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Symmetric scattering in electron and positron impact ionization of metastable 2*s*-state hydrogen atoms

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Abstract. Triple differential cross sections for ionization of hydrogen atoms in the metastable 2*s*-state by the impact of electrons and positrons have been calculated for coplanar symmetric geometry. In this calculation a multiple scattering theory due to Das [10] and Das and Seal [11] has been used. An analysis of the results reveals that unlike scattering from the ground state, scattering from 2*s*-state is essentially a higher order process except for the binary collision direction. Moreover, here, the cross section results for 2*s*-state are much larger compared to those for scattering from the ground state. It is also found that the ionization mechanism at large scattering angles for ionization from the 2*s*-state is different from that for ionization from the ground state.

Keywords. Cross section; collision; ionization; scattering; electron; positron.

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1. Introduction

Coplanar symmetric scattering in electron-atom and positron-atom ionization collisions is now an important field of study [1–9]. Results for ionization from the ground state reveals the existence of double peak structure for the cross section curves. The first peak is the usual binary peak which occurs at about 45° for high energies of incident electrons or positrons. The second peak occurs at a large scattering angle and was explained by Briggs [3,4] as due to a double collision effect, first a backward elastic scattering from the ion followed by an ionization collision. It will be interesting to see if similar double peak structure exist for ionization collisions from excited states. Studies of relative magnitudes of cross sections for ionization from the ground state, ionization from the 2*s*-state and the study of ionization mechanism in such scatterings will be interesting. Hence we made a calculation of ionization cross sections of hydrogen atoms in the metastable 2*s*-state by the impact of electrons and positrons at high energies. In this study we used the multiple scattering theory due to Das [10] and Das and Seal [11]. The above theory was successfully used by Das and Seal in studies of ionization of hydrogen and helium atoms under different kinematic conditions [11, 12]. Incidentally the wave function for the final three-particle continuum state used in this theory is the same as the first order Faddeev wave function [13] except for a normalization factor. For ionization from excited states there exist at present very few calculations. The first Born and second Born calculation of Vučič *et al* [14], BBK calculation of Hafid *et al* [15] and multiple scattering theory calculation of Dhar [16] for 250 eV energy and asymmetric geometry may be mentioned for ionization from 2*s*-state and the calculation of Born, BBK and DWIA theory of Berakdar *et al* [17] may be mentioned for ionization from 2*p*-state. Absence of experimental results is responsible for very slow development of this field of research.

In § 2 we describe, in brief, the structure of the scattering amplitude in the multiple scattering theory. Cross section and other results are described in § 3 and certain concluding remarks are made in § 4.

2. Scattering amplitude

The form of the scattering amplitude in the multiple scattering theory [11] is

$$f(\bar{p}_1,\bar{p}_2)=N[-2f_{\mathrm{PWB}}+f_{eT}+f_{PT}+f_{Pe}], \tag{1a}$$

where the different terms within the braces are given by expressions of the form

$$-(2\pi)^{-1}\int\phi^{(-)*}(\bar{r}_1,\bar{r}_2)(v_{12}+v_2)\exp(i\bar{p}_i\cdot\bar{r}_2)\varphi_{2s}(\bar{r}_1)/(2\pi)^{3/2}. \tag{1b}$$

where $v_{12}=Z/r_{12}$, $v_2=-Z/r_2$, $Z=1$ for electron and $Z=-1$ for positron and N is a normalizing factor.

For f_{PWB}, $\phi^{(-)}(\bar{r}_1,\bar{r}_2)$ is given by $\exp(i\bar{p}_1\cdot\bar{r}_1+i\bar{p}_2\cdot\bar{r}_2)$, corresponding to the final two particles represented by plane waves. For f_{eT}, which is also the first Born amplitude, $\phi^{(-)}(\bar{r}_1,\bar{r}_2)=\varphi^{(-)}_{\bar{p}_1}(\bar{r}_1)\times\exp(i\bar{p}_2\cdot\bar{r}_2)$, corresponding to plane wave for the scattered particle and Coulomb wave (due to Coulomb potential of the target nucleus and the ejected electron) for the atomic electron. The term f_{PT} is similar to f_{eT} except that the role of the electron and the projectile is interchanged. For f_{Pe}, $\phi^{(-)}(\bar{r}_1,\bar{r}_2)$ is given by $\varphi^{(-)}_{\bar{p}}(\bar{r})\exp(i\bar{P}\cdot\bar{R})$, where $\bar{r}=(\bar{r}_2-\bar{r}_1)/2$, $\bar{R}=(\bar{r}_2+\bar{r}_1)/2$, $\bar{p}=\bar{p}_2-\bar{p}_1$ and $\bar{P}=(\bar{p}_2+\bar{p}_1)$. In this last term the projectile electron interaction is exactly treated in the final channel, where centre of mass moves as a plane wave.

Now each of the scattering amplitude contains two parts, corresponding to v_{12} and v_2 of the interaction potential V_i in the initial channel.

Thus one has for example

$$f_{PT}=f_{PT}(v_{12})+f_{PT}(v_2). \tag{2}$$

3. Results and discussion

A. *Ionization mechanism*

The present form for the scattering amplitude is specially suitable for an analysis of the scattering mechanism. If in any situation contribution from a single term is dominant, it is indicative of the fact that in the kinematic condition the particular potential, whose effect is taken into account in the corresponding final channel wave function plays the prime role in the scattering process. Thus to unveil the scattering mechanism we look at different components of the scattering amplitude over the entire angular region presented in table 1 for a particular case. We note that except near the binary direction,

Table 1. Different components of scattering amplitude for symmetric ionization of hydrogen atoms in the metastable 2*s*-state by incident electron energy of 500 eV.

$\theta_1 = \theta_2$ (deg.)	f_{PWB}	$f_{eT}(f_B)$		f_{PT}		f_{Pe}	
5	-0·3877E-02	-0·1926E-02	0·4563E-03*i*	0·9051E-01	-0·6833E-01*i*	-0·9855E-01	-0·1178E-01*i*
15	0·4163E-02	-0·2166E-02	0·5148E-03*i*	0·7523E-01	-0·5046E-01*i*	-0·2455E-01	0·4836E-03*i*
30	-0·1123E-01	-0·7426E-02	0·2260E-02*i*	0·1018E+00	-0·2605E-01*i*	-0·5465E-01	-0·3220E-01*i*
45	0·5507E-00	0·3917E-00	-0·3775E+00*i*	0·4963E+00	-0·2186E+00*i*	-0·1859E+00	-0·5982E-01*i*
60	-0·1506E-02	-0·2113E-02	0·3343E-03*i*	0·7365E-02	0·1017E-01*i*	-0·9665E-02	-0·5472E-02*i*
75	-0·2157E-04	-0·1275E-03	-0·1266E-04*i*	0·2637E-02	0·2479E-02*i*	-0·2234E-02	-0·5132E-03*i*
90	0·2457E-04	-0·2049E-04	-0·5022E-05*i*	0·9259E-03	0·9520E-03*i*	-0·7522E-03	-0·9468E-04*i*
120	0·2169E-04	-0·2243E-05	-0·9480E-06*i*	0·2219E-03	0·3128E-03*i*	-0·1789E-03	-0·6095E-06*i*
150	0·1793E-04	-0·7385E-06	-0·3812E-06*i*	0·1030E-03	0·1817E-03*i*	-0·6817E-04	0·1222E-04*i*
175	0·1685E-04	-0·5284E-06	-0·2880E-06*i*	0·8129E-04	0·1545E-03*i*	0·1806E-05	0·4015E-05*i*

Table 2. Contribution to the component f_{PT} from projectile electron (v_{12}) and projectile target (v_2) potentials for the case considered in table 1.

$\theta_1 = \theta_2$ (deg.)	$f_{PT}(v_{12})$		$f_{PT}(v_2)$	
5	0·8980E−01	−0·6813E−01i	0·7093E−03	−0·1935E−03i
15	0·7473E−01	−0·5037E−01i	0·4954E−03	−0·8890E−04i
30	0·1015E+00	−0·2605E−01i	0·2465E−03	−0·2599E−05i
45	0·4961E+00	−0·2186E+00i	0·1350E−03	0·1745E−04i
60	0·7282E−02	0·1015E−01i	0·8356E−04	0·2011E−04i
75	0·2580E−02	0·2460E−02i	0·5708E−04	0·1890E−04i
90	0·8838E−03	0·9349E−03i	0·4214E−04	0·1709E−04i
120	0·1944E−03	0·2987E−03i	0·2749E−04	0·1415E−04i
150	0·8133E−04	0·1691E−03i	0·2168E−04	0·1255E−04i
175	0·6116E−04	0·1425E−03i	0·2012E−04	0·1206E−04i

$f_{eT}(=f_B)$ and f_{PWB} are much small compared to f_{PT} and f_{Pe} in magnitude. Thus except near the binary peak direction the scattering is essentially a double or a multiple scattering event. For a large scattering angle, f_{PT} is the most dominating term in the expression 1(a). This indicates further that the projectile nucleus interaction is most important in the final channel. Next we refer to table 2 where separate contribution to f_{PT} from potentials v_{12} and v_2 are presented. From the table it is clear that in the entire angular region, v_{12} gives the dominating contribution. Thus for scattering at a large angle, the projectile first ionizes the atom and then it is back-scattered elastically from the nucleus. In this way we have a good understanding of the ionization mechanism in the present case.

B. *Differential cross sections*

Differential cross section results of our present calculation are presented in figures 1(a)–1(c). Figure 1(a) shows cross section results for 200 eV incident energy. Here we compare our computed results with the first Born results and with the results for ionization from the ground state for a similar calculation [13]. Figures 1(b) and 1(c) show similar results for incident energies of 500 eV and 1000 eV. The results presented here show that unlike for scattering from the ground state there is only one peak, the binary peak, close to 45°. Present cross section results are, generally, much larger than the corresponding Born results. This shows that the coplanar symmetric ionization scattering from the 2s-state is essentially a higher order process. From the figure, it appears that present results for $\theta_1 < 25°$ are unlikely to be accurate. There does not exist, at present, measured cross section results for these scattering at high incident energies (however there exists one set of results for low energies [18] in case of ionization from the ground state). The wide difference between the results of the multiple scattering theory and the first Born results calls for other theoretical calculations also, such as by BBK method [8] for the present case. Experimental measurements are most welcome for ionization from the 2s-state for different kinematic conditions, such as that considered here.

4. Conclusion

The present calculation shows that for ionization of the 2*s*-metastable state for symmetric geometry, there exist only binary peaks in the cross-section curves. It is also seen that the cross section results are much larger compared to the corresponding Born results or the results for scattering from the ground state. Except at the binary peak

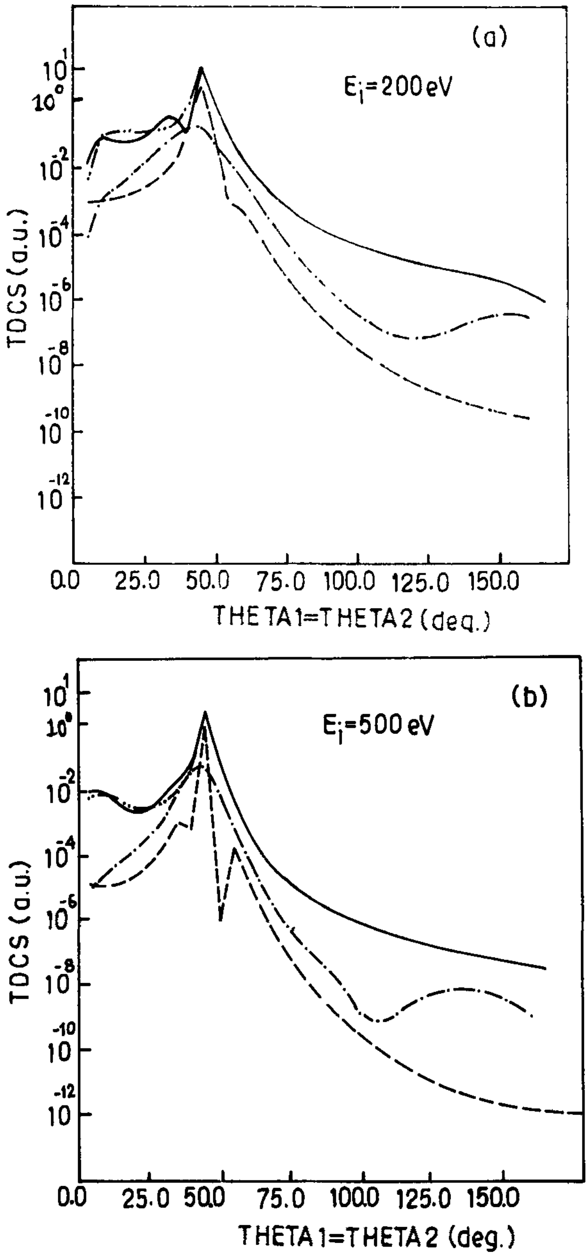

Figure 1.

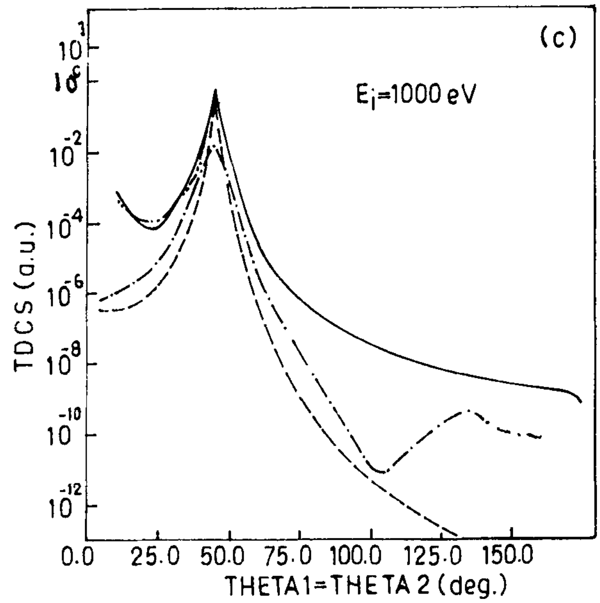

Figure 1. Triple differential cross section with equal energies and angles for symmetric scattering for ionization of hydrogen atoms in the 2*s*-state by electrons and positrons for (**a**) 200 eV energy, (**b**) 500 eV energy, (**c**) 1000 eV energy. Theory: Continuous curve, present calculation for electron; dash double-dotted curve, present calculation for positron; dashed curve, first Born approximation; dash dotted curve, ground state results of Das and Seal [9].

direction the scattering is essentially a double or a multiple scattering event. It is also found that the ionization mechanism for large scattering angles are different for ionization from 2*s*-state. For ionization from 2*s*-state, first a small angle ionization of the atom occurs and then a large angle elastically back-scattering from the atomic nucleus takes place, while it is just the opposite in case of ionization from the ground state.

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