THE REAL PROCESS IN THE FRANCK-HERTZ TUBE

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Abstract

The periodicity of the Franck-Hertz curve is reproduced under our model. The new feature which was put forward by G. Rapior at Ref.2 is reconsidered with the consideration of mean free path and surplus energy. We haven't made the assumption of sequential excitation energy levels, therefore we solved the contradiction between the model of Ref.2 and experiment results. We believe the descriptions here the real process in the Franck-Hertz tube.

I. INTRODUCTION

Once the Franck-Hertz experiment was one of the key demonstrations of the quantum behaviour of atoms and provided a nonoptical demonstration of the existence of stationary energy levels in atom which was first illuminated by Bohr. For this, Franck and Hertz received the Nobel Prize in 1925.

The proof comes from the Franck-Hertz curve, which presents curtain periodicity. It is general assumed that the periodicity of maxima or minima should be strict and stands for the lowest excitation energy of atoms (6^3P_1 state). It is also widely used to fix the lowest excitation energy by calculating the mean value of the spacings between maxima or minima through Franck-Hertz experiment, with no regard to the visible change of the spacing, which usually shows a continuous increase.

If the spacings are not fixed, how can we claim it to be an evidence for stationary energy levels? Or what exactly happens in the Franck-Hertz tube can result in the changing of the spacing? It is urgently needed to explain the seemingly contradiction between the stationary energy and the changing periodicity. By taking into consideration the influence of the mean free path, authors of Ref.2 supplied us a model, claiming that they have solved the problem with that model. But there is an additional assumption in their model which cannot be satisfied in the experiment.

In this article, we provide an ideal model that can reproduce the strict periodicity. Then, by introducing the influence of the mean free path and the surplus energy, we describe the real process in the Franck-Hertz tube and explain the increase of spacing.

II. APPARATUS AND GENERAL RESULTS

The apparatus we used is just the one of used in Ref.3. Electrons releasing from the heater F will be extracted by V_{G1k}, and enter into the accelerating and collision area. If the electron's energy is high enough, it will overcome the retarding voltage V_{G2p} and contribute to the anode current in P. The mercury tube is a Fudan Franck-Hertz tube which is cylindrically shaped.
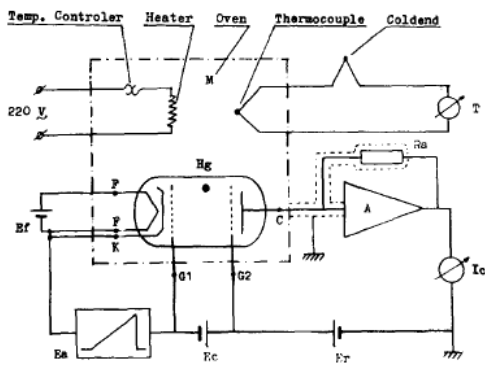
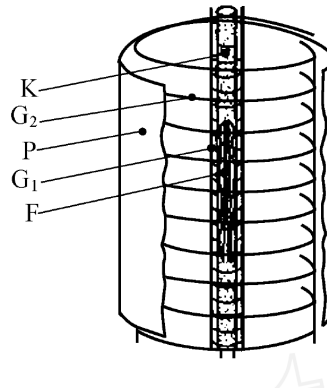Fig. 1. Schematic diagram of the Franck-Hertz experiment.

Fig. 2. Sketch of a Fudan Franck-Hertz tube.

The mercury atom states depend on two outside electrons. Ground state and some important low states are as follows. In the Franck-Hertz experiment , the most important ones are the lowest three states $6^3P_{0,1,2}$. In many experiment descriptions, the 6^3P_1 excitation determines the result, as the other two are metastable states, which has a longevity about 10^5 s, that is thousands times larger than the longevity of 6^3P_1. But this is not enough to remove their influence in Franck-Hertz experiment. If the electrons received in one second are comparable with the quantity of Hg gas atoms in the tube, then, anytime there is at most one atom in 10^5 that may stay in these states. As a result, all the three excitation states should be taken into consideration in order to understand the real process of the experiment.

Fig 4 is the typical Franck-Hertz curve at the temperature T=180℃. The periodicity of the maxima or minima is clearly showed. It also shows an increase of the spacing from about 4.6 volt to 5.1 volt. The mean spacing from the first maximum to the last one is (87.9 V)/18=4.88 V.
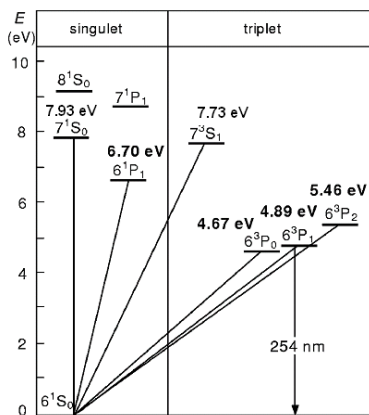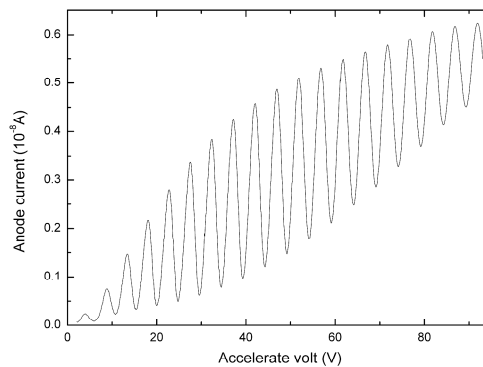

Fig. 3. Lowest energy levels in mercury.

Fig. 4. Typical Franck-Hertz curve at 180℃. The precision of the Accelerating voltage is 0.1 V.

III. AN IDEAL MORDEL AND THE PERIODICITY

To reproduce the periodicity, we assume that there is only one excitation level effecting in this experiment, and inelastic collision happens as soon as the electron gains corresponding energy, and at the same time, its kinetic energy reduces to zero.

Further more, we take into consideration the dispersion of electron energy, which always happens in physical processes. That is to say, the electrons will have different kinetic energy when they come into the accelerating and collision area. In the energy representation, the electrons will form a distribution curve. For simplicity, we suppose that the distribution curve is across all the energy space from zero to the excitation energy. Notice that the distribution curve stands for the energy distribution of electrons at a fixed distance between G_1 and G_2, for example at G_1 or G_2.
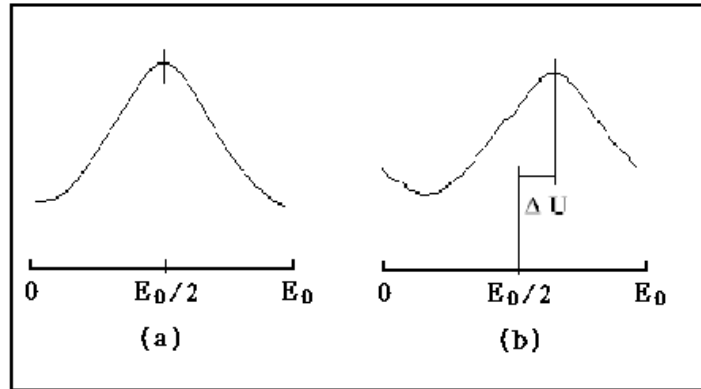

Fig. 5. The distribution curve in the energy presentation.

In this aspect, as the moving forward of the electrons from G_1 to G_2 under a fixed V_{G1G2}, the distribution curve at the distance where these electrons located will move forward by relevant distance in energy representation. And for former supposition, the over part of the energy distribution curve will add in from the left due to the immediate inelastic collisions. So electrons transmitting through the tube under a certain accelerating voltage will experience relevant number of inelastic collision cycle before the final arrival at G_2.
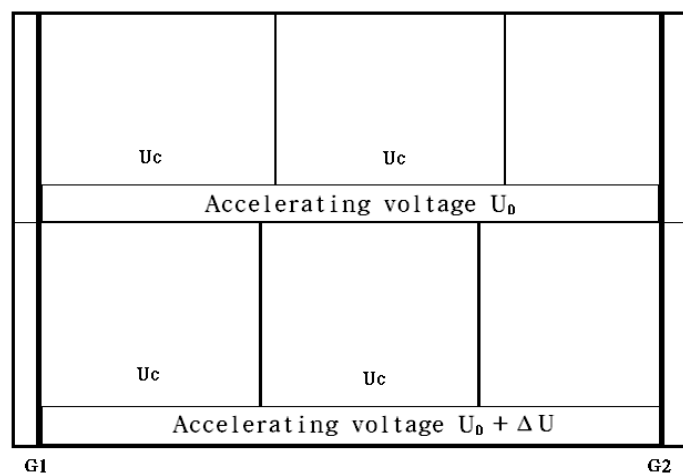

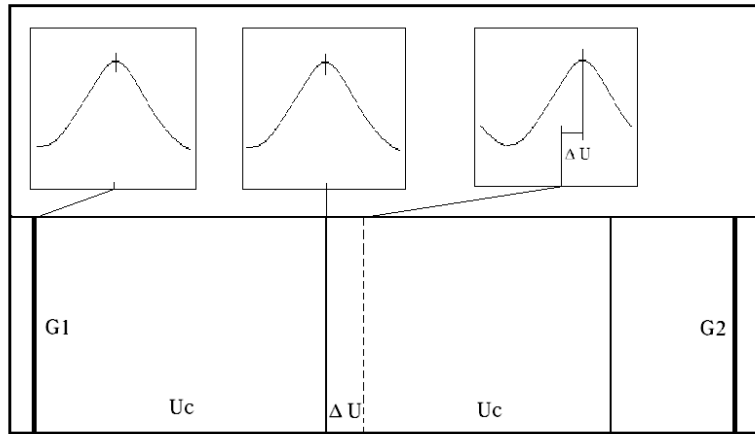Fig. 6. The change of cycles according to V_{G1G2}.

Fig. 7. The distribution curve at different distance between G1 & G2.

If we set the retarding voltage V_{G2p} at one energy value (the black line) of this range, as is always done in Franck-Hertz experiment, electrons arriving G_2 with lower energy will not contribute to the anode current in P. The effective ones are the electrons with energy higher than eV_{G2p}. So it is easy to understand that the anode current will be determined by the integral of electron energy distribution curve above the retarding voltage.
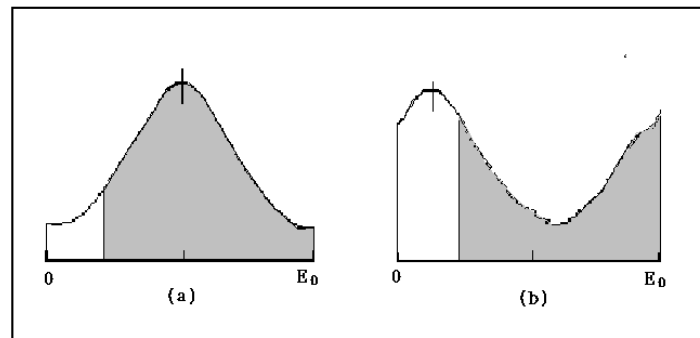

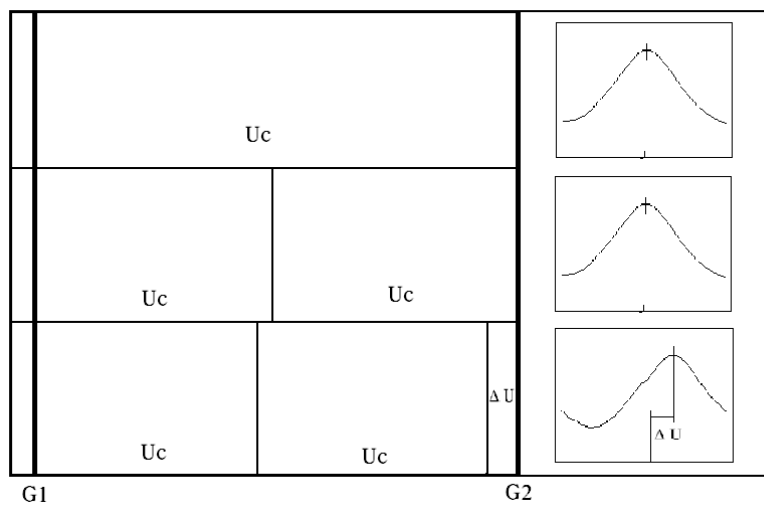Fig. 8. The integral of electrons above eV_{G2P}.

Fig. 9. The distribution curve at G2 changes according to the increase of Accelerating voltage.

As the accelerating voltage grows, which is similar to the movement from G_1 to G_2 under a fixed V_{G1G2} in this ideal model, the distribution curve of G_2 will move forward at the energy presentation. As a result, the integral of distribution curve above the retarding voltage will change from the smallest to the biggest, then smallest, and the periodicity is equal to the energy range. That is why this experiment could be used to test the first excitation energy, provided that there is only one excitation effecting.
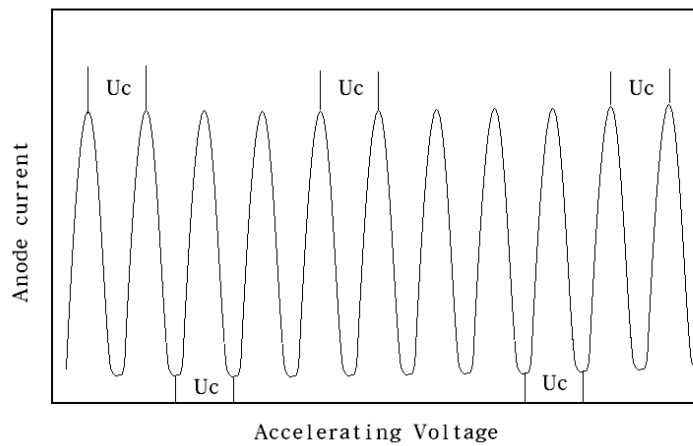

Fig. 10. The ideal periodicity based on this model.

Consider of the different directional velocities, the electrons releasing at the same time but with different energy will not always move equal distance forward in the same time. So the distribution curve will have some change when moving forward. But it will keep relative stabilization under this ideal model for the continuous process.

III. THE INCREASE OF SPACING BETWEEN MAXIMA OR MINIMA

The real process in a Franck-Hertz is much more complicated than the model above. There are more than one excitation levels, and inelastic collision will not happen soon after the electron gains enough energy. These should be taken into consideration to explain the experiment record.

Let's analyze the record curve first. When the accelerating voltage is fixed on 3th maximum, electrons will have to experience 3 inelastic collision cycles (energy cycle) before the arrival to G_2, and 19th maximum 19 cycles. If n^{th} maximum appears when the accelerating voltage is U_0, then the equal energy cycle will be $(U_0-\delta)/n$, where δ is a little adjustment varies from different V_F and V_{G1K}. In this article, the energy cycle is replaced by the average of all spacings before the relevant maximum for simplicity. Therefore, the energy cycle is close to 4.88eV when the accelerating voltage is 91.9V (the 19th maximum) for the record curve of Figure 4.
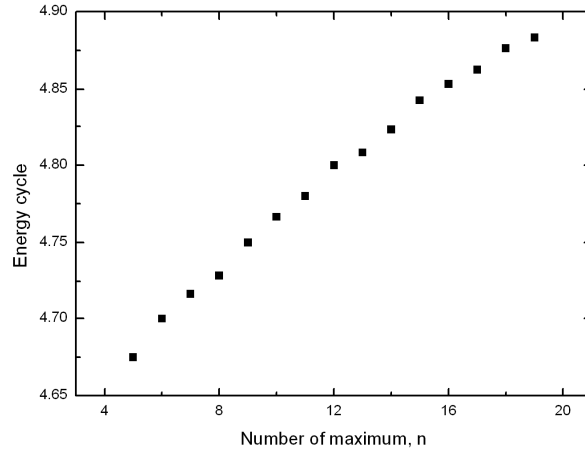
Fig. 11. The energy cycle as a function of the number of maximum at temperature T=180℃.

Since the energy cycle is the cell process, the increase of spacing between maxima or minima should be solved by analysis of the energy cycle. To begin with our discussion, we shall introduce the concept of mean free path first. Here, the mean free path stands for the average directional distance that the electron moves before an inelastic collision takes place after the excitation energy has reached. The mean free path mainly depend on the inelastic collision cross section which differs from different excitation levels. The cross section depends on pressure of mercury, equal to say the temperature in this case, and varies with the energy of electrons. We take the total inelastic collision section of $6^3P_{0,1,2}$ to determine the mean free path, and regard it to be independent of electrons' energy since it varies not much around the energy of 5.0eV, which is the effecting energy scope of this experiment. Although the mean free path keeps the same if the temperature remains, 'mean free energy' grows with the increase of accelerating voltage. Here the 'mean free energy' is the mean free path multiplies the electric field intensity which stands for energy electron gains in one mean free path.

So it is possible that the mean free energy causes the increase of energy cycle. Here we shall introduce the work of G. Rapior (Ref.2). In that paper, authors also introduced mean free path to explain the increase of spacing. But they add an additional presupposition which says as soon as the inelastic collision happens, no matter what energy they have brought, they will lose almost all of them, assuming that there are many higher energy excitation levels ensuring this. From their model, it can be deduced that

$$\frac{l}{L_{G_1G_2}/n} = \frac{E_{mfree}}{E_c} \qquad (1)$$

So the mean free path calculated from (1) is about 0.011mm at the temperature T=180℃ according to Figure 11. And the inelastic collision cross section defined as $s = k_B T / l\, p$ will be 4.8×10^{-19} m^2. This is much bigger than the excitation cross sections of $6^3P_{0,1,2}$ given in Ref.4.

Their model also violates the following experimental phenomenon. Figure 12 shows the records with retarding voltage at 4.5V, 5.0V, 5.5V, and 6.0V separately, keeping other conditions the same.

If their model is true, then there will be little electrons which have energy higher than $(4.67+2\Delta E)$ eV, equal to 5.09 eV at 19th maximum. This violates the record curves.
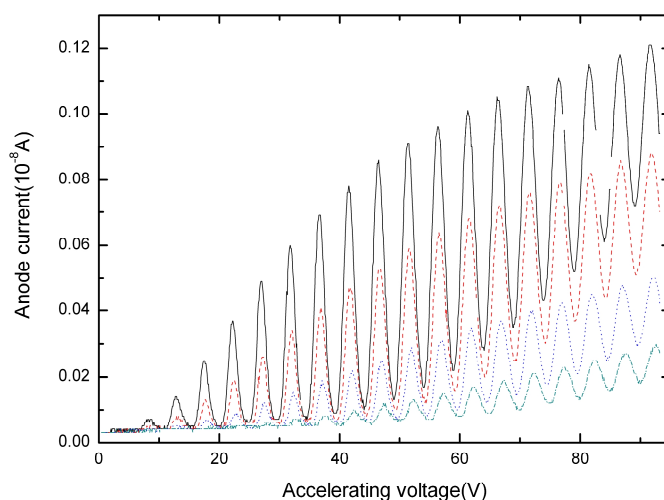

Fig. 12. Records with retarding voltage at 4.5V, 5.0V, 5.5V, and 6.0V separately. The temperature T=180 ℃.

In fact, according to Figure 12, the mean free energy will be close to (or above) 5.5eV at 19th maximum, provided that the mean free energy is close to the place (of the energy) which separates the electrons (electrons with energy above 4.67eV) into two equal parts (see the heights of peaks at about 92V). To estimate the real mean free path, we choose the mean free energy at 19th maximum to be 1.0eV. So the mean free path reads 0.045mm, the cross section of inelastic collision is 9.4×10^{-20} m^2. This agrees with the total cross section for the electron excitation of mercury states $6^3P_{0,1,2}$ given in Ref.4.

The violation of their model and experiment lays on the additional presupposition that as soon as the inelastic collision happens, no matter what energy they have, they will lose almost all of them. In fact, for the range of 4.5eV to 6.0eV, there are not many energy levels effecting. So it is unjustified to take the excitation energy levels after 4.67eV to be sequential.

In our concern, as has stated before, the three levels $6^3P_{0,1,2}$ determining the experiment together. And for the change of energy, they have only three possibilities, 4.67eV, 4.89eV, or 5.46eV. That is to say, an electron with 4.80eV will lose 4.67eV, an electron with 5.60eV will lose 4.67eV, or 4.89eV, or 5.46eV, but not all the energy after an inelastic collision. As a result, not all of the electrons will reduce back to near zero energy state. Indeed, only a few of them will, when the mean free energy is large. In other word, many electrons don't begin to accelerate with zero energy. Because of this, the mean inelastic collision energy (that is the lowest excitation energy plus the mean free energy) cannot stand for an energy cycle.
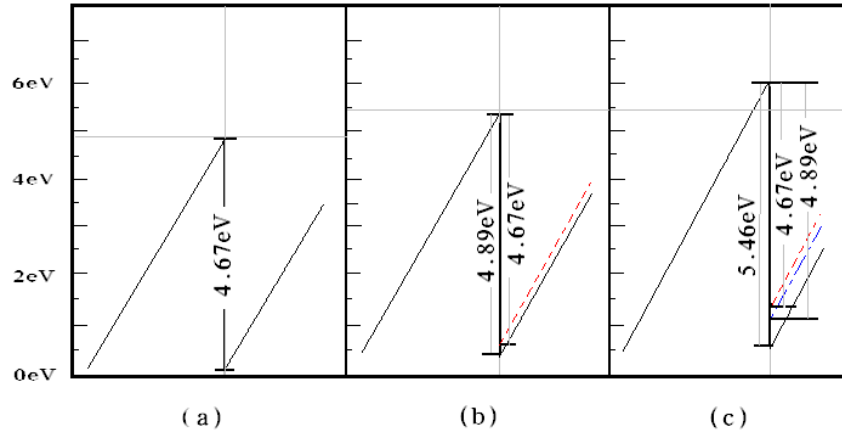
Fig. 13. Surplus energy after inelastic collision.

So what on earth causes the change of spacing? Let's describe the process from the view of mean free path, without the additional presupposition of Ref.2. At the beginning, accelerating voltage is small that few electrons have excrescent energy larger than 0.22eV when inelastic collision takes place, which is the gap of 4.67eV and 4.89eV. At that time, 4.67eV excitation is dominating and consequentially the energy cycle is close to 4.67eV. As the accelerating voltage grows, the effect of 4.89eV excitation grows. When some electrons' plus energy reaches to 0.79eV, the 5.46eV excitation enters in. With the increase of accelerating voltage, more and more electrons will experience relative higher excitation. And the proportions of the three excitations determine the energy cycle. For simplicity, we can write the energy cycle as,

$$\bar{U}_C = 4.67a + 4.89b + 5.46g \tag{2}$$

α,β,γ are the percentages of relevant excitations respectively. Notice that, consider of different cross sections, α, β, γ could not be found so easily.
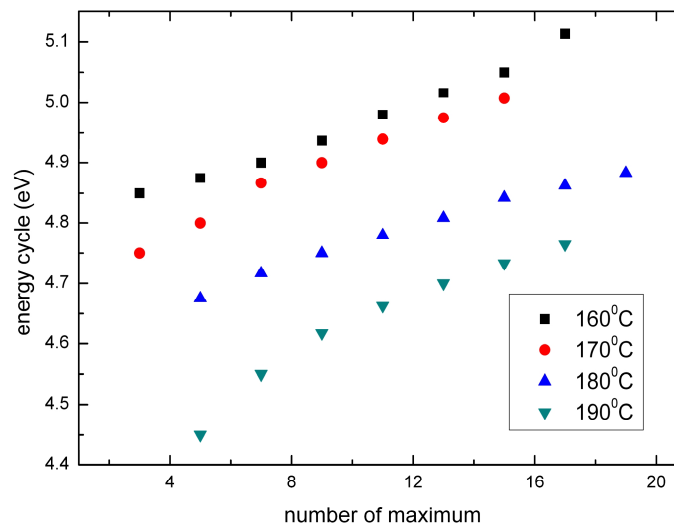

Fig. 14. The energy cycle as a function of the number of maximum at different temperatures.

The above expression is valid with definite temperature scope, for example, higher than 150℃, but lower than 180℃. For lower temperature, the mean free path will be longer, which will bring the influence of higher excitations (6.70eV, etc.; see Ref.7). For higher temperature, the starting spacings always read to be around 4eV. This may be coursed by other effects, for example the unobserved $6s6p^2\,^4P_{1/2,3/2,5/2}$ ion resonances which were predicted by Heddle in Ref.8. Discussion on this subject is beyond this article.

Ⅳ. SUMMARY

We established an ideal model that reproduces the periodicity of the maxima or minima in the Franck-Hertz curve. To explain the increase of the spacings between maxima or minima, we discussed the mean free path and the surplus energy after inelastic collision. The influence of the mean free path is used to introduce the influence of higher excitations, and the surplus energy is the key to solve the seeming contradiction between the observed mean inelastic collision energy and the mean energy that electrons will gain during one inelastic collision cycle. We consider it to be the real process happens in the Franck-Hertz tube.

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