INSTANTANEOUS X-RAY EMISSION INDUCED BY ION-ATOM COLLISIONS

K. Hino, T. Watanabe

To cite this version:


HAL Id: jpa-00227365
https://hal.archives-ouvertes.fr/jpa-00227365
Submitted on 1 Jan 1987

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
INSTANTANEOUS X-RAY EMISSION INDUCED BY ION-ATOM COLLISIONS

K. HINO and T. WATANABE

Atomic Processes Laboratory, The Institute of Physical and Chemical Research (RIKEN), Wako, Saitama, 351-01, Japan

Abstract - X-Ray emission in ion-atom collision is considered from the standpoint of theoretical consistency. Particular attention is paid for radiative electron capture (REC). It is shown that a guide principle to obtain the formula is the gauge invariance requirement. We have obtained a results that the impulse approximation and the strong-potential Born approximation for REC satisfy approximately this requirement. An application is made for REC process in Xe$^{34+}$ and U$^{92+}$ impacts on Be target.

Instantaneous X-ray emission processes induced by the interaction of an energetic heavy ion with an target atom are considered from the standpoint of theoretical consistency.

It is known that there are some inconsistencies in the theoretical treatment on radiative processes induced by ion-atom collisions. Particularly the calculated cross section for radiative electron capture (REC) process from a neutral target atom by a high velocity projectile ion does depend on the coordinate frame employed in the formula of non-relativistic quantum mechanics/1/. The cross section obtained in the projectile coordinate frame is different from that obtained in the target coordinate frame. It was pointed out by Shakeshaft and Spruch in 1977 /2/ that this is due to the difference of the basic equations which satisfy for particle motions and for field interaction. The former follows the Schroedinger equation which is invariant in the Galilean transformation and the latter does the Maxwellian equation which is invariant in the Lorentz transformation. The photons which are relevant to the motion of the center-of-mass of the total system is derived and it is named by Shakeshaft and Spruch as "spurious radiation" and it has been told that if one take the center-of-mass coordinate system, this spurious radiation term can be eliminated.

It was, however, shown by Hino in 1984 /3/ that the so called "spurious radiation" can not be removed by the full quantum mechanical calculation (Born approximation) using the center-of-mass coordinate frame. This calculation predicted also the fact that the REC cross section depends on the mass of the target atom. The cross section for REC in collision of a Ne$^{10+}$ on a $^4$He is expected to be about two times as much as the cross.
section of the same ion impact on $^3$He in the Born calculation using center-of-mass frame but it was denied by an experiments. The both cross sections were measured to be the same within 7% error by Kambara et. al. /4/. Furthermore, it was found that the usual S matrix for REC process written by Fermi's golden rule have counted the same physical process (the Feynman diagramme) by two times in the lowest order. It was found out that this double counting comes from the fact that we do not know the exact solution of scattering state of three particles. There exists some ambiguity in choosing the scattering state wavefunctions of initial and final states. Here the initial and the final states do mean those just before and after the X-ray emission and these are different from asymptotic formulas in scattering problems.

We have come to the conclusion that the gauge invariance property should be examined throughout the whole formulation of the present problem. In the present research, we are mainly concerned with electron bremsstrahlung (EB), atomic bremsstrahlung (AB), radiative electron capture (REC) and molecular orbital X-ray emmission (MO X-ray). Particular attention is paid for REC process. The radiation process treated here classified into three, i.e. two-body collision process and the interaction with radiation fields, three-body non-rearrangement collision processes and the interaction with radiation fields, and three-body rearrangement collision process and the interaction with radiation fields. For simplicity it is assumed that the system consists of Coulomb-interacting two or three particles, i.e. an electron (e) and a nucleus (A) or a parojectile nucleus (A) and a hydrogen-like target atom [(B,e)].

Firstly we consider the radiative process on the occasion of two-body collisions as a preliminary discussion on the problems which concerns three bodies and radiation fields. The S matrix formulas for bremsstrahlung and radiative recombination, i.e.

$$e + A \rightarrow e + A + \gamma$$  \hspace{1cm} (1)

and

$$e + A \rightarrow (A,e) + \gamma$$  \hspace{1cm} (2)

are known to maintain the gauge invariance property if we use the exact initial and final wavefunctions. We examine how the validity of gauge invariance property holds in the perturbation (Born) expansion series on scattering states. We have found that the gauge invariance holds in the respective order of Born expansion series in the case of bremsstrahlung, but the gauge invariance does not necessarily hold in the respective order of the series in the case of radiative recombination processes.

Secondly, the discussion is made on the three-body collision processes and the reconsideration is made from the viewpoint of gauge invariance requirement. When we make a similar consideration on three-body problems by using perturbation expansion method. We take the case of radiative electron capture (REC) as a typical example;

$$A + (B,e) \rightarrow (A,e) + B + \gamma$$  \hspace{1cm} (3)

the initial and the final state wavefunctions can only be given in terms of a perturbation expansion series, because we do not have the exact forms of three-body scattering states; $A + (B,e)$ and $(A,e) + B$. It can be shown that all these unreasonable points such as frame dependent results and double counting of Faynman's diagramme etc. are removed by taking gauge invariance requirement into consideration for the expression of the initial and the final state wavefunctions.

We have been investigated how the gauge invariance property maintain in
repective order of potential powers in various perturbation expansions. In
the Brinkman-Kramers approximation (that ignores the internuclear
interaction, $V_{AB}$, and expands the S matrix in terms of the interaction
between A and e, $V_{Ae}$, or B and e, $V_{Be}$, with no-potential Green's function)
and in the Born approximation (that expands the S matrix in terms of $V_{AB} +
V_{Ae}$ or $V_{AB} + V_{Be}$, with no-potential Green's function) the gauge invariance
does not hold. The impulse approximation (IA) and the strong-potential Born
approximation (SPB) /5/ (that expands the S matrix in terms of $V_{Ae}$ with
Green's function under $V_{Ae}$ without (IA) and with (SPB) off-shell
contributions) holds the gauge invariance for the respective order of power
expansion. We also have a conclusion that when we use the Born
approximation for the calculation of REC cross section, the projectile
frame is most proper among three coordinate reference frames (projectile,
target, and center-of-mass) from the viewpoint of the gauge invariance. In
this sense, the concept that "REC is regarded as a reverse process of
photoionization" is valid within the velocity region of "not-extremely
relativistic".

In the case of radiative deexcitation and radiative excitation:

$$A + (B,e)^* + A + (B,e) + \gamma \quad (4)$$

and

$$A + (B,e) + A + (B,e)^* + \gamma \quad (5)$$

the gauge invariance holds even in the Born approximation (that expands the
S matrix in terms of $V_{Ae}$ with no-potential Green's function).

A remark is due about the X-ray angular distribution for REC processes in a
relativistic range. The angular distribution of photons from moving particles
in the moving projectile frame deviates from the $\sin^2 \theta$-rule. By the Lorentz
transformation from the moving frame into the laboratory frame, however,
this deviation is almost canceled out. We obtain an angular distribution
approximately proportional to $\sin^2 \theta_L$, where $\theta_L$ is the photoemission angle
with respect to the projectile direction in the laboratory frame. The
present formalism warns, however, that this kind of treatment requires a
careful study of the reference frame from the viewpoint of gauge
invariance. It has been proved that a proper angular distribution can be
obtained only by calculations in the moving projectile frame followed by the
transformation into the laboratory frame, if we employ an approximation
that destroys the gauge invariance. According to the argument given above,
a proper angular distribution can be obtained using the laboratory frame
from the beginning. However, the use of the SPB approximation that
satisfies the gauge invariance avoids such a difficulty completely.

Finally we have calculated the total cross sections for the radiative
electron capture by Xe$^{5+}$ and U$^{92+}$ projectile ions on Be targets and the
angular distributions of emitted X-rays using the relativistic strong-
potential Born (RSPB) approximation /5,6/ and also using other methods. We
have compared the results with experimental data /7/ and with the
calculations using other theories /6/. In Figs. 1 and 2 the total cross
section for REC by RSPB approximation are shown together withexperimental data and the results of calculation by other theoris.

REFERENCES

/3/ K. Hino, M.S Thesis, Department of Applied Physics, The University of
Fig. 1.

Fig. 2.

Figs. 1 and 2. Total cross sections for the radiative electron capture processes in the $\text{Xe}^{54+}$- and $\text{U}^{92+}$-Be collisions versus the incident velocity $v/c$ and the Coulomb parameter between an active electron and the projectile ion /6/. Solid line (———): the relativistic strong potential Born (RSPB) approximation, chain line (— — —): the RSPB calculation without the Lorentz contraction factor based on the motion of a target nucleus in the moving frame (RSPB-11), dotted chain line (— • —): the relativistic Born calculation (RB), break line (— — — —): the non-relativistic SPB calculation, dotted line (— — — — —): the relativistic impulse approximation calculation (RIA) and Experimental results are quoted from the paper by Meyerhof et al. /7/.