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W. W. Craig, C. J. Hailey, R. I. Morales
Laboratory for Experimental Astrophysics
University of California
Lawrence Livermore National Laboratory
Livermore, California 94550

S. M. Kahn, B. W. Wargelin
Department of Physics
University of California
Berkeley, California 94720

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W. W. Craig†, C. J. Hailey†, R. I. Morales

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Lawrence Livermore National Laboratory
P.O. Box 808 L-401
Livermore, California 94550

DE88 017021

S. M. Kahn†, B. J. Wargelin†

Department of Physics & Space Sciences Laboratory
University of California, Berkeley
Berkeley, California 94720

ABSTRACT

An x-ray calibration facility for use in the 0.2-25 keV region is described. The facility employs several types of specially modified sources and detectors to produce and detect both line and continuum radiation in this energy range. We describe an inexpensive commercial x-ray source which has been modified for efficient high intensity operation as well as production of x-rays up to 25 keV. We also describe a system that utilizes multilayer mirrors alone or in a double Bragg geometry to select an energy bandpass. This system is controlled by a microcomputer which translates and rotates the multilayers to provide an easily selectable monochromatic beam with good resolution over a broad energy range. A long focal length Kirkpatrick-Baez mirror pair has been coupled to a pivoting beam line in order to accurately characterize gratings for use in soft x-ray astronomy. The beam line is scanned through the various grating orders. All aspects of the facility incorporate a high degree of flexibility so that a wide variety of calibrations can be easily performed.

1. INTRODUCTION

A calibration facility should be able to perform accurate measurements on virtually any piece of apparatus in its particular range of energies. We have attempted to construct a facility that can measure the quantum efficiency of a new detector, the transmission of a thin window, or the efficiency of an x-ray optic with relative ease. As the facility performs calibrations in support of x-ray astronomy, the primary energy ranges are fixed by the regions of the x-ray spectrum that are most likely to be of interest. At the lower energy end of the x-ray spectrum, missions now on the drawing board use low to moderate resolution dispersive elements to investigate the energy range from 200-2000 eV. This soft x-ray region includes the K-shell transitions of Carbon, Nitrogen and Oxygen as well as the L-shell transitions of Iron. Spectral features due to these elements have been identified in many x-ray sources detected by earlier x-ray satellites. At the higher energies, solid state detectors as well as the more traditional crystals and scintillation devices will be used.

Ongoing work at the Laboratory for Experimental Astrophysics at LLNL includes development of an x-ray bolometer and hard x-ray imaging detectors as well as low blaze angle reflection gratings. The facility now in operation was designed to support the needs of all of these projects while also handling routine calibration work. We will describe the sources that have been developed to supply the x-rays, a multi-use chamber utilizing the various sources, a monochromator to provide wide band continuous coverage, and a special long beam facility used in the development of x-ray optics.

2. SOURCES

There are numerous ways of producing x-rays for calibration purposes. Storage rings, for example, provide a tunable, monochromatic, high intensity beam. The rings are, however, quite bulky and expensive, restricting their use to a few, specially equipped locations. Radioactive sources are useful for producing line radiation and are quite

† Affiliated with the Laboratory for Experimental Astrophysics, Lawrence Livermore National Laboratory

portable but are restricted by the relative lack of available lines, particularly in the sub-5 keV range. Various other more exotic sources exist; in general they require fairly complex mechanisms to produce the x-rays.

In practice most laboratory x-ray sources consist of a hot filament that produces electrons which are then accelerated by an applied potential to an anode of the desired target material. These sources are compact, reliable and inexpensive and produce a reasonable x-ray flux. Their spectra are easily calculable¹ and various experimental data exist on the features and intensity to be expected².

In an electron impact source both characteristic line and continuum radiation is emitted. The continuum is mostly bremsstrahlung and for a thick target is of the form

$$I(\nu) = CZ(\nu - \nu_0) \quad (1)$$

where C is a constant determined empirically³. This continuum radiation makes it difficult to obtain a sufficiently monochromatic beam to perform calibrations. A judicious selection of anode material and edge filters makes most calibrations possible if a characteristic line may be generated in the energy region of interest. Some calibrations, however, require a cleaner beam than filters can provide.

To more nearly monochromatize the beam produced by an electron impact source, the initial x-rays may be aimed at a secondary target, producing fluorescence photons at the characteristic line energies of the secondary material. This method requires a large flux of primary photons to produce useful numbers of fluorescent photons. Monochromators may also be used to select out sections of the continuum, providing a continuous spectrum. Either method requires a high input intensity to produce useable flux.

An electron impact source without active cooling can achieve no intensity higher than about 10^{10} γ/s $ster^{-1}s^{-1}$ integrated over an emission line. In a multi-purpose system the sources and detectors tend to be loosely coupled to allow for various size samples or instrumentation, the resultant loss due to apertures and collimators can be 3-5 orders or more in intensity. If a monochromatic beam is needed, then any mechanism used to strip unwanted spectral features will reduce the flux by 1-3 orders of magnitude more. Calibrations of inefficient detectors or dispersive elements are difficult and time consuming with such a source.

Electron impact sources are typically less than 1% efficient, most of the energy in the electron beam being thermally dissipated. Thus to obtain a large flux the anode must be cooled or rotated to always present a fresh surface to the electron beam. In order to obtain the 10^{13} – 10^{14} γ/s $ster^{-1}s^{-1}$ needed to perform calibrations easily, the primary source for the fluorescent photons, or the input to the monochromator must be actively cooled. Many cooling methods have been reported⁴; the rotating anode principle yields the most flux but is quite complex as it involves a high speed rotational vacuum seal. The water cooled source is far easier to construct and can easily produce produce 10^{14} γ/s $ster^{-1}s^{-1}$ per kilowatt of input power.

2.1 Facility X-ray sources

Our facility utilizes two water cooled sources, one a direct emitter, the other an electron impact source coupled to fluorescent targets. The fluorescent source is modeled after the device constructed by Henke⁵. As shown to the side in figure 2 the x-ray tube illuminates a carousel of various fluorescence targets which can be rotated into position, producing characteristic line emission. The x-rays from the direct source are not collimated or focussed, yielding a rather diffuse emission from the target with the emission zone limited only by the size of the target. The output from this source is limited in energy by the available target materials as well as by the upper energy limits set by the anode material of the direct source. The primary Henke tube produces a broadband spectrum that may be used directly if needed. The available flux is limited however, as the emission comes from a large 1.5 cm^2 area, thus any collimators or apertures cut down the flux significantly.

To produce a more nearly pointlike, high brilliance source of x-rays over a wide range of energy we modified a commercial x-ray source sold by the J.E. Manson Co. This source as supplied was passively cooled and thus could support input power of only a few watts, resulting in fewer than 10^{10} γ/s $ster^{-1}s^{-1}$ from a spot size on order 200 microns in diameter. We have used these sources frequently in the past. They are simple to operate and maintain, and are compact enough to fit through a standard 2.75 inch vacuum inlet making them easy to adapt to various uses. As shown in figure 1 we modified the source by replacing the anode and anode feedthrough by a bored out shaft which allows water to pass within 4 mm of the anode surface. The shaft is separated from the walls by

ceramic (Macor) insulators allowing operation up to 25 keV. The removable anodes are sealed to the shaft using an Indium O-ring. The original design utilized Viton O-rings to seal the anode to the shaft and tended to produce excessive carbon buildup on the anode. The carbon buildup is an intrinsic problem with this type of source and may only be avoided by careful cleaning and adequate pumping.

Figure 1 - A modified x-ray source utilizing active water cooling. The source extends 200 mm past the vacuum seal into the source chamber. X-rays are emitted in two beams separated by 120 degrees. The anode is easily interchanged with several materials currently available.

Cooling water is brought in and out through a long coiled section of plastic tubing. The tubing, high voltage connector, and filament leads are protected by a plexiglass shield. The area around the anode and filament is covered by an aluminum shroud that limits the x-ray beam to selected beam paths. The apertures in the shroud can be easily changed in both size and location to fit the specific needs of a calibration project. Generally they are on opposite sides of the shroud, at an angle of 30-45 degrees with respect to the plane containing the anode. One beam is used for calibration purposes, the other is directed at a reference detector that monitors source stability. The two beam lines have been measured to be equivalent to within 2%.

This source is inexpensive and very reliable, allowing the generation of a significant amount of x-rays over a wide energy range. This source has a brightness of $\sim 10^{13}-10^{14} \text{ } \gamma \text{ s}^{-1} \text{ cm}^{-2}$ in the emission lines with Al and Cu anodes from a 1 mm^2 spot size. Typically the source is operated with less than 1 kilowatt of input power. Graphitized copper can be used to produce Carbon K α radiation at a slightly higher flux level.

We also use a multi-anode source supplied by the J.E. Manson Co. that incorporates the same design as the single anode version as described above. This source contains six anodes on a carousel, all connected to a common high voltage. The carousel can be rotated while under vacuum, enabling simple, rapid changes in the x-ray spectrum being used to do a calibration. This source is not cooled, limiting its input power to a few watts. The source produces two beam lines, separated by 90 degrees, as shown in Figure 2.

3. DETECTORS

Two main types of detectors have been used in our calibration work. For most tasks we have used flow type proportional counters. These counters generally are used at atmospheric pressure for work above about 900 eV, with a pressure regulating system reducing the pressure down to a limit of a few torr for lower energy work. The windows are either thin beryllium or .8 μ m polypropylene stretched over a 70% transmissive nickel grid. The counters are generally mounted inside the vacuum chambers on either remotely controlled translation tables or on rotary feedthroughs so that they may be scanned while under vacuum. For work requiring higher resolution, we have adapted a windowless lithium-drifted silicon (SiLi) detector to a bellows that allows it to be attached to a chamber and scanned over a limited range ($\pm$ 10 degrees). The SiLi detector has a typical resolution $E/\Delta E$ of 30 at 6 keV, and can resolve Boron and Carbon K α 's at the lower energies.

4. CALIBRATION SETUP

The various sources and detectors are combined with translation and rotation stages in a multi-use chamber as shown in figure 2. As depicted, the chamber is configured to measure the efficiency of a multilayer. The multilayer can be moved out of the beam for an I_0 measurement, then returned into the path of the beam and rotated to the desired angle θ .

Figure 2 - Multi-use calibration chamber in a typical configuration. The multilayer may be illuminated by either of the two sources. Diffracted x-rays can be viewed with either a scanning proportional counter or a SiLi detector mounted on a bellows allowing 20 degrees of angular motion.

The proportional counter is then rotated through 2θ and the measurement taken. The multilayer can also be used as a predisperser with its output beam directed at the filter or crystal to be calibrated. The chamber itself is ~40cm in diameter and the proportional counter is free to rotate through ~320 degrees. The large available area and dual sources enable a wide variety of calibrations to be made.

5. DOUBLE MULTILAYER MONOCHROMATOR

Although the combination of fluorescent and direct electron impact sources serves many purposes, the wavelengths available are, in general, limited to a few lines, particularly below about 1 keV. Providing, from these sources, a continuous spectrum throughout the energy ranges of interest requires a dispersive monochromator. To maintain reasonable throughput while maintaining moderate resolution, synthetic multilayers are the best choice as dispersing elements. For flexibility and ease of use, fixed entrance and exit slits are desirable.

A design of this sort is not particularly novel. Barbee⁵, for example, has described a double multilayer monochromator that maintains this relationship by using a multilayer pair with a layer pair spacing that is graded along the length of the multilayer. This sort of system can maintain a fixed exit slit by translating one mirror over a limited range.

The fixed entrance and exit slit relationship for various energies can also be maintained by using identical multilayer pairs in a parallel configuration. Both multilayers must be rotated and one translated along the beam path. This arrangement has been used in double crystal spectrometers⁶. By simply following the corrected Bragg formula

$$m\lambda = 2d \sin(\theta)(1 - \delta/\sin^2\theta_0) \quad (2)$$

where $\delta = 1 - n_0$ with n_0 being the refractive index of the material, the multilayer elements can be rotated and the second multilayer translated to the proper position to maintain the fixed exit beam.

This arrangement is shown in Figure 3. The entrance slit is attached to a front baffle plate, which when combined with a back baffle plate, totally excludes all light except that which is diffracted, or specularly reflected, off the multilayer mirrors. The stages are driven by small dc motors with integral encoders. The motors are controlled by an IBM PC through an RS-232 compatible motor controller. The vertical distance between the two mirrors is mechanically fixed. The horizontal distance is determined during initial alignment. After establishing the correct angles by calibrating off of a known spectrum, i.e. locating a strong single line, the monochromator can maintain the correct energy, to within a few eV, throughout a scan. The mirrors can be moved independently to allow final fine adjustment to maximize flux at a given wavelength.

Figure 3 - Schematic of a double multilayer monochromator. The lower rotation stage translates along the beam direction to keep the exit beam at the same position as the mirrors are rotated.

There are three sets of multilayers currently available. One pair with a 2d spacing of 120 angstrom, consisting of layer pairs of tungsten and silicon, covers an energy range from ~200 to 500 eV. A second pair with a 2d spacing of 60 angstroms and layer pairs of tungsten and carbon, covers the 500 to 1100 eV range. For the range above 1 keV, a pair of tungsten/carbon mirrors with a 2d spacing of 30 angstroms will be used. The mirrors are approximately 30 by 80 mm in size and are deposited on a .25 mm silicon wafer. The multilayers were purchased from Ovonic Synthetic Materials.

The performance of multilayers, i.e. their reflectivity and resolution, can be easily calculated⁷. Using the parameters for the multilayer as supplied by the vendor, and verified in our own setup, we calculated an expected resolution, $\lambda/\Delta\lambda \sim 80$ at 900 eV, as compared to an expected resolution of about 50 for a single multilayer of this type at this energy. As shown in figure 4, the FWHM of the Cu L α line at 929 eV is ~16eV, yielding a $\lambda/\Delta\lambda$ of > 60. The small peak at 950 eV is the Cu L β_1 line. For these parameters the beam is only 60% σ polarized. As the angle increases toward 45 degrees, the beam becomes more nearly polarized. If the 2d=30 mirrors were used in the above case, the beam would be 90% σ polarized.

Figure 4 - Result of a scan by the double multilayer monochromator while illuminated by an electron impact source with Cu anode. The Cu L α line is at 929 eV. The smaller feature is Cu L β_1 at 950 eV. The dashed lines are gaussian fits to the peaks. Exhibited resolution is $\lambda/\Delta\lambda > 60$.

To be useful the monochromator must be efficient enough not only to pull out a characteristic line, but also must be able to separate sections of the continuum out. Cohen and Deslattes⁸ calculate the amount of flux available in a bremsstrahlung continuum.

$$N_B = ViZ(1-E/E_0) \gamma s^{-1} \text{ m}^{-2} \text{ per } 10^{-3} \Delta E/E. \quad (3)$$

V is the accelerating voltage and i the current $E_0 = Ve$. The water cooled source described in section 2 is typically operated at about 6.5 kV and 90 mA. With a copper anode, a total combined efficiency of the mirrors of 10%, and including the geometric factors, equation (3) predicts about $5 \times 10^3 \gamma s^{-1}$ per 16 eV energy interval at 800 eV. We measured a count rate of $3 \times 10^3 \gamma s^{-1}$ in the 16 eV interval around 800. This count rate, contained in a very slowly diverging beam, is sufficient to perform most calibrations. The performance of the system at higher energies with the multilayer pairs with a 2d of 30 angstroms has not been tested but is expected to be roughly comparable.

6. LONG BEAM LINE ASSEMBLY

The next generation of x-ray observatories will include high throughput missions that couple moderate resolution telescopes (1 arcmin) with reflection gratings to provide medium resolution spectroscopic information in the 200-2000 eV region⁹. These reflection gratings are likely to be characterized by a low blaze angle (< 1 degree), and a varied line spacing to maintain resolution in a converging beam¹⁰. Such low blaze angles are technically difficult to produce, and in practice many such gratings need to be tested before acceptable samples are found. To properly test the resolving power of the gratings, they must be placed in a converging beam with a long focus approximating that of the eventual x-ray telescope focus.

To test sample gratings intended for use in such an experiment we have configured existing x-ray calibration facility equipment into a 8 meter facility as shown in figure 5. This facility uses either an actively or passively cooled electron impact source to produce x-rays. The converging beam is produced by a Kirkpatrick-Baez mirror pair placed in close proximity to the source. These mirrors employ a unique dual lever arm tension arrangement to bend gold coated float glass in a nearly perfect ellipse¹¹. The mirrors focus the x-ray source on the detector, in the smaller chamber, some 7.5 meters away. Because of their proximity to the source, the mirrors act as magnifiers, requiring the use of a pinhole in front of the x-ray source to limit the size of the focal spot to a maximum of one half the size of the detector window. The mirrors are focussed under vacuum, in the x-ray, through use of remote controlled dc motors.

Figure 5 - The long beam facility for measuring the performance of varied line space reflection gratings. The x-rays from the source at the left are focussed by the two mirrors in a Kirkpatrick-Baez configuration, the grating then disperses the orders where they are scanned by moving the entire beam line with the leadscrew at the far right.

With the x-ray beam focussed, a slit is placed between the mirrors and the test grating so that various sections of the grating can be illuminated independently. The grating is mounted on a combination rotation and translation stage and is moved into the beam and rotated to its proper angle. The spectral orders are dispersed along a line perpendicular to the grating surface. The entire beam line pivots on a bellows, allowing the spectrum to be scanned through several orders. A low backlash leadscrew and position indicator on the detector chamber end give angular accuracies of better than 10 arcseconds, much better than that required by the grating or telescope parameters. Several grating samples and calibrated mirrors have been tested in the facility with results consistent with other reported figures¹².

7. CONCLUSION

We have constructed a very flexible calibration facility that allows us to perform accurate measurements on a wide variety of optical elements, filters and detectors. The facility can operate in a continuous fashion from 200 eV to more than 2000 eV with the capability of calibrations up to 25 keV. This facility currently supports several ongoing x-ray astronomy experiments as well as performing routine calibration work. We have constructed a double multilayer monochromator that operates with near theoretical resolution over a wide energy range. A long beam facility to test low blaze angle, varied line space gratings is in operation and producing useful results.

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