

# Amplification of Gamma Radiation from X-Ray Excited Nuclear States \*

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## Abstract

In this paper we discuss the possibility of the excitation of nuclear electromagnetic transitions by the absorption of X-ray quanta produced in appropriate inner-shell atomic transitions, and the relevance of this process for the amplification of the gamma radiation from the excited nuclear states. It is concluded that the X-ray pumping technique might provide a useful approach for the development of a gamma ray laser.

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# 1 Introduction

The observed trend [1, 2] toward short-wavelength coherent sources of electromagnetic radiation from stimulated atomic transitions is presently confronted with difficulties inherent to the shorter atomic life-times of the excited states, smaller cross sections for the stimulated emission, and the lack of resonators appropriate at these frequencies. On the other hand, because of their small dimensions, the atomic *nuclei* have comparatively long-lived excited states, while the Breit-Wigner cross section for the interaction with the electromagnetic radiation is essentially the same for atoms and nuclei at a given wavelength. Considerable effort has been therefore directed toward the development of stimulated emission devices which would use the Mössbauer effect in nuclear transitions for the generation of electromagnetic radiation in the 1 ... 100 keV range of photon energy. The difficulties in the development of the coherent gamma ray sources and the perceived reward of success have been recently reviewed by Baldwin, Solem and Gol'danskii [2] with the general conclusion that while no scientific principle has yet been shown to prohibit gamma ray lasers, further progress in this direction is dependent upon research and technological advances in many areas.

Most of the earlier proposals for a gamma ray laser [3 – 12] involved neutrons, either for *in situ* pumping [5, 7 – 9] or for the production of long-lived nuclear isomers [10, 6, 11, 12]. However, the relatively low intensities of the available fluxes of neutrons and the difficulties inherent in the narrowing of the effective widths in the case of the isomers [13 – 17] create major obstacles along these lines. In this context attention was given to the excitation of nuclear electromagnetic transitions, and among the processes considered are the use of bremsstrahlung radiation [18], characteristic X radiation [19, 20], resonant Mössbauer radiation [9, 21, 22], optical laser radiation [23 – 31], and synchrotron radiation [32, 33].

In this paper we shall discuss the possibility of the excitation of nuclear electromagnetic transitions by the absorption of X-ray quanta produced in the inner-shell atomic transitions, and the relevance of this process for the amplification of the gamma radiation from the excited nuclear states. It is shown that a significant level of nuclear excitation can be obtained by an appropriate choice of the atomic X-ray transition. The X-ray power required for the pumping of a gamma ray laser is compared with the parameters of existing X-ray flash devices. The

nuclides whose level structure appears to be favorable for the gamma-ray amplification are tabulated together with the X-ray pumping transitions. It is concluded that the X-ray flash pumping technique might provide a useful approach for the development of a gamma ray laser, and motivated further investigation of the process of excitation of nuclear electromagnetic transitions.

## 2 Basic concepts

According to the general quantum mechanical description, the atomic nucleus can exist in a series of stationary states characterized by their energy, spin and parity. If the nucleus is in one of its excited states it generally undergoes a transition to a lower state which is accompanied by a corresponding energy transfer to the radiation field, atomic electrons, or other particles. When the transition energy is converted into a gamma-ray photon, a small amount of the total energy appears in the final state as kinetic energy of the whole nucleus. Since this recoil energy is generally large compared to the nuclear level width, the gamma-ray emission and absorption lines of the free nuclei are shifted and broadened, and the cross section for the resonant interaction is correspondingly reduced. This difficulty can be avoided by making use of the Mössbauer effect [34] for nuclei bound in a crystalline lattice for transition energies which do not exceed 100 keV

The dominant multipolarity of low gamma-ray transitions is M1, although E1 and E2 transitions also occur, and the typical life-time of these states is in the nanosecond range. The conventional method for the excitation of low-lying nuclear states is through beta decay or orbital electron capture from the contiguous nuclides. However, since the life-times of the decaying nuclei are very much longer than the life-times of the excited states, the concentration of the latter is extremely small. Another excitation technique would be the irradiation with a flux of neutrons, but again impractically large neutron fluxes are required to obtain significant population of the nanosecond excited states.

On the other hand, the excitation of the nuclear states with electromagnetic radiation of appropriate energy appears to produce a significant level of population in the upper state. The electromagnetic radiation can be produced in X-ray transitions between the states of

the atomic electron shell, and since the X-ray line spectrum involves energies up to about 100 keV for the heavy elements it seems appropriate for the excitation of the Mössbauer transitions. The width of the X-ray states are 0.1 . . . 1 eV, and therefore the very short-lived atomic states are not suitable for direct amplification of the radiation.

### 3 Amplification of gamma radiation

Provided that a reasonable matching between the nuclear and the atomic transition energies could be obtained, an X-ray flash might be used to raise the nuclei from the ground state,  $a$ , to an upper state,  $b$ , in a process analogous to the optical pumping of the atomic transitions (Fig. 1). Now the process of transition to a lower state,  $c$ , through the emission of a gamma ray photon would be greatly enhanced in the presence of a large population in the upper state,  $b$ . As pointed out by several authors [2] the development of a gamma ray pulse would require the population inversion between the states  $b$  and  $c$ , and also the resonant gain must exceed the non-resonant losses.

Since it is generally accepted that the gamma ray laser would be a single pass device [2], the number of photons in the cascade induced by the spontaneously emitted gamma ray quanta must be of the order of the total number of nuclei in the upper state  $b$ ,

$$e^{\sigma_{bc}n_bL} \leq n_bLa^2, \tag{1}$$

where  $\sigma_{bc}$  is the cross section for the transition  $b \rightarrow c$ ,  $n_b$  is the concentration of nuclei in the state  $b$ ,  $L$  is the length and  $a$  is the transverse dimension of the nuclear sample. Moreover, in order to have negligible diffraction losses, it is necessary [2] that

$$L\lambda \leq \frac{1}{3}a^2, \tag{2}$$

where  $\lambda$  is the gamma ray wavelength.

The conditions, Eqs. (1) and (2), define the upper state concentration  $n_b$  and the area,  $a^2$ , as functions of the length  $L$  of the nuclear sample. Increasing the length  $L$  results in a larger transverse dimension  $a$ , but generally in a lower threshold *density* of the nuclei in the upper state. However, the total number  $N_b = n_bLa^2$  of nuclei in the upper state increases

with  $L$ , provided that  $N_b\sigma_{bc} > L\lambda$ . On the other hand, increasing the wavelength  $\lambda$  for fixed dimensions  $L, a$  results in lower threshold values for the concentration  $n_b$  and the total number of excited nuclei  $N_b$ .

## 4 The X-ray pumping of nuclear electromagnetic transitions

The building up of a large concentration of nuclei in the excited state  $b$  is facilitated by the fact that the atomic electrons screen the nucleus from interactions which otherwise would lead to the broadening of lines. In fact, although the concentration of nuclei in the upper state turns out to be large compared with typical inversion densities at optical frequencies, it represents a small fraction of the ground state concentration. The probability,  $w$ , for the excitation of a nucleus by an X-ray pulse on  $\mathcal{N}_x$  quanta per  $\text{cm}^2$  having a spectral width  $\Gamma_x$  around the nuclear transition energy is

$$w = \sigma_{ab}\mathcal{N}_x\frac{\Gamma_b}{\Gamma_x}, \quad (3)$$

where  $\sigma_{ab}$  represents the cross section for resonant nuclear excitation and  $\Gamma_b$  is the width of the upper state  $b$ . In general, the X-ray lines are broad compared to the widths of the nuclear levels, and only a small fraction  $\Gamma_b/\Gamma_x$  of the X-ray quanta is effective in the excitation process. On the other hand, the relatively large X-ray width facilitates the matching of the resonance condition between the X and the gamma transitions.

Since it is the *density* of the X-ray photons which determines the pumping rate, Eq. (3), it seems that a suitable X-ray source would be a filamentary plasma in the immediate proximity of the nuclear sample, as represented in Fig. 2. Among the devices which produce such flashes are the vacuum sparks, the exploding wires, the plasma focus, and the laser focus [36].

## 5 Case study and tabulation

The minimum fluence  $\mathcal{E}$  of the X-ray energy that must be injected into the sample is proportional to the nuclear transition energy  $E_{ab}$ , to the population of the upper state,  $N_b$ , and to the ratio  $\Gamma_x/\Gamma_b$  of the atomic and nuclear widths:

$$\mathcal{E} = E_{ab}N_b \frac{\Gamma_x}{\Gamma_b}. \quad (4)$$

The quantity  $\mathcal{E}$  is represented in Fig. 3 for values of the parameters likely to be encountered for gamma ray devices. The total energy in the X-ray flash must probably be at least one order of magnitude higher than that represented in Fig. 3 because of solid angle problems. For comparison, the presently available X-ray devices provide flashes with a duration as short as 10 ps and X-ray powers in excess of  $10^{10}$  watts [37], thus being able to provide about  $10^{-1}$  Joules in periods of time which are short relative to the nuclear life-times.

Assuming that the cross section for stimulated emission of the gamma rays is  $10^{-18}$  cm<sup>2</sup>, the length  $L$  of the nuclear sample of 1 cm, then in order to obtain the significant gain of 1/cm it is necessary a concentration of  $n_b = 10^{18}$  nuclei/cm<sup>3</sup>. Since according to Eq. (2),  $a = 10^{-4}$  cm, the number of excited nuclei is  $N_b = 3 \times 10^{10}$ . Therefore, the energy stored in the nuclear excitation is about  $6 \times 10^{-6}$  Joules, and the energy of the gamma ray pulse would be of the order of  $10^{-6}$  Joules. The intensity of the gamma ray pulse at 10 cm from the source would be of the order of  $10^9$  watts/cm<sup>2</sup>, or about  $10^{14}$  Ci/cm<sup>2</sup>.

Further tabulated are those nuclides which appear to be of interest for the electromagnetic excitation with atomic X rays.

## 6 Conclusions

We have shown in this paper that the X-ray excitation of nuclear electromagnetic transitions might provide a technique for the pumping of a gamma ray laser. The performances of existing pulsed X-ray sources are one or two orders of magnitude below the threshold for the gamma amplification. Additional investigation is needed to ensure that the nuclear sample is stable enough against the high intensity X-ray pulse. This is consistent with the

general conclusion that further progress in this direction is dependent upon research and technological advances in many areas.

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Table 1: Nuclear transitions which can be excited with atomic X-rays (Compiled from C. M. Lederer and V. S. Shirley, *Table of Isotopes*, 7<sup>th</sup> edition, J. Wiley & Sons, 1978)

Nuclear transition to the upper state			Atomic X-ray transition		Stimulated transition
Element	Transition energy, keV	Ground state life-time	Element	Transition and energy, keV	Energy, keV
<sup>66</sup> Ga	66.32	9.4 h	<sup>79</sup> Au	66.369, <i>KL<sub>I</sub></i>	22.43
<sup>100</sup> Rh	74.8	20.8 h	<sup>83</sup> Bi	74.815, <i>KL<sub>II</sub></i>	42.1
<sup>140</sup> La	43.81	40.3 h	<sup>61</sup> Pm	43.821, <i>KM<sub>II</sub></i>	13.85
<sup>143</sup> Ce	42.3	33.0 h	<sup>64</sup> Gd	42.308, <i>KL<sub>II</sub></i>	23.4
<sup>144</sup> Pm	66.63	349.1 d	<sup>74</sup> W	66.706, <i>KM<sub>I</sub></i>	5.89
<sup>151</sup> Sm	69.69	87.9 y	<sup>75</sup> Re	69.726, <i>KM<sub>IV</sub></i>	64.87
<sup>161</sup> Dy	43.84	stable	<sup>61</sup> Pm	43.821, <i>KM<sub>IV</sub></i>	18.19
<sup>162</sup> Tm	66.9	21.7 m	<sup>79</sup> Au	66.989, <i>KL<sub>II</sub></i>	22.2
<sup>165</sup> Er	62.68	10.3 h	<sup>77</sup> Ir	62.692, <i>KL<sub>I</sub></i>	15.52
<sup>167</sup> Yb	33.91	17.5 m	<sup>58</sup> Ce	33.895, <i>KL<sub>I</sub></i>	4.25
<sup>175</sup> Ta	51.38	10.5 h	<sup>70</sup> Yb	51.354, <i>KL<sub>II</sub></i>	14.98
<sup>191</sup> Pt	30.36	2.9 d	<sup>55</sup> Cs	30.272, <i>KL<sub>I</sub></i>	20.80
<sup>201</sup> Hg	32.19	stable	<sup>56</sup> Ba	32.194, <i>KL<sub>II</sub></i>	30.61
<sup>223</sup> Ra	61.52	11.4 d	<sup>76</sup> Os	61.486, <i>KL<sub>II</sub></i>	31.61
<sup>237</sup> U	56.3	6.7 d	<sup>73</sup> Ta	56.277, <i>KL<sub>II</sub></i>	44.9
<sup>245</sup> Am	28.0	2.0 h	<sup>53</sup> I	27.982, <i>KL<sub>I</sub></i>	8.8
<sup>246</sup> Am	43.81	25.0 m	<sup>65</sup> Tb	43.742, <i>KL<sub>II</sub></i>	27.6

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