

Shell-to-shell ionization cross sections of antiprotons, H^+ , He^{2+} , Be^{4+} , C^{6+} and O^{8+} on H, C, N, O, P, and S neutral atoms

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Abstract

Total ionization cross sections of H, C, N, O, P and S neutral atoms by impact of antiprotons, H^+ , He^{2+} , Be^{4+} , C^{6+} and O^{8+} . were calculated using the CDWEIS (continuum distorted wave -Eikonal Initial state) theoretical method. Cross section depending on of initial the quantum numbers n and l are reported in Tables for a range of impact energies covering from 100 keV/amu to 10 MeV/amu

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Total ionization cross sections of H, C, N, O, P and S neutral atoms by impact of \bar{p} (antiprotons), H^+ , He^{2+} , Be^{4+} , C^{6+} and O^{8+} . were calculated using the CDWEIS (continuum distorted wave -Eikonal Initial state) theoretical method. The total ionization cross section of an electron in the nlm initial state, due to the interaction with a projectile of charge Z_P and impact velocity v , is given by the four-dimensional integral

$$\sigma_{nl} = \sum_{m=l}^l \frac{(2\pi)^2}{v^2} \int d\vec{E} \int d\vec{\eta} \left| T_{\vec{k},nlm}(\vec{E}, \vec{\eta}) \right|^2 \quad (1)$$

where $T_{\vec{k},nlm}(\vec{E}, \vec{\eta})$ is the transition matrix as a function of is the component of the momentum transfer $\vec{\eta}$ perpendicular to the incident velocity \vec{v} . In our theoretical treatment we expand our final continuum wave function on the target atom in the usual form

$$\psi_{\vec{k}}^-(\vec{r}) = \sum_{l=0}^{l_{\max}} \sum_{m=-l}^l R_{kl}^-(r) Y_l^m(\hat{r}) Y_l^{m*}(\hat{k}), \quad (2)$$

We are confident with our calculations up to $l_{\max} \sim 30$. As the impact velocity v increases we would require of larger l_{\max} in (1). At the highest impact energies here reported we estimate a deficiency of our results of about 2-3%. The wave functions of initial bound state characterized by the quantum numbers nlm and final continuum state $\psi_{\vec{k}}^-(\vec{r})$ were obtained by using the RADIALF code developed by Salvat and co-workers using a Hartree Fock potential obtained the Depurated Inversion Model [1, 2]. Details of the calculation can be seen in [3], and for proton in Refs.[4, 5]. In parallel to this article, we will be presenting ionization cross sections of biomolecules of interest by using these results along with the stoichiometric approximation [6].

The Tables that follows reports the calculated cross section σ_{nl} in atomic units

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TABLE I: Total ionization cross sections for multicharge bare ions on Hydrogen at different impact energies. Cross sections are in atomic units divided Z_P^2 , and projectile energies are in MeV/amu.

To save space, throughout these tables the subindex n replaces the 10^n factor.

Z_P	nl	0.1	0.2	0.3	0.4	0.5	0.7	1	2	3	5	7	10
-1	1s	3.30	2.33	1.77	1.43	1.20	9.11 ₋₁	6.75 ₋₁	3.71 ₋₁	2.59 ₋₁	1.64 ₋₁	1.22 ₋₁	8.82 ₋₂
1	1s	4.24	2.64	1.91	1.50	1.25	9.34 ₋₁	6.86 ₋₁	3.73 ₋₁	2.69 ₋₁	1.70 ₋₁	1.26 ₋₁	8.82 ₋₂
2	1s	3.13	2.33	1.77	1.43	1.20	9.09 ₋₁	6.74 ₋₁	3.70 ₋₁	2.67 ₋₁	1.69 ₋₁	1.25 ₋₁	8.81 ₋₂
4	1s	1.66	1.67	1.41	1.20	1.04	8.24 ₋₁	6.29 ₋₁	3.58 ₋₁	2.53 ₋₁	1.67 ₋₁	1.24 ₋₁	8.76 ₋₂
6	1s	9.39 ₋₁	1.22	1.12	1.00	8.94 ₋₁	7.33 ₋₁	5.76 ₋₁	3.41 ₋₁	2.53 ₋₁	1.64 ₋₁	1.23 ₋₁	8.67 ₋₂
8	1s	5.60 ₋₁	9.08 ₋₁	9.05 ₋₁	8.42 ₋₁	7.72 ₋₁	6.54 ₋₁	5.28 ₋₁	3.23 ₋₁	2.36 ₋₁	1.60 ₋₁	1.20 ₋₁	8.55 ₋₂

TABLE II: Total ionization cross sections for multicharge bare ions on Carbon at different impact energies. Cross sections are in atomic units divided Z_P^2 , and projectile energies are in MeV/amu

Z_P	nl	0.1	0.2	0.3	0.4	0.5	0.7	1	2	3	5	7	10
-1	2p	3.74	2.95	2.38	1.99	1.71	1.34	1.02	5.89 ₋₁	4.21 ₋₁	2.74 ₋₁	2.06 ₋₁	1.51 ₋₁
-1	2s	1.49	1.05	7.90 ₋₁	6.34 ₋₁	5.30 ₋₁	4.01 ₋₁	2.95 ₋₁	1.60 ₋₁	1.11 ₋₁	6.95 ₋₂	5.11 ₋₂	3.68 ₋₂
-1	1s	2.26 ₋₃	5.19 ₋₃	7.33 ₋₃	8.77 ₋₃	9.67 ₋₃	1.05 ₋₂	1.06 ₋₂	8.83 ₋₃	7.22 ₋₃	5.23 ₋₃	4.11 ₋₃	3.14 ₋₃
-1	Total	1.05 ₁	8.01	6.35	5.26	4.50	3.51	2.66	1.51	1.08	6.97 ₋₁	5.22 ₋₁	3.82 ₋₁
1	2p	4.82	3.39	2.59	2.10	1.78	1.38	1.04	5.92 ₋₁	4.23 ₋₁	2.74 ₋₁	2.06 ₋₁	1.51 ₋₁
1	2s	1.69	1.14	8.38 ₋₁	6.63 ₋₁	5.49 ₋₁	4.10 ₋₁	2.99 ₋₁	1.61 ₋₁	1.11 ₋₁	6.96 ₋₂	5.11 ₋₂	3.68 ₋₂
1	1s	2.02 ₋₃	7.13 ₋₃	1.09 ₋₂	1.31 ₋₂	1.42 ₋₂	1.46 ₋₂	1.36 ₋₂	9.95 ₋₃	7.75 ₋₃	5.41 ₋₃	4.20 ₋₃	3.18 ₋₃
1	Total	1.30 ₁	9.07	6.87	5.56	4.69	3.60	2.71	1.53	1.08	6.99 ₋₁	5.22 ₋₁	3.83 ₋₁
2	2p	3.26	2.81	2.29	3.79 ₁	1.67	1.32	1.01	5.84 ₋₁	4.19 ₋₁	2.73 ₋₁	2.05 ₋₁	1.51 ₋₁
2	2s	1.08	9.30 ₋₁	7.44 ₋₁	1.09 ₁	5.17 ₋₁	3.95 ₋₁	2.92 ₋₁	1.59 ₋₁	1.10 ₋₁	6.94 ₋₂	5.10 ₋₂	3.68 ₋₂
2	1s	5.22 ₋₄	3.74 ₋₃	7.54 ₋₃	1.60 ₋₄	1.22 ₋₂	1.36 ₋₂	1.34 ₋₂	1.01 ₋₂	7.82 ₋₃	5.43 ₋₃	4.21 ₋₃	3.19 ₋₃
2	Total	8.69	7.48	6.09	9.77 ₁	4.39	3.45	2.63	1.51	1.08	6.96 ₋₁	5.21 ₋₁	3.82 ₋₁
4	2p	1.57	1.80	1.65	1.49	1.35	1.13	9.04 ₋₁	5.54 ₋₁	4.05 ₋₁	2.68 ₋₁	2.02 ₋₁	1.50 ₋₁
4	2s	4.68 ₋₁	5.87 ₋₁	5.42 ₋₁	4.82 ₋₁	4.28 ₋₁	3.47 ₋₁	2.68 ₋₁	1.53 ₋₁	1.08 ₋₁	6.85 ₋₂	5.06 ₋₂	3.65 ₋₂
4	1s	1.98 ₋₅	6.27 ₋₄	2.29 ₋₃	4.38 ₋₃	6.30 ₋₃	8.95 ₋₃	1.05 ₋₂	9.34 ₋₃	7.54 ₋₃	5.34 ₋₃	4.17 ₋₃	3.17 ₋₃
4	Total	4.07	4.77	4.39	3.95	3.56	2.96	2.37	1.43	1.04	6.83 ₋₁	5.14 ₋₁	3.79 ₋₁
6	2p	8.75 ₋₁	1.23	1.22	1.15	1.08	9.43 ₋₁	7.89 ₋₁	5.14 ₋₁	3.88 ₋₁	2.64 ₋₁	1.99 ₋₁	1.47 ₋₁
6	2s	2.25 ₋₁	3.89 ₋₁	4.01 ₋₁	3.80 ₋₁	3.52 ₋₁	2.99 ₋₁	2.41 ₋₁	1.45 ₋₁	1.04 ₋₁	6.73 ₋₂	5.00 ₋₂	3.62 ₋₂
6	1s	6.75 ₋₇	9.66 ₋₅	6.37 ₋₄	1.67 ₋₃	2.93 ₋₃	5.24 ₋₃	7.33 ₋₃	8.03 ₋₃	6.90 ₋₃	5.11 ₋₃	4.05 ₋₃	3.11 ₋₃
6	Total	2.20	3.23	3.24	3.07	2.87	2.50	2.08	1.33	9.97 ₋₁	6.72 ₋₁	5.06 ₋₁	3.74 ₋₁
8	2p	5.40 ₋₁	8.91 ₋₁	9.38 ₋₁	9.19 ₋₁	8.81 ₋₁	7.98 ₋₁	6.90 ₋₁	4.73 ₋₁	3.70 ₋₁	2.55 ₋₁	1.97 ₋₁	1.45 ₋₁
8	2s	1.15 ₋₁	2.70 ₋₁	3.05 ₋₁	3.05 ₋₁	2.92 ₋₁	2.60 ₋₁	2.17 ₋₁	1.37 ₋₁	1.00 ₋₁	6.56 ₋₂	4.91 ₋₂	3.57 ₋₂
8	1s	2.28 ₋₈	1.51 ₋₅	1.80 ₋₄	6.46 ₋₄	1.37 ₋₃	3.06 ₋₃	5.06 ₋₃	6.70 ₋₃	6.15 ₋₃	4.79 ₋₃	3.88 ₋₃	3.02 ₋₃
8	Total	1.31	2.32	2.49	2.45	2.35	2.12	1.82	1.23	9.51 ₋₁	6.51 ₋₁	4.99 ₋₁	3.67 ₋₁

TABLE III: Total ionization cross sections for multicharge bare ions on Nitrogen at different impact energies. Cross sections are in atomic units divided Z_P^2 , and projectile energies are in MeV/amu

Z_P	nl	0.1	0.2	0.3	0.4	0.5	0.7	1	2	3	5	7	10
-1	2p	2.21	1.87	1.56	1.33	1.16	9.23 ₋₁	7.13 ₋₁	4.17 ₋₁	3.01 ₋₁	1.97 ₋₁	1.49 ₋₁	1.10 ₋₁
-1	2s	9.16 ₋₁	6.97 ₋₁	5.42 ₋₁	4.42 ₋₁	3.73 ₋₁	2.85 ₋₁	2.12 ₋₁	1.16 ₋₁	8.13 ₋₂	5.13 ₋₂	3.78 ₋₂	2.73 ₋₂
-1	1s	7.54 ₋₄	2.00 ₋₃	3.08 ₋₃	3.92 ₋₃	4.54 ₋₃	5.29 ₋₃	5.71 ₋₃	5.28 ₋₃	4.53 ₋₃	3.41 ₋₃	2.73 ₋₃	2.11 ₋₃
-1	Total	8.46	7.02	5.77	4.88	4.23	3.35	2.58	1.50	1.07	7.01 ₋₁	5.27 ₋₁	3.88 ₋₁
1	2p	2.95	2.24	1.75	1.44	1.23	9.58 ₋₁	7.29 ₋₁	4.21 ₋₁	3.02 ₋₁	1.97 ₋₁	1.49 ₋₁	1.10 ₋₁
1	2s	1.04	7.69 ₋₁	5.82 ₋₁	4.67 ₋₁	3.90 ₋₁	2.94 ₋₁	2.16 ₋₁	1.17 ₋₁	8.16 ₋₂	5.14 ₋₂	3.79 ₋₂	2.73 ₋₂
1	1s	5.69 ₋₄	2.52 ₋₃	4.40 ₋₃	5.76 ₋₃	6.65 ₋₃	7.48 ₋₃	7.60 ₋₃	6.14 ₋₃	4.97 ₋₃	3.57 ₋₃	2.81 ₋₃	2.15 ₋₃
1	Total	1.09 ₁	8.26	6.42	5.26	4.48	3.48	2.64	1.51	1.08	7.02 ₋₁	5.28 ₋₁	3.88 ₋₁
2	2p	1.89	1.82	1.53	1.31	1.14	9.13 ₋₁	7.06 ₋₁	4.15 ₋₁	3.00 ₋₁	1.97 ₋₁	1.48 ₋₁	1.09 ₋₁
2	2s	6.11 ₋₁	6.04 ₋₁	5.04 ₋₁	4.23 ₋₁	3.63 ₋₁	2.81 ₋₁	2.10 ₋₁	1.16 ₋₁	8.11 ₋₂	5.12 ₋₂	3.78 ₋₂	2.73 ₋₂
2	1s	1.36 ₋₄	1.24 ₋₃	2.88 ₋₃	4.39 ₋₃	5.55 ₋₃	6.90 ₋₃	7.44 ₋₃	6.25 ₋₃	5.05 ₋₃	3.61 ₋₃	2.83 ₋₃	2.16 ₋₃
2	Total	6.88	6.66	5.62	4.79	4.17	3.31	2.55	1.49	1.07	6.99 ₋₁	5.26 ₋₁	3.87 ₋₁
4	2p	8.22 ₋₁	1.11	1.07	9.86 ₋₁	9.04 ₋₁	7.69 ₋₁	6.26 ₋₁	3.91 ₋₁	2.89 ₋₁	1.92 ₋₁	1.46 ₋₁	1.08 ₋₁
4	2s	2.26 ₋₁	3.51 ₋₁	3.46 ₋₁	3.18 ₋₁	2.89 ₋₁	2.40 ₋₁	1.90 ₋₁	1.11 ₋₁	7.89 ₋₂	5.05 ₋₂	3.74 ₋₂	2.71 ₋₂
4	1s	4.08 ₋₆	1.72 ₋₄	7.54 ₋₄	1.63 ₋₃	2.59 ₋₃	4.20 ₋₃	5.55 ₋₃	5.75 ₋₃	4.87 ₋₃	3.56 ₋₃	2.81 ₋₃	2.15 ₋₃
4	Total	2.92	4.04	3.90	3.60	3.30	2.80	2.27	1.41	1.03	6.85 ₋₁	5.19 ₋₁	3.84 ₋₁
6	2p	4.24 ₋₁	7.35 ₋₁	7.69 ₋₁	7.46 ₋₁	7.09 ₋₁	6.33 ₋₁	5.39 ₋₁	3.60 ₋₁	2.77 ₋₁	1.89 ₋₁	1.45 ₋₁	1.07 ₋₁
6	2s	9.41 ₋₂	2.18 ₋₁	2.44 ₋₁	2.41 ₋₁	2.29 ₋₁	2.02 ₋₁	1.67 ₋₁	1.04 ₋₁	7.57 ₋₂	4.93 ₋₂	3.71 ₋₂	2.68 ₋₂
6	1s	1.02 ₋₇	2.09 ₋₅	1.73 ₋₄	5.31 ₋₄	1.05 ₋₃	2.23 ₋₃	3.63 ₋₃	4.84 ₋₃	4.41 ₋₃	3.39 ₋₃	2.72 ₋₃	2.11 ₋₃
6	Total	1.46	2.64	2.80	2.72	2.59	2.31	1.96	1.30	9.92 ₋₁	6.73 ₋₁	5.15 ₋₁	3.78 ₋₁
8	2p	2.42 ₋₁	5.21 ₋₁	5.81 ₋₁	5.84 ₋₁	5.69 ₋₁	5.27 ₋₁	4.65 ₋₁	3.29 ₋₁	2.56 ₋₁	1.81 ₋₁	1.41 ₋₁	1.05 ₋₁
8	2s	4.16 ₋₂	1.43 ₋₁	1.79 ₋₁	1.87 ₋₁	1.85 ₋₁	1.71 ₋₁	1.47 ₋₁	9.69 ₋₂	7.21 ₋₂	4.79 ₋₂	3.63 ₋₂	2.64 ₋₂
8	1s	2.47 ₋₉	2.52 ₋₆	3.96 ₋₅	1.73 ₋₄	4.25 ₋₄	1.17 ₋₃	2.33 ₋₃	3.92 ₋₃	3.87 ₋₃	3.16 ₋₃	2.60 ₋₃	2.05 ₋₃
8	Total	8.10 ₋₁	1.85	2.10	2.13	2.08	1.93	1.70	1.19	9.19 ₋₁	6.46 ₋₁	5.00 ₋₁	3.70 ₋₁

TABLE IV: Total ionization cross sections for multicharge bare ions on Oxygen at different impact energies. Cross sections are in atomic units divided Z_P^2 , and projectile energies are in MeV/amu

Z_P	nl	0.1	0.2	0.3	0.4	0.5	0.7	1	2	3	5	7	10
-1	2p	1.61	1.41	1.19	1.02	8.99 ₋₁	7.23 ₋₁	5.63 ₋₁	3.33 ₋₁	2.41 ₋₁	1.59 ₋₁	1.20 ₋₁	8.87 ₋₂
-1	2s	5.68 ₋₁	4.68 ₋₁	3.77 ₋₁	3.13 ₋₁	2.67 ₋₁	2.06 ₋₁	1.55 ₋₁	8.62 ₋₂	6.06 ₋₂	3.84 ₋₂	2.84 ₋₂	2.06 ₋₂
-1	1s	2.74 ₋₄	8.28 ₋₄	1.38 ₋₃	1.85 ₋₃	2.23 ₋₃	2.77 ₋₃	3.19 ₋₃	3.28 ₋₃	2.93 ₋₃	2.32 ₋₃	1.89 ₋₃	1.49 ₋₃
-1	Total	7.58	6.56	5.51	4.73	4.13	3.31	2.57	1.51	1.09	7.16 ₋₁	5.40 ₋₁	3.99 ₋₁
1	2p	2.15	1.71	1.36	1.13	9.65 ₋₁	7.57 ₋₁	5.79 ₋₁	3.36 ₋₁	2.43 ₋₁	1.59 ₋₁	1.20 ₋₁	8.87 ₋₂
1	2s	6.30 ₋₁	5.22 ₋₁	4.09 ₋₁	3.34 ₋₁	2.81 ₋₁	2.14 ₋₁	1.59 ₋₁	8.71 ₋₂	6.09 ₋₂	3.85 ₋₂	2.85 ₋₂	2.06 ₋₂
1	1s	1.75 ₋₄	9.47 ₋₄	1.85 ₋₃	2.62 ₋₃	3.21 ₋₃	3.93 ₋₃	4.32 ₋₃	3.92 ₋₃	3.30 ₋₃	2.46 ₋₃	1.96 ₋₃	1.52 ₋₃
1	Total	9.86	7.90	6.26	5.18	4.43	3.46	2.64	1.53	1.10	7.18 ₋₁	5.41 ₋₁	3.99 ₋₁
2	2p	1.35	1.38	1.19	1.02	8.98 ₋₁	7.21 ₋₁	5.61 ₋₁	3.32 ₋₁	2.40 ₋₁	1.58 ₋₁	1.20 ₋₁	8.85 ₋₂
2	2s	3.41 ₋₁	3.93 ₋₁	3.45 ₋₁	2.97 ₋₁	2.58 ₋₁	2.03 ₋₁	1.54 ₋₁	8.61 ₋₂	6.05 ₋₂	3.84 ₋₂	2.84 ₋₂	2.06 ₋₂
2	1s	3.97 ₋₅	4.45 ₋₄	1.17 ₋₃	1.93 ₋₃	2.61 ₋₃	3.55 ₋₃	4.20 ₋₃	4.01 ₋₃	3.37 ₋₃	2.50 ₋₃	1.98 ₋₃	1.53 ₋₃
2	Total	6.08	6.31	5.45	4.70	4.11	3.30	2.56	1.51	1.09	7.15 ₋₁	5.39 ₋₁	3.98 ₋₁
4	2p	5.67 ₋₁	8.34 ₋₁	8.22 ₋₁	7.65 ₋₁	7.06 ₋₁	6.04 ₋₁	4.95 ₋₁	3.12 ₋₁	2.31 ₋₁	1.55 ₋₁	1.18 ₋₁	8.76 ₋₂
4	2s	1.06 ₋₁	2.10 ₋₁	2.23 ₋₁	2.13 ₋₁	1.99 ₋₁	1.70 ₋₁	1.36 ₋₁	8.17 ₋₂	5.86 ₋₂	3.78 ₋₂	2.81 ₋₂	2.04 ₋₂
4	1s	1.00 ₋₆	5.34 ₋₅	2.69 ₋₄	6.46 ₋₄	1.11 ₋₃	2.02 ₋₃	2.99 ₋₃	3.65 ₋₃	3.25 ₋₃	2.47 ₋₃	1.97 ₋₃	1.52 ₋₃
4	Total	2.48	3.75	3.74	3.49	3.22	2.76	2.26	1.42	1.05	7.00 ₋₁	5.31 ₋₁	3.95 ₋₁
6	2p	2.83 ₋₁	5.47 ₋₁	5.88 ₋₁	5.76 ₋₁	5.50 ₋₁	4.95 ₋₁	4.25 ₋₁	2.87 ₋₁	2.21 ₋₁	1.51 ₋₁	1.16 ₋₁	8.62 ₋₂
6	2s	3.69 ₋₂	1.22 ₋₁	1.50 ₋₁	1.55 ₋₁	1.52 ₋₁	1.38 ₋₁	1.18 ₋₁	7.59 ₋₂	5.59 ₋₂	3.68 ₋₂	2.78 ₋₂	2.02 ₋₂
6	1s	1.99 ₋₈	5.35 ₋₆	5.25 ₋₅	1.83 ₋₄	3.99 ₋₄	9.80 ₋₄	1.84 ₋₃	2.98 ₋₃	2.91 ₋₃	2.35 ₋₃	1.91 ₋₃	1.50 ₋₃
6	Total	1.20	2.43	2.65	2.61	2.51	2.26	1.94	1.31	1.00	6.84 ₋₁	5.25 ₋₁	3.88 ₋₁
8	2p	1.56 ₋₁	3.86 ₋₁	4.43 ₋₁	4.50 ₋₁	4.41 ₋₁	4.11 ₋₁	3.65 ₋₁	2.61 ₋₁	2.04 ₋₁	1.45 ₋₁	1.12 ₋₁	8.44 ₋₂
8	2s	1.37 ₋₂	7.50 ₋₂	1.06 ₋₁	1.17 ₋₁	1.19 ₋₁	1.14 ₋₁	1.02 ₋₁	7.00 ₋₂	5.28 ₋₂	3.56 ₋₂	2.72 ₋₂	1.99 ₋₂
8	1s	0.37 ₋₉	5.22 ₋₇	1.01 ₋₅	5.11 ₋₅	1.42 ₋₄	4.64 ₋₄	1.09 ₋₃	2.34 ₋₃	2.51 ₋₃	2.17 ₋₃	1.82 ₋₃	1.45 ₋₃
8	Total	6.53 ₋₁	1.69	1.98	2.03	2.00	1.87	1.66	1.19	9.27 ₋₁	6.54 ₋₁	5.05 ₋₁	3.80 ₋₁

TABLE V: Total ionization cross sections for multicharge bare ions on Phosphorous at different impact energies. Cross sections are in atomic units divided Z_P^2 , and projectile energies are in MeV/amu

Z_P	nl	0.1	0.2	0.3	0.4	0.5	0.7	1	2	3	5	7	10
-1	3p	4.43	2.95	2.19	1.74	1.45	1.08	7.95 ₋₁	4.36 ₋₁	3.02 ₋₁	1.87 ₋₁	1.39 ₋₁	9.88 ₋₂
-1	3s	1.67	1.06	7.70 ₋₁	6.03 ₋₁	4.95 ₋₁	3.65 ₋₁	2.63 ₋₁	1.38 ₋₁	9.36 ₋₂	5.74 ₋₂	4.22 ₋₂	2.95 ₋₂
-1	2p	2.04 ₋₂	3.20 ₋₂	3.77 ₋₂	4.03 ₋₂	4.12 ₋₂	4.04 ₋₂	3.73 ₋₂	2.87 ₋₂	2.21 ₋₂	1.53 ₋₂	1.19 ₋₂	9.05 ₋₃
-1	2s	9.82 ₋₃	2.01 ₋₂	2.44 ₋₂	2.55 ₋₂	2.53 ₋₂	2.35 ₋₂	2.04 ₋₂	1.40 ₋₂	1.04 ₋₂	7.01 ₋₃	5.35 ₋₃	3.99 ₋₃
-1	1s	7.52 ₋₇	4.44 ₋₆	1.12 ₋₅	2.03 ₋₅	3.09 ₋₅	5.44 ₋₅	9.01 ₋₅	2.05 ₋₄	2.50 ₋₄	2.68 ₋₄	2.54 ₋₄	2.25 ₋₄
-1	Total	1.68 ₁	1.12 ₁	8.38	6.72	5.62	4.27	3.17	1.78	1.25	7.81 ₋₁	5.84 ₋₁	4.18 ₋₁
1	3p	4.83	3.10	2.26	1.78	1.47	1.10	8.00 ₋₁	4.36 ₋₁	3.02 ₋₁	1.87 ₋₁	1.39 ₋₁	9.88 ₋₂
1	3s	1.72	1.09	7.85 ₋₁	6.12 ₋₁	5.02 ₋₁	3.69 ₋₁	2.65 ₋₁	1.38 ₋₁	9.36 ₋₂	5.74 ₋₂	4.22 ₋₂	2.95 ₋₂
1	2p	1.92 ₋₂	4.22 ₋₂	5.18 ₋₂	5.44 ₋₂	5.41 ₋₂	5.01 ₋₂	4.35 ₋₂	2.87 ₋₂	2.21 ₋₂	1.53 ₋₂	1.19 ₋₂	9.05 ₋₃
1	2s	8.78 ₋₃	2.15 ₋₂	2.70 ₋₂	2.84 ₋₂	2.80 ₋₂	2.57 ₋₂	2.19 ₋₂	1.40 ₋₂	1.04 ₋₂	7.01 ₋₃	5.35 ₋₃	3.99 ₋₃
1	1s	1.93 ₋₇	2.65 ₋₆	9.26 ₋₆	1.99 ₋₅	3.34 ₋₅	6.51 ₋₅	1.14 ₋₄	2.05 ₋₄	2.50 ₋₄	2.68 ₋₄	2.54 ₋₄	2.25 ₋₄
1	Total	1.81 ₁	1.18 ₁	8.70	6.94	5.79	4.38	3.23	1.78	1.25	7.81 ₋₁	5.84 ₋₁	4.18 ₋₁
2	3p	3.27	2.60	2.03	1.65	1.39	1.06	7.82 ₋₁	4.36 ₋₁	3.02 ₋₁	1.87 ₋₁	1.39 ₋₁	9.88 ₋₂
2	3s	1.10	9.00 ₋₁	7.00 ₋₁	5.66 ₋₁	4.74 ₋₁	3.56 ₋₁	2.59 ₋₁	1.38 ₋₁	9.36 ₋₂	5.74 ₋₂	4.22 ₋₂	2.95 ₋₂
2	2p	5.82 ₋₃	2.42 ₋₂	3.77 ₋₂	4.45 ₋₂	4.73 ₋₂	4.68 ₋₂	4.21 ₋₂	2.87 ₋₂	2.21 ₋₂	1.53 ₋₂	1.19 ₋₂	9.05 ₋₃
2	2s	2.52 ₋₃	1.16 ₋₂	1.84 ₋₂	2.17 ₋₂	2.30 ₋₂	2.28 ₋₂	2.04 ₋₂	1.40 ₋₂	1.04 ₋₂	7.01 ₋₃	5.35 ₋₃	3.99 ₋₃
2	1s	3.62 ₋₈	1.04 ₋₆	4.97 ₋₆	1.27 ₋₅	2.39 ₋₅	5.32 ₋₅	1.04 ₋₄	2.05 ₋₄	2.50 ₋₄	2.68 ₋₄	2.54 ₋₄	2.25 ₋₄
2	Total	1.20 ₁	9.76	7.75	6.39	5.45	4.21	3.16	1.78	1.25	7.81 ₋₁	5.84 ₋₁	4.18 ₋₁
4	3p	1.58	1.72	1.53	1.33	1.18	9.42 ₋₁	7.23 ₋₁	4.10 ₋₁	2.89 ₋₁	1.83 ₋₁	1.35 ₋₁	9.88 ₋₂
4	3s	4.70 ₋₁	5.80 ₋₁	5.20 ₋₁	4.54 ₋₁	3.99 ₋₁	3.17 ₋₁	2.41 ₋₁	1.32 ₋₁	9.15 ₋₂	5.67 ₋₂	4.12 ₋₂	2.95 ₋₂
4	2p	3.62 ₋₄	5.66 ₋₃	1.46 ₋₂	2.23 ₋₂	2.78 ₋₂	3.29 ₋₂	3.37 ₋₂	2.66 ₋₂	2.11 ₋₂	1.50 ₋₂	1.17 ₋₂	9.05 ₋₃
4	2s	1.45 ₋₄	2.45 ₋₃	6.33 ₋₃	9.75 ₋₃	1.22 ₋₂	1.47 ₋₂	1.53 ₋₂	1.24 ₋₂	9.76 ₋₃	6.79 ₋₃	5.24 ₋₃	3.99 ₋₃
4	1s	0.57 ₋₉	8.05 ₋₈	7.62 ₋₇	2.91 ₋₆	7.17 ₋₆	2.26 ₋₅	5.85 ₋₅	1.90 ₋₄	2.64 ₋₄	2.99 ₋₄	2.82 ₋₄	2.25 ₋₄
4	Total	5.68	6.35	5.72	5.06	4.52	3.69	2.88	1.68	1.20	7.68 ₋₁	5.70 ₋₁	4.18 ₋₁

TABLE VI: Phosphorous Continued

Z_P	nl	0.1	0.2	0.3	0.4	0.5	0.7	1	2	3	5	7	10
6	3p	8.79 ₋₁	1.18	1.16	1.07	9.79 ₋₁	8.23 ₋₁	6.56 ₋₁	3.91 ₋₁	2.80 ₋₁	1.80 ₋₁	1.34 ₋₁	9.88 ₋₂
6	3s	2.26 ₋₁	3.89 ₋₁	3.92 ₋₁	3.64 ₋₁	3.33 ₋₁	2.78 ₋₁	2.20 ₋₁	1.27 ₋₁	8.91 ₋₂	5.59 ₋₂	4.09 ₋₂	2.95 ₋₂
6	2p	2.33 ₋₅	1.37 ₋₃	5.61 ₋₃	1.09 ₋₂	1.55 ₋₂	2.16 ₋₂	2.51 ₋₂	2.31 ₋₂	1.92 ₋₂	1.42 ₋₂	1.13 ₋₂	9.05 ₋₃
6	2s	8.24 ₋₆	5.32 ₋₄	2.21 ₋₃	4.33 ₋₃	6.26 ₋₃	8.95 ₋₃	1.08 ₋₂	1.04 ₋₂	8.77 ₋₃	6.43 ₋₃	5.06 ₋₃	3.99 ₋₃
6	1s	5.76 _{**}	4.38 ₋₉	8.49 ₋₈	4.93 ₋₇	1.61 ₋₆	7.29 ₋₆	2.59 ₋₅	1.30 ₋₄	2.13 ₋₄	2.74 ₋₄	2.71 ₋₄	2.25 ₋₄
6	Total	3.09	4.34	4.29	4.01	3.71	3.17	2.58	1.59	1.15	7.50 ₋₁	5.61 ₋₁	4.18 ₋₁
8	3p	5.40 ₋₁	8.55 ₋₁	8.99 ₋₁	8.71 ₋₁	8.22 ₋₁	7.19 ₋₁	5.94 ₋₁	3.70 ₋₁	2.69 ₋₁	1.76 ₋₁	1.31 ₋₁	9.88 ₋₂
8	3s	1.16 ₋₁	2.72 ₋₁	3.01 ₋₁	2.95 ₋₁	2.80 ₋₁	2.44 ₋₁	2.00 ₋₁	1.21 ₋₁	8.64 ₋₂	5.49 ₋₂	4.04 ₋₂	2.95 ₋₂
8	2p	1.63 ₋₆	3.59 ₋₄	2.31 ₋₃	5.60 ₋₃	9.07 ₋₃	1.45 ₋₂	1.87 ₋₂	1.96 ₋₂	1.72 ₋₂	1.33 ₋₂	1.08 ₋₂	9.05 ₋₃
8	2s	4.72 ₋₇	1.21 ₋₄	8.19 ₋₄	2.04 ₋₃	3.39 ₋₃	5.65 ₋₃	7.61 ₋₃	8.63 ₋₃	7.73 ₋₃	5.98 ₋₃	4.82 ₋₃	3.99 ₋₃
8	1s	4.72 _{**}	0.21 ₋₉	8.39 ₋₉	7.50 ₋₈	3.27 ₋₇	2.14 ₋₆	1.05 ₋₅	8.19 ₋₅	1.60 ₋₄	2.38 ₋₄	2.50 ₋₄	2.25 ₋₄
8	Total	1.85	3.11	3.32	3.24	3.09	2.75	2.31	1.49	1.10	7.29 ₋₁	5.50 ₋₁	4.18 ₋₁

TABLE VII: Total ionization cross sections for multicharge bare ions on Sulfur at different impact energies. Cross sections are in atomic units divided Z_P^2 , and projectile energies are in MeV/amu

Z_P	nl	0.1	0.2	0.3	0.4	0.5	0.7	1	2	3	5	7	10
-1	3p	4.18	2.91	2.21	1.78	1.50	1.14	8.48 ₋₁	4.67 ₋₁	3.28 ₋₁	2.08 ₋₁	1.54 ₋₁	1.12 ₋₁
-1	3s	1.18	7.83 ₋₁	5.76 ₋₁	4.55 ₋₁	3.76 ₋₁	2.80 ₋₁	2.03 ₋₁	1.07 ₋₁	7.31 ₋₂	4.51 ₋₂	3.28 ₋₂	2.34 ₋₂
-1	2p	1.16 ₋₂	1.94 ₋₂	2.38 ₋₂	2.61 ₋₂	2.72 ₋₂	2.76 ₋₂	2.62 ₋₂	2.01 ₋₂	1.59 ₋₂	1.14 ₋₂	8.92 ₋₃	6.81 ₋₃
-1	2s	5.45 ₋₃	1.29 ₋₂	1.66 ₋₂	1.81 ₋₂	1.84 ₋₂	1.76 ₋₂	1.57 ₋₂	1.08 ₋₂	8.23 ₋₃	5.63 ₋₃	4.32 ₋₃	3.24 ₋₃
-1	1s	3.78 ₋₇	2.37 ₋₆	6.21 ₋₆	1.16 ₋₅	1.81 ₋₅	3.30 ₋₅	5.68 ₋₅	1.22 ₋₄	1.59 ₋₄	1.86 ₋₄	1.86 ₋₄	1.72 ₋₄
-1	Total	1.50 ₁	1.04 ₁	7.96	6.46	5.45	4.19	3.14	1.76	1.24	7.95 ₋₁	5.91 ₋₁	4.31 ₋₁
1	3p	4.47	3.04	2.27	1.82	1.52	1.15	8.53 ₋₁	4.68 ₋₁	3.28 ₋₁	2.08 ₋₁	1.54 ₋₁	1.12 ₋₁
1	3s	1.20	8.07 ₋₁	5.89 ₋₁	4.63 ₋₁	3.82 ₋₁	2.83 ₋₁	2.05 ₋₁	1.07 ₋₁	7.33 ₋₂	4.52 ₋₂	3.28 ₋₂	2.34 ₋₂
1	2p	1.01 ₋₂	2.49 ₋₂	3.26 ₋₂	3.57 ₋₂	3.64 ₋₂	3.50 ₋₂	3.12 ₋₂	2.17 ₋₂	1.67 ₋₂	1.16 ₋₂	9.03 ₋₃	6.86 ₋₃
1	2s	4.87 ₋₃	1.37 ₋₂	1.84 ₋₂	2.02 ₋₂	2.05 ₋₂	1.94 ₋₂	1.70 ₋₂	1.13 ₋₂	8.48 ₋₃	5.72 ₋₃	4.37 ₋₃	3.26 ₋₃
1	1s	9.04 ₋₈	1.34 ₋₆	5.11 ₋₆	1.09 ₋₅	1.89 ₋₅	3.86 ₋₅	7.08 ₋₅	1.55 ₋₄	1.96 ₋₄	2.17 ₋₄	2.08 ₋₄	1.87 ₋₄
1	Total	1.59 ₁	1.09 ₁	8.23	6.64	5.59	4.27	3.19	1.77	1.25	7.97 ₋₁	5.92 ₋₁	4.31 ₋₁
2	3p	2.86	2.47	2.00	1.66	1.42	1.10	8.29 ₋₁	4.63 ₋₁	3.26 ₋₁	2.08 ₋₁	1.54 ₋₁	1.12 ₋₁
2	3s	7.17 ₋₁	6.47 ₋₁	5.16 ₋₁	4.23 ₋₁	3.57 ₋₁	2.72 ₋₁	2.00 ₋₁	1.06 ₋₁	7.29 ₋₂	4.50 ₋₂	3.28 ₋₂	2.34 ₋₂
2	2p	2.89 ₋₃	1.37 ₋₂	2.31 ₋₂	2.87 ₋₂	3.14 ₋₂	3.25 ₋₂	3.03 ₋₂	2.16 ₋₂	1.67 ₋₂	1.16 ₋₂	9.02 ₋₃	6.86 ₋₃
2	2s	1.34 ₋₃	7.20 ₋₃	1.23 ₋₂	1.52 ₋₂	1.66 ₋₂	1.71 ₋₂	1.58 ₋₂	1.11 ₋₂	8.40 ₋₃	5.70 ₋₃	4.36 ₋₃	3.26 ₋₃
2	1s	1.68 ₋₈	5.22 ₋₇	2.62 ₋₆	6.92 ₋₆	1.34 ₋₅	3.12 ₋₅	6.37 ₋₅	1.57 ₋₄	2.04 ₋₄	2.26 ₋₄	2.17 ₋₄	1.92 ₋₄
2	Total	1.00 ₁	8.80	7.19	6.03	5.20	4.08	3.10	1.75	1.24	7.95 ₋₁	5.91 ₋₁	4.31 ₋₁
4	3p	1.26	1.53	1.43	1.29	1.16	9.53 ₋₁	7.51 ₋₁	4.42 ₋₁	3.17 ₋₁	2.04 ₋₁	1.52 ₋₁	1.11 ₋₁
4	3s	2.71 ₋₁	3.94 ₋₁	3.69 ₋₁	3.29 ₋₁	2.93 ₋₁	2.37 ₋₁	1.83 ₋₁	1.03 ₋₁	7.14 ₋₂	4.45 ₋₂	3.25 ₋₂	2.33 ₋₂
4	2p	1.49 ₋₄	2.80 ₋₃	8.10 ₋₃	1.34 ₋₂	1.75 ₋₂	2.22 ₋₂	2.39 ₋₂	1.98 ₋₂	1.58 ₋₂	1.13 ₋₂	8.87 ₋₃	6.78 ₋₃
4	2s	6.51 ₋₅	1.37 ₋₃	3.93 ₋₃	6.46 ₋₃	8.42 ₋₃	1.07 ₋₂	1.16 ₋₂	9.83 ₋₃	7.85 ₋₃	5.52 ₋₃	4.27 ₋₃	3.22 ₋₃
4	1s	0.26 ₋₉	3.95 ₋₈	3.93 ₋₇	1.56 ₋₆	3.94 ₋₆	1.30 ₋₅	3.54 ₋₅	1.27 ₋₄	1.87 ₋₄	2.26 ₋₄	2.21 ₋₄	1.97 ₋₄
4	Total	4.32	5.40	5.08	4.61	4.17	3.49	2.78	1.67	1.20	7.82 ₋₁	5.84 ₋₁	4.27 ₋₁

TABLE VIII: Sulfur Continued

Z_P	nl	0.1	0.2	0.3	0.4	0.5	0.7	1	2	3	5	7	10
6	3p	6.65 ₋₁	1.01	1.04	9.93 ₋₁	9.31 ₋₁	8.07 ₋₁	6.65 ₋₁	4.15 ₋₁	3.04 ₋₁	1.99 ₋₁	1.50 ₋₁	1.10 ₋₁
6	3s	1.17 ₋₁	2.53 ₋₁	2.69 ₋₁	2.57 ₋₁	2.39 ₋₁	2.04 ₋₁	1.64 ₋₁	9.75 ₋₂	6.91 ₋₂	4.38 ₋₂	3.22 ₋₂	2.31 ₋₂
6	2p	7.47 ₋₆	5.73 ₋₄	2.78 ₋₃	6.00 ₋₃	9.20 ₋₃	1.40 ₋₂	1.73 ₋₂	1.70 ₋₂	1.44 ₋₂	1.07 ₋₂	8.56 ₋₃	6.62 ₋₃
6	2s	3.06 ₋₆	2.61 ₋₄	1.26 ₋₃	2.67 ₋₃	4.09 ₋₃	6.26 ₋₃	7.94 ₋₃	8.19 ₋₃	7.02 ₋₃	5.21 ₋₃	4.12 ₋₃	3.14 ₋₃
6	1s	2.53 _{**}	2.08 ₋₉	4.23 ₋₈	2.56 ₋₇	8.57 ₋₇	4.07 ₋₆	1.53 ₋₅	8.51 ₋₅	1.49 ₋₄	2.06 ₋₄	2.12 ₋₄	1.95 ₋₄
6	Total	2.23	3.53	3.67	3.53	3.33	2.93	2.44	1.56	1.15	7.61 ₋₁	5.74 ₋₁	4.22 ₋₁
8	3p	3.94 ₋₁	7.05 ₋₁	7.81 ₋₁	7.84 ₋₁	7.59 ₋₁	6.89 ₋₁	5.88 ₋₁	3.87 ₋₁	2.89 ₋₁	1.94 ₋₁	1.47 ₋₁	1.08 ₋₁
8	3s	5.39 ₋₂	1.69 ₋₁	2.01 ₋₁	2.04 ₋₁	1.97 ₋₁	1.76 ₋₁	1.47 ₋₁	9.22 ₋₂	6.66 ₋₂	4.29 ₋₂	3.17 ₋₂	2.29 ₋₂
8	2p	3.98 ₋₇	1.26 ₋₄	1.02 ₋₃	2.82 ₋₃	5.02 ₋₃	9.00 ₋₃	1.26 ₋₂	1.43 ₋₂	1.28 ₋₂	9.99 ₋₃	8.15 ₋₃	6.41 ₋₃
8	2s	1.43 ₋₇	5.19 ₋₅	4.20 ₋₄	1.17 ₋₃	2.08 ₋₃	3.79 ₋₃	5.47 ₋₃	6.69 ₋₃	6.13 ₋₃	4.82 ₋₃	3.91 ₋₃	3.04 ₋₃
8	1s	1.97 _{**}	9.30 _{**}	3.99 ₋₉	3.73 ₋₈	1.67 ₋₇	1.15 ₋₆	5.96 ₋₆	5.24 ₋₅	1.10 ₋₄	1.77 ₋₄	1.94 ₋₄	1.86 ₋₄
8	Total	1.29	2.45	2.75	2.78	2.71	2.48	2.15	1.45	1.09	7.36 ₋₁	5.60 ₋₁	4.15 ₋₁