sponding *nd* amplitudes and coherent addition of the pure Coulomb amplitude.[11] This amounts to neglecting the Coulomb modifications of the strong *nd* amplitudes which, in the present formalism, means neglect of all shorter-range Coulomb effects in $\tilde{V}'^{(\mu)}$ and $G_0^{(\mu)}$. However, we are now in the position to check the reliability of such a procedure. For this purpose we have included in Fig. 2 the cross sections obtained in such a way. It appears that at low energies this approximate treatment is rather unsatisfactory, whereas it may become more reliable at higher energies.

In conclusion we emphasize once more that our approach to the Coulomb corrections in *pd* scattering is not only mathematically correct but also well suited for practical applications with no need for drastic approximations. (This is in contrast to the use of the formalism of Ref. 2 made in Ref. 4. Indeed, the results obtained there bear only a faint resemblance to ours or to the experimental data.) Apart from employing separable nuclear potentials, *only one* approximation has been made in the present calculations. Namely, the effective potentials and Green's functions which determine, via Eq. (7), the Coulomb-modified strong amplitude $T_{sc}^{(\mu)}$, are evaluated to lowest order in e^2 only. However, the neglect of higher-order terms can and will be checked. Furthermore, the difficult question which is bound to plague most other approaches of how many partial waves in the *pp* subsystem should be taken into account never does arise in our method where, characteristically, the full three-dimensional Coulomb potential is built in.

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[1]For a recent review see P. U. Sauer, in *Few Body Dynamics*, edited by A. N. Mitra *et al.* (North-Holland, Amsterdam, 1976).

[2]J. V. Noble, Phys. Rev. 161, 945 (1967).

[3]Gy. Bencze, Nucl. Phys. A196, 135 (1972).

[4]S. Adya, Phys. Rev. 177, 1406 (1969).

[5]A. M. Veselova, Teor. Mat. Fiz. 3, 326 (1970).

[6]E. O. Alt, W. Sandhas, H. Zankel, and H. Ziegelmann, to be published. For a short account of this method and first results for the quartet effective-range parameters and *S*-wave phase shifts, see E. O. Alt, in *Few Body Dynamics*, edited by A. N. Mitra *et al.* (North-Holland, Amsterdam, 1976).

[7]E. O. Alt, P. Grassberger, and W. Sandhas, Nucl. Phys. B2, 167 (1967).

[8]V. G. Gorshkov, Zh. Eksp. Teor. Fiz. 40, 1481 (1961) [Sov. Phys. JETP 13, 1037 (1961); W. F. Ford, Phys. Rev. B 133, 1616 (1964); M. D. Semon and J. R. Taylor, Nuovo Cimento 26A, 48 (1975); J. Zorbas, unpublished.

[9]D. C. Kocher and T. B. Clegg, Nucl. Phys. A132, 455 (1969).

[10]E. O. Alt and B. L. G. Bakker, Z. Phys. A273, 37 (1975); H. Ziegelmann, Z. Naturforsch. 30a, 434 (1975).

[11]J. Bruinsma, W. Ebenhöh, J. H. Stuivenberg, and R. van Wageningen, Nucl. Phys. A228, 52 (1974).

Generation of Coherent Radiation at 53.2 nm by Fifth-Harmonic Conversion*

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The generation of coherent radiation of 53.2 nm by fifth-harmonic conversion of laser pulses at 266.1 nm in both Ne and He is reported.

Frequency upconversion using third-harmonic generation and four-wave mixing has received attention in recent years for the generation of coherent radiation in the vacuum ultraviolet (VUV) region of the spectrum.[1-3] Such processes have been used to produce coherent radiation at wavelengths as short as 57.0 nm.[4] The generation of coherent light in the extreme ultraviolet region by third-order processes becomes increasingly difficult because of the scarcity of intense coherent sources at the required pumping wavelengths. The development of frequency conversion techniques utilizing higher-order nonlinearities offers an attractive alternative to this approach, since it would allow larger steps along the frequency scale to be made in a single conversion process.

Several of these processes have been suggested in the literature.[5,6] Although reasonable conversion efficiencies have been predicted for some of these interactions, the only published experimental evidence of such processes has been the fifth-harmonic conversion of Nd:glass radiation (1.06 μm) in calcite.[7] No experimental evidence has been published for the generation of fifth or higher harmonics in vapors or in the VUV.[8]

In this Letter we report the generation of coherent radiation at 53.2 nm. To our knowledge this is the shortest-wavelength coherent radiation reported to date.[9] It was achieved through fifth-harmonic conversion of laser pulses at 266.1 nm [the fourth harmonic of a Nd:YAlG (yttrium aluminum garnet) laser]. This process was observed in both He gas and Ne gas. The present work represents the first application of higher-order nonlinearities in the generation of coherent radiation in the extreme ultraviolet and indicates the feasibility of use of such processes for the generation of still shorter wavelengths.

Energy level diagrams for Ne and He are shown in Fig. 1. The fifth-order susceptibility in Ne at 266.1 nm is dominated by a near four-photon resonance ($\Delta\tilde{\nu} = 12$ cm^{-1}) between the ground state and the $3p\ [1\frac{1}{2}]\ J=2$ level. The wavelength of the generated radiation lies in the ionizing continuum. Efficient fifth-harmonic conversion is therefore limited to tight focusing arrangements in which the focal depth is shorter than the absorption length. The four-photon resonance is not nearly as exact in He ($\Delta\tilde{\nu} \approx 16\,000$ cm^{-1}). However, the generated radiation lies below the continuum, at a level 1760 cm^{-1} above the $3p$ state. Calculations of the refractive index which include the effects of the continuum indicate that He is negatively dispersive for this process. Thus, optimization by tight focusing in He should be possible.[10]

The pump pulses at 266.1 nm were derived from a mode-locked Nd:YAlG laser followed by two successive stages of second-harmonic generation with about 70% conversion in each stage.[11] Quartz prisms were used to separate the fourth-harmonic pulses. The pump pulses entered a sample cell through a MgF_2 window. The cell was attached to a 1-m normal-incidence vacuum spectrometer. A CaF_2 lens was used to focus the radiation at the center of a 500-μm-diam aperture which replaced the entrance slit of the spectrometer. The gas used for nonlinear mixing flowed into the cell and was differentially pumped behind the entrance aperture. The energy in the pump pulses was measured with a calibrated joulemeter after the focusing lens, indicating a peak power of 330 MW. The infrared and second-harmonic pulses were observed with a 5-psec-resolution streak camera which showed pulse durations of about 30 psec with no amplitude substructure. The experiments were performed using lenses of both 5- and 10-cm focal lengths. The characteristics of the beam in the focus of both lenses were measured with a Si photodiode array. A Gaussian profile was observed in each case, with spot sizes ($1/e$ field radius) of 10 and 5 μm and confocal parameters of 2 and 0.5 mm for the 10- and 5-cm lenses, respectively.

The radiation at 53.2 nm was observed both photographically and photoelectrically. A microdensitometer tracing of the spectrum of fifth-harmonic light generated in Ne at a pressure of 40 Torr is shown in Fig. 2. The spectrum was recorded on Kodak 101-01 film through a 1200-Å-thick Al filter. A single spectral line is seen in

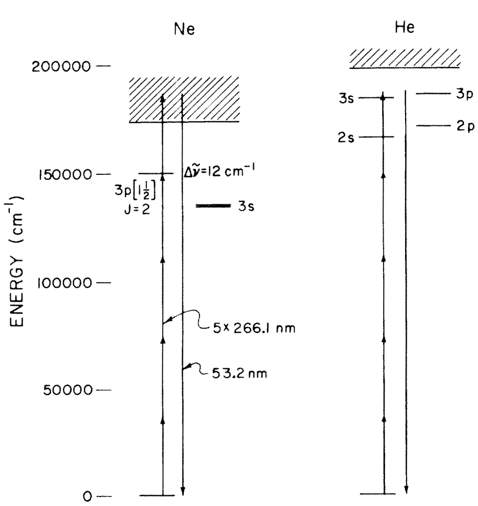

FIG. 1. Partial energy level diagrams of Ne and He showing states involved in fifth-harmonic conversion of 266.1 to 53.2 nm.

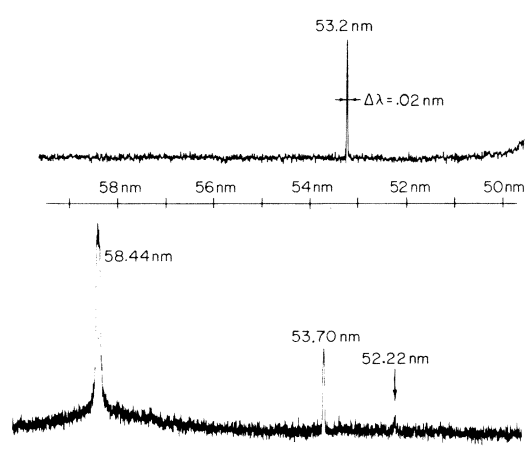

FIG. 2. Microdensitometer traces of a fifth-harmonic spectrum in Ne (top) and a He discharge comparison spectrum (bottom).

the range covered. Its width of 0.02 nm is limited by the size of the beam at the focus. A comparison tracing of a spectrum from a He arc source in the same spectral region is also shown, with three of the He emission lines evident.

Photoelectric signals were observed through two 1200-Å Al filters with an EMI 9750QA photomultiplier tube and a sodium salicylate scintillator. For wavelength measurements, the spectrometer dial was calibrated against the He discharge spectrum to an accuracy of ± 0.05 nm. Using a 200-μm exit slit, the center wavelength of the fifth-harmonic signal was determined by tuning the monochromator dial to 53.2 ± 0.1 nm for both gases. This measured value is in excellent agreement with the expected value of 53.225 which was determined from calibration of the laser second-harmonic wavelength with a Ne discharge spectrum.

The variation of the fifth-harmonic signal with pump intensity was measured in neon at a pressure of 40 Torr with use of the 10-cm focusing lens. Data are shown in Fig. 3 for 24 laser shots. The pump intensity in the focus at the highest level shown is approximately 3×10^{14} W/cm^2. A least-squares fit to the data points (solid line) gave a power-law dependence with a slope of 4.7 on a log-log scale, in excellent agreement with the expected value of 5. The proper power-law dependence of signal strength with pump intensity, along with the exact agreement of the wavelength measurement, was taken as confirmation that fifth-harmonic generation had been observed.

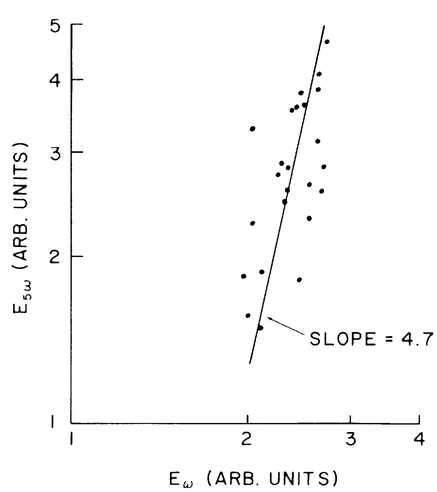

FIG. 3. Variation of fifth-harmonic signal with pump intensity in neon at at pressure of 40 Torr. The highest pump intensity shown is approximately 3×10^{15} W/cm^2. The solid line is a least-squares fit to the data points.

Relative signal levels were compared for the two gases at various pressures with use of both the 5- and 10-cm-focal-length lenses. When the 10-cm lens was used, the signal level in neon was about twice as strong as that in helium at the same pressure. For these conditions the highest signal levels were observed in neon at a pressure of 40 Torr. The conversion efficiency was estimated from the photomultiplier response to be of the order of 10^{-6} to 10^{-7} for an intensity at 266.1 nm of 3×10^{14} W/cm^2. Higher conversion was obtained when the 5-cm-focal-length lens was used with a pump intensity in the focus of 10^{15} W/cm^2. Under these conditions the fifth-harmonic signal in helium was greater than that in neon, and an estimated conversion level of 10^{-5} to 10^{-6} was observed at a helium pressure of 160 Torr. This conversion level is already greater than that reported for some third-order conversion processes.[3]

Conversion in neon appears to be limited by breakdown which was observed to occur at a pressure of 60 Torr for the weaker focusing arrangement (10-cm lens) and at lower pressures for the tighter focus. Abrupt cutoff of the 53.2 nm signal on the strongest laser pulses was taken as preliminary evidence of breakdown, with confirmation of the process being provided by the observation of Ne III emission lines at 37.93 and 48.95 nm. No signals at all were observed at 53.2 nm for either focusing arrangement for neon pressures greater than 80 Torr. Breakdown in He as evidenced by either of these two effects has not yet been seen at pressures up to 160 Torr.

The fifth-harmonic processes reported here have not yet been optimized for either gas. In neon the absorption length at 40 Torr is 0.7 mm, shorter than the depth of focus of the 10-cm lens and comparable to that of the 5-cm lens. Increased conversion may be possible by further reduction of the focal depth, although breakdown may become important in limiting conversion at the higher intensities. Still higher conversions should be possible in helium, since the negative dispersion allows conversion to be optimized in a tight focus region. Calculations show that optimum conversion should occur at a pressure of 640 Torr when the 5-cm lens is used. Such high pressures could not be reached with the existing pumping system. Increased conversion is thus expected in helium when the system is operated at the optimum pressure.

In summary, we have used fifth-harmonic generation in He and Ne to extend the range of coherent wavelengths to 53.2 nm. Conversion is in the range of 10^{-5} to 10^{-6} with further optimization believed to be possible. This work represents the first application of frequency upconversion to the extreme ultraviolet with use of optical nonlinarities of higher order than third, and indicates the feasibility of using such processes to extend the range of available coherent wavelengths ever closer to the soft x-ray range.

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[1]A. H. Kung, J. F. Young, G. C. Bjorklund, and S. E. Harris, Phys. Rev. Lett. 29, 985 (1972).

[2]R. T. Hodgson, P. P. Sorokin, and J. J. Wynne, Phys. Rev. Lett. 32, 343 (1974).

[3]A. H. Kung, Appl. Phys. Lett. 25, 653 (1974).

[4]M. H. R. Hutchinson, C. C. Ling, and D. J. Bradley, Opt. Commun. 18, 203 (1976).

[5]S. E. Harris, Phys. Rev. Lett. 31, 341 (1973).

[6]I. V. Tomov and M. C. Richardson, IEEE J. Quant. Electron. QE-12, 521 (1976).

[7]S. A. Akhmanov, V. A. Martynov, S. M. Saltiel, and V. G. Tunkin, Pis'ma Zh. Eksp. Teor. Fiz. 22, 143 (1975) [JETP Lett. 22, 65 (1975)].

[8]A. H. Kung, private communication. Although a preliminary observation of the process 5×532.0 nm $=106.4$ nm was noted in Ref. 5, no record of this observation has been published.

[9]Prelimimary results were presented by J. Reintjes, R. C. Eckardt, C. Y. She, N. E. Karangelen, and R. A. Andrews at the International Conference on the Physics of X-ray Spectra, National Bureau of Standards, Gaithersburg, Maryland, August 1976.

[10]G. C. Bjorklund, IEEE J. Quant. Electron QE-11, 287 (1975).

[11]J. Reintjes and R. C. Eckardt, to be published.

Production of Intense Proton Beams in Pinched-Electron-Beam Diodes*

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A polarity-reversed 10^{12}-W relativistic-electron-beam generator operating in the self-pinched mode is used to produce and propagate intense proton beams. Charge-neutralized beams of 30–50 ns duration consisting of over 4×10^{16} 0.5–0.8-MeV protons distributed over a 120-cm^2 cross-sectional area are routinely produced. The 150–200-kA average ion currents deduced from these measurements are in good agreement with theoretical calculations.

High-power relativistic-electron-beam generators have recently been used to create high-current proton beams in both reflex-triode[1,2] and magnetically-insulated-diode[3] modes of operation. These ion beams may have application to controlled fusion research in the areas of diffuse-plasma heating,[4] magnetic confinement (field reversing p layers),[5] and pellet fusion.[6] Here, we report on the efficient production of intense proton beams using the 10^{12}-W Gamble II pulser[7] driving a field-emission diode in the self-pinching mode.[8] Charge-neutralized beams of 0.5–0.8-MeV protons with average ion currents of up to 200 kA have been propagated 50 cm in the present experiments. The measured ion-beam characteristics are in good agreement with theoretical calculations.[9,10]

Experiments were performed on the Naval Research Laboratory Gamble II generator operated in positive polarity so that ions accelerated by the diode voltage could be extracted from the outer (negative) electrode at ground potential and drifted in an evacuated tube. Approximately 25–30 kJ were delivered to the nominal 1.5-Ω diode during the 50-ns electrical pulse with peak currents (ion + electron) of 500–600 kA flowing across it. *In situ* measurements of intense deuteron currents flowing in the diode with Gamble II operated in negative polarity have been reported elsewhere.[11] Lower-intensity ion beams from pinched-beam diodes have also been reported.[12]

A schematic diagram of the experimental setup