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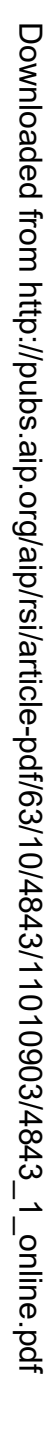

PIXE x rays: From $Z=4$ to $Z=92$

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(Presented on 17 March 1992)

A high-intensity, charged-particle-induced x-ray (PIXE) source has been developed for the purpose of characterizing x-ray detectors and optics, and measuring filter transmissions. With energetic proton beams up to 165 keV, intense line x radiations (0.5 Å$\leqslant\lambda\leqslant$111 Å) have been generated from the *K, L, M,* and *N* shells of elements $4\leqslant Z\leqslant 92$. The PIXE spectrum has orders-of-magnitude lower background continuum than a conventional electron beam or radioactive α-fluorescence source [C. K. Li, R. D. Petrasso, K. W. Wenzel *et al.* (to be published)].

I. INTRODUCTION

For characterizing x-ray detectors and optics, a high-intensity, selectable-wavelength source is often desirable. A conventional electron-beam x-ray source often emits significant thick-target bremsstrahlung because of the $1/m_e$ dependence in the differential radiative cross section. Such sources typically exhibit characteristic lines superimposed on a continuum. One method of avoiding this problem is to utilize filters, often of the same Z as the target, to selectively reduce the continuum.[1,2] Unfortunately, this technique can also significantly reduce the intensity of the desired line radiations. To eliminate this problem, and for other reasons, we are developing the PIXE source.

In the past three decades, the basic physical characteristics of PIXE (ionization cross sections, stopping power, and fluorescence yields, etc.) have been carefully studied.[3,4] X-ray emission induced by heavy charged particles is a well established technique with many applications. To the best of our knowledge, however, the applications have concentrated on analyzing elemental composition of materials. Thus little effort has been expended on exploiting the high intensities of PIXE as a tool for characterizing x-ray instrumentation.

In Sec. II we describe the experimental arrangement and technical details of our PIXE source. In Sec. III we show typical PIXE *K*-, *L*-, *M*-, and *N*- line spectra as well as measured *K*-, *L*-, *M*-, and *N*-shell x-ray production efficiencies for various elements.

II. EXPERIMENTAL ARRANGEMENT

The experimental arrangement is depicted in Fig. 1. Fluorescent x rays generated by energetic ions are detected by diagnostics in two "arms" offset by 116° with respect to the beam. In order to adjust the x-ray flux and to expedite the identification of characteristic x rays, an aperture/filter chamber is placed between the detector(s) and the PIXE source. Each chamber has a 24-position aperture wheel and a 24-position filter wheel, both independently rotatable through 360°.

A. Cockcroft–Walton linear accelerator

The ion beam is provided by a Cockcroft–Walton linear accelerator, large sections of which have been recently rebuilt.[5] Its principal components are: an rf-excited ion source, a solenoid beam focus and electrostatic ion extraction system, an accelerating column, a beam collimation system, water-cooled target(s), and a Faraday cup. The uncertainty in the ion-beam energy is $\lesssim 5\%$, and the ion current for conducting (nonconducting) targets is known to within $\lesssim 10\%$ (15%). The accelerator can be operated with voltages up to 165 kV and ion currents of 300 μA. Several charged species—such as H^+, D^+, $^3He^+$, and $^4He^+$— have been used as projectile ions; here we are concentrating only on proton-induced x rays.

B. Targets

Target preparation is one of the central issues for PIXE experiments. The targets are "thick" and made using one of six methods: (1) direct machining for materials such as Al, Cu, Mo,...; (2) vacuum deposition for materials such as Cr, Ti, ...; (3) epoxy-bonding of pure metal foils such as Be, Zn, Ta, ...; (4) electric discharge machining

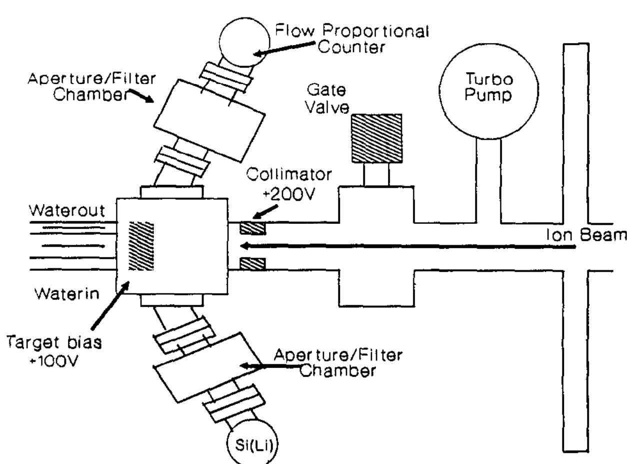

FIG. 1. Schematic diagram of the PIXE experimental arrangement.

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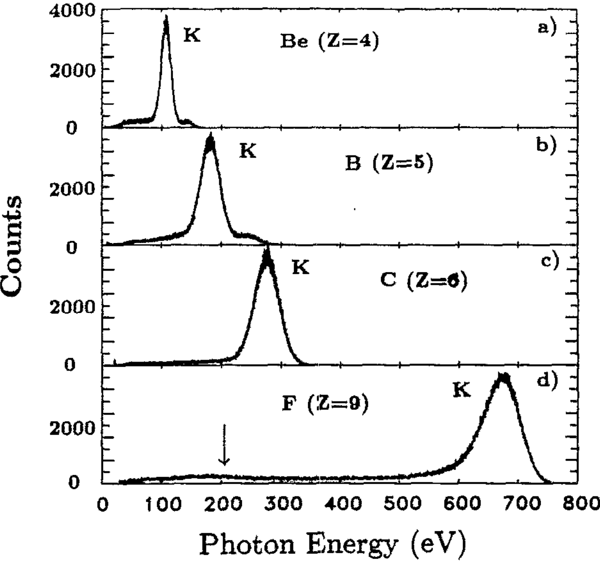

FIG. 2. The PIXE spectra of (a) beryllium, (b) boron, (c) carbon, and (d) fluorine. The K lines are at 0.108, 0.183, 0.277, and 0.68 keV, respectively. The spectra are measured by a flow proportional counter with a 0.5-μm mylar window. The flow gas is either 99.05% He+0.95% isobutane or 90% Ar+10% methane (P10). The proton beam energy was 150 keV, for which the maximum secondary-electron generated bremsstrahlung energy is about 0.3 keV. [This bremsstrahlung component is indicated by the arrow in (d)].

(EDM) for difficult-to-machine materials like W, Ta, ...; (5) pressed powders on a metal substrate using a man-powered press or a locomotive crusher (for Li, B, Si, ...); and (6) special vacuum depositions done at LLNL (such as B, U, Ti, ...). The method chosen depends on such factors as the mechanical, thermal, and electric properties of the specific material as well as the cost.

C. Diagnostics

Three energy-dispersive detectors [two Si(Li) spectrometers and a flow proportional counter] have been used to characterize the PIXE source: (1) an ORTEC Si(Li) spectrometer with an 8-μm beryllium window and energy resolution $R \simeq 160$ eV (for ^{55}Fe), which can measure photons of energy between $\simeq 0.6$ and ~ 30 keV (the crystal is 2.71-mm thick and the efficiency for 30-keV x rays is about 40%), (2) a Kevex Si(Li) spectrometer with a 25-μm beryllium window, and (3) a flow proportional counter with a thin window (for example, we have used a 0.5-μm mylar film coated with $\simeq 100$-Å aluminum).Using this proportional counter, we have measured very low-energy x rays (such as the Be K-line, $E=0.111$ keV; B K-line, $E=0.183$ keV; and the C K-line, $E=0.277$ keV; see Fig. 2). A leak valve and a manometer have been used to control and measure the flow gas pressure, which is either atmospheric or subatmospheric. A microcomputer-based ADC and MCA have been utilized for data acquisition.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

Characteristic x rays have been generated from the K, L, M, and N shells of elements with $4 \leqslant Z \leqslant 92$, with wave-

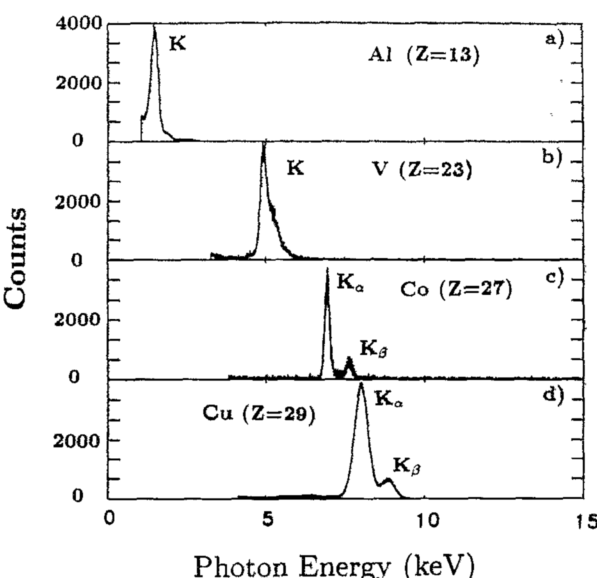

FIG. 3. The PIXE spectra of (a) aluminum (K_α line at 1.485 keV), (b) vanadium (K_α line at 4.95 keV), (c) cobalt (K_α line at 6.95 keV and K_β line at 7.65 keV), and (d) copper (K_α line at 8.05 keV and K_α line at 8.9 keV). When the incident beam consisted of protons accelerated to 150 keV two different Si(Li) detectors were used for these measurements.

lengths from 0.5 to 111 Å. Typical PIXE spectra are shown in Figs. 2–5. Figure 2 shows the measured K-line PIXE spectra of Be($Z=4$), B ($Z=5$), C ($Z=6$), and F($Z=9$). These spectra were obtained with a flow proportional counter. Figure 3 shows the Si(Li) PIXE spectra of K lines from Al ($Z=13$), V ($Z=23$), Co ($Z=27$), and Cu ($Z=29$). Figure 4 shows the Si(Li) spectra of L lines

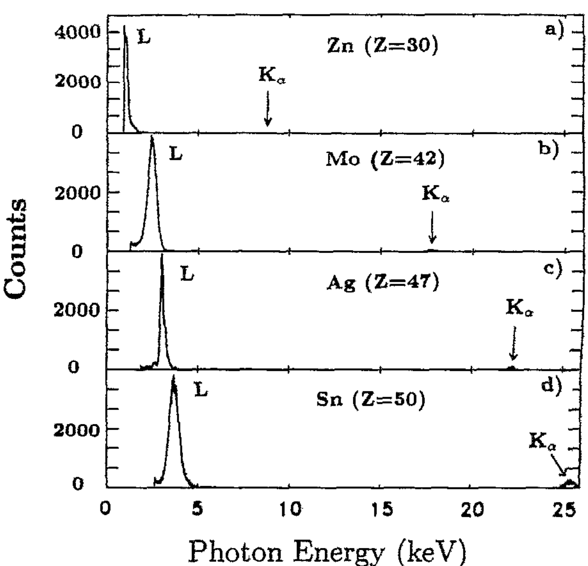

FIG. 4. The PIXE spectra of (a) zinc [the L lines are around 1.01 keV and the K lines are around 8.6 keV (see arrow)]; (b) molybdenum [the L lines are around 2.29 keV and the K_α line is at 17.5 keV (see arrow)]; (c) silver [the L lines are around 2.98 keV and the K_α line is at 22.16 keV (see arrow)]; (d) tin (the L lines are around 3.44 keV and the K_α line is at 25.27 keV). Two different Si(Li) detectors were used for these measurements. For these spectra, protons were accelerated to 150 keV.

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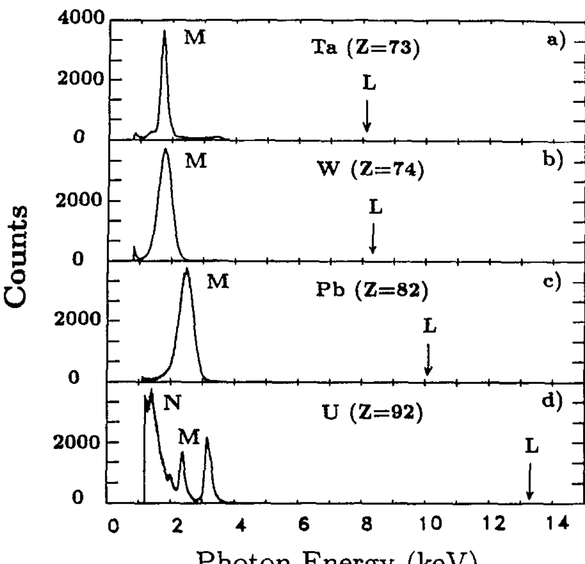

FIG. 5. The PIXE spectra of (a) tantalum [the M lines are around 1.71 keV and the L lines are around 8.14 keV (see arrow)]; (b) tungsten [the M lines are around 1.77 keV and the L lines are around 8.39 keV (see arrow)]; (c) lead [the M lines are around 2.4 keV and the L lines are around 10.5 keV (see arrow)]; (d) uranium [the N lines are around 1.4 keV, the M_α line is at ~2.5 keV and M_ζ line is at ~3.16 keV, and the L lines are around 13.65 keV (see arrow)]. Two different Si(Li) detectors were used for these measurements. For these spectra, protons were accelerated to 150 keV.

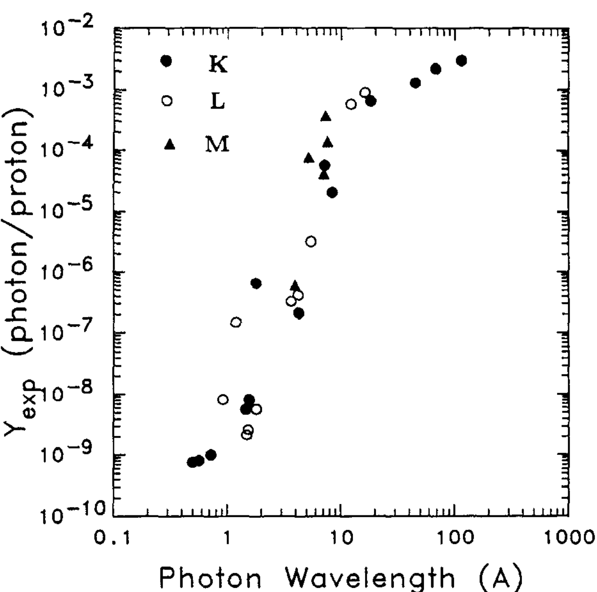

FIG. 6. The PIXE x-ray yields are plotted as a function of the photon wavelength for K lines (solid circle), L lines (open circle), and M lines (solid triangle). For these data, protons were accelerated to 150 keV.

from Zn ($Z=30$), Mo ($Z=42$), Ag ($Z=47$), and Sn ($Z=50$). Figure 5 shows Si(Li) spectra of M lines from Ta ($Z=73$), W ($Z=74$), Pb ($Z=82$), and U ($Z=92$). From Fig. 5. one can also see that the N lines of uranium are more intense than the M lines. (In fact the N lines consist of wavelengths at 8.60, 8.76, 8.81, 10.09, and 10.40 Å.) From these spectra, it is clear that the background continuum is negligible compared to the lines.

Generally speaking, for these accelerating voltages the PIXE background continuum is mainly bremsstrahlung from secondary electrons,[6] which has an endpoint energy of $4(m_e/m_p)E_p$ ($\simeq 300$ eV for our case, where the proton energy E_p is 150 keV). Note in Fig. 2 [especially part (d)] that this continuum is detectable, but at a low level.

To a good approximation, the characteristic x radiation is distributed isotropically. Experimentally, therefore, one can measure the fraction of emitted photons per unit ion charge striking the target. This yield is defined by

$$Y_{\exp}(E)=\frac{4\pi}{\Omega}\frac{1.6\times 10^{-13}N(E)}{T_Z(E)\epsilon(E)}, \tag{1}$$

where $N(E)$ is the experimentally measured number of photons (of energy E) per microcoulomb of ions, $T_Z(E)$ is the transmission of the windows and filters associated with the x-ray detector, Ω is the solid angle subtended by the detector (assuming a point source at the target), and $\epsilon(E)$ is the intrinsic detector efficiency. Figure 6 shows a log-log plot of measured x-ray yields as a function of x-ray wavelength. These efficiencies, which roughly agree with the results of other researchers,[7] generally increase with the x-ray wavelength and the principal quantum number of the target.

IV. CONCLUSION

A charged particle induced x-ray emission source (PIXE) has been developed for the purpose of characterizing x-ray detectors and optics, and filter transmissions. It produces intense line x radiations from 0.5 to 111 Å. The background continuum is orders of magnitude lower than that from a conventional electron-beam x-ray source. For these reasons we conclude that PIXE has important features as a tool for characterizing x-ray instrumentation.

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