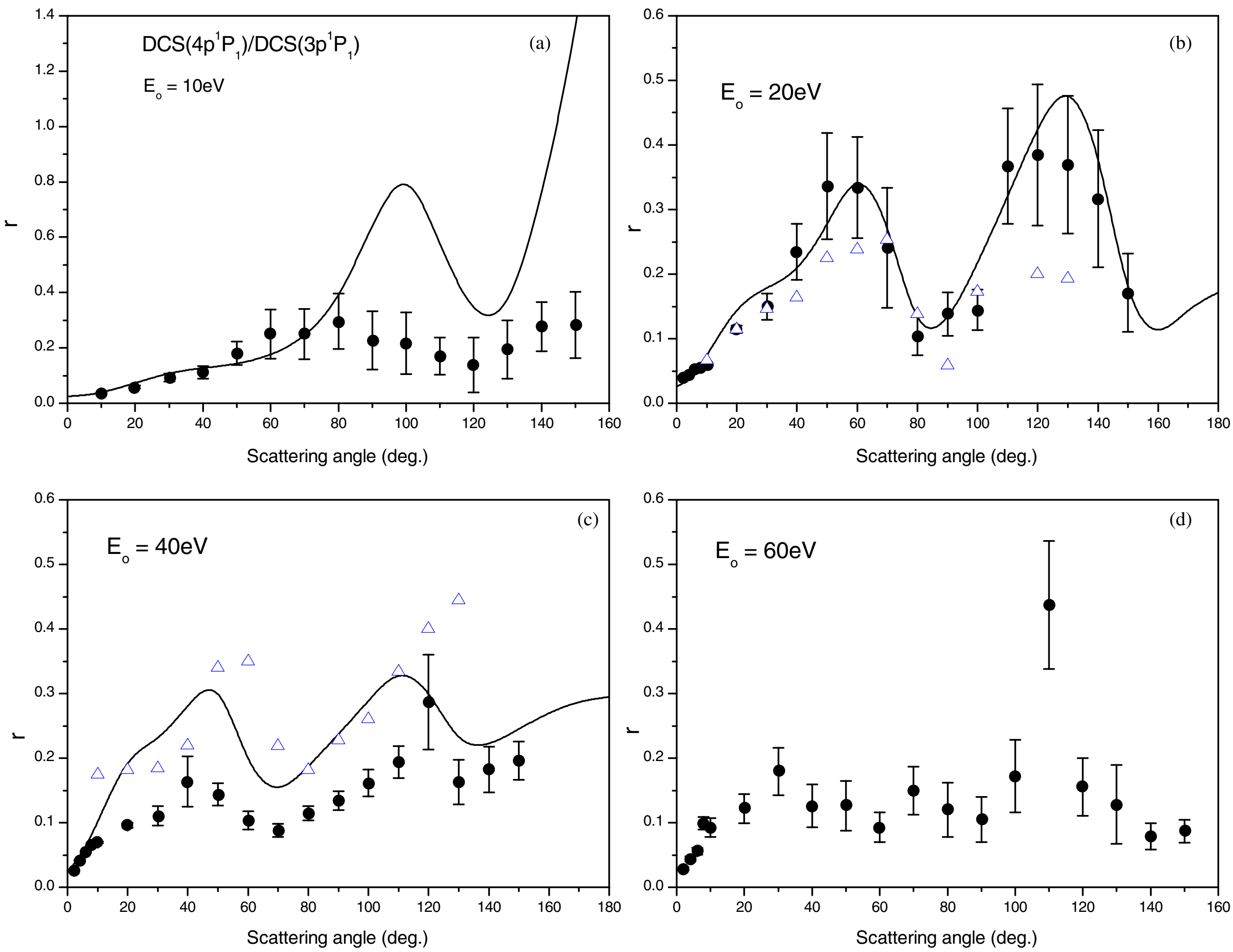

Figure 6. The ratios $r = \mathrm{DCS}(4\mathrm{p}\,^1\mathrm{P}_1)/\mathrm{DCS}(3\mathrm{p}\,^1\mathrm{P}_1)$ versus scattering angle at 10, 20, 40 and 60 eV. ●, present experiment (total error bars are indicated); △, Williams and Trajmar (1978); ——, CC5 (Mitroy and McCarthy 1989).

considerably smaller than the theoretical, but agreement in shape is relatively good.

In summary, we have presented DCSs and integrated cross sections for excitation of the 3s4s ^{1}S$_0$, 3s3d ^{1}D$_2$ and 3s4p ^{1}P$_1$ states in Mg for a relatively large range of the impact energies and scattering angles and thereby have improved the experimental situation that existed before our measurements. Experimental DCSs and integral cross sections for electron impact excitation of the 3s4s ^{1}S$_0$, 3s3d ^{1}D$_2$ and 3s4p ^{1}P$_1$ states of Mg at 60 eV and 3s4s ^{1}S$_0$ and 3s4p ^{1}P$_1$ at 10 eV are reported for the first time in this work. We hope that our results will encourage further experimental and theoretical efforts in investigations of the excitation of the magnesium atom.

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