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The resonant crystal cavity makes X-ray lasers

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Abstract : The surface of single crystals of Ni and Cu, cut parallel to planes (111) is excited by intense X-rays, above the K-ionization potential, to produce an intense directed and monochromatic beam of $K\alpha_1$ photons. A nonlinear gain at higher tube currents and the surprise absence of $K\alpha_2$ line characterize the emission of the directed $K\alpha_1$ beam

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The K-shell electrons of single crystals of Cu and Ni, located at the surface layer of lattice planes parallel to face (111) are subject to resonance ionization. This produces the initial K-hole states, at a fast rate. A well defined collimated beam of X-rays from a Cu/W target X-ray tube, strikes the crystal face at Bragg angle for $K\alpha_1$ of Cu and Ni, in different sets of experiments. The reorganization of the K-hole states produces $K\alpha_1$ photons associated with an oscillation frequency between K- and L_3-hole states. The sets of parallel lattice planes, at the crystal face (111), separated by the angstrom order d 111 spacing, plays more or less the same role of a Fabry-Perot interferometer in optics. Like basic optical laser resonant cavity, the parallel sets of crystal lattice planes, play a vital role of X-ray laser resonant cavity of extremely high resolving power. In laser optics, one set of such parallel mirrors, act like a Fabry-Perot interferometer. In X-ray optics, thousand to ten thousand such parallel sets of lattice planes at the surface level act simultaneously as Bragg mirrors. This plays the vital role, to sustain the Bragg resonance standing mode and store $K\alpha_1$ photons in a resonant crystal cavity. Standing modes of $K\alpha_1$ photons lie, sandwiched between the bragg reflecting planes, parallel to the lattice planes (111). P P Ewald [1] in his dynamical theory of X-ray diffraction, includes the process of anomalous Borrmann transmission of characteristic X-rays by an apparent energy flow along the Bragg reflecting planes. A detail discussion of the Bragg standing modes, as in a Fabry-Perot interferometer, associated with the Bragg-Borrmann modes along the lattice planes as the forward X-ray diffraction, will appear elsewhere. The discussion will include the fundamental distribution character of small mosaic crystallites at the surface layer of single crystals of Ni and Cu.

Three fundamental features of a laser source are : brightness, nondivergence and monochromaticity. This is an order-disorder phase transition. When the source atoms are independent oscillators, with no surrounding sink atoms, there is no stable, collective source - sink coupling, to store lasing photons. The situation is altogether different, in the case of a Ni-111 face single crystal, or Cu-111 face single crystal subject to Bragg resonance states. The resonance pumping device produces K-hole states at the crystal surface-layer with a highly symmetric distribution of Ni-atoms, surrounding any Ni-K hole state and Cu-atoms, surrounding any Cu-K hole state. The direction of emission of a photon from an independent oscillator is isotropic and unpredictable. The direction of emission of $K\alpha_1$ photons from excited K-hole states of atoms, located at the crystal surface layer, is highly predictable due to the creation of a collective Bragg-resonance state of $K\alpha_1$. The emission is no longer isotropic. The direction of $K\alpha_1$ emission is accurately defined by the Bragg angle of Ni-$K\alpha_1$ for 111-planes. At any orientation of Ni-111 planes with respect to the pumping beam, elongated curved lines of $K\alpha$, $K\beta$ appear quickly on an X-ray film (see Figure 1). As the crystal face-111 is tuned for Ni-$K\alpha_1$ the long curve lines shrink dramatically to a highly reduced size and is of unusual high intensity. The beam demonstrates a high nonlinear gain and gain coefficients increase with an increased rate of pumping (Figure 2). Surprisingly, the weaker Ni-$K\alpha_2$ line is suppressed on tuning of Ni-$K\alpha_1$ line, and Cu-$K\alpha_2$ is suppressed on tuning Cu-$K\alpha_1$ line.

In existing lasers, a population inversion is a prerequisite, which is absent or not essential in a crystal cavity X-ray laser, since $K\alpha_1$ can never ionize K-electrons. To maintain the steady *cw* photon energy flow, an equal number of $K\alpha_1$ photons had to be added to the standing mode at the same rate, from excited K-hole state atoms. The adherence to Einstein's oft-quoted high value of A/B ratio proportional to ν^3, which is unfavourable to high X-ray lasing frequencies and also the stumbling block of the population inversion, for short life-time X-ray states, has been circumvented by adhering to the novel outcome of quantum statistics of Bose for identical photons, the lasing photons of $K\alpha_1$. If there are n identical Ni-$K\alpha_1$ laser photons (bosons), in a standing Bragg resonance mode, at the crystal-surface-layer cavity, defined by energy, momentum and polarization, the probability that an excited atom in a K-hole state will emit a Ni-$K\alpha_1$ photon into the same Bragg-resonance state, is increased by the famous bose-factor [2] $(n + 1)$, if there are already n Ni-$K\alpha_1$ photons in that state. The same argument applies to Cu$K\alpha_1$ photons, as well. The key point is to find a novel experimental device [3] to exploit the most attractive feature of connecting a high value n of laser photons, in Bragg-resonance standing mode, with an enhanced emission rate of laser photons from K-hole states. This is the crucial point of the experimental setup, which demonstrated the X-ray laser in Ni [4] and Cu [5] crystals. This has also been verified for Fe$K\alpha_1$ in Fel 110 crystal, to be communicated.

At the Bragg-resonance standing mode of Ni-$K\alpha_1$, the lasing frequency is localized at the surface layer of the active laser medium of the Ni-111 lasing crystal. Such states of an

(a) (b)

Figure 1. Enlarged prints of (a) Ni$K\alpha_1$ and (b) Ni$K\beta_1$ lines when Ni (111) face is set at arbitrary angles. $K\alpha_1$ is weaker on the left at larger angles and $K\beta_1$ is weaker on the right at smaller angles.

assembly of identical photons (bosons) are identified with the state of nickel atom oscillators, constituting the Ni-111 lattice planes as a parallel set of reflecting mirrors. The dynamical system consists of atom oscillators located at the periodic lattice planes at the surface layer.

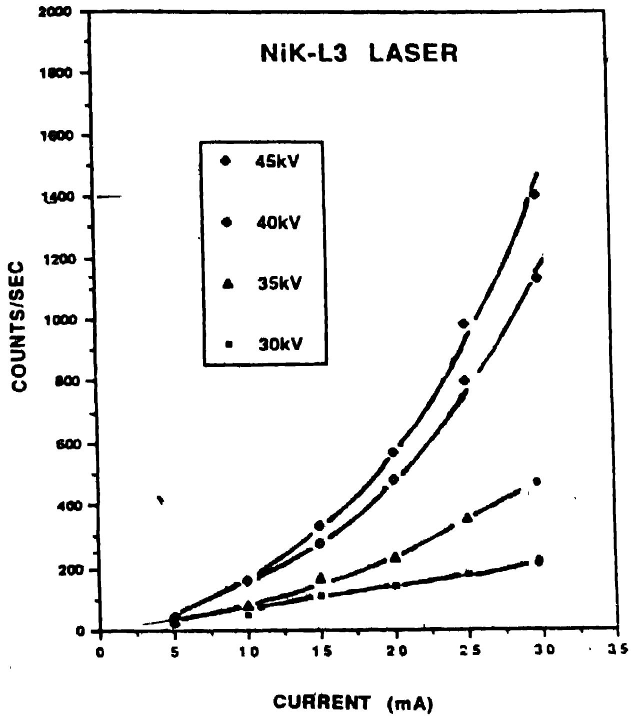

Figure 2. A non-linear gain in count rate of Ni $K\alpha_1$ line At constant operating potential of 45 KV, the tube current is increased by a factor 3, from 10 mA to 30 mA. The count number of Ni$K\alpha_1$ increases by a factor 9. At 40 KV, the count number increases by a factor 8.

The lasing quanta are sandwiched between the parallel planes subject to the multiple reflection at $\lambda = 2d_{111}\sin\theta$. The maintenance of the macroscopic oscillation at the Bragg angle, involves the scattering form factor of Ni crystal atoms as a whole, contributing to the lattice form factor. Such oscillations involving the Ni atom scattering form factor are simple harmonic oscillations of the atom as a whole. This has nothing to do with the life-time of the excited K-hole state emitting Ni-$K\alpha_1$ photons to feed the standing Bragg-resonance mode. The maintenance of the standing Bragg-resonance mode of Ni-$K\alpha_1$ laser photons and their localization at the antinodal planes sustain the macroscopic oscillation in a typical unobservable domain.

In Figure 1, a number of elongated Ni-$K\alpha_1$ lines appear in a few seconds for any arbitrary position of the Ni-111 face. The line shrinks in size and focuses a sharp and intense $K\alpha_1$ only when Ni-111 face makes the correct resonance tuning angle for the lasing frequency of $K\alpha_1$. The experimental set-up is very simple and unique in character, to obtain the internal Bragg-resonance for the lasing frequency $K\alpha_1$, when a little higher frequency at K-absorption edge in the same pumping beam, ionizes K-electrons at the same crystal face, which is a prerequisite for $K\alpha_1$ emission. The observed $K\alpha_1$ beams from Ni-111 [4] and Cu-111 [5] are directed, monochromatic and bright. This is attributable to the enhanced transition probability jump of electrons from $2p_{3/2}$ to $1s_{1/2}$, due to the bose-factor $n + 1$ [2], when there are already a large number of n identical $K\alpha_1$ lasing photons, accumulated at the crystal surface, maintaining a sustained standing internal Bragg-resonance mode. A line focus Cu X-ray tube is coated with W-vapor to emit Cu$K\alpha$, $K\beta$ and W$L\alpha$, $L\beta$, plus the bremsstrahlung of continuous X-rays. The experimental set-up is the same as in Cu$K\alpha_1$ X-ray laser by the author [5]. The pumping frequencies of Cu$K\beta$ and W $L\alpha$ from Cu-W X-ray tube are ideally suitable to produce K-hole states of Ni atoms, at the surface layer, by resonance absorption of K-electrons of Ni. The signal to noise ratio of Ni$K\alpha_1$ laser is unusually high. At 45 KV, 30 mA, the count rate for the Ni$K\alpha_1$ beam through a 0.3 mm slit lie in the range of 4 to 5 hundred thousand counts per second, although there is no Ni atoms in binary Cu-W alloy target X-ray tube [4].

The characteristic feature of Bose's method of counting of states, that a permutation of n identical photons does not give a new state, led Bose to derive Planck's radiation formula. The probability of a transition in which a photon is emitted into a particular final state, is proportional to the number of photons that already exist in that state, plus one [2]. The unpredictable direction of emission of $K\alpha_1$ photons becomes highly predictable due to the crystal symmetry of Bragg-resonance standing mode in our experimental set up. The standing Bragg mode of $K\alpha_1$ of a large value of n, guides the direction of emission from the surrounding K-hole states enhancing the concentration of $K\alpha_1$, to increase the number density of the standing Bragg mode of $K\alpha_1$ laser photons. At the steady state of cw $K\alpha_1$ laser, the leakage rate of $K\alpha_1$ from crystal 111 face must equal the enhancement rate of emission of $K\alpha_1$ from K-hole states, by $n + 1$ Bose-factor. It is interesting to note that R P Feynman remarked [6] that the enhanced transition probability is a key feature of Bose statistics, which makes the laser work.

Acknowledgment

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