PHYSICAL REVIEW A VOLUME 34, NUMBER 4 OCTOBER 1986

K-shell x-ray production by 0.5–2.5-MeV ${}^{9}_{4}\mathrm{Be}^{+}$ ions incident upon selected elements from fluorine to potassium

J. L. Price, J. L. Duggan, and F. D. McDaniel
Department of Physics, North Texas State University, Denton, Texas 76203

G. Lapicki and R. Mehta
Department of Physics, East Carolina University, Greenville, North Carolina 27834

(Received 10 March 1986)

K-shell x-ray production cross sections are reported for ${}^{9}_{4}\mathrm{Be}^{+}$ ions incident upon thin ${}_{9}\mathrm{F}$, ${}_{11}\mathrm{Na}$, ${}_{13}\mathrm{Al}$, ${}_{14}\mathrm{Si}$, ${}_{15}\mathrm{P}$, ${}_{17}\mathrm{Cl}$, and ${}_{19}\mathrm{K}$ targets. Incident-beam energies range from 0.5 to 2.5 MeV. It is found that the first Born approximation (plane-wave Born approximation plus the Oppenheimer-Brinkman-Kramers treatment by Nikolaev) greatly overpredicts the data, while the predictions of the perturbed-stationary-state theory with energy-loss, Coulomb deflection, and relativistic corrections (ECPSSR) are generally in good agreement with the data. There is a low-velocity discrepancy between the data and the ECPSSR predictions which may be due to multiple ionization effects on the fluorescence yields used to convert total ionization to x-ray production cross sections.

I. INTRODUCTION

In past decades, inner-shell ionization of an atom by incident charged particles has been discussed and examined extensively. Several theories have been developed and refined in order to explain certain data characteristics. For K-shell ionization of an atom, the direct ionization (DI) of a target electron to the continuum and the K-electron capture (EC) to incident-ion bound states have been shown to be the principal modes of interaction for the region $Z_1 \ll Z_2$ and $v_1 \gg v_{2K}$ (Ref. 1) where Z_1 and Z_2 refer to incident and target atomic numbers while v_1 and v_{2K} refer to incident-ion and target K-shell electron velocities, respectively. These processes were successfully described by the plane-wave Born approximation (PWBA) developed by Merzbacher and coworkers[2] for the direct ionization process and the Oppenheimer-Brinkman-Kramers treatment by Nikolaev[3] (OBKN) for the electron capture to the projectile. Brandt and co-workers[4] have taken these approximations beyond the first Born term by including perturbed (PSS) and relativistic (R) wave functions of the target electron, and the energy loss (E) and Coulomb deflection (C) projectile in the target material. This theory (ECPSSR) extended the region of validity to $Z_1 < Z_2$ and $v_1 < v_{2K}$.

The ECPSSR theory has been shown to be in excellent agreement with the data for light incident ions $(Z \leq 3)$ (Refs. 5–9) and it has also been successful for heavier ions at moderate and high velocities.[6,7,10–13] For very low velocities $(v_1 \ll v_{2K})$, Meyerhof and co-workers have shown that for symmetric and near-symmetric $(Z_1 \approx Z_2)$ collisions, the electron promotion model agrees quite well with the data.[14] This model assumes the formation of a quasi-molecular-orbital system during the interaction of projectile and target atoms based upon the studies of Lichten and co-workers.[15]

In the intermediate region, between the domains where the molecular-orbital excitation and the direct ionization processes may be described by the first Born approximation, there is little experimental data available for theoretical assessment. This can be attributed to many reasons, not the least of which are the lack of suitable ion sources, accelerators, and analytical equipment available for such a study. A recent compilation[16] of K-shell ionization cross sections lists no ${}^{9}\mathrm{Be}$ data in the range $Z_1 = 1$–9. This is the only element in this relatively light projectile ion range for which we are not aware of any K-shell x-ray measurements.

In this work, we report K-shell x-ray production cross sections for 0.5–2.5-MeV ${}^{9}_{4}\mathrm{Be}^{+}$ ions incident upon thin ${}_{9}\mathrm{F}$, ${}_{11}\mathrm{Na}$, ${}_{13}\mathrm{Al}$, ${}_{14}\mathrm{Si}$, ${}_{15}\mathrm{P}$, ${}_{17}\mathrm{Cl}$, and ${}_{19}\mathrm{K}$ targets. The ranges of the Z_1/Z_2 and v_1/v_{2K} parameters are $0.21 \leq Z_1/Z_2 \leq 0.44$ and $0.080 \leq v_1/v_{2K} \leq 0.36$. The data are compared to the predictions of the first Born approximation (PWBA for DI and OBKN for EC) and the ECPSSR theory. The theoretical ionization cross sections were converted to x-ray production cross sections by using the single-hole fluorescence yields.[17] There are a number of problems encountered in examining these collisions, some of which are (i) the uncertainties in the determination of the absolute efficiency of the Si(Li) detector for such low-energy x rays, (ii) the difficulties in the construction of a suitable source of ${}^{9}\mathrm{Be}^{+}$ ions for a 2.5-MV Van de Graaff accelerator, (iii) the low fluorescence yields for the target atoms which lead to long counting times, and (iv) the radical Z_2 dependence of the cross sections themselves which make trend determination difficult.

II. EXPERIMENTAL PROCEDURE

Ion beams of ${}^{9}\mathrm{Be}^{+}$ were obtained by sputtering a beryllium exit canal with ${}^{4}\mathrm{He}^{+}$ ions in the radio-frequency ion source of the 2.5-MV Van de Graaff accelerator at North Texas State University. This method is similar to that described by Norbeck and York[18] except that we used boron nitride and quartz bushings and did not introduce any

TABLE I. Target specifications.

Element	Compound	Thickness (μg/cm^2)
${}_9$F	LiF	12.6
${}_{11}$Na	NaCl	2.13
${}_{13}$Al	Al	7.85
${}_{14}$Si	Si	10.2
${}_{15}$P	Zn_3P_2	12.6
${}_{17}$Cl	NaCl	3.23
${}_{19}$K	KBr	19.7

Be metal dust or BeO inside the bottle. The ion beams were mass-energy analyzed with a High Voltage Engineering Corporation bending magnet. Typical beam currents ranged from 0.5 to 2.0 nA at the target. These currents, though very much smaller than those reported by Norbeck and York,[18] were adequate for the atomic studies reported here.

Targets (see Table I) were prepared by vacuum evaporation and deposition of the elements on thin (5 to 10 μg/cm^2) carbon foils. Precautions were taken to ensure that the targets were as contaminant free as possible by using methods similar to those previously reported.[19,20]

Simultaneous measurement of Rutherford-scattered particle yield and the *K*-shell x-ray yield from the ion-target collision was used to extract the total *K*-shell x-ray production cross section. This simultaneous measurement minimized nonuniform target-thickness problems and eliminated the need to determine the exit charge state of the beryllium beam. A 50-mm^2 silicon-surface barrier detector and a Si(Li) x-ray detector with a 3.81-μm Mylar absorber were placed at 160° and 90° from the forward beam direction, respectively. Targets were positioned at 45° with respect to the beam. The details of the experimental arrangement, the method used for determining the efficiency of the Si(Li) detector, and the processes of data analysis are all similar to that described by Mehta *et al.*[19]

The absolute uncertainties for this experiment range from 11–53 %. These experimental errors are primarily due to (i) background subtraction and polynomial fitting of the raw spectra (with the largest error for particle spectra at low beam energies and for x-ray spectra at high beam energies), (ii) steepness of the efficiency curve and the presence of the Au *M*-shell and Si *K*-shell absorption peaks at the low 0.6–3.3-keV energy ranges in the Si(Li) detector, and (iii) multiple ionization effects in the target atoms resulting in a change in the efficiency of the Si(Li) detector because of shifting x-ray line energies.

III. RESULTS AND DISCUSSION

The results of our measurements are given in Table II along with the ECPSSR theoretical predictions. The theoretical ECPSSR x-ray production cross sections were calculated from ionization cross sections by using the single-hole fluorescence yields of Krause.[17] The electron-capture contribution is small, ranging form less than 1% in ${}_{19}$K to less than 9% in ${}_9$F according to the ECPSSR theory. The first Born theory predicts an electron capture of less than 2% in ${}_{19}$K to about 12% in ${}_{11}$Na and up to 50% in ${}_9$F.

Figure 1 presents the *K*-shell x-ray production cross sections of ${}^9_4\mathrm{Be}^+$ ions incident upon ${}_9$F, ${}_{13}$Al, ${}_{15}$P, and ${}_{19}$K targets versus the incident ion energy. Notice that the first Born theory overpredicts the data everywhere by a

TABLE II. X-ray production cross sections (b) for incident ${}^9\mathrm{Be}^+$ ions.

Target Element	Source	Energy (MeV) 0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50
${}_9$F	Measured			127	858	688	1570	3470	4100	
	ECPSSR	4.13	39.2	185	570	1320	2500	4110	6070	8340
${}_{11}$Na	Measured	6.32	11.0	24.6	58.7	135		319		884
	ECPSSR	0.614	4.97	21.7	66.8	162	331	597	970	1460
${}_{13}$Al	Measured	0.440	1.34	3.64	10.9	26.7	32.7	68.6		189
	ECPSSR	0.145	1.10	4.48	13.2	31.3	64.4	118	199	312
${}_{14}$Si	Measured	0.195	0.774	1.98	5.48	8.07	18.3	35.7	51.3	84.6
	ECPSSR	0.0785	0.592	2.37	6.84	16.1	32.8	60.1	101	160
${}_{15}$P	Measured	0.0834	0.325	0.691	2.33	4.83	9.50	15.3		40.9
	ECPSSR	0.0439	0.335	1.32	3.77	8.75	17.7	32.3	54.4	86.0
${}_{17}$Cl	Measured	0.0570	0.176	0.507	1.24	3.00		10.5		25.9
	ECPSSR	0.0153	0.124	0.491	1.38	3.16	6.30	11.4	19.1	30.1
${}_{19}$K	Measured	0.005 07	0.0522	0.227	0.615	1.10	2.27	3.40	5.32	
	ECPSSR	0.005 40	0.0485	0.197	0.556	1.27	2.52	4.52	7.52	11.8

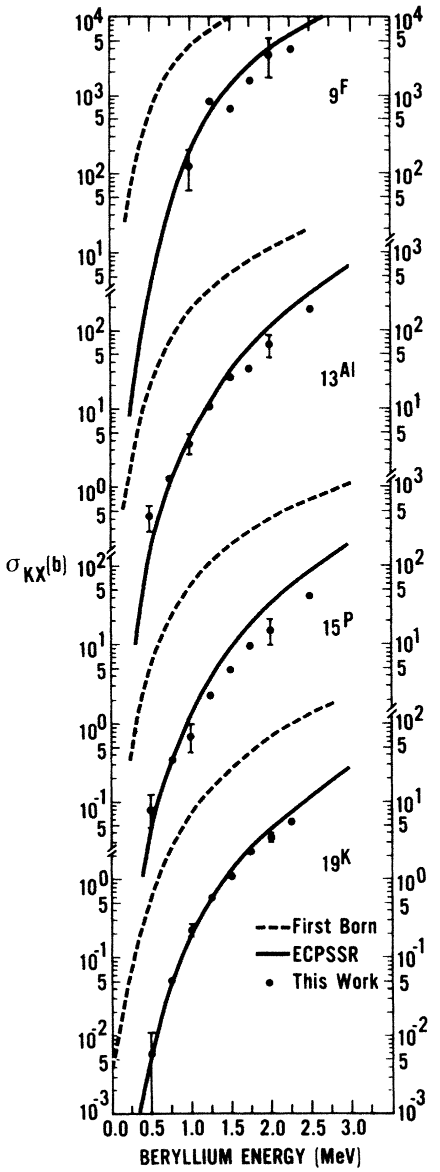

FIG. 1. K-shell x-ray production cross sections for ^{9}Be$^+$ ions incident upon fluorine, aluminum, phosphorus, and potassium as a function of incident-beam energy. Data are compared to the first Born approximation (PWBA plus OBKN) and the ECPSSR theory.

significant amount (almost 2 orders of magnitude at low energies), while the ECPSSR theory shows much better agreement in general. For low energies ($E_1 \leq 0.75$ MeV), the ECPSSR theory tends to underpredict the data. At higher energies the theory tracks the data well within the experimental uncertainty. At the highest energies, ($E_1 \geq 2.0$ MeV) the theory slightly overpredicts the data, especially for lower Z_2 targets.

Figure 2 presents the K-shell x-ray production cross section as a function of the atomic number (Z_2) of the target. Notice that at the lowest energy ($E_1 = 0.5$ MeV), the ECPSSR theory underpredicts the data everywhere

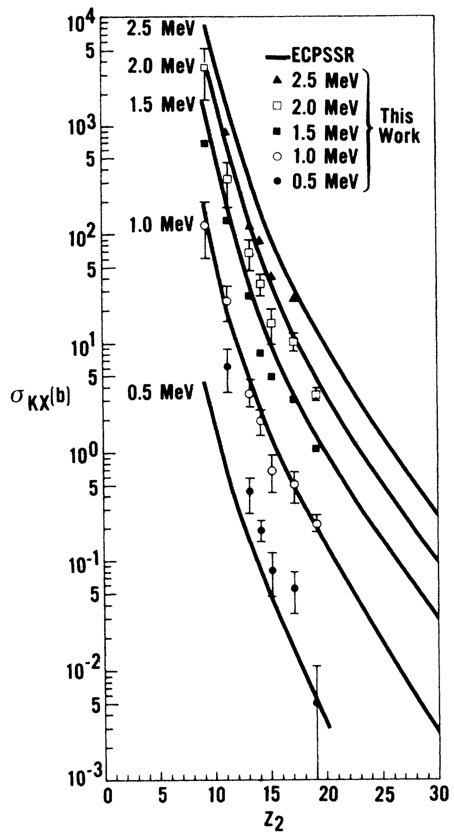

FIG. 2. K-shell x-ray production cross sections for ^{9}Be$^+$ ions incident upon various targets ($9 \leq Z_2 < +19$) as a function of target atomic number. Data and ECPSSR theory predictions are shown for incident-beam energies of 0.5, 1.0, 1.5, 2.0, and 2.5 MeV.

but is slightly better for larger Z_2. At moderate energies ($E_1 = 1.0$ and 1.5 MeV), the theory fits the data well everywhere. At higher energies ($E_1 = 2.0$ and 2.5 MeV) the theory overpredicts the data everywhere with better fitting for larger Z_2 energies. The ECPSSR theory does accurately predict the data and gives the overall energy dependence of the cross sections. The results for the ECPSSR appear to be better at higher Z_2 where one is approaching the $Z_1 \ll Z_2$ region. The theory systematically underestimates the data at lower velocities. This trend could be explained since the total ionization cross section calculations were converted to x-ray production cross sections using single-hole fluorescence yields. Multiple ionization—although not detected by x-ray energy shifts in our experiments— are important, especially for lower velocities, and result in higher fluorescence yields than those used for the cross-section conversion above. This could explain the discrepancy between the ECPSSR theory and the low-energy data. The reason for the residual high-energy discrepancy is still not clear.

ACKNOWLEDGMENTS

The work performed at North Texas State University was supported in part by the Robert A. Welch Foundation and the State of Texas Organized Research Fund.

[1] D. H. Madison and E. Merzbacher, in *Atomic Inner-Shell Processes,* edited by B. Craseman (Academic, New York, 1975), Vol. I, p.1.

[2] E. Merzbacher and H. Lewis, *Handbuch der Physik,* edited by S. Flügge (Springer-Verlag, Berlin, 1958), Vol. **34**, p.166; G. S. Khandelwal, B. H. Choi, and E. Merzbacher, At. Data **1**, 103 (1969).

[3] J. R. Oppenheimer, Phys. Rev. **31**, 349 (1928); H. C. Brinkman and H. A. Kramers, Proc. Acad. Sci. (Amsterdam) **33**, 973 (1930); V. S. Nikolaev, Zh. Eksp. Teor. Fiz. **51**, 1263 (1966) [Sov. Phys.—JETP **24**, 847 (1967)].

[4] G. Basbas, W. Brandt, and R. Laubert, Phys. Rev. A **7**, 983 (1973); G. Basbas, W. Brandt, and R. H. Ritchie, *ibid.* **7**, 1971 (1973); W. Brandt and G. Lapicki, *ibid.* **10**, 474 (1974); G. Lapicki and W. Losonsky, *ibid.* **15**, 896 (1977); G. Basbas, W. Brandt, and R. Laubert, *ibid.* **17**, 1655 (1978); W. Brandt and G. Lapicki, *ibid.* **20**, 465 (1979); G. Lapicki and W. Losonsky, *ibid.* **20**, 481 (1979); G. Lapicki and F. D. McDaniel, *ibid.* **22**, 1896 (1980); **23**, 975 (E) (1981); W. Brandt and G. Lapicki, *ibid.* **23**, 1717 (1981).

[5] N. Cue, V. Dutkiewicz, P. Sen, and H. Bakhru, Phys. Rev. Lett. **32**, 1155 (1974).

[6] R. Anholt, Phys. Rev. A **17**, 983 (1978).

[7] R. K. Rice, T. M. Button, J. L. Duggan, and F. D. McDaniel, IEEE Trans. Nucl. Sci. **NS-26**, 1150 (1979).

[8] R. K. Rice, F. D. McDaniel, G. Basbas, and J. L. Duggan, IEEE Trans. Nucl. Sci. **NS-28**, 1103 (1981).

[9] B. Raith, S. Divoux, and B. Gonsior, in *Proceedings of the 13th International Conference on the Physics of Electronic and Atomic Collisions, Berlin, 1983* (ICPEAC, Berlin, 1983), p. 425.

[10] G. Monigold, F. D. McDaniel, J. L. Duggan, R. Rice, A. Toten, R. Mehta, and P. D. Miller, Phys. Rev. A **18**, 380 (1978).

[11] R. Mehta, F. D. McDaniel, J. L. Duggan, and P. D. Miller, Phys. Rev. A **19**, 1363 (1979).

[12] G. D. O'Kelley, R. L. Auble, L. D. Hulett, Jr., H. J. Kim, W. T. Milner, S. Raman, O. Shahal, C. R. Vane, J. P. Young, and G. Lapicki, Nucl. Instrum. Methods Phys. Res. B **3**, 78 (1984).

[13] J. A. Tanis, S. M. Shafroth, W. W. Jacobs, T. McAbee, and G. Lapicki, Phys. Rev. A **31**, 750 (1985).

[14] W. E. Meyerhof, R. Anholt, T. K. Saylor, S. M. Lazarus, A. Little, and L. F. Chase, Jr., Phys. Rev. A **14**, 1653 (1976); W. E. Meyerhof, R. Anholt, and T. K. Saylor, *ibid.* **16**, 169 (1977); R. Anholt and W. E. Meyerhof, *ibid.* **16**, 190 (1977); W. E. Meyerhof, *ibid.* **18**, 414 (1978); **20**, 2235 (1979).

[15] U. Fano and W. Lichten, Phys. Rev. Lett. **14**, 627 (1965); W. Lichten, Phys. Rev. **164**, 131 (1967); M. Barat and W. Lichten, Phys. Rev. A **6**, 211 (1972); G. Lapicki and W. Lichten, *ibid.* **31**, 1354 (1985).

[16] H. Paul and J. Muhr, Phys. Rep. (to be published).

[17] M. O. Krause, J. Phys. Chem. Ref. Data **8**, 307 (1979).

[18] E. Norbeck and R. York, Nucl. Instrum. Methods **118**, 327 (1974).

[19] R. Mehta, J. L. Duggan, J. L. Price, F. D. McDaniel, and G. Lapicki, Phys. Rev. A **26**, 1883 (1982).

[20] P. M. Kocur, J. L. Duggan, R. Mehta, J. Robbins, and F. D. McDaniel, IEEE Trans. Nucl. Sci. **NS-30**, 1580 (1983).