M-shell x-ray production cross sections for 0.5–2.5-MeV Be^{+} ions incident upon selected elements from praseodymium to bismuth

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M-shell x-ray production cross sections are reported for ${}^{9}_{4}Be^{+}$ ions incident upon thin ${}_{59}Pr$, ${}_{60}Nd$, ${}_{63}Eu$, ${}_{66}Dy$, ${}_{67}Ho$, ${}_{72}Hf$, ${}_{74}W$, ${}_{79}Au$, ${}_{82}Pb$, and ${}_{83}Bi$ targets. Incident-beam energies range from 0.5 to 2.5 MeV (55.6–267 keV/u). The results are compared to the predictions of the first–Born-approximation theory and the perturbed-stationary-state theory with energy-loss, Coulomb-deflection, and relativistic corrections (ECPSSR). The first–Born-approximation theory overpredicts the measured cross sections everywhere, especially at high energies, while the ECPSSR theory tends to underpredict them, especially at low energy. This discrepancy between the measurements and the ECPSSR theory may be due in part to multiple-ionization effects which could change the fluorescence yields from the single-hole values used to convert total ionization to x-ray production cross sections in the theoretical calculations.

I. INTRODUCTION

Ionization of atomic inner-shell electrons by incident charged particles has been examined extensively over the years. There have been several theories proposed to explain the observations. One of the approaches used most often has been the plane-wave Born approximation (PWBA),[1] which describes the direct ionization (DI) process for high-velocity projectiles. This formalism is an evaluation of the process by which an inner-shell electron is ejected from its orbit into the continuum under the restrictions of $Z_1/Z_2 \ll 1$ and $v_1/v_{2S} \gg 1$, where Z_1/Z_2 refers to the ratio of the atomic numbers for the projectile to the target and v_1/v_{2S} refers to the ratio of the projectile's velocity to the velocity of the electron in the S shell ($S = K$, L, or M) of the target atom. This formalism was extended to describe the direct ionization process for the M shell by Khandelwal and Merzbacher,[2] and Choi.[3] At lower velocities, another process could have a more pronounced effect, especially when the ratio of Z_1/Z_2 is not restricted to be much less than unity. The inner-shell electron of the target atom might be captured to an unoccupied state of the projectile. This electron-capture (EC) process has been evaluated using a Born-approximation technique resulting in the Oppenheimer-Brinkman-Kramers approach of Nikolaev (OBKN).[4] By combining the PWBA formalism for DI and the OBKN treatment for EC, the first–Born-approximation theories have been extended to intermediate velocities, $v_1 \simeq v_{2S}$.

The first-Born theories have been refined and further extended to lower projectile velocities by incorporating modifications to certain parameters in the formalism. Brandt, Lapicki, and co-workers[5] have accounted for perturbed-stationary-state (PSS) and relativistic (R) wave functions for the target electron. They have also included the energy-loss (E) and Coulomb-deflection (C) corrections for the projectile as it traverses the target. This ECPSSR theory has successfully lowered the ratio restrictions to $Z_1/Z_2 < 1$ and $v_1/v_{2S} < 1$. There have been a few studies of M-shell ionization to test ECPSSR (Ref. 6) and the theory agrees quite well with the data for light ions from low to high velocities and for heavy ions at moderate to high velocities.

In this work we extend the M-shell ionization studies by examining the M-shell x-ray production cross sections for a moderately light ion incident at low velocities upon several rare-earth elements. We report the M-shell x-ray production cross sections for 0.5–2.5-MeV ${}^{9}_{4}Be^{+}$ ions (55.6–267 keV/u) bombarding thin targets of ${}_{59}Pr$, ${}_{60}Nd$, ${}_{63}Eu$, ${}_{66}Dy$, ${}_{67}Ho$, ${}_{72}Hf$, ${}_{74}W$, ${}_{79}Au$, ${}_{82}Pb$, and ${}_{83}Bi$. The ratios of the atomic numbers and velocities cover the ranges $0.048 < Z_1/Z_2 < 0.068$ and $0.06 < v_1/v_{2M} < 0.26$. The data are compared to the predictions of the first-Born (PWBA plus OBKN) and the ECPSSR theories by converting the theoretical ionization cross sections to x-ray production cross sections using the single-hole fluorescence yields of Krause[7] and the transition rates of McGuire.[8]

II. EXPERIMENTAL PROCEDURE

Ion beams of ${}^{9}_{4}Be^{+}$ were produced by using ${}^{4}_{2}He^{+}$ ions to sputter the beryllium exit canal in a radio-frequency ion source of the 2.5-MeV Van de Graaff accelerator at North Texas State University. This method has been described in an earlier paper.[9] Thin targets (Table I) were prepared by vacuum evaporation and deposition of the compounds or elements onto thin carbon foils. The process used for target preparation which ensures very clean

TABLE I. Target specifications.

Element	Compound	Thickness ($\mu g/cm^2$)
$_{59}Pr$	PrF_3	15.0
$_{60}Nd$	NdF_3	17.9
$_{63}Eu$	EuF_3	15.2
$_{66}Dy$	DyF_3	13.0
$_{67}Ho$	HoF_3	14.5
$_{72}Hf$	Hf	14.2
$_{74}W$	W	0.5
$_{79}Au$	Au	14.4
$_{82}Pb$	Pb	5.80
$_{83}Bi$	Bi	4.40

targets has also been reported earlier.[10] By simultaneous measurements of the M-shell x-ray yields and the Rutherford-backscattered (RBS) particle yields, the total M-shell x-ray production cross sections were determined. The experimental setup, electronics, Si(Li) x-ray detector efficiency determination, and methods of data analysis have all been described in previous papers.[9,11]

The absolute uncertainties in this experiment range from 12–45 %, with the largest ones due primarily to (i) the uncertainty in the x-ray efficiency of the Si(Li) detector for the lower-energy x-rays (e.g., from Pr and Nd) because of the sharp energy dependence of the efficiency of the detector, (ii) the presence of the gold and silicon absorption edges of the x-ray detector, and (iii) the statistical variations in the background fitting and subtraction techniques for the low-beam-energy RBS and high-beam-energy x-ray spectra. Multiple-ionization effects in the target (not corrected for in the theoretical predictions reported here) could have a significant effect. The observed x-ray line energies would be shifted, thus changing the actual Si(Li) detector efficiency. In addi-

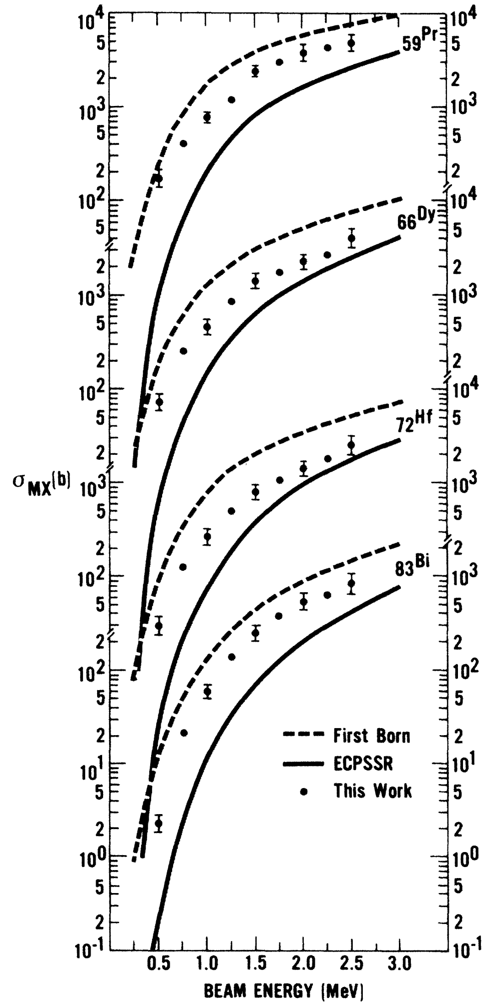

FIG. 1. M-shell x-ray production cross sections (σ_{Mx}) for ${}^{9}_{4}Be^{+}$ ions incident upon praseodymium, dysprosium, hafnium, and bismuth targets are shown as functions of the ion-beam energy. The predictions of the first-Born and ECPSSR theories are shown for comparison as dashed and solid lines, respectively. Both theories include contributions from direct ionization and electron capture.

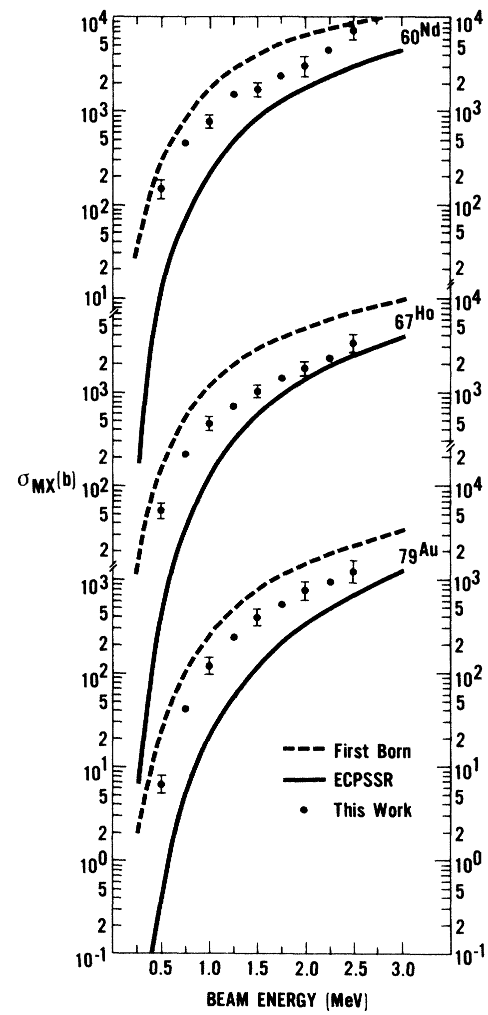

FIG. 2. M-shell x-ray production cross sections for ${}^{9}_{4}Be^{+}$ ions incident upon neodymium, holmium, and gold targets are shown as functions of ion-beam energy. The predictions of the first-Born and ECPSSR theories are shown for comparison as dashed and solid lines, respectively. Both theories include contributions from direct ionization and electron capture.

TABLE II. M-shell x-ray production cross sections for incident ${}^{9}_{4}Be^{+}$ ions.

Target		BEAM ENERGY (MeV) 0.5	0.75	1.0	1.25	1.5	1.75	2.0	2.25	2.5
${}_{59}Pr$	Measured	1.75×10^{2}	4.01×10^{2}	7.69×10^{2}	1.20×10^{3}	2.37×10^{3}	3.10×10^{3}	3.93×10^{3}	4.33×10^{3}	4.92×10^{3}
	ECPSSR	1.06×10^{1}	6.39×10^{1}	2.01×10^{2}	4.47×10^{2}	7.87×10^{2}	1.21×10^{3}	1.70×10^{3}	2.24×10^{3}	2.81×10^{3}
${}_{60}Nd$	Measured	1.50×10^{2}	4.73×10^{2}	7.81×10^{2}	1.53×10^{3}	1.66×10^{3}	2.41×10^{3}	3.05×10^{3}	4.67×10^{3}	7.55×10^{3}
	ECPSSR	1.12×10^{1}	6.63×10^{1}	2.07×10^{2}	4.62×10^{2}	8.17×10^{2}	1.27×10^{3}	1.79×10^{3}	2.37×10^{3}	2.99×10^{3}
${}_{63}Eu$	Measured	1.01×10^{2}	3.12×10^{2}	5.48×10^{2}	9.80×10^{2}	1.48×10^{3}	1.78×10^{3}	2.83×10^{3}	3.01×10^{3}	4.44×10^{3}
	ECPSSR	8.57×10^{0}	5.45×10^{1}	1.77×10^{2}	4.05×10^{2}	7.51×10^{2}	1.19×10^{3}	1.72×10^{3}	2.31×10^{3}	2.96×10^{3}
${}_{66}Dy$	Measured	7.52×10^{1}	2.57×10^{2}	4.69×10^{2}	8.64×10^{2}	1.38×10^{3}	1.70×10^{3}	2.29×10^{3}	2.70×10^{3}	3.93×10^{3}
	ECPSSR	6.18×10^{0}	4.22×10^{1}	1.40×10^{2}	3.30×10^{2}	6.29×10^{2}	1.02×10^{3}	1.50×10^{3}	2.05×10^{3}	2.67×10^{3}
${}_{67}Ho$	Measured	5.51×10^{1}	2.40×10^{2}	4.73×10^{2}	7.05×10^{2}	1.01×10^{3}	1.43×10^{3}	1.79×10^{3}	2.34×10^{3}	3.41×10^{3}
	ECPSSR	5.42×10^{0}	3.80×10^{1}	1.27×10^{2}	3.02×10^{2}	5.78×10^{2}	9.52×10^{2}	1.40×10^{3}	1.93×10^{3}	2.52×10^{3}
${}_{72}Hf$	Measured	3.10×10^{1}	1.28×10^{2}	2.64×10^{2}	5.02×10^{2}	7.96×10^{2}	1.09×10^{3}	1.36×10^{3}	1.70×10^{3}	2.83×10^{3}
	ECPSSR	2.58×10^{0}	2.16×10^{1}	7.66×10^{1}	1.88×10^{2}	3.73×10^{2}	6.38×10^{2}	9.84×10^{2}	1.38×10^{3}	1.85×10^{3}
${}_{74}W$	Measured	2.68×10^{1}	1.48×10^{2}	3.29×10^{2}	6.58×10^{2}	9.15×10^{2}	1.46×10^{3}	1.88×10^{3}	2.43×10^{3}	3.13×10^{3}
	ECPSSR	1.66×10^{0}	1.53×10^{1}	5.57×10^{1}	1.39×10^{2}	2.78×10^{2}	4.82×10^{2}	7.55×10^{2}	1.08×10^{3}	1.46×10^{3}
${}_{79}Au$	Measured	6.54×10^{0}	4.20×10^{1}	1.20×10^{2}	2.45×10^{2}	4.06×10^{2}	5.81×10^{2}	7.73×10^{2}	9.62×10^{2}	1.25×10^{3}
	ECPSSR	4.99×10^{-1}	5.90×10^{0}	2.34×10^{1}	6.06×10^{1}	1.25×10^{2}	2.22×10^{2}	3.56×10^{2}	5.29×10^{2}	7.39×10^{2}
${}_{82}Pb$	Measured	2.69×10^{0}	2.37×10^{1}	7.77×10^{1}	1.46×10^{2}	2.50×10^{2}	3.66×10^{2}	5.01×10^{2}	6.51×10^{2}	9.73×10^{2}
	ECPSSR	2.28×10^{-1}	3.30×10^{0}	1.41×10^{1}	3.78×10^{1}	7.95×10^{1}	1.44×10^{2}	2.34×10^{2}	3.52×10^{2}	5.00×10^{2}
${}_{83}Bi$	Measured	2.34×10^{0}	2.17×10^{1}	5.85×10^{1}	1.37×10^{2}	2.41×10^{2}	3.75×10^{2}	5.12×10^{2}	6.29×10^{2}	8.60×10^{2}
	ECPSSR	1.74×10^{-1}	2.70×10^{0}	1.19×10^{1}	3.22×10^{1}	6.83×10^{1}	1.24×10^{2}	2.04×10^{2}	3.08×10^{2}	4.38×10^{2}

tion, multiple ionizations of the outer shells of the target atoms would change the Auger and Coster-Kronig transition rates and also the fluorescence yields for the atomic decay resulting in a net increase in the effective fluorescence yields of the targets.

III. RESULTS AND DISCUSSION

The total M-shell x-ray production cross sections were measured and the results are listed in Table II along with the predictions of the ECPSSR theory. The electron-capture contribution to these cross sections is estimated by the ECPSSR theory to be small, ranging from less than 0.7% in ${}_{83}$Bi to 21% in ${}_{59}$Pr, while the unmodified first-Born theory predicts the electron-capture contribution to range from 1.0% in ${}_{83}$Bi up to 44% in ${}_{59}$Pr.

Figures 1,2, and 3 present the total M-shell x-ray production cross sections as functions of incident ion beam energy. Both the first-Born and the ECPSSR predictions are shown. The first-Born predictions generally overestimate the measured results by a significant amount. In the worst cases, these discrepancies range up to factors of 3 for the higher-energy holmium results. The first-Born predictions tend to have better agreement with the measured results at lower beam energies than at the higher energies (especially for lower-Z_2 targets). The ECPSSR theory tends to underestimate the measured results everywhere. At low beam energies this discrepancy is large (up to a factor of 20 for bismuth in the worst case); while at higher energies, the agreement with the data is much better (nearly within the calculated error for holmium and hafnium measurements). As the beam energy is increased, the ECPSSR theoretical predictions systematically show better agreement with the measured results.

Figure 4 shows the measured cross sections for specific beam energies as functions of target atomic number. The ECPSSR theory is also illustrated. At higher

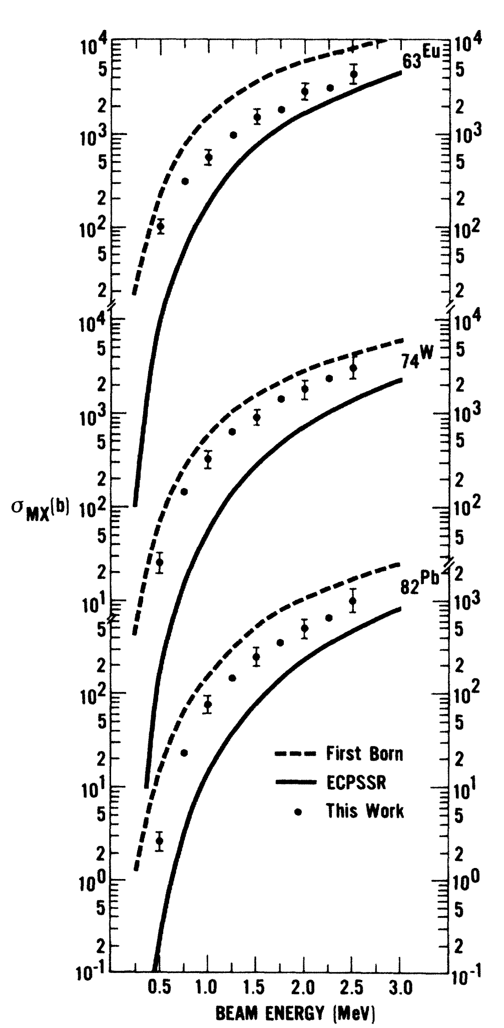

FIG. 3. M-shell x-ray production cross sections for ${}^9_4$Be$^+$ ions incident upon europium, tungsten, and lead targets are shown as functions of the ion-beam energy. The predictions of the first-Born and ECPSSR theories are shown for comparison as dashed and solid lines, respectively. Both theories include contributions from direct ionization and electron capture.

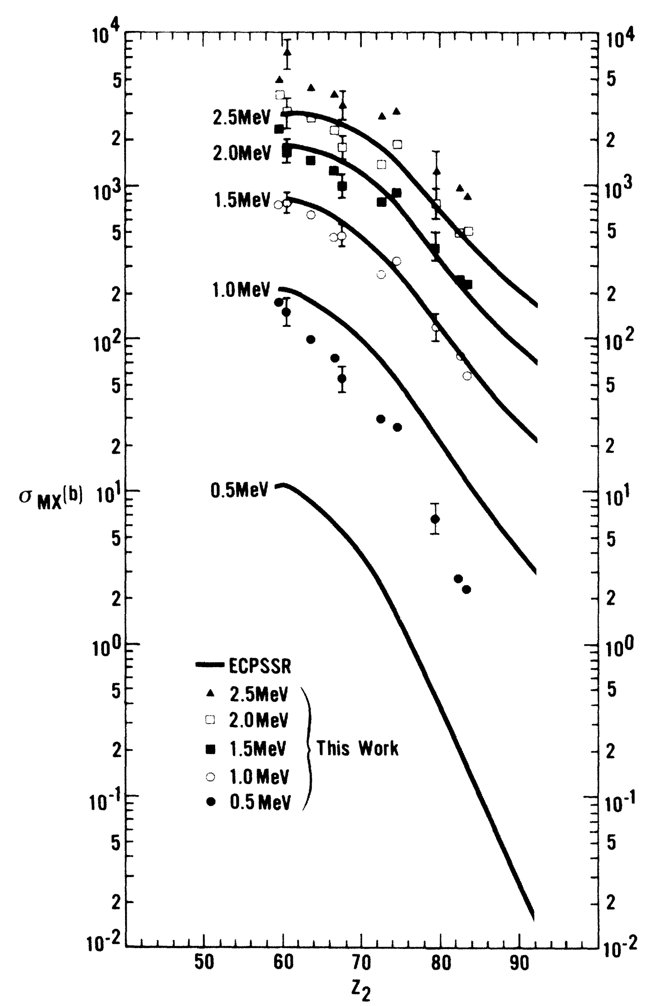

FIG. 4. ${}^9_4$Be-ion-induced M-shell x-ray production cross sections are shown as functions of target atomic number (Z_2) for the selected energies 0.5, 1.0, 1.5, 2.0, and 2.5 MeV. Only the ECPSSR theoretical values are shown for comparison.

energies, this theory does predict the data better than at lower energies. There is no distinguishable Z_2 dependence between the data and the ECPSSR theory except for $_{74}$W. In the case of tungsten, the target used was very thin and was measured by Rutherford backscattering to be 0.5 $\mu g/cm^2$ (see Table I). It was therefore possible that contaminant K-shell x rays from $_{14}$Si at 1.740 keV interfered with the $_{74}$W M-shell x rays at 1.775 keV. This is the only target element where the data might be in jeopardy because of this effect. All the other targets were at least a factor of 10 thicker, resulting in negligible contaminant background.

The ECPSSR theory does well at predicting the trend of the data, especially the energy dependence of the M-shell cross sections. The theory, however, systematically underpredicts the results at low beryllium-ion-beam energies. This tendency may be attributed to the effects of multiple ionizations in the target atoms which were not accounted for in the calculations. If a correction is made for these effects, then the theoretical predictions at low projectile velocities would be raised to some extent. Thus, the difference between the ECPSSR theoretical predictions and the measured values would be reduced, especially at the lower energies where this multiple-ionization effect is larger.[11] Similarly, the first-Born predictions would be raised and the divergence from the measured results would increase substantially, thus underscoring the inadequacy of the first-Born calculations.

Similar results are observed for the light ions $^1H^+$ and $^4He^+$ incident upon similar target elements, especially for ratios of incident energy of ion beam to its atomic mass less than 0.25 MeV/u reported in our earlier work [see Mehta *et al.* (1982) and Mehta *et al.* (1983) in Ref. 6]. The results for that low-velocity range reported in those two papers show the same relationship between the experiment and the theories as that reported here.

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