Ultra-high Energy Resolution of the Undulator Beamline

With the advance in electronics and instrument design, modern spectroscopy has provided us with a wealth of information on the interaction of electromagnetic radiation with matters. The light sources used for spectroscopy evolved from lamps to lasers and synchrotron radiation, which progressively extended the probing energy range and detectability of a wide variety of sample forms. In the vacuum ultraviolet region from about 5 eV to 20 eV where many electronic transitions of atoms and molecules occur, lamps and lasers were the major light sources in the laboratory before the appearance of synchrotron radiation beamlines that operate in this energy range. Though laser still offers the highest intensity in this spectral region, the wide tuning range of synchrotron radiation source presents new possibilities in scientific research, such as spectroscopic and dynamic studies near ionization thresholds of atoms and molecules. Above 20 eV into the extreme ultraviolet and soft X-ray region, where laser generation is difficult, synchrotron radiation takes over as the choice of light source. In particular, with the high brightness and small beam size of undulator sources in third generation rings, the beamline designer is able to optimize the monochromator for very high resolving power while still maintaining a realistic amount of photon flux necessary for experiments of low signal levels or dilute samples. We have constructed such a high resolution and high photon flux beamline from the output of the U9 undulator at the Taiwan Light Source (TLS). This beamline employs a cylindrical grating monochromator (CGM) and is capable of providing high resolution over an extended energy range from 5 eV to 100 eV, with peak resolving power above 100,000 in the low energy branch (5-30 eV), and above 40,000 in the high energy branch (15-100 eV). Based on the novel design of the Wide-Range Beamline at TLS, this broad range and high resolution capability is achieved by using separate entrance slit for each branch following the vertical focusing mirror, thus allowing optimization with different grating included angles. At the time of writing, this is the only undulator beamline that covers both VUV and most of EUV range and at the same time attains resolving power of 100,000.

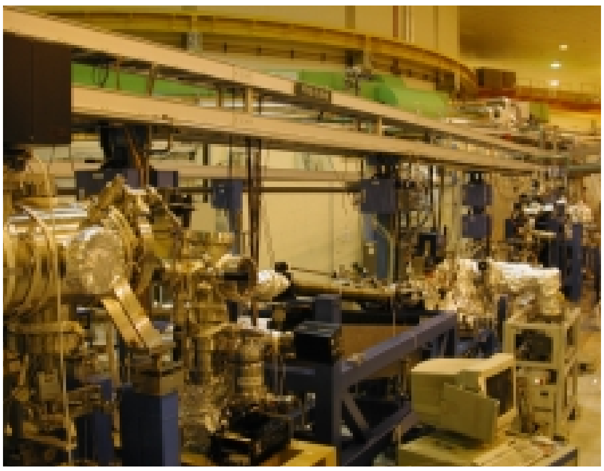

Fig. 1: The U9-CGM beamline.

A view from the end station to the beamline front end is shown in Fig. 1. The optical layout of this beamline is shown in Fig. 2. Photon beam generated from the U9 undulator is first aligned and confined by two pinholes and then focused horizontally by a water-cooled, spherical horizontal-focusing mirror (HFM) made of silicon. After HFM, the photon beam is focused by the spherical vertical-focusing mirror (VFM) onto the entrance slit of either the high-energy or low-

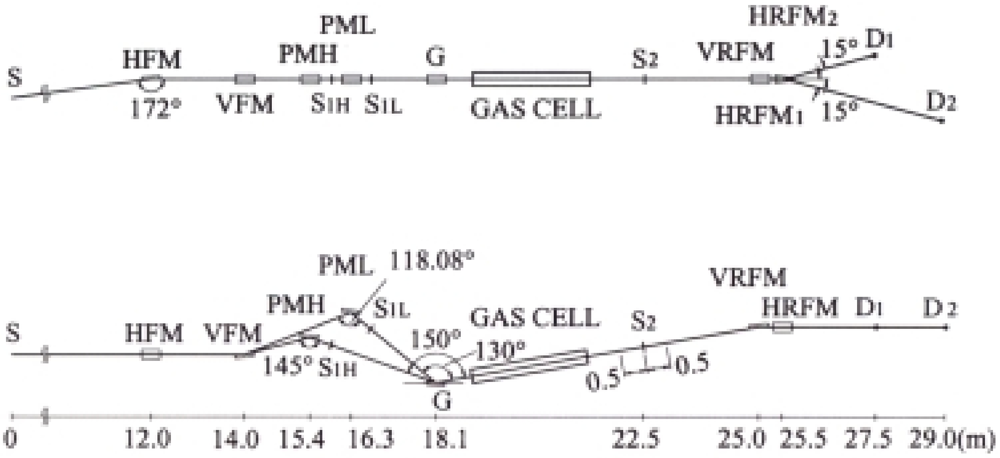

Fig. 2: The optical layout of U9-CGM beamline.

energy branch, selected by changing the reflecting angle of VFM. Following VFM, each branch has its own plane mirror (PMH and PML) to reflect the photon beam onto the grating. Energy resolution is optimized for each branch with the incidence angles: 150 degrees for the high energy branch (15 - 100 eV), and 130 degrees for the low energy branch (5 - 30 eV). Four cylindrical gratings with ruling densities of 1000, 1800, 800, and 1600 lines/mm are used to cover photon energies from 5 to 100 eV. A laminar ruling profile is used for each grating to reduce high-order scattered light. The entire energy range is covered by a common movable exit slit, followed by a bendable, cylindrical vertical-refocusing mirror (VRFM). Finally two cylindrical horizontal-refocusing mirrors (HRFM1 and HRFM2) branch the light horizontally into two experimental end stations.

The beamline performance is characterized by measuring the photon flux, energy resolving power, and the ability to reject high order light, as described in the following paragraphs.

The full-width half-maximum (FWHM) of the focused photon beam at the sample position is smaller than 200 μm × 40 μm (H × V). The photon flux measured with a silicon photodiode averages about 6×10^{13} photons/sec at 200 mA ring current when the energy resolving power is set at 1000, which is about 30 times higher than that obtained from the bending-magnet High Flux beamline at SRRC. An average photon flux of 3×10^{11} photons/sec was measured with slit openings of 10 μm /10 μm, corresponding to resolving power of 30,000 to 90,000 in the 5-100 eV energy range. The photon flux is about 1×10^{10} photons/sec with resolving power at about 100,000, when the entrance and exit slit openings are set at 3 μm and 5 μm, respectively.

The energy resolution is determined by measuring the photoabsorption or photoionization line widths of krypton or argon gases. Absorption spectra are acquired by detecting the fluorescence from sodium salicylate coated on a glass plate positioned at the end of a gas cell with a photomultiplier tube. Photoionization spectra are obtained by intersecting a free-jet of atomic gas with synchrotron light and detecting ions with a quadrupole mass spectrometer.

Energy resolution is expressed by the resolving power, defined as $E/\triangle E$ where E is the energy of photon and $\triangle E$ the full width at half maximum of the gaussian curve deconvoluted from the spectral line measured around energy E. It is a measure of the ability of monochromator to differentiate adjacent spectral peaks. For example in the vacuum ultraviolet range, a resolving power of a few thousands is enough to separate the vibrational structures of the ground ionic state of molecular nitrogen, while tenths of thousand is needed to unravel the manifold of rotational lines in each vibrational band. The resolving power of our U9 undulator beamline is well suited for the study of rotationally-resolved spectra of molecular ion in the vacuum ultraviolet range. Another research area that requires high level of resolving power is the study of photoionization of atomic species. For example the double ionization of helium gas atom around 65 eV lies in the extreme ultraviolet region where only a synchrotron beamline offers continuous energy scanning. With every new beamline attaining higher resolution, new information is obtained for comparison with theoretical calculation. In general the natural line widths of atomic ions are much narrower than what a synchrotron radiation beamline can resolve, and often are used to derive the resolving power of synchrotron beamlines, as will be demonstrated in the following paragraphs.

Fig. 3 shows the $4p^5ns(3/2)_1{}^0$ and $4p^5(n-2)d(3/2)_1{}^0$ series for n≧16 states of krypton. The pressure of Kr in the gas cell is 3×10^{-4} torr and the slit openings are 5 μm/5 μm. The energy scale is calibrated against the peak 26d/28s at 13.9776 eV. Assuming the natural width is negligible, the full-width half-maximum of the peak 16d at 13.9391 eV obtained by Gaussian curve fitting is 0.155 meV, which gives E/△E of 90,000 for a combined instrument resolution of photon beam and detection system.

Fig. 4 shows the photoabsorption spectrum in the autoionization region of argon, $3p^5ns'(1/2)_1{}^0$, for n≧11 and $3p^5nd'(3/2)_1{}^0$, for n≧9. The gas pressure is set at 2×10^{-5} torr and the slit settings are 3 μm/5 μm. The ns'/nd' series from 11s'/9d' to 49s'/47d' are clearly observed. The energy scale is calibrated against the peak 11s' and 49s'. In the insert of Fig. 4 the curve for the background subtraction is the Fano profile of 9d', and with the background-subtracted 11s' peak fitted with a Fano profile, the instrument Gaussian curve gives a FWHM of 0.145 meV, which is equivalent to energy-resolving power of higher than 100,000 at 15.76 eV. Peak 11s' measured with slit openings of 10 μm /10 μm has Gaussian FWHM of 0.265 meV, equivalent to resolving power of 60,000.

In order to eliminate high order light generated by undulator and grating, a sophisticated differential-pumping gas cell was designed. Fig. 5 shows that high order light can be reduced by four orders of magnitude with helium at 3 torr, while keeping both ends of the gas cell in UHV condition. The alignment of gas cell is critical since scattered light generated along the gas cell channel would easily degrade the ultra-high resolution.

The photon flux measured with both slits set at

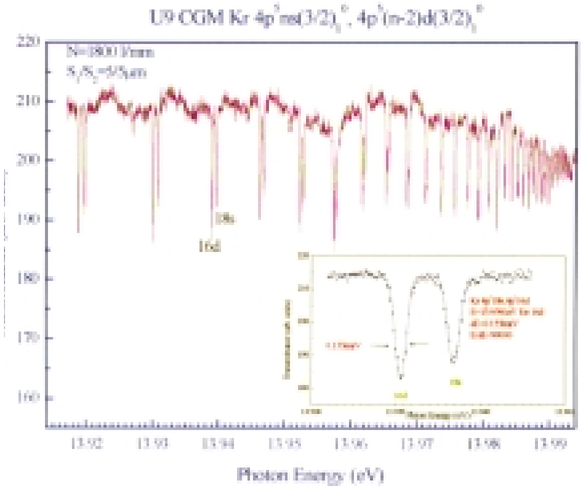

Fig. 3: The absorption spectrum of the krypton series $4p^5ns(3/2)_1{}^0$ and $4p^5(n-2)d(3/2)_1{}^0$, for n=16 to 51 .

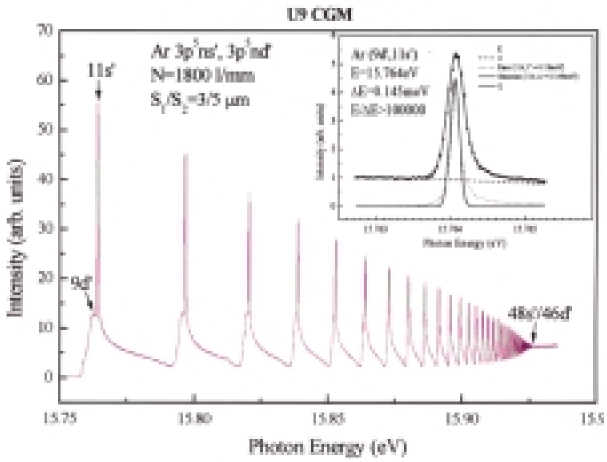

Fig. 4: Autoionzation spectrum of argon. The Rydberg series resonance lines of $3p^5ns'$, n=11 to 48, and $3p^5nd'$, n=9 to 46.

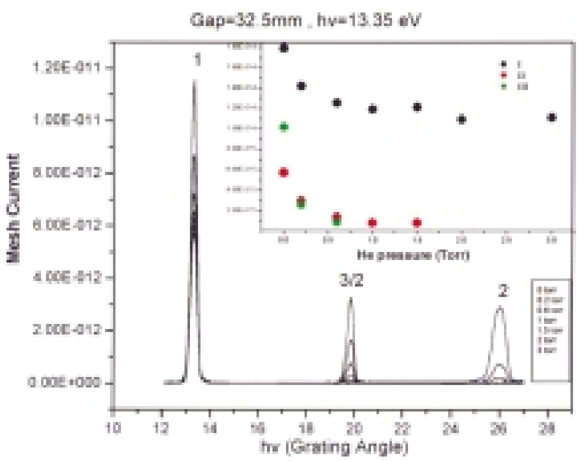

Fig. 5: Intensity of fundamental and harmonics as a function of gas cell He pressure.

10 μm is lower than the calculated value, due to the fact that actual photon source size is larger than the theoretical value, and the slope errors of the focusing mirrors are slightly larger than we expected. The flux only reaches 1×10^{10} photons/sec with the slit openings of 3 μm /5 μm, because the defocused beam caused by the effect of grating slope error (about 0.25 arcsec) becomes significant at smaller slit openings.

The energy resolution of the photon beam can be influenced by many factors, such as the imperfection of optics (slits, mirrors, and grating), alignment, and the stability of the mechanical supporting structure. It is also sensitive to the positions of both entrance and exit slits. Since both slits are movable we can find a best combination of slit positions that provides the highest resolution. The stability and reproducibility of the grating scanning mechanism are also important. Ours is about 0.1 arc sec, which corresponds to an energy uncertainty of about 0.05 meV at 16 eV when using the 1800 l/mm grating. The amplitudes of vertical vibration of the grating and slit holders measured with the Polytec fiber interferometer are about 0.2 μm peak to peak, which gives an energy broadening of 0.05 meV. Thus the total energy broadening from mechanical instability is about 0.07 meV. From the Gaussian width of 0.145 meV measured at 15.76 eV, we derive the resolution of the beamline with entrance and exit slit openings of 3 μm and 5 μm to be 0.127 meV, which is very close to the design value.

The performance of the U9-CGM spectroscopy undulator beamline at SRRC has been characterized and is summarized as follows: The photon flux measured at 200 mA ring current are: 6×10^{13} photons/sec at low resolving power (<1000) mode, 3×10^{11} photons/sec with 10 μm /10 μm slit openings, and 1×10^{10} photons/sec at entrance and exit slit openings of 3 μm and 5 μm. Energy resolving power as high as 100,000 has been achieved at 15.76 eV using the 1800 l/mm grating. The efficient differential pumping gas cell can be fully utilized to reduce high order light contamination by four orders of magnitude. These results show that the beamline performance has reached its design goal and we expect the U9-CGM beamline to be a powerful tool for ultra-high resolution spectroscopic studies.

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Publications

- Y. F. Song, P. C. Tseng, L. R. Huang, S. C. Chung, T. E. Dann, C. T. Chen, and K. L. Tsang, Nucl. Instrum. Methods **A 467**, 496 (2001).
- Y. F. Song, J. Y. Yuh, S. C. Chung, P. C. Tseng, L. R. Huang, T. E. Dann, Y. Y. Lee, K. D. Tsuei, G. Y. Hsiung, D. J. Wang, H. S. Fung, C. T. Chen, and K. L. Tsang, paper in preparation.
- J. C. Lee, SRRC Newsletter **50**, 15 (2002).