СООБЩЕНИЯ
ОБЪЕДИНЕННОГО
ИНСТИТУТА
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ
ДУБНА

E7 - 11431

P.Gippner

EVALUATION OF NUCLEAR BREMSSTRAHLUNG FOR SPECIAL HEAVY ION-ATOM COLLISION SYSTEMS

1978

E7 - 11431

P.Gippner

EVALUATION OF NUCLEAR BREMSSTRAHLUNG FOR SPECIAL HEAVY ION-ATOM COLLISION SYSTEMS

Гиппнер П.

E7 - 11431

Вычисление спектров ядерного тормозного излучения для избранных систем ион-атом в столкновениях тяжелых ионов

Вычислены вклады спектров ядерного тормозного излучения в сплошные спектры рентгеновских лучей, обнаруженные при столкновениях систем Ni + ^{60}Ni (67 МэВ), ^{74}Ge + ^{74}Ge (54 МэВ) и ^{93}Nb + ^{93}Nb (67 МэВ). В расчете тормозного излучения использована модель, которая учитывает и дипольную и квадрупольную части электромагнитной радиации и их интерференцию. Спектры, полученные после введения поправок на тормозное излучение и радиационный фон, приписывают квазимолекулярному излучению, возникающему при адиабатических столкновениях тяжелых ионов с атомами мишеней. Результаты измерений и расчета приведены в виде 2 графиков и 3 рисунков.

Работа выполнена в Лаборатории ядерных реакций ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна 1978

Gippner P.

E7 - 11431

Evaluation of Nuclear Bremsstrahlung for Special Heavy Ion-Atom Collision Systems

The contributions of nuclear bremsstrahlung to the X-ray continua observed by investigating the collision systems ^{nat}Ni + ^{60}Ni (67 MeV), ^{74}Ge + ^{74}Ge (54 MeV) and ^{93}Nb + ^{93}Nb (67 MeV) were calculated taking into account the interfering E1 and E2 emission components. The X-ray spectra corrected for the evaluated bremsstrahlung intensity and for the delayed background are attributed to quasimolecular KX-radiation originating from adiabatic heavy ion-atom interactions.

The investigation has been performed at the Laboratory of Nuclear Reactions, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna 1978

1. *Introduction*

Nuclear and secondary electron bremsstrahlung are intensive radiation components in most of the X-ray continua, arising from interaction of heavy ions with target materials. In a previous work /1/ we estimated the contributions of these radiations to the X-ray spectra, which were measured by the Dubna group in investigating the symmetric collision systems ^{93}Nb + ^{93}Nb (65 *MeV*, 96 *MeV*) and ^{nat}Ni + ^{60}Ni (67 *MeV*) /2/ . Doing this we carried out the calculations for secondary electron bremsstrahlung (SEB) according to the model of Folkmann et al. /3/ . For nuclear bremsstrahlung (NB) calculations we used in /1/ the theory of Alder et al. /4/ taking into consideration only the dipole (E1) term and neglecting the quadrupole (E2) term as well as the coherent interference between them. However, in a more recent theoretical investigation, Reinhardt et al. /5/ showed, that the E2 -component can become a dominant contributor to the measured continuous bremsstrahlung intensity and the interference term can influence both intensity and angular distribution. These predictions have been confirmed experimentally by Trautvetter et al. /6/ by bombarding ^{58}Ni atoms with ^{18}O and ^{12}C ions, respectively. The authors demonstrated in an excellent manner the importance of the interference term by comparing the angular distribution of the X -ray continua arising in the collision systems ^{58}Ni + ^{12}C (13.3 *MeV*) and ^{12}C + ^{58}Ni (60 *MeV*). These successes in the description of nuclear bremsstrahlung have stimulated us to evaluate carefully the contributions of the E2 -component and of the interference term for all the collision systems in the region of medium and high atomic numbers investigated in refs. [2,10,11]. It is the aim of this work to report on our first numerical results.

2. *The Differential Cross Section*

In the notation of refs. [5,7], the differential cross section for the emission of nuclear bremsstrahlung (E_x, θ_x) originating from a collision of an ion (Z_1, A_1, v_1) with a target atom (Z_2, A_2) is given by

$$\frac{d\sigma(E_x, \theta_x)}{dE_x d\Omega'_x} = \frac{1}{4\pi} \cdot \frac{\alpha^3}{E_x}\left(\frac{c}{v_1}\right)^2 Z_1^2 Z_2^2 \left(\frac{\hbar c}{Mc^2}\right)^2 \nu \{ f_1^2 (g_1^{(0)} +$$

$$+ g_1^{(2)} P_2(\cos\theta_x)) - f_1 f_2 A_R \frac{v_1}{c} (g_{12}^{(1)} P_1(\cos\theta_x) + g_{12}^{(3)} P_3(\cos\theta_x))$$

$$+ f_2^2 A_R^2 \left(\frac{v_1}{c}\right)^2 (g_2^{(0)} + g_2^{(2)} P_2(\cos\theta_x) + g_2^{(4)} P_4(\cos\theta_x))\}, \qquad (1)$$

where the emission angle (polar angle) θ_x of the NB quanta and the solid angle $d\Omega'_x$ are defined in the center-of-mass system [7]. The g-coefficients are expressed [5] by Macdonald functions $K_\lambda(\nu)$ in the form

$$g_1^{(0)} = -\frac{16}{3} e^{-\pi\nu} K_{i\nu}(\nu) K'_{i\nu}(\nu), \qquad (2a)$$

$$g_1^{(2)} = e^{-\pi\nu} \left[\frac{16}{3} K_{i\nu}(\nu) K'_{i\nu}(\nu) + 8\nu K_{i\nu}^2(\nu) \frac{d}{d\nu} \frac{K'_{i\nu}(\nu)}{K_{i\nu}(\nu)}\right], \qquad (2b)$$

$$g_{12}^{(1)} = e^{-\pi\nu} \left[\frac{64}{5} K_{i\nu}(\nu) K'_{i\nu}(\nu) + \frac{16}{5} \nu K_{i\nu}^2(\nu) \frac{d}{d\nu} \frac{K'_{i\nu}(\nu)}{K_{i\nu}(\nu)}\right], \qquad (2c)$$

$$g_{12}^{(3)} = -e^{-\pi\nu} \left[\frac{64}{5} K_{i\nu}(\nu) K'_{i\nu}(\nu) + \frac{96}{5} \nu K_{i\nu}^2(\nu) \frac{d}{d\nu} \frac{K'_{i\nu}(\nu)}{K_{i\nu}(\nu)}\right], \qquad (2d)$$

$$g_2^{(0)} = e^{-\pi\nu} \left[\frac{16}{3} \nu K'^2_{i\nu}(\nu) - \frac{16}{5} K_{i\nu}(\nu) K'_{i\nu}(\nu)\right], \qquad (2e)$$

$$g_2^{(2)} = e^{-\pi\nu} \left[\frac{32}{21} \nu K'^2_{i\nu}(\nu) - \frac{16}{7} K_{i\nu}(\nu) K'_{i\nu}(\nu) - \frac{8}{7} \nu K_{i\nu}^2(\nu) \frac{d}{d\nu} \frac{K'_{i\nu}(\nu)}{K_{i\nu}(\nu)}\right], \qquad (2f)$$

$$g_2^{(4)} = e^{-\pi\nu} \left[-\frac{32}{21} \nu K'^2_{i\nu}(\nu) + \left(\frac{80}{3}\nu^2 + \frac{192}{35}\right) K_{i\nu}(\nu) K'_{i\nu}(\nu) - \frac{32}{3} \nu K_{i\nu}^2(\nu) + \left(80\nu^3 + \frac{64}{7}\nu\right) K_{i\nu}^2(\nu) \frac{d}{d\nu} \frac{K'_{i\nu}(\nu)}{K_{i\nu}(\nu)}\right], \qquad (2g)$$

where

$$K_{i\nu}^2(\nu) \frac{d}{d\nu} \frac{K'_{i\nu}(\nu)}{K_{i\nu}(\nu)} = K_{i\nu}(\nu) \frac{d}{d\nu} K'_{i\nu}(\nu) - K'_{i\nu}(\nu) \frac{d}{d\nu} K_{i\nu}(\nu).$$

The quantity

$$\nu = E_x \cdot \frac{v_0}{v_1} \frac{Z_1 Z_2}{2E_1} \cdot \frac{A_1 + A_2}{A_2} \qquad (3)$$

is identical with the parameter of adiabaticity ξ in the model of Alder et al. [4] provided that the terms of the order of $(E_x / E_1^{cm})^2$ are neglected. The $K_{i\nu}(\nu)$ denote the Macdonald functions with imaginary index λ. They have been calculated by using the integrals given in refs. [5,7]. The expression $K'_{i\nu}(\nu) = \frac{d}{dZ} K_{i\nu}(Z)$ is a derivative with respect to the argument, whereas $\frac{d}{d\nu} K_{i\nu}(\nu)$ characterizes the total derivative with respect to ν. The remaining quantities in eq. (1) are the proton mass M, the reduced atomic mass number $A_R = \frac{A_1 \cdot A_2}{A_1 + A_2}$ and the amplitudes f_1, f_2 defined by $f_1 = \frac{Z_1}{A_1} - \frac{Z_2}{A_2}$ and $f_2 = \frac{Z_1}{A_1^2} + \frac{Z_2}{A_2^2}$, respectively. We checked carefully the formulae (2a) - - (2e) and found, in accordance with ref. [5] but contrary to the results given in [7], that the sign of the interference term in (1) must be negative when the coefficients $g_{12}^{(1)}$ and $g_{12}^{(3)}$ are used in the representation of (2c) and (2d).

Going from the center-of-mass system to the laboratory system one has to transform the emission angle θ_x and the differential cross section $\frac{d\sigma}{d\Omega_x'}$. For the transformation of θ_x, we assume that (i) $E_x \ll E_1$ and (ii) that the c.m. system moves approximately with the uniform velocity v_{cm} along the ion beam axis in the lab.system. In this case the angle of observation Θ_{Lab} for X-ray quanta is related to the emission angle θ_x by the equation [8]

$$\tan\Theta_{Lab} = \sqrt{1-K^2}\,\frac{\sin\theta_x}{\cos\theta_x + K}, \tag{4}$$

where $K = v_{cm}/c$. In the collision systems investigated in this work, we have $K \lesssim 0.02$ for all energies of incident particles. Thus it follows from eq. (4) that for NB quanta emitted in the c.m. system under $\theta_x = 90°$ the aberration in the lab. system is lower than the acceptance angle of the detector used [2]. Therefore, we assume that $\Theta_{Lab} = 90°$ when $\theta_x = 90°$. Similar arguments hold for the transformation of the differential cross section, where the relation $\frac{d\sigma}{d\Omega_x'} = \frac{d\sigma}{d\Omega_x}$ is fulfilled approximately for $\Theta_{Lab} = 90°$ and $K \lesssim 0.02$.

3. *Numerical Results and Discussion*

Taking into account the significant slowing-down of the projectiles in the thick targets used, we supposed the targets to consist of a number N of thin foils. By assuming a constant ion energy E_i inside each foil, the contribution of the foil $\{i\}$ to the measured bremsstrahlung intensity $\frac{dI(90°)}{dE_x}$ is given by

$$\frac{dI(E_i, E_x, 90°)}{dE_x} = 4\pi \cdot N_{at} \cdot N_{ion} \frac{d\sigma(E_i, E_x, 90°)}{dE_x d\Omega_x} \Delta x_i \times$$

$$\times \frac{\Delta\Omega}{4\pi} \epsilon_{rel}(E_x) A_i S_i, \tag{5}$$

where $\frac{\Delta\Omega}{4\pi}\epsilon_{rel}(E_x) = \epsilon_{abs}(E_x)$ is the absolute efficiency of the X-ray detector calibrated by standard radioactive sources mounted at the target position; Δx_i is the thickness of the target foil, whereas the quantities N_{at} and N_{ion} denote the number of target atoms per mass unit and the number of incident ions, respectively. The symbols S_i and A_i characterize the corrections for selfabsorption inside the foil and for absorption in the dead layer between the foil considered and the target surface. The factor A_i includes also the attenuation of the bremsstrahlung intensity by additional absorbers. For comparison with the measured spectrum of nuclear bremsstrahlung the expressions (5) have to be summed over i.

Figure 1 shows, as an example of our numerical results, the predicted angular distribution of the cross sections $\frac{d\sigma(\theta_x)}{dE_x d\Omega_x}$ for nuclear bremsstrahlung arising in the collision system $^{60}Ni + {}^{58}Ni$ (60 *MeV*). In the upper part we compare for $E_x = 30$ *keV* the differential

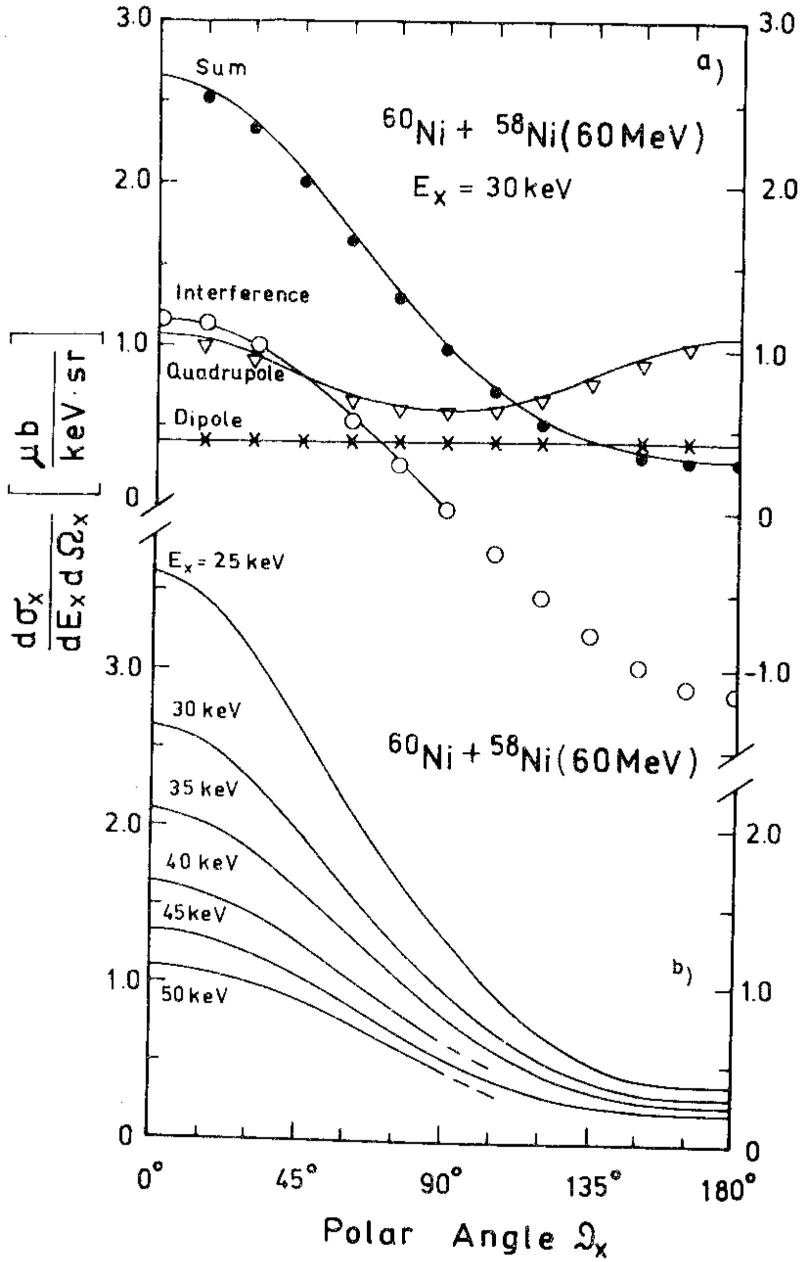

Fig. 1. Calculated angular distributions of the cross section $\frac{d\sigma}{dE_x d\Omega_x}$ *for nuclear bremsstrahlung arising in the collision system* $^{60}Ni + ^{58}Ni$ *(60 MeV). Upper part: Comparison between numerical results of ref.* /5/ *and of the present work for* $E_x = 30$ *keV. Full lines represent the results of ref.* /5/. *Crosses, triangles and circles give our values for the dipole and the quadrupole term as well as the interference between them. The points show our results for the summed angular distributions* $\frac{d\sigma}{dE_x d\Omega_x}$. *Lower part: The dependence of the cross section on* θ_x *for various* X *-ray energies in the range of 25 - 50 keV.*

cross section evaluated using eqs. (1) and (2) with the results obtained by Reinhardt et al. /5/. The crosses, circles and triangles denote our calculated values and not experimental results. This comparison should be a good proof for the correct work of our computer code. The differences between the two calculations, which amount to about 5%, may be caused by deviation between the two sets of the $g_\lambda^{(1)}$ used. The lower part of *fig. 1* shows the angular distribution of cross sections for various X- ray energies in the range of 25 - 50 *keV*.

The amplitude f_1 changes the sign if the collision partners are interchanged. Therefore, completely different angular distributions of NB are expected for the collision systems $^{60}Ni + ^{58}Ni$ (60 *MeV*) and $^{58}Ni + ^{60}Ni$ (60 *MeV*). In order to illustrate this effect, we present in *fig. 2* our numerical results for $^{58}Ni + ^{60}Ni$ (60 *MeV*). The upper part of this figure shows for $E_x = 30$ *keV* the strengths of the dipole, quadrupole and interrefence terms versus θ_x . The lower part gives the cross sections of nuclear bremsstrahlung for various X-ray energies in the range of 25 - 50 *keV*. By comparing *figs. 1* and *2* the influence of f_1 can be easily seen.

The contributions of nuclear bremsstrahlung to an X -ray continuum measured by investigation of the

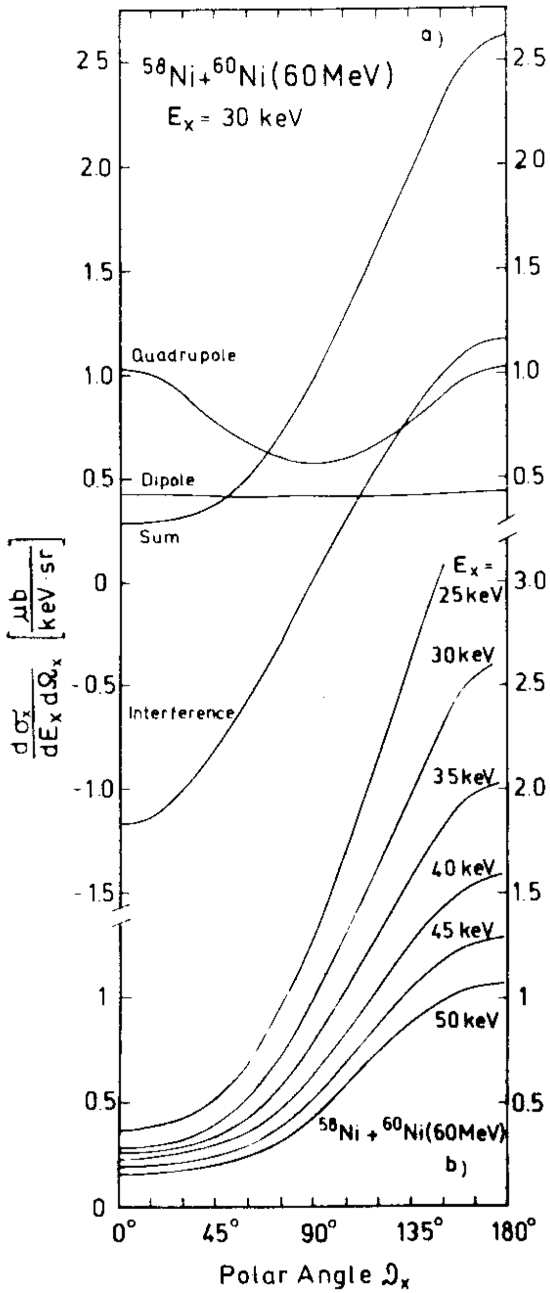

Fig. 2. Angular distribution of the cross section $\frac{d\sigma}{dE_x d\Omega_x}$ for nuclear bremsstrahlung arising in the collision system $^{58}Ni + ^{60}Ni$ (60 MeV). The upper part shows the strength of the dipole, quadrupole and interference term versus θ_x for $E_x \approx 30$ keV. The lower part presents the dependence of the cross section on θ_x for various X-ray energies in the range of 25 - 50 keV.

collision system $^{nat}Ni + ^{60}Ni$ (67 *MeV*) /2,9/ are presented in *fig. 3*. This spectrum was obtained with a Ge(Li) - detector exposed at $\Theta_{Lab} \approx 90°$ with respect to the beam direction. According to eq. (1) the interference term vanishes for this angle of observation.

Figure 3 shows clearly, that for $E_x < 40$ *keV* the summarized intensities of room background and nuclear bremsstrahlung were much lower than the intensity of quasimolecular KX -radiation. Contrary to this, in the energy region $E_x > 50$ *keV* the observed X-ray spectrum can be explained by the calculated nuclear bremsstrahlung and the measured room background. There is no necessity to introduce MO radiation in this region. Moreover, the intensity of secondary electron bremsstrahlung was always found to be negligible compared to those of the E1 and E2 components of nuclear bremsstrahlung.

Figure 4 shows the experimental X -ray spectrum together with the results of numerical calculations for SEB and NB obtained by investigating the collision system $^{74}Ge + ^{74}Ge$ (54 *MeV*) /11/. The target used had a thickness of 500 $\mu g/cm^2$ and was enriched to 98.8% with ^{74}Ge. The Ge layer was evaporated on a thick backing of pure aluminium. The target and backing were exposed at an angle of 45° with respect to the beam direction, but the X -rays were measured perpendicularly to the beam. Since the ^{74}Ge ions, passing through the Ge foil with an energy of about 44.75 *MeV* stopped in the Al backing, we had to consider the contribution of secondary electron and nuclear bremsstrahlung from $Al + ^{74}Ge$ too. In *fig. 4* triangles denote the sum of delayed background, SEB and NB(E1 +E2) for both reactions, $^{74}Ge + ^{74}Ge$ (54 *MeV*) and $Al + ^{74}Ge$ (44.75 *MeV*). As can be seen,

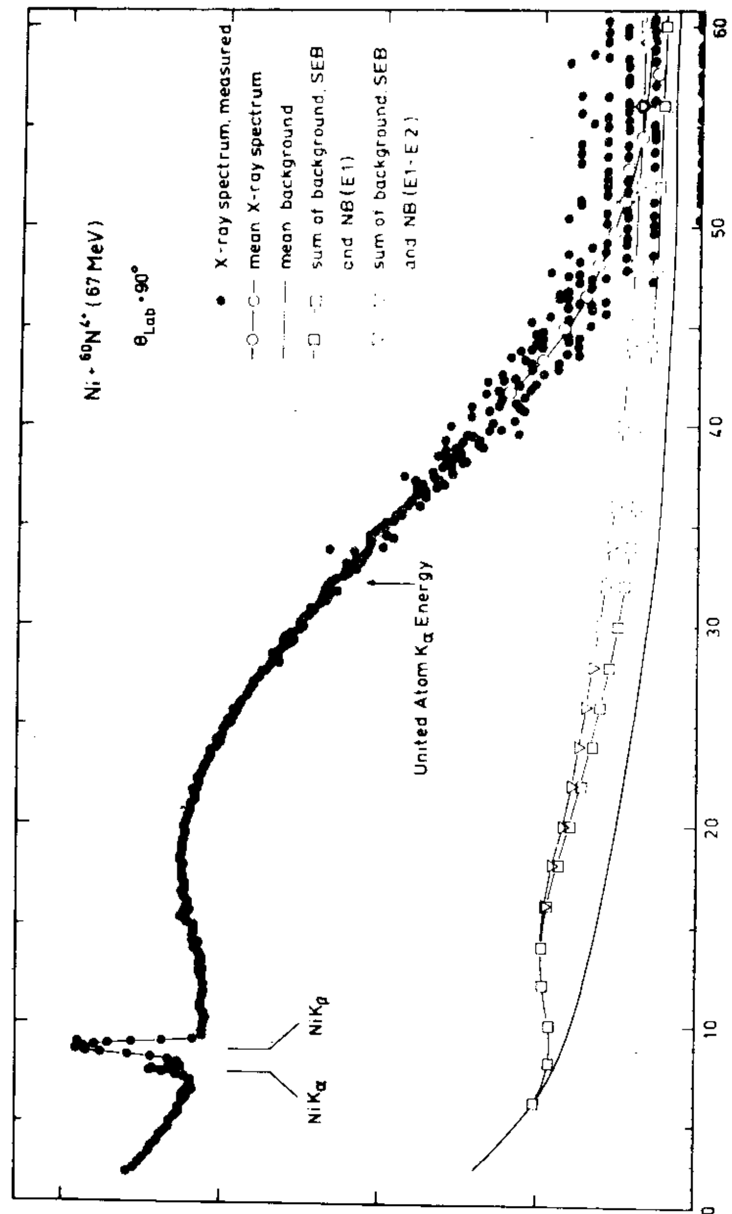

Fig. 3. Calculated contributions of bremsstrahlung to the X-ray continuum obtained on $^{nat}Ni + {}^{60}Ni^{4+}$ *(67 MeV)* /2,9/

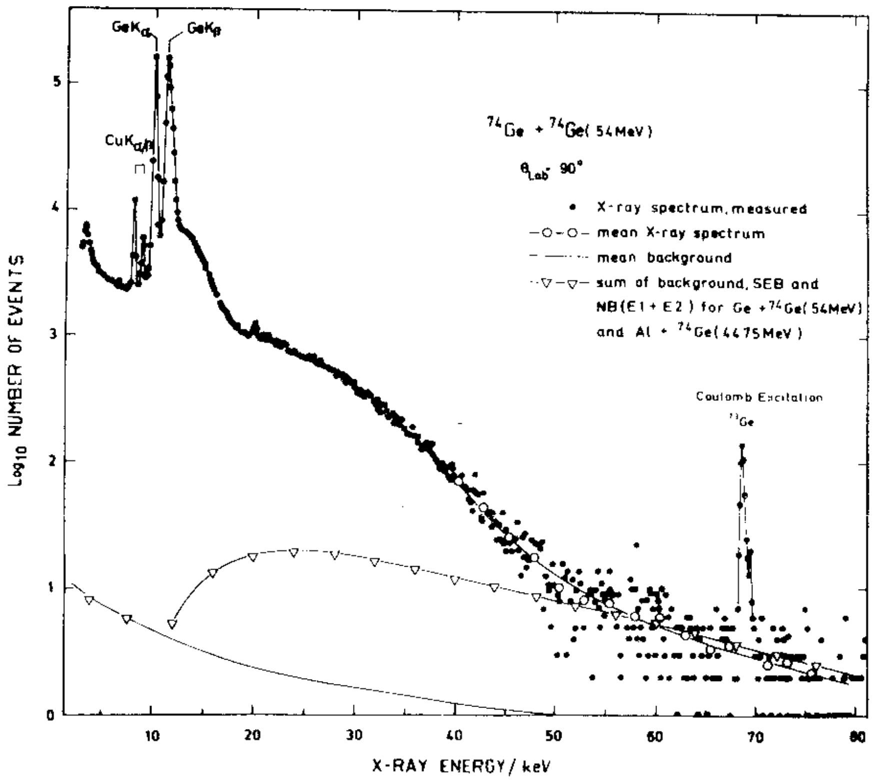

Fig. 4. Calculated contributions of bremsstrahlung to the X-ray continuum obtained in $^{74}Ge + {}^{74}Ge$ *(54 MeV)* /11/. *The* Ge *target (500 μg/cm²) was evaporated on a thick* Al *backing, which stopped the heavy ions passing through the* Ge *layer with an energy of about 44.75 MeV.*

quasimolecular KX-radiation dominates again in the energy region $E_x < 50$ *keV*, whereas for energies far from the united atom limit ($E_x^{ua} \approx 43$ *keV*) the observed X-ray continuum can be attributed to room background and nuclear bremsstrahlung only.

The data obtained in $^{93}Nb + {}^{93}Nb$ (67 *MeV*) experiments /2/ are presented in *fig.* 5. In measuring this intensity distribution a thick Nb target and an intrinsic Ge-detector exposed at a standard 45°/90° geometry were applied. According to eq. (1), the E1 component of nuclear

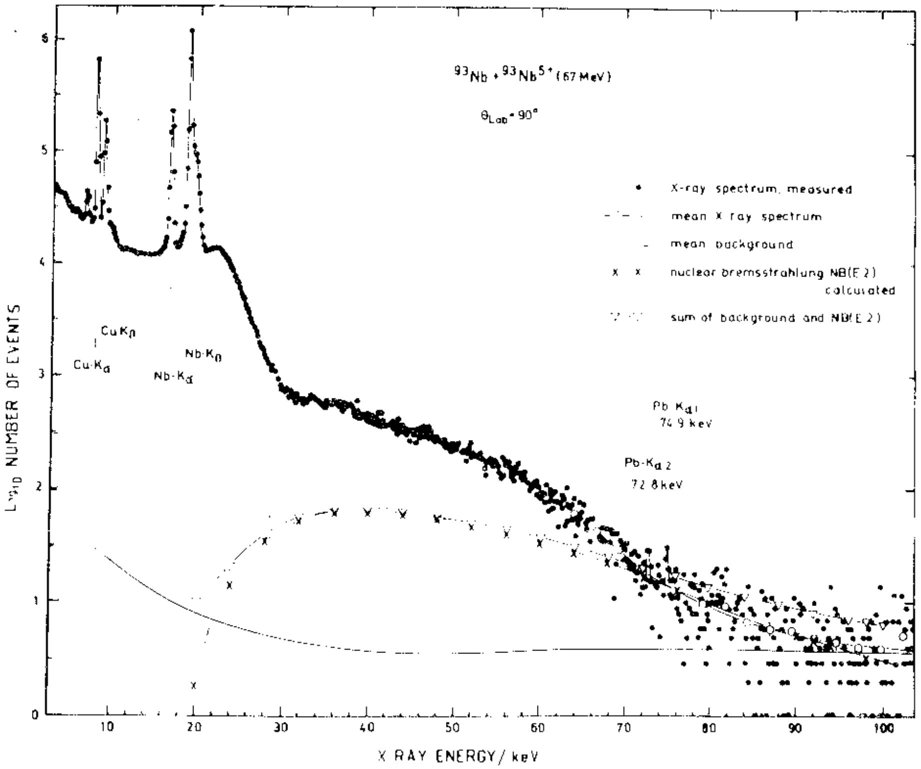

Fig. 5. The calculated contribution of the quadrupole (E2) *component of nuclear bremsstrahlung to the* X *-ray continuum obtained in* ^{93}Nb + ^{93}Nb *(67 MeV)* /2,10/

bremsstrahlung disappears if a symmetric collision system such as Nb + Nb is considered. Consequently, the NB spectrum shown in *fig. 5* was obtained taking into account only the E2 component, whose intensity is remarkably high. This may partially be explained by the fact that the differential cross section $\frac{d\sigma}{dE_x d\Omega_x}$ is proportional to the expression $Z_1^2 Z_2^2$. For $E_x < 70$ *keV* the measured X-ray spectrum can be interpreted by the continua C1 and C2 of quasimolecular KX-radiation well known from former experimental and theoretical investigations /12/. On the other hand, the sum of nuclear

bremsstrahlung and room background dominates beyond the energy value $E_x \approx 70$ *keV*. A slight deviation of this spectrum from the mean values of experimental data indicates an overestimation of the NB intensity. This is due to an error on the determination of the absolute number of incident ions.

The author would like to thank Academician G.N.Flerov for his support to this work, Prof. K.-H.Kaun for his stimulating interest and helpful discussions and Mrs. L.Kumpf for the preparation of the drawings.

References

1. *Gippner P. JINR, E7-8843, Dubna, 1975.*
2. *Frank W. et al. Z.f.Physik, 1976, A277, p. 333.*
3. *Folkmann F. et al. Nucl.Instr. and Meth., 1974, 116, p. 487.*
4. *Alder K. et al. Rev.Mod.Phys., 1956, 28, p. 432.*
5. *Reinhardt J., Soff G., Greiner W. Z.f.Physik, 1976, A276, p. 285.*
6. *Trautvetter H.P., Greenberg J.S., Vincent P. Phys. Rev.Lett., 1976, 37, p. 202.*
7. *Malkov E.I., Shmushkevich I.M. JETP, 1960, 39, p.1837.*
8. *Jackson J.D. Classical Electrodynamics. John Wiley and Son, New York, 1962, p. 362.*
9. *Frank W. et al. JINR, E7-9065, Dubna, 1975.*
10. *Frank W. et al. JINR, E7-9427, Dubna, 1975.*
11. *Kaun K., Manfrass P., Frank W. Particles and Nucleus, Moscow Atomizdat, 1977, vol. 8, part 6, p. 1246 (in Russian).*
12. *Heinig K.H. et al. J.Phys. B: Atom.Molec.Phys., 1977, 10, p. 1321.*

Received by Publishing Department
on March 31, 1978.