interpretation can also be made equally accurately. In general it would seem simpler to try to find regions where the effects are larger and thus where small ambiguities in the theory would be less important.

Finally, it should be emphasized that while kinematic arguments of the type given here can be very useful and suggestive they are not definitive. It is fairly clear that Δm^2 and k/E_0 large in some sense are *necessary* to see interesting off-shell effects, but it is not clear that large values are *sufficient*. One must eventually do model calculations with models which allow variation of off-shell information while holding on-shell information constant.

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Enhancement of γ-Ray Absorption in the Radiation Field of a High-Power Laser

C. B. Collins
Center for Quantum Electronics, The University of Texas at Dallas, Richardson, Texas 75080

and

S. Olariu, M. Petrascu, and Iovitzu Popescu
Central Institute of Physics, Bucharest/Magurele, Rumania

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This paper reports an analytic estimate of the cross section for the absorption of a γ-ray photon when the nuclear recoil is compensated by the simultaneous absorption of an optical photon from the radiation field of a high-power laser. A multiphonon transition model is developed and cross sections of the order of 1 fm^2 are obtained when nearly resonant intermediate states of nuclear excitation are assumed to lie within a few tens of eV of the transition energy.

In atomic physics the resonant absorption and fluorescence of electromagnetic radiation are important and easily observed phenomena which provide detailed information about the structure of absorbing systems. However, attempts to extend the specific methods to nuclear radiations have usually met with difficulty because the energies lost in the recoils of the absorbers are generally greater than the bandwidths of the absorption resonances. Techniques, such as Mössbauer spectroscopy, for overcoming this problem have been limited in their successes to a few systems and those for energies up to a few hundred keV.[1]

For the absorption of a γ ray of an energy of the order of 1 MeV, the recoil of a nucleus typically corresponds to the energy of an optical photon. In 1975, Petrascu proposed[2] that the energy lost in the recoil of the nuclei both in a source and in an absorber be compensated by the simultaneous absorption of a second photon of energy equal to the total lost. It is the purpose of this paper to report analytic considerations of the cross sections for the absorption of γ radiation when the recoil is compensated by the simultaneous absorption of optical photons from the radiation field supplied by a high-power laser.

Essentially, the transition probability for a two-photon process involving photons of differing energy can be treated in the same manner as in the better-known computations for the absorption of two optical photons.[3-6] However, the problem of the gauge of the electromagnetic field is extremely critical in this case[7,8] because of the large difference in the energies of the photons. Although it has been shown[8] that the transition probabilities are gauge invariant when summed over all intermediate states, in the case of resonant two-photon absorption the leading terms in the sums for the two commonly used gauges, the dipole interaction, $\vec{E}\cdot\vec{r}$, and the Coulomb-gauge interaction, $\vec{A}\cdot\vec{p}$, differ by five orders of magnitude. Since only the leading term will be retained in the work reported here, differences of 10^{10} in the calculated transition probabilities result from a change of gauge. It has been recently shown that the dipole-interaction term, $\vec{E}\cdot\vec{r}$, leads to the most rapid convergence,[9] and that representation, which also gives the smaller transition probability, has been used in this work.

If we assume the Hamiltonian of the perturbation to be of the form $-\vec{E}\cdot\vec{r}$, conventional time-dependent, second-order perturbation theory yields for the cross section for the absorption of γ photons in the field of the optical photons

$$\sigma = 2\pi^3 K\left(\frac{e^2}{\hbar c}\right)^2 R^4 \frac{\omega_1\omega_2}{\omega_{nn_0}{}^2}\,|Q_{nn_0}|^2 \frac{N_2}{\mathrm{Max}(\Gamma_1,\Gamma_2)}, \qquad (1)$$

where ω_1 and ω_2 are the frequencies of the γ and optical photons, respectively, ω_{nn_0} is the transition frequency, N_2 is the optical photon flux, $\mathrm{Max}(\Gamma_1,\Gamma_2)$ is the larger of the frequency bandwidths of the two photons, R is the nuclear radius $(r_0 A^{1/3})$, K is the integral over line-shape functions and is of the order of unity, and Q_{nn_0} is a dimensionless matrix element given by

$$Q_{nn_0} = \frac{\omega_{nn_0}}{R^2}\sum_{n'}\left(\frac{(\vec{e}_1\circ\vec{r}_{nn'})(\vec{e}_2\cdot\vec{r}_{n'n_0})}{\omega_{n'n_0}-\omega_2} + \frac{(\vec{e}_2\circ\vec{r}_{nn'})(\vec{e}_1\circ\vec{r}_{n'n_0})}{\omega_{n'n_0}-\omega_1}\right), \qquad (2)$$

where $\vec{e}_1$ and $\vec{e}_2$ are the dimensionless polarization vectors of the electromagnetic radiations and the r_{ij} are matrix elements of the radius vector between initial, n_0, intermediate, n', and final, n, states. When n' is energetically near to either the initial or final state and when $\omega_1 \gg \omega_2$, the lead term in the sum is $Q \sim \omega_{nn_0}/\Delta\omega$ where $\Delta\omega$ is the smaller of $\omega_{n'n_0}-\omega_2$ and $\omega_{n'n_0}-\omega_1$, the frequency corresponding to the energy defect by which the γ photon misses being resonant with a transition from either the initial or final state to the intermediate state. Substituting this value into (1) and converting the units gives

$$\sigma = 4.3\times 10^{-36}\frac{E_\gamma \Phi_2 A^{4/3}}{(\Delta E)^2\,\mathrm{Max}(\Gamma_1,\Gamma_2)}, \qquad (3)$$

where σ is in cm^2, E_γ is the γ energy in MeV, ΔE is in keV, Φ_2 is the optical flux in $\mathrm{W/cm}^2$, and the Γ's are the spectral widths in sec^{-1}.

Since the matrix elements introduced in Eq. (2) were limited to electric dipole transitions, it is necessary that the intermediate state differ from the initial and final states by $\Delta J = \pm 1$ or 0 and the parity change be given by $\Delta\Pi = \pm 1$. These are the same conditions necessary for the existence of $E1$ transitions between the intermediate and the initial and final states. Further, since $\omega_1 \gg \omega_2$ the maximum cross section will be achieved when the intermediate state is nearly degenerate with either the initial or final state. However, the shell model for single-particle states of spherical nuclei suggests that such changes of parity are associated only with changes of principal quantum number and thus represent transition energies of the order of 1 MeV.[10] Consequently, the odd deformed nuclei appear to offer the best possibilities for the development of absorption cross sections of detectable magnitude. In the mass regions for which large eccentricities are observed, Nilsson diagrams[11] show many occurrences of degeneracy between single-particle states satisfying the selection rules for dipole transitions. Almost all cases also show another state separated by energies of the order of 0.1–20 MeV which could serve as either the initial or final state of a multiphoton transition.

In addition, however, other factors must be favorable, since the widths Γ appearing in the expression for the cross section are not free parameters. If it is assumed that the γ photons from the source are derived from the lowest-order allowed transition between the initial and final states of nuclei in a similar sample, the corresponding level width, Γ_1, may be obtained from the Weisskopf estimates.[12] For transition energies in the range of interest it is generally larger than a typical laser linewidth. Since the bandwidth of the laser radiation needs only to be less than the level width, Γ_1, in order to maximize the cross section of the induced absorption in Eq. (3), it can be assumed that $\mathrm{Max}(\Gamma_1, \Gamma_2) = \Gamma_1$.

Table I summarizes typical values of cross section which might be achieved in an optical field of 10^{10} W/cm^2 for the various types of spontaneous transitions determining the level width, Γ_1, of the final state[13] for several model nuclei. It can be seen that the cross section for the absorption of γ radiation induced by an optical field of reasonable magnitude could be as large as 1 fm^2 for a favorable case.

In a hypothetical experiment if a detection geometry were assumed in which the laser illumination was nearly collinear with the direction to the γ-ray source and if the absorber were enclosed by a resonator for the optical frequency providing a mean photon lifetime of 1 μsec, then each optical photon would illuminate nuclei along a path having the average folded length of 3×10^4 cm. If the area of the beam waist were a, and if it lay in a sample containing 10^{22} cm^{-3} active nuclei, then $3\times10^{26}\sigma a N_1$ absorption events per second would occur for a γ-ray flux of N_1 at a cost in laser power of $\Phi_2/(3\times10^{26}\sigma N_1)$, an expression independent of laser power. For an induced cross section of 1 fm^2 at 10^{10} W/cm^2 this would become $3.33\times10^9/N_1$ joules/count. Thus, for a γ flux of 3.33×10^9 cm^{-2} sec^{-1} there would be a cost of 1 J per event which would be possible with existing lasers with the bandwidth requirements already established. For example, the minimum practical counting rate with reasonable resolution is of the order[14] of 0.02 sec^{-1} so that a laser of about 20-mW average power would be sufficient.

TABLE I. Summary of cross sections calculated for the absorption of γ radiation induced by the fields associated with an optical power density of 10^{10} W/cm^2 by model nuclei of mass $A\sim200$ having nearly degenerate excited states separated in energy from each other by ΔE and from the ground state by 0.1 MeV. The widths Γ correspond to the lifetimes of the final state of the two-photon absorptions as determined by single-photon spontaneous emissions of the multipolarity indicated.

Multipole type	Γ (Hz)	ΔE (eV)	σ (cm^{-2})
$E1$	1.1×10^{12}	21	10^{-32}
$M1$	1.0×10^{10}	22	10^{-30}
$E2$	2.8×10^{5}	42	10^{-26}

Although a tunable laser would be the natural choice if the wavelength were appropriate, it is more reasonable to expect that the precise adjustment to the transition energy of the sum of the energies of the γ and of the optical photon less the recoil would be generally made by Doppler shifting the source of γ radiation. Since the main part of the recoil would be compensated by the absorption of the optical photon, the requirements on velocity would be modest. From expressions for the conservation of energy and momentum and the magnitude of the Doppler shift, the energy of the optical photon, E_2, required for resonance is found to be

$$E_2 = E^2/Mc^2 + Ev/c , \tag{4}$$

where E is the transition energy in the nucleus, and v can be positive or negative. Since the optical photon energy E_2 is assumed fixed, Eq. (4) implicitly defines the transition energy to the recoil-compensated final state as a function of relative velocity. For nuclei having masses consistent with the assumption of deformed spheres, the transition energy compensated at rest varies from about 150 keV in the field of a CO_2 laser to 1 MeV for an ArF laser.

A cursory survey of tabulated data[15] has indicated $_{64}\mathrm{Gd}^{155}$ to be the candidate having the most nearly degenerate levels of the proper spins and parities, resolved by conventional methods. The two excited states of opposite parity near 488 keV are reported to be separated by only $\Delta E = 0.05$ keV and their respective spins and parities satisfy the selection rules summarized above. Unfortunately, the single-photon transition connecting initial and final states is of the $M1$ type and use of the Weisskopf estimate for the level width gives $\Gamma_1 = 0.2 \times 10^{12}\ \mathrm{sec}^{-1}$. The resulting absorption cross section of $6\times10^{-33}\ \mathrm{cm}^2$ given by Eq. (3) at $10^{10}\ \mathrm{W/cm}^2$ is a factor of 1.7×10^6 below the illustrative case discussed above. The γ source might be assumed a factor of 30 larger at maximum so that a laser of about 1 kW would be required to induce a measurable level of absorption. Equation (4) is satisfied with $v=0$ for a photon energy corresponding to a laser wavelength of 750 nm which places the experimental realization of this specific example beyond the current limits of technology. Other comparable examples exist in the literature for which transition energies are lower, thus requiring levels of power which might be obtained from CO_2 lasers of realistic size, but those absorbers are not stable and densities of $10^{22}\ \mathrm{cm}^{-3}$ are not realistic.

It can be reasonably concluded that recoil compensation through the absorption of an optical photon from a laser field, in principle, represents a means for implementing γ-ray absorption and fluorescence spectroscopy at energies in the 0.1–1.0-MeV range. The fine tuning of the absorption resonance with the conventional techniques of Doppler shifting offers a way of obtaining much higher resolution at these energies than has been previously possible. With not unreasonable assumptions concerning level widths and the existence of unresolved degeneracies of some nuclear levels, appreciable cross sections can be realized. While the successful implementation of this technique of recoil compensation would provide for the measurement of transition energies to those nuclear levels with very high precision, in the absence of these techniques, it is difficult to identify the most promising absorbers, *a priori*. More refined calculations over greater numbers of intermediate states and transition moments are needed to determine whether the values presented here underestimate potential cross sections to an extent that more known transitions offer the potential for recoil compensation or whether an *ad hoc* search for accidental degeneracies must suffice. In any case, it appears that the recoil resulting from the absorption of γ rays will be effectively compensated in the radiation field from a laser at least for selected transitions.

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