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ACCELERATION OF MOVING ATOMS IN X-RAY BEAMS

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ՇԱՐԺՎՈՂ ԱՏՈՄՆԵՐԻ ԱՐԱԳԱՑՈՒՄԸ ՌԵՆՏԳԵՆՅԱՆ ՃԱՌԱԳԱՅԹՄԱՆ ՓՆՋԵՐՈՒՄ

Քննարկված է ատոմների սկզբնական արագության ազդեցությունը ֆոտոէֆեկտի ընթացքում նրանց ձեռք բերած արագացման վրա: Ցույց է տրված, որ սկզբնական արագության հաշվի առնելը բերում է ատոմի էներգիայի սահմանափակմանը, մինչև որը կարելի է արագացնել ռենտգենյան ճառագայթման փնջում շարժվող ատոմները իրար հետևող ֆոտոէֆեկտի ակտերի ժամանակ: Գնահատված են արագացման տեմպը, առավելագույն ձեռք բերվող էներգիան, ինչպես նաև ռենտգենյան փնջերի անհրաժեշտ հզորության խտությունները ֆոտոնի էներգիայի տարբեր արժեքների համար արգոնի ատոմների արագացման դեպքում:

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УСКОРЕНИЕ ДВИЖУЩИХСЯ АТОМОВ В ПОТОКЕ РЕНТГЕНОВСКОГО ИЗЛУЧЕНИЯ

Рассмотрено влияние начальной скорости атома на приобретенное им ускорение в процессе фотоэффекта. Показано, что учет начальной скорости приводит к ограничению энергии, до которой можно ускорять атомы в последующих друг за другом актах фотоэффекта при их движении в потоке рентгеновского излучения. Оценены величины темпов ускорения, приобретенные предельные энергии и необходимые плотности потока излучения для различных энергий фотонов в случае ускорения атомов аргона.

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ACCELERATION OF MOVING ATOMS IN X-RAY BEAMS

The influence of the initial velocity of atoms on their acceleration due to photoeffect is considered. It is shown that if one takes into account the initial velocity of atoms the energy up to which one can accelerate them in a series of subsequent photoeffect processes during their motion in a X-ray beam is limited. The acceleration rate, the maximal achievable energy as well as the necessary power density of various energy X-ray photon beams are estimated in the case of acceleration of argon atoms.

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Recently the possibility of acceleration of particles (atoms) with the help of X-ray beams has been considered in the works [1,2]. Despite to the method of [1] , requiring still inavailable monochromatic high intensity X-ray beams in the work [2] it has been suggested to accelerate atoms (ions) in the flux of X-ray radiation with relatively wide spectrum due to the momentum transfered to the atoms in the process of inner shell photoeffect. The atom acceleration takes place due to the fact that in the case of X-ray photoeffect the even weak relativism of photoelectrons results in their directed angular distribution and therefore the atoms in the mean get some momentum directed forward (or backward) to the X-ray incidence. These problems are considered in detail in A.Sommerfeld's book [3]. However in [3] the photoeffect process is, naturally, considered for atoms in rest, while in the work [2] it is assumed that during each consequent photoeffect process the atoms are in rest taking into account that the atoms get nonrelativistic velocities. In present work the influence of the initial velocity of the atoms on their acceleration is studied theoretically and it is shown that this influence changes the whole picture of atom acceleration even at nonrelativistic atom velocities leading to limitation of the energy region of the accelerated atoms.

Let in the laboratory frame an X-ray photon with energy ω and momentum $\vec{K}$ $(\hbar = c = 1)$ collides with an atom of momentum $\vec{P}_1$. Then in the result of photoeffect in its rest frame as in [2] the atom receives in the average momentum $\vec{P}'_2 = \overline{\Delta p}\,\vec{K}'/\omega$ where ω' and $\vec{K}'$ are the photon energy and momentum in the atom rest frame, and $\overline{\Delta p} = 1.6E_K - 0.6\omega$ where E_K is the K-shell ionization energy. Carrying out Lorentz transformation of the corresponding quantities from the atom rest frame to the laboratory frame one obtains the following formula for the magnitude and direction of the atom momentum $\vec{P}_2 = \vec{P}_1 + \Delta\vec{P}$ in the laboratory frame:

$$\Delta\vec{P} = \overline{\Delta p}\,\gamma\,\frac{\vec{K}\vec{n} - \beta\omega}{\omega - \beta\vec{K}\vec{n}}\,\vec{n} + \gamma\beta(E'_2 - M_1)\vec{n} + \overline{\Delta p}\,\frac{\vec{K} - (\vec{K}\vec{n})\vec{n}}{\gamma(\omega - \beta\vec{K}\vec{n})}, \quad (I$$

where $\vec{n} = \vec{P}_1/P_1$, $\beta = P_1/E_1$ and M_1 are the velocity and mass of the atom before photoeffect process $\gamma = 1/\sqrt{1-\beta^2}$, $E'_2 = \sqrt{\overline{\Delta p}^2 + M_2}$, E'_2 and M_2 being the energy and mass of the atom (ion) after photoeffect.

For the two following particular cases corresponding to the cases considered in the work [2], one has from (1):

1, The initial atom and the photon move in the same direction $\vec{n} = \vec{P}_1/P_1 = \vec{K}/\omega$:

$$\Delta\vec{P} = \gamma\left[\overline{\Delta p} + \beta(E'_2 - M_1)\right]\vec{n} = \gamma(\overline{\Delta p} - \beta m)\vec{n}. \quad (2)$$

2. The momenta of the initial atom and the photon are directed against each other $\vec{n} = \vec{P}_1 / P_1 = -\vec{k}/\omega$:

$$\vec{\Delta P} = \gamma\left[-\overline{\Delta p} + \beta\left(E_2' - M_1\right)\right]\vec{n} = -\gamma\left(\overline{\Delta p} + \beta m\right)\vec{n} \, . \qquad (3)$$

Since for real possible cases $\overline{\Delta p} \ll M_2$ then in furher calculations with good approximation one can assume $E_2' - M_1 \doteq \approx \overline{\Delta p}^2/2M_2 + M_2 - M_1 \approx M_2 - M_1 = -m$ where m is the electron mass. The term $\Delta p^2/2M_2$ would slightly change the further estimates since this term enters into (2) and (3) with an additional small coefficient m/M_2 . From formulae (2) and (3) it follows that the atom acceleration takes place due to the term $\overline{\Delta p}$ while the term βm results in deceleration. Indeed when the first term is absent, say when $\Delta p \ll \beta m$ one has $\vec{\Delta P} = -\gamma\beta m\vec{k}/\omega$ and $\vec{\Delta P} = \gamma\beta m\vec{k}/\omega$ for the first and second cases, respectively, and in both cases in the process of photoeffect the atoms will be decelerated.

From Lorents transformation formulae one has $\omega' = \omega\gamma(1-\beta)$ and $\omega' = \omega\gamma(1+\beta)$ for the first and second cases, respectively, and the formulae (2) and (3) take the form:

$$\vec{\Delta P} = m\gamma\left(b - \beta - a\sqrt{\frac{1-\beta}{1+\beta}}\right)\vec{n} \quad \text{in the case 1,} \qquad (2')$$

$$\vec{\Delta P} = m\gamma\left(a\sqrt{\frac{1+\beta}{1-\beta}} - b - \beta\right)\vec{n} \quad \text{in the case 2,} \qquad (3')$$

where $a = 0.6\omega/m$ and $b = 1.6E_k/m$. Taking into account that $\vec{n} = \vec{k}/\omega$ and $\vec{n} = -\vec{k}/\omega$ for the cases 1 and 2 , respectively, the formulae (2), (3) and (2'), (3') give $\vec{\Delta P} = \overline{\Delta p}\,\vec{k}/\omega$ as in the work [2] when $\beta \to 0$.

For the given values of ω and E_K the resulting process namely the acceleration, deceleration or constancy of the velocity of the atom, depends on the fact that in what regions of β values the parentheses of the formulae (2') and (3') are positive, negative or equal to zero. Therefore it is necessary to determine the regions of β values in which these parentheses are positive, and consequently the acceleration is possible.

Consider the case 1. As it is seen from (2') for the existence of acceleration region of β it is necessary $b>a$, while the ion velocity must be $\beta<b$. The acceleration takes place in the region $0<\beta<\beta^{(1)}_{lim}$ where $\beta^{(1)}_{lim}$ is the root of the expression in the parenthesis of (2) and presents the limiting value of β up to which the atom acceleration is possible. Thus in the case 1 when $b>a$ the atom which is initially in rest in a incident X-ray beam begins to be accelerated in consequent photoeffect processe in the direction of the incident X-ray beam, but just as the atom velocity becomes greater than $\beta^{(1)}_{lim}$ in the result of further photoeffect processes the atom begins to be decelerated. For small values $a\ll 1$ and $b\ll 1$ the approximate value of $\beta^{(1)}_{lim}$ is equal to $\beta^{(1)}_{lim}\approx b-a-a^2+2ab$. Let us note that the value of $\beta^{(1)}_{lim}$ is very small. Since $a<b$ or $E_K<\omega<2.7E_K$, when $\omega\approx E_K$ we have for instance, in case of argon ($Z=18$, $E_K=3.203$ KeV) $\beta^{(1)}_{lim}=0.006$ or $E_2^{kin}\approx 0.75$ MeV.

Consider the case 2. As it follows from (3') for the existence of acceleration region it is necessary $a>b$ or $\omega>$ $>2.7E_K$. In this case there are two regions of β in which th atom acceleration is possible: $0 < \beta < \beta_1$ and $\beta_2 < \beta < 1$. For small a and b the approximate values of β_1 and β_2 are equal to $\beta_1 \approx a - b + a^2 - 2ab$ and $\beta_2 = 1 - 2a^2$. Since the magnitude $a = 0.6\omega/m$ is small for ω for which the photoeffect cross section σ_{ph} is larger than the scattering cross section σ_{sc} then the region $\beta_2 < \beta < 1$ is very narrow and presents no interest. Therefore it remains the case when the atoms initially in rest will be accelerated in the X-ray beam up to velocity $\beta^{(2)}_{lim} = \beta_1$ against the direction of the X-ray beam. One may increase the value of $\beta^{(2)}_{lim}$ by increasing the photon energy, however it is necessary to take into account that σ_{ph} decreases with the increase of ω. In the case of Ar atoms one has: ω =50 KeV, $\beta^{(2)}_{lim} \simeq$ 0,052, $E^{kin}_2 \simeq$ 52MeV; ω =100KeV, $\beta^{(2)}_{lim} \simeq$ 0.123, $E^{kin}_2 \simeq$ 283 MeV; ω =200 KeV, $\beta^{(2)}_{lim} \simeq$ 0.316, $E^{kin}_2 \simeq$ 2 GeV.

Let us note that as it follow from (3') in the case 2 the atom acceleration is possible in the whole region $0 < \beta < 1$ for sufficiently great values of the parameter $a > a_{crit}$ where

$$a^2_{crit} = -5.5 + 7b - b^2 + 4(1.25 - b)^{3/2}. \qquad (4)$$

However this requires relatively high energy photons $\omega > \omega_{crit} = (5/3)\, m\, a_{crit}$ for which σ_{ph} becomes comparable or less than σ_{sc}. In Table 1 it is given the values of ω_{crit} for some atoms and using the tables for photon interaction cross sections [4] the values $\tilde{\omega}$ for which σ_{ph} becomes of the order of σ_{sc}. As it is seen from Table 1 for light and medium atoms $\omega_{crit} < \tilde{\omega}$ and the acceleration is possible in the region $0 < \beta < \beta^{(2)}_{lim}$ while for heavy atom the acceleration is possible in the whole region $0 < \beta < 1$.

Let us also note that due to the dependence of the acceleration in a number of consequent photoeffect processes on the atom velocity the acceleration rate is not constant along all the path of interaction of atoms with X-ray beam and in all cases it decrease with the increase of β . For comparison with the estimates of the work [2] let us give the averaged values of the corresponding magnitudes in the case of A_r atom acceleration.

The averaged acceleration rates ($\bar{T}=\overline{\Delta P}f$, for $f=1/\tau$ where τ is the K -vacancy lifetime [6], f is the maximal possible frequency of the photoeffect process) in the acceleration regior $0<\beta<\beta_{lim}^{(1,2)}$ for small a and b are equal to

$$\bar{T}_1 \approx \frac{m}{2\tau}\left(b-a-ab\right) \quad , \bar{T}_2 \approx \frac{m}{2\tau}\left(a-b+ab\right) \qquad (5)$$

for the cases 1 and 2 , respectively. For $\omega \simeq E_K$ and $\omega = 50$ KeV one has: $\bar{T}_1 \simeq 5.4$ GeV/m and $\bar{T}_2 \simeq 42$ GeV/m. For such accelerations the required X-ray power densities ($W = \omega/\tau\,\sigma_{ph}$) are respectively equal to $W_1 \simeq 5.10^{18}$ W/cm^2 and $W_2 \simeq 2.7.10^{23}$ W/cm^2 as in the work [2].

The mean fractions of the X-ray energy ($K = E^{kin}/\bar{n}\omega$ where E^{kin} is the atom energy after acceleration, $\bar{n}$ is the mean number of photons absorbed by the atom) used for the acceleration of an atom initially in rest up to the limiting velocities $\beta_{lim}^{(1)}$ and $\beta_{lim}^{(2)}$ in both cases are determined by the formula $K_{1,2} \simeq (m/4\omega)(a-b)^2$ and are equal to $K_1 \simeq 0.16\%$($E_1^{kin} \simeq 0.75$ MeV) and $K_2 \simeq 0,6\%$ ($E_2^{kin} \simeq 50$ MeV) respectively, when a and b are small.

Without discussing the difficulties (filling the vacant shells by electrons) and possible (laboratory and astrophysical) realisation of the atom acceleration method under investigation (see [2]) we would like in conclusion of this short note once again to underline that the accounting of the atom motion limits strongly the possibilities of the method.

Table 1.

	Ar	Fe	Cu	Sn	J	W	Pt	Pb	U
Z	I8	26	29	50	53	74	78	82	92
E_K (KeV)	3.203	7.II2	8.979	29.2	33.I7	69.52	78.4	88	II5.6
$\tilde{\omega}$ (KeV)	70	I20	I50	250	250	450	500	500	650
ω_{cri} (KeV)	260	265	268	295	300	353	367	382	426
	$0 < \beta < \beta^{(2)}_{lim}$					$0 < \beta < 1$			

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УСКОРЕНИЕ ДВИЖУЩИХСЯ АТОМОВ В ПОТОКЕ РЕНТГЕНОВСКОГО ИЗЛУЧЕНИЯ

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