Total cross sections for electron scattering from noble-gas atoms in near- and below-thermal energy collisions

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Abstract. Absolute total cross sections for electron scattering from He, Ne, Ar, Kr and Xe at very low electron energies are presented. The cross sections were obtained using the threshold-photoelectron source, which employs a combination of the penetrating field technique together with the threshold photoionization of atoms by synchrotron radiation. Obtained total cross sections for electron scattering from these noble gas atoms generally agree well with those obtained in the previous experiments above 100 meV, where several experimental works have been reported. Comparison of the measured cross section for He with that of theoretical ones shows very good agreement at very low energies even below 10 meV, which confirms the validity of theoretical cross sections of He which have been regarded as the ‘standard’ cross sections. Scattering lengths for the e⁻ - noble gas scatterings determined from the our cross sections using the modified effective range theory (MERT) showed that scattering lengths for He and Ne agree well with the values obtained in the previous experimental and theoretical studies. On the other hand, in case of heavier noble gas atoms, significant discrepancies were found between the scattering lengths derived from MERT analysis to our total cross sections and those reported in previous studies.

1. Introduction
Accurate absolute cross sections for electron scattering from atoms and molecules are of great importance not only in understanding the fundamental physics of electron collisions but also in many fields such as electron - driven processes in the Earth and planetary phenomena, gaseous discharges, plasmas, and radiation chemistry [1]. One of the key factors in these practical applications is the knowledge on cross sections in the very low energy region, such that the energy of the electrons become near and below the thermal energy, which is hardly accessible experimentally. When the collision energy becomes very low, several interesting phenomena appear in the scattering cross sections, such as Ramsauer-Townsend minimums, shape resonances, vibrational Feshbach resonances, threshold structure due to a virtual state and so on [2, 3]. The low energy behaviors of the collision cross sections are also related to the scattering length which gives zero-energy scattering cross section. Though the long-range polarization potential dominates the scattering at the limit of zero energy, existence of short-range interaction makes low-energy electron scatterings from atoms and molecules still more attracting subjects.
Considerable number of experimental cross section data for electron scattering from noble gas atoms has been reported due to its importance. Beam experiments with hot-filament electron sources have provided grand total cross sections in a wide energy range [4–20]. Although, producing an electron beam at energy below a few hundred meV was a formidable task using the conventional technique based on a hot-filament electron source, the energy range of the total cross-section measurements have been extended down to below 100 meV utilizing the time of flight technique [8, 11, 12, 15–18]. As an alternative for hot-filament electron source, measurements of total cross sections of electron scattering from noble gas atoms have been carried out employing photoelectrons of energies varying from 0.7 to 10 eV using the resonant emission lines of He and Ne in the VUV region [13, 14].

At lower electron energies, electron-swarm techniques have provided the information of electron scattering from noble gases [21–29]. However, difficulty arises in determining the accurate cross section uniquely by the swarm techniques, since the microscopic properties of electron-atom or -molecule collision have to be determined in a complicated unfolding procedure by self-consistent set of cross sections that will reproduce the macroscopic experimental results such as transport coefficients, drift velocity or mobility, via solution of energy distribution function [28, 30].

Measurements of total cross sections for electron scattering from various molecules below thermal energies under the single collision condition were achieved by Field and Ziesel, with co-workers, making use of photoelectron source together with high-resolution Synchrotron Radiation (SR) [31, 32]. They measured the total cross sections as well as backward scattering cross sections for electron scattering from various molecules below 100 meV where the de Broglie wavelength of electrons becomes very much greater than the typical size of an atom or a molecule, quantum effects dominate the resulting ‘cold electron collisions’ [33]. Several fundamental quantum phenomena of cold electron collision such as cross section enhancement due to a virtual state, rotationally inelastic scattering, giant resonances have been revealed in their work [34–37]. However, cross sections for electron scattering from noble-gas atoms at very low energies have not been reported by the group.

Recently, we have developed a new method so-called threshold photoelectron source for producing an ultra-low-energy electron beam [38]. The method employs a combination of the penetrating field technique and the threshold photoionization of noble-gas atoms using SR as an electron source to produce a high-resolution electron beam at a very low energy. Total cross sections for electron scattering from He, Ne [39], Ar, Kr and Xe [38, 40] in the energy range from 20 eV down to 10 meV were obtained using the threshold photoelectron source. Here we present our results of the absolute total cross section measurements for electron scattering from He, Ne, Ar, Kr and Xe at very low electron energies together with the scattering length obtained through the analysis with the modified effective range theory.

2. Experimental

In the present setup, a threshold photoelectron source was employed. The method combines threshold photoionization of atoms and the penetrating field technique developed by Cvejanović and Read [41]. An overview of the experimental setup is shown in figure 1. The setup consists of an electron scattering apparatus with a photoelectron source, a photon flux monitor and a micro channel plate (MCP). The electron scattering apparatus consists of a photoionization cell, three electrostatic lens systems, a collision cell and a channel electron multiplier (CEM).

The monochromatized synchrotron radiation is focused onto the center of the photoionization cell filled with argon atoms for producing photoelectrons. The threshold photoelectrons produced are extracted by a weak electrostatic field formed by 1st electron lens system and introduced into the electron scattering apparatus. In the penetrating field technique, a very weak field is produced in the photoionization region formed by an extraction electrode.
penetrating through a screening electrode. The penetrating field forms a saddle point in the potential distribution that has the effect of focusing and enhancing the extraction efficiency of photoelectrons of particular energy. The energy of the electron beam is tuned by the 2nd lens system and transmitted through the collision cell filled with target gas. The electrons passing through the collision cell without any collision with the target are angular discriminated and refocused by the 3rd lens system and detected by a CEM. The counting rates of the detected electrons in the presence and absence of target gas are converted to the total cross section for electron scattering according to the attenuation law.

The whole of the photoionization cell and scattering apparatus are placed inside the double \( \mu \)-metal shields to attenuate the earth’s magnetic field. The stray magnetic field is estimated to be less than \( 10^{-7} \) T which is sufficiently small not to interact with the lowest energy electron in the present experiment. The flux of the ionizing photon beam was monitored by the Au mesh. The MCP was set in order to measure the photoion yield spectra of Ar during the tuning of the electron scattering apparatus. The experiment has been carried out at the beam line 20A of Photon Factory, KEK in Japan. A 3 m normal incidence monochromator equipped with a 2400 lines/mm grating is installed in this beamline [42].

One of the advantages in using the penetrating field technique is that energy broadening of the ionization radiation has little effect in broadening the energy width of the electron beam from the threshold photoelectron source. The energy width of the electron beam, on the other hand, depends on the initial energy distribution of the extracted photoelectrons. By tuning the penetrating field, only the photoelectrons having energies less than 1 meV can be extracted from the photoionization cell and transmitted to the 2nd lens system, while the energetic photoelectrons rapidly diverge [38,43]. Threshold photoelectron source also has another advantage of weakening the electrostatic field for the collection of the photoelectrons in the photoionization region. Since the electric field applied across the photoionization region degrades the energy resolution of the electron beam, a narrow photon beam is necessary for the formation of a high resolution electron beam. The size of the ionization photon beam was confined to 1 mm in diameter by an aperture placed in front of the photoionization cell. The space charge

**Figure 1.** Overview of the experimental apparatus. The apparatus consists of an electron scattering apparatus with a photoionization cell, a micro channel plate (MCP) to collect photoions and a photon flux monitor of the monochromatized synchrotron radiation.
effect is negligible due to the low flux density of the ionization photon beam.

In the present method, stability of the intensity of the electron beam depends on the intensity and the energy of the photon beam. The stability of the photon beam intensity was achieved by the Top-up operation of the Photon Factory facility that has been available in the recent operation. Since the instability of the energy of the photon beam at small photon energy width causes fluctuation in the electron beam intensity, photon energy band width was set to about 3 to 5 meV.

The energy position and the width of the electron beam was determined by fitting the theoretical cross sections convoluted with a Gaussian function representing the resolution to those measured at around the Feshbach resonances of each target atoms. The energy widths of the electron beam were ranging from 6 to 15 meV depending on the target gas, which seem rather wider than those of expected from the analysis of the photoelectron yield spectrum. The uncertainty of the energy position is 5 meV for He, Ne and Ar, 12 meV for Kr and 16 meV for Xe. The broadening of the electron energy seems to be caused by the electric noise from the power supplies feeding the electrodes and also the surface potential variations inside the collision cell due to the work function of the materials and the shape of the electrode.

3. Results and discussion

Total cross sections for electron scattering from He, Ne, Ar, Kr and Xe obtained using the threshold photoelectron source [38–40] with the results of previous experimental and theoretical work in figures 2. The well-known Ramsauer-Townsend minimums are seen for Ar, Kr and Xe. Since the resolution of the present set-up is sufficiently high, sharp structures due to the Feshbach resonances can be seen on each of the present cross section curves as marked by arrows in figures 2 for every targets. In general, our results agree with the previous experimental results above 100 meV where experimental data are available in the literature.

Below 100 meV, a brief comparison with theoretical cross sections is given here. Comparison of the cross sections are ideal test for theoretical treatment of scattering especially concerning electron correlations of a few particle many body systems. As was pointed out by Saha [48], theoretical treatment becomes very difficult due to strong contribution of electron correlation and polarization at very low energies close to the zero energy limit. Therefore comparison of experimental and theoretical cross sections at very low energies would be necessary for critical assessment of the theoretical treatment. Since inelastic scatterings are energetically inaccessible below the energy of the lowest excited states of the target atoms, present total cross sections are guides for the theoretical elastic cross section calculations at low energies.

In case of He, attempt to obtain accurate theoretical cross section below the first excited state gave results that agree very well with the previously reported experimental cross sections above 100 meV [44–48]. Figure 2(a) shows excellent agreements between our experimental cross sections and the theoretical cross sections even below 100 meV. This fact confirms that modern theoretical treatment for the electron scattering from small simple system is adequate.

The cross section for Ne obtained with the present technique also confirmed the theoretical cross sections at very low energies as shown in figure 2(b). Here, among the theoretical cross sections for electron scattering from Ne, the elastic integral cross sections of McEachran and Stauffer [49], and those of Saha [50,51] together with the theoretical total cross sections of the recent large scale R-matrix calculation by Zatsarinny and Bartschat [52] are shown in figure 2(b) for the comparison.

For the heavier noble gas atoms, the situation becomes rather complicated. For Ar, among the theoretical work, cross sections of Minnagh et al. [54] show fairly good agreement with our cross sections. Although the cross sections at around the Ramsauer-Townsend minimum were better reproduced by the the relativistic version of Minnagh et al. reported by McEachran and Stauffer [56] than the results of Minnagh et al. [54], discrepancies between our cross sections
Figure 2. Comparison of the total cross sections for electron scattering from He, Ne, Ar, Kr and Xe. Arrows in each figure indicate the positions of the Feshbach resonances for each target atoms.

become larger at very low energies. The results of Saha [55] also show larger cross sections compared to our results at very low energy region. This shows the difficulty in theoretical treatment of electron scattering from Ar. In case of Kr and Xe, discrepancies between the theoretical results and our results become large at low energy region.

In table 1, comparison of scattering length obtained in various studies is made. Scattering lengths of Shigemura et al. [39] and Kurokawa et al. [40] were derived with the modified effect range theory (MERT) [60, 61] analysis using the cross sections measured with the present experimental technique. Scattering lengths for He and Ne obtained from our cross sections agrees well with the values obtained in the previous experimental and theoretical studies. For
Table 1. Comparison of scattering length obtained in various studies. B stands for beam experiment, S for swarm experiment and T for theoretical work.

| method                      | Scattering length ($a_0$) |
|-----------------------------|---------------------------|
|                            | He | Ne | Ar | Kr | Xe |
| Shigemura et al. [39]       | B  | 1.194(6) | 0.206(19) |     |     |
| Kurokawa et al. [40]        | B  |     | -1.365(5) | -3.06(2) | -5.13(3) |
| Ferch et al. [8]            | B  | 1.195 |     |     |     |
| Ferch et al. [11]           | B  |     | -1.449 |     |     |
| Buckman and Lohmann [12]    | B  | 1.16 |     | -1.492 |     |
| Buckman and Lohmann [15]    | B  |     |     | -3.19 |     |
| Buckman and Mitroy [63]     | B  | 0.206 |     | -1.442 | -3.279 |
| Crompton et al. [21]        | S  | 1.19 |     |     |     |
| O’Malley and Crompton [23]  | S  |     |     | 0.2135 |     |
| Milloy et al. [22]          | S  |     |     | -1.50 |     |
| Haddad and O’Malley [24]    | S  |     |     | -1.488 |     |
| Petrović et al. [29]        | S  |     |     | -1.459 |     |
| Hunter et al. [25]          | S  |     |     | -3.36 | -6.09 |
| England and Elford [26]     | S  |     |     | -3.43 |     |
| Brennan and Ness [27]       | S  |     |     | -3.3528 |     |
| O’Malley et al. [44]        | T  | 1.177 |     |     |     |
| Nesbet [45]                 | T  | 1.1835 |     |     |     |
| Saha [48]                   | T  | 1.1784 |     |     |     |
| Saha [51]                   | T  |     | 0.2218 |     |     |
| Saha [55]                   | T  |     |     | -1.486 |     |
| McEachran and Stauffer [49] | T  | 0.2012 |     |     |     |
| Cheng et al. [62]           | T  | 1.189 | 0.224 |     | -3.23 |

Heavier noble gases, the values of scattering lengths obtained from our cross sections which have been measured in the extended energy range are rather smaller in absolute value than the previously reported values for each atom, especially for Xe. In Table 1, there is a tendency that absolute values of the swarm derived scattering length of Ar, Kr and Xe are larger compared to those obtained from the previous beam experiments. Our results for Ar, Kr and Xe are even smaller in absolute values compared to the previous ones obtained by the beam experiments.

Scattering lengths for Ar, Kr and Xe obtained from beam measurements other than Kurokawa et al. [40] may have uncertainty in extrapolating the cross section curve down to zero-energy by MERT fit, due to the restricted energy range of measurements. The energy range of the validity in applying the MERT has been investigated in several reports [11, 15, 63]. We have found that in order to give satisfactory fit to our total cross sections of Ar, Kr and Xe including very low energy region below 100 meV, standard form of MERT was not sufficient [40]. Restricted energy range of the cross sections used in the MERT fit in the previous beam experiments may have gave scattering length of rather larger magnitude. On the other hand, although very low electron energy region as low as 10 meV is accessible in swarm experiments, deriving the momentum transfer cross sections from macroscopic experimental results includes complicated and cumbersome unfolding procedure [28, 30] which also may use MERT analysis.

Recently, re-analysis of several cross section data in the literature using an alternative MERT fit were reported by Fedus et al. [64–66]. The energy range of the validity in applying the MERT
has extended to higher energies in their approach. Fedus et al. have re-analyzed the scattering length of Ar using the cross sections Kurokawa et al. and obtained similar value of $-1.40 a_0$ [64]. It is interesting that magnitude of the effective range for $s$-wave is larger compared to that derived from other cross section data of beam experiments whose energy range were restricted.

Although it has been shown that the modern theoretical treatment for the electron scattering from simple closed-shell targets such as He and Ne is valid even at the very low energies, the need of further high precision experiments in the very low energy region as well as theoretical studies for electron scattering from heavier noble gases is emphasized.

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