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LETTER TO THE EDITOR

Projectile charge state dependence of binary electron production for 1 MeV u^{-1} Au^{q+} (q = 12–37) ion impact on He

M Sataka†, M Imai†, Y Yamazaki‡, K Komaki‡, K Kawatsura§, Y Kanai‖, H Tawara¶, D R Schultz* and C O Reinhold*#

† Department of Materials Science and Engineering, Japan Atomic Energy Research Institute, Tokai, Ibaraki 319-11, Japan

‡ Institute of Physics, College of Arts and Sciences, University of Tokyo, Meguro, Tokyo 153, Japan

§ Department of Chemistry, Faculty of Engineering and Design, Kyoto Institute of Technology, Matsugasaki, Sakyo, Kyoto 606, Japan

‖ The Institute of Physical and Chemical Research (RIKEN), Wako, Saitama 351-01, Japan

¶ National Institute for Fusion Science, Nagoya 464-01, Japan

* Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831-6372, USA

Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996-1200, USA

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Abstract. The absolute cross section for the production of binary encounter electrons has been studied at zero degree for highly charged, clothed ions. Experimental and theoretical results for 1 MeV u^{-1} Au^{q+} (q = 12–37) colliding with helium are presented. It is found experimentally that as the charge state of the incident ion is increased (1) the binary peak magnitude increases, (2) the electron energy at which the peak occurs decreases, and (3) the peak broadens. Classical trajectory Monte Carlo (CTMC) calculations are found to give good account for the magnitude and the shift to lower electron energy of the peak, the continuum distorted wave-eikonal initial state (CDW-EIS) approximation is shown to yield cross sections which are much smaller in magnitude than the experiments, but to reproduce well the relative magnitudes and shapes of the peaks for these ions. It is noted that the increase in the binary peak magnitude with increasing ionic charge state is in distinction to previous measurements which showed enhancement of the binary peak with decreasing charge state for clothed ions.

Binary encounter (BE) electron production is a well known process originating from a close collision between a fast charged particle and a target electron. For fully stripped ions, this process can be reduced to a two-body interaction (the Rutherford scattering between the projectile and a quasifree electron) for large collision velocities, v_p, and small projectile charges, Z_p. That is, for values of the Sommerfeld parameter $\eta = Z_p/v_p \ll 1$ (Bonsen and Vriens 1970, Rudd and Macek 1975, Stolterfoht 1978). In this scheme, the signature of BE electrons is a prominent peak in the ejected electron spectrum, whose centroid energy E_b is expected to appear at $4\lambda E_p \cos^2\theta$, where E_p is the projectile energy, θ the observation angle with respect to the beam axis, and λ the electron–projectile mass ratio m/M. The initial momentum distribution of the electron and the fact that it is initially bound to the target cause the peak to be slightly shifted and have a full width of $\sim 4(\epsilon_b E_p \lambda)$ at $\theta = 0°$, where ϵ_b is the binding energy of the electron.

We note that a number of departures from this simple behaviour have been observed. For example, considering bare ions and relatively small values of η, the BE electron intensity has been demonstrated to be proportional to Z_p^2 (Lee *et al* 1990) in accord with this model. However, as η increases, the BE peak broadens beyond the width of the atomic Compton profile and its position shifts to an energy much lower than E_b (Lee *et al* 1990, Pedersen *et al* 1990, 1991). This phenomenon has been ascribed to so-called two-centre effects (see Fainstein *et al* 1991) and is due to the fact that ionization for large Sommerfeld parameters must be treated as a three-body Coulomb problem. In other words, the target nucleus also plays an important role in the emission of fast electrons. Recent success has also been obtained in explaining the mechanism responsible for the shift of the peak using the 'resonant tunnelling model' (Bohr and Lindhard 1954, Fainstein *et al* 1992). Regarding the target electron as quasi-free, the energy in the projectile frame is conserved in its binary collision with the projectile. However, if its initial binding to the target core is accounted for, this conservation of energy can be applied only after the electron is 'released' from the atom. Assuming that the release occurs when the field strength of the projectile at the position of the electron exceeds that of the target (Bohr and Lindhard 1954), the amount of the energy shift is estimated to be proportional to $Z_p^{1/2}$, which is in qualitative accordance with experiment.

Another departure from the behaviour predicted on the basis of two-body dynamics has been observed for partially stripped ions. In this case, the BE peak intensity has been for a long time believed to be proportional to the square of some effective charge, $Z_{\rm eff}$, which takes a value between the ionic charge q and nuclear charge Z_p (Toburen and Wilson 1979, Toburen *et al* 1980). This behaviour is what we will hereafter refer to as 'normal' q-dependence. In contrast, investigations by Richard *et al* (1990) for 1–2 MeV u^{-1} F^{q+} ($q = 3$–9) colliding with He and H$_2$ have shown that the BE electron intensity for ejection near zero degrees increases with decreasing q under certain conditions. This 'anomalous' charge state dependence has been investigated experimentally by several groups mainly for light to medium heavy projectiles (Hvelplund *et al* 1991, González *et al* 1991, 1992, Sataka *et al* 1993, Shinpaugh *et al* 1993). The theoretical model explaining how this seemingly anomalous charge state dependence comes about has been given by Olson *et al* (1990), Reinhold *et al* (1990), Shingal *et al* (1990) and Taulbjerg (1990), and is based on the fact that the scattering of the target electron by the partially clothed ion differs markedly from scattering from a bare ion.

Finally, pronounced diffraction structures have also been observed in the region near E_b at larger ejection angles by Kelbch *et al* (1989, 1992) and Hagmann *et al* (1992). In this case, projectile ions with very many electrons, e.g. U^{21+}, produce strongly non-monotonic behaviour of the non-Coulomb phaseshifts which result in a rapidly oscillating elastic scattering cross section. Therefore, in the convolution of this scattering of the target electron by the projectile with its momentum distribution, the strong oscillations persist in the ejected electron spectrum near the binary peak (Reinhold *et al* 1991, Schultz and Olson 1991).

Our purpose here is make a systematic study of a collision system, from both an experimental and theoretical point of view, which could potentially be sensitive to these anomalous effects. To this end, we have investigated the ejected electron spectrum at zero degrees for partially stripped gold ions (Au^{q+}, $q = 12$–37) colliding at 1 MeV u^{-1} with helium. In this case, the Sommerfeld parameter is moderately large ($1.9 < \eta < 5.8$) and therefore significant shifts of the binary peak are expected. At the same time, these partially stripped ions carry many electrons and, on the basis of the aforementioned works, one would expect that consequently the binary peak intensity could manifest significant enhancement with respect to the binary peak produced in collisions at the same velocity with the fully stripped ion. Experimentally, we have performed measurements which we have placed on an absolute scale, as described below. In contrast, we note that relative cross sections for a similar problem have been recently reported by Jagutzki *et al* (1991) and Wolff *et al* (1993).

For comparison, we have computed the same cross sections with two distinct theoretical approaches which have been widely and successfully applied to the treatment of collisions involving two-centre effects. the first is the continuum distorted wave-eikonal initial state (CDW-EIS) approximation (Crothers and McCann 1983). This treatment is a first-order, perturbative, distorted wave approximation in which the distortion in the entrance channel is described by an eikonal phase and where the final state is represented by a product of continuum Coulomb states centred on both the target and projectile. We emphasize that this model has only been developed thus far to treat problems involving pure Coulomb interactions. Motivated by the desire to realistically model the non-Coulomb interaction of the target electron with the partially-stripped projectile ion, we have also utilized the classical trajectory Monte Carlo (CTMC) technique (Abrines and Percival 1966, Olson and Salop 1977). In the present treatment utilizing this model, the interactions of the electron with the target and projectile cores are represented by a model potential to simulate the distance dependent screening (Toburen *et al* 1990).

The experiment has been performed at the tandem accelerator facility at the Japan Atomic Energy Research Institute of Tokai. The experimental setup and procedures used have been described in detail before (Kawatsura *et al* 1990, 1991), and so only a brief survey will be given here. A Au^{12+} ion of 1 MeV u^{-1} was provided by the accelerator and post-stripped to get higher charge state. To get absolute cross sections, an electron spectrum for 2 MeV u^{-1} F^{9+} ion on He measured with the same detection system, was compared with the absolute data by Lee *et al* (1990). The uncertainties of the cross section were estimated to be less than 20%. The BE peak energy for a free electron at rest, which will be termed as free binary energy, was defined as four times the measured ECC and/or ELC peak energy. In order to get correct electron spectra, the background spectra measured without target gas are subtracted from the spectra with target gas.

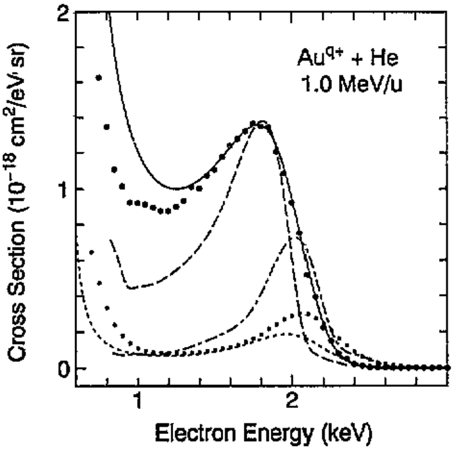

Figure 1. Double differential cross sections at 0° as a function of electron energy for 1 MeV u^{-1} Au^{q+} impact of He. Experiment: ·, 12+ ion impact; ●, 37+ ion impact. CDW-EIS calculations: full curve, 37+; dotted curve, 12+. CTMC calculations: broken curve, 37+; chain curve, 12+. The CDW-EIS cross sections are multiplied by 20.

Observed doubly differential spectra at 0° for Au^{q+} ($q = 12$ and 37) impact on He are shown in figure 1 together with our CDW-EIS and CTMC calculations. The experimental results have been placed on an absolute scale according to the procedure given above. Since the CDW-EIS calculations grossly underestimate the measurements, we have multiplied them by a factor of 20 in order to bring them onto the same scale as the experimental data. After this renormalization, the peak shape predicted by the CDW-EIS calculation is reasonably good for $q = 37$, even though this model treats the projectile as being a bare ion with atomic number equal to the ionic charge. This indicates that the primary mechanisms which determine the shift and width of the peak are not dependent upon the screening of the projectile nuclear charge, for this charge state. Similar conclusions have been recently reached by Wolff *et al* (1993). However, for the lower charge state $q = 12$, the peak's shape and position are not so well reproduced, and again noting that the magnitude differs from the experimental value by about a factor of 30.

From this figure we may also see that the observed binary peak intensity is fairly well reproduced by the CTMC results for Au^{37+} ions. For $q = 12$, the CTMC result is about two times larger than the observed cross section, which, however, is still much better than the CDW-EIS. In comparison to the experimental peak width, however, the CTMC peak is much more narrow. This behaviour originates from the classical scattering of an electron by a non-Coulomb potential. In particular, for scattering to exactly zero degrees in the laboratory the classical elastic cross section possesses a singularity, known as the glory (Reinhold *et al* 1991, Schultz and Olson 1991). In the present case, the singularity is rather narrow and angular acceptances of two and five degrees give essentially the same result for the CTMC calculation. In the following discussion, we will focus on three features which characterize the BE peak structure, (1) the peak intensity, (2) the peak energy shift, and (3) the peak width.

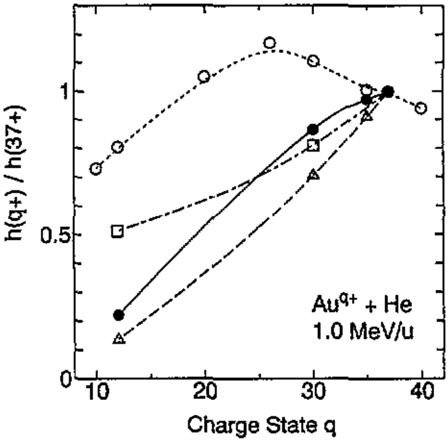

Figure 2. The ratio of the BE peak height for 1 MeV u^{-1} Au^{q+} impact on He to the height for Au^{37+} on He; experiment: •, calculations: ○, binary encounter approximation; △, CDW-EIS; □, CTMC.

Figure 2 summarizes the BE peak height as a function of q with respect to that of $q = 37$. First, one notices that the peak height increases with increasing ionic charge, yielding essentially a 'normal' q-dependence. This is in contrast to the results of Richard *et al* (1990) for fluorine ions for which the lower charges states, at approximately the same velocity as the present gold ions, produced larger binary peaks than the ions of higher charge state. As a reference, we also display the ratios obtained from a quantum mechanical calculation of the elastic cross sections (binary encounter or impulse approximation) which used the same model potentials as employed in the CTMC calculation for various charge states of the gold ions (Schultz and Olson 1991). We note that the binary encounter model, computed using model potential interactions yielded excellent agreement (Reinhold *et al* 1990) with the measurements of Richard *et al* (1990) for the degree of enhancement that those authors observed. The deviations of these ratios from the present experiment clearly indicate the importance of two-centre effects in the determination of the peak heights. In fact, the agreement between the data and CDW-EIS calculations may imply that two-centre effects seem to dominate the behaviour of the peak height as a function of q. A similar conclusion may be drawn from the trend of the CTMC results although they give a little weaker dependence with increasing q.

Table 1. The BE peak energy shifts ΔE_b for 1 MeV u^{-1} Au^{q+} impact of He, which are measured from the position of the free binary peak ($E_b = 2.18$ keV) determined relative to the energy of ECC and ELC peaks. Experimental uncertainties are less than 0.05 keV. ΔE_b(CDW-EIS) and ΔE_b(CTMC) are obtained from CDW-EIS and CTMC calculations, respectively.

Projectile charge	ΔE_b(exp) (keV)	ΔE_b(CDW-EIS) (keV)	ΔE_b(CTMC) (keV)
12+	0.12	0.24	0.17
30+	0.33	0.37	0.31
35+	0.40	0.42	
37+	0.42	0.43	0.37

As noted in the discussion of figure 1, it may be seen that the qualitative trends of the peak shift as a function of charge state are reasonably described by both of the present theories, as opposed to result of the first Born (FBA) or binary encounter (BEA) approximations using Coulomb interactions. We note that if model potentials are used in FBA or BEA slight shifts can be produced for different ions, but the size of the shift is too small to explain the experimental observations (Wolff *et al* 1993). Table 1 summarizes the energy shifts from the 'free' binary energy, E_b, that we have obtained. The energy shifts of the observed BE peak from the free binary energy range from 0.12 keV to 0.42 keV for incident charge states of 12 to 37, respectively, and in particular, the result is only roughly consistent with the $q^{1/2}$ dependence mentioned above. We note that a good fit to the q-dependence could be obtained by using the so-called resonant tunnelling model (Wolff *et al* 1993).

The present BE spectra are compared in figure 3 together with that for 1 MeV u^{-1} F^{9+} (Lee *et al* 1990), which is expressed in a fitting curve, as a function of electron momentum. The heights and the positions of the BE peaks have been adjusted so as to superimpose the curves. It is seen that the peak shape for Au^{37+} is wider than that for Au^{12+}. This seems to indicate that the two-centre effects for Au^{12+} might be less important than for Au^{37+}. This observation implies that the electric field in the asymptotic region is responsible for the broadening of the BE peak. The absolute cross sections, on the other hand, are fairly well reproduced by the CTMC calculation, which is not the case for the CDW-EIS calculation. In other words, the total 'reaction rate' depends on an effective charge at the moment of the BE electron production, very close to the charge of bare ion. Comparison between the BE peak widths for Au^{12+} and F^{9+} shows that the BE peak width for clothed Au^{12+} ion is

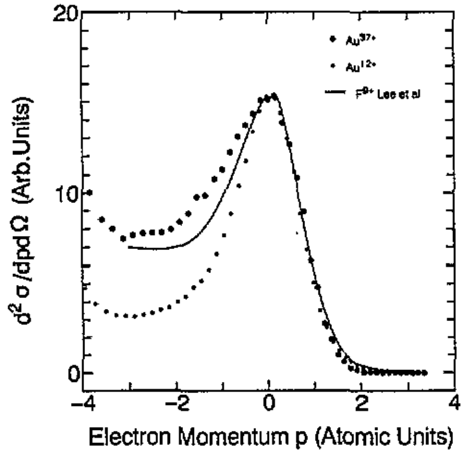

Figure 3. Comparison of the double differential cross sections as a function of electron momentum. The peak positions are shifted and the peak heights are normalized so that they are synchronized at the peak. Large full circle, Au^{37+} ion impact on He; full circle, Au^{12+} impact on He; full curve, F^{9+} impact on He (Lee *et al* 1990).

narrower than that for bare F^{9+} ion, although wider peak width is expected for higher ionic charge state (12+) according to the dependence for clothed ions described above.

It is noted that on the high energy side, the Au^{12+} and Au^{37+} spectra overlap with each other, and their tails are shorter than F^{9+}. The behaviour of the high energy tail is consistent with the fact that these electrons originate very close to the target core and thus have a large initial momentum and are decelerated considerably during their escape (see Jagutski *et al* 1990). This feature is successfully described by approximations such as CTMC and CDW-EIS which incorporate two-centre effects.

Summarizing, absolute cross sections for binary electron production for 1 MeV u^{-1} Au^{q+} (q = 12–37) ions bombarding He have been measured and compared with CTMC and CDW-EIS calculations. It is found that the absolute cross sections for all charge states measured are fairly well reproduced by the CTMC calculations whereas the CDW-EIS approximation gives values smaller by a factor of 20. We conclude that treatment of these partially stripped ions using a bare Coulomb interaction is not sufficient to approximate the magnitude of binary electron production. However, shifts of the peak from the position predicted on the basis of quasifree scattering of target electrons are reasonably reproduced by both two-centre theories. The trend of binary peak heights as a function of increasing ionic charge state is consistent with the 'normal' q-dependence, in distinction from enhancements observed previously for other partially stripped ions where lower charge states produced larger binary peaks than more highly stripped ions. The observed q-dependence of the peak heights is found to be strongly related to two-centre effects. In addition, the experimentally observed prominently broadened peak for q = 37 may be explained by either CDW-EIS or CTMC calculations using Coulomb interactions. We note that when a model potential is utilized in the CTMC technique to simulate the screening of the projectile nuclear charge, the resulting binary peak is narrower due to the existence of a classical glory. Hence, the next logical step towards the understanding of ionization would be to develop a quantum mechanical two-centre theory which incorporates the short distance screening through model potentials. Experimentally, studies exploring more comprehensively the impact energy dependence of these effects, and for ionic charge states bridging the region between the normal 'q-dependence' and the enhancement apparent for lower charge states, would seem in order.

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