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n-p Bremsstrahlung in Heavy Ion Collision Processes

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1. Introduction

The goal of this presentation is to summarize the current status of the interpretation of energetic γ-rays in heavy ion collisions via the n-p-bremsstrahlung mechanism. An essential element of the topic is a transport equation to approximate the fast non-equilibrium nucleon-nucleon cascade/emission stage of the heavy ion reactions. It is during this stage that we expect the n-p-bremsstrahlung processes to produce energetic photons.

I shall begin with a very brief description of the Boltzmann master equation (BME) model(1-4) which will be used as the transport code, deferring to earlier works for a more complete description,(3-5) and present but a single representative comparison with an experimental neutron emission spectrum. I shall then summarize the status of the elementary n-p-γ cross section needed to extend the transport code to photon emission in heavy ion reactions, and summarize the status of these comparisons with data.

2. Boltzmann master equation

The BME(1-5) is defined by the set of coupled differential equations for the time-dependent change in the number of nucleons of type x in a bin at energy i (above the bottom of the nucleon potential well) as

$$\frac{dN_i^x}{dt} = g_i^x \sum_y \sum_{jkl}{}' [\omega_{kl\to ij}^{xy}\, g_k^x g_l^y g_j^y n_k^x n_l^y (1 - n_i^x)(1 - n_j^y)$$

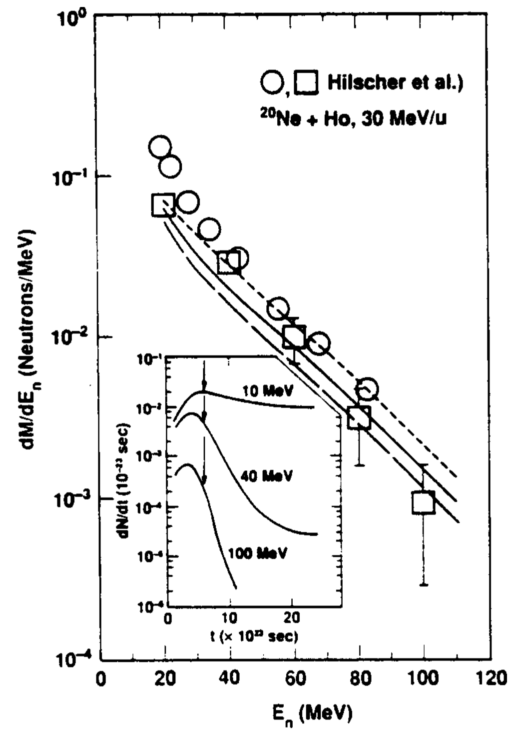
$$- \omega_{ij\to kl}^{xy}\, g_j^y g_k^x g_l^y n_i^x n_j^y (1 - n_k^x)(1 - n_l^y)] - n_i^x \omega_{i\to i'} + f_i(p,n), \qquad (1)$$

Here the superscripts x and y take on the values p and n; g_m^x represents the number of x (proton or neutron) single-particle states (in the 1 MeV wide bin used in our code) at energy m; n_m^x represents the fraction of g_m which is occupied. The $\omega_{ij \to kl}^{xy}$ represent the rates for a single nucleon of type x at energy i to scatter with a single nucleon of type y at energy j to give final nucleon energies k and l. These rates are based on free N-N scattering cross sections due to Chen _et al_.[6] for type pp, nn, or np scattering as appropriate. The Pauli exclusion principle is entered via the terms $(1 - n_m^x)$ in Eq. (1). The next to the last term in Eq. (1) represents the rate of emission of nucleons in bin i into the continuum, where $w_{i \to i'}^x$ is calculated on the basis of the usual statistical inverse cross section method as the rate of capture of particle x at laboratory energy i' into the nucleus at energy i and B_x is the binding energy of particle x. The final term, $f_i(p,n)$, is the rate of insertion of nucleons into bin i from the coalescing projectile. For this term we assume a constant velocity of approach based on projectile c.m. energy reduced by the Coulomb-barrier height. We calculate the energy distribution of the coalescing nucleons as the distribution of n particles sharing U units of excitation randomly.[4,5]

We show the success of the BME in reproducing experimental neutron spectra in Fig. 1, for the case of ^{20}Ne + Ho at 30 MeV/nucleon.[7] Similarly good predictive ability has been demonstrated for the same target and projectile at 11, 15 and 20 MeV/nucleon, for ^{12}C induced reactions at 25 MeV/nucleon and for ^{40}Ar induced reactions at 20 MeV/nucleon.[8] We therefore have evidence that the model approach provides a good description of nature, and wish to add the inelastic npγ cross sections to Eq. (1) in order to see if experimental photon spectra in heavy ion reactions might reasonably be interpreted in terms of this simple n-p collision mechanism, treated as an incoherent sum over neutron-proton collisions.

3. <u>n-p-bremsstrahlung elementary cross sections</u>

Many of the analyses of heavy ion/photon spectra yields[9-19] have been done in terms of an elementary npγ cross section based on a semi-classical radiation[20] expression. These results have generally been normalized to the experimental p(d,γ) spectrum for 140 MeV protons which was reported by Edgington and Rose.[21] More recently the Grenoble group[22,23] has made some (p,nucleus)γ measurements which may be compared with some of the earlier data; these results are shown in Figs. 2 and 3. The results calculated with the



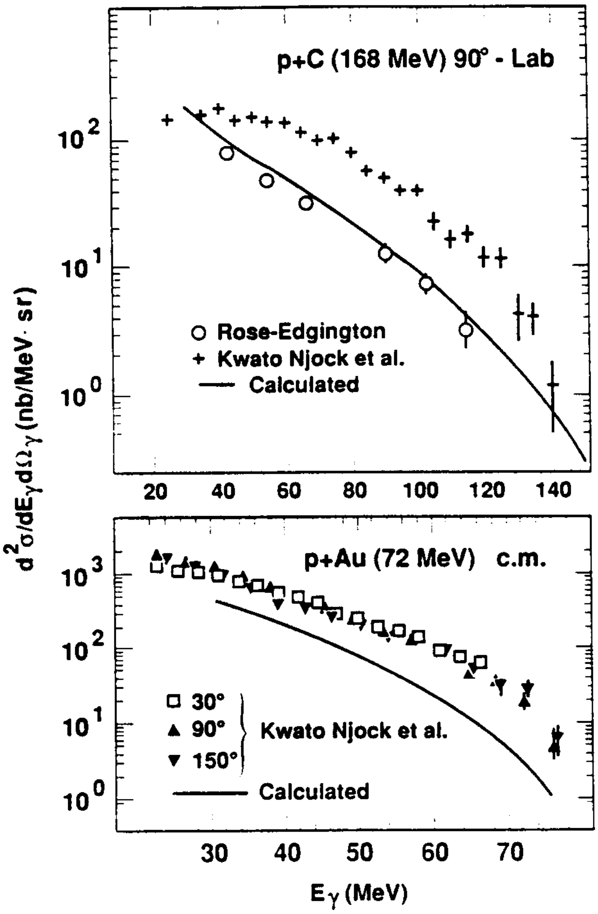


Fig. 1.(right) Experimental and calculated neutron energy spectra from 30 MeV per nucleon ^{20}Ne on Ho. The squares represent the preequilibrium yields deduced by Hilscher (7) by fitting an assumed isotropically emitting moving source to the high energy data. The circles represent the total differential data of Hilscher et al., integrated directly. The solid line is the BME result; the short and long dashed lines correspond to increasing and decreasing the nucleon mean free path by 50%. The insert shows the calculated time dependence of the emission of 10, 40 and 100 MeV neutrons. The arrows represent the time at which fusion is assumed complete in the calculation.

Fig. 2. (left) The solid curves are results of a semi-classical radiation formula from (22) compared (upper) with 168 MeV p + ^{12}C gamma ray spectra from (22). The results of Rose and Edgington scaled from 140 MeV by multiplication of ordinate and abcissa by 168/140 are shown for comparison. In the lower section data for p + Au with 72 MeV protons from (23) are shown versus predictions of the same semi-classical radiation formula. All results are taken from (22,23).

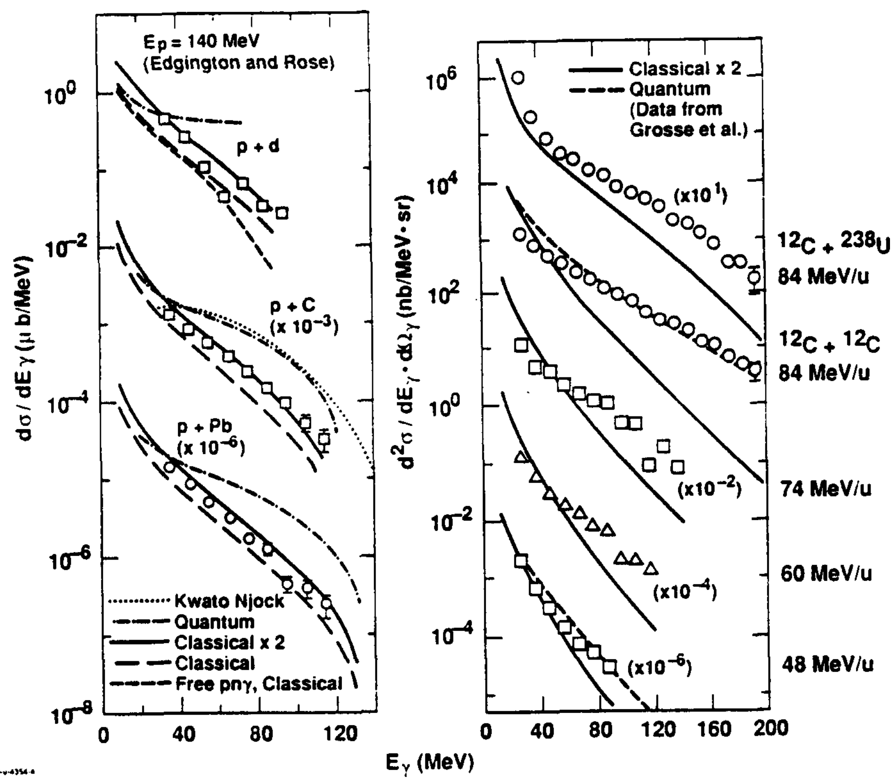


Fig. 3. (left): Comparisons of calculations with high energy γ-ray data of Edgington and Rose(23) for a 140 MeV proton beam. At the top, the p+d data are used as a standard with which to "normalize" the semiclassical pnγ bremsstrahlung equation. The short-dashed line is the same, only with the momentum distribution of the target neutron in deuterium taken into account. The solid line corresponds to the deuteron calculation multiplied by two to crudely account for the effect of meson exchange. The dotdashed line corresponds to folding the quantum bremsstrahlung result of Neuheuser and Koonin (26) into the deuteron calculation. The lower two spectra show γ-ray data for p+^{12}C and p+Pb. The curves represent calculations with the master equation using the semiclassical bremsstrahlung cross sections (dashed lines), the semi-classical cross sections multiplied by two (solid lines), and the quantum bremsstrahlung cross sections (dot-dashed lines). For C+p, the dotted curve is the experimental result of Kwato Njock _et al_. (24) for 168 MeV protons, scaled in magnitude by 140/168, but not scaled for energy.

Fig. 3. (right): γ-ray data (30) for ^{12}C + ^{238}U at 84 MeV/nucleon (top), ^{12}C + ^{12}C at 84, 74, 60 and 48 MeV/nucleon. The solid lines represent the master equation calculation for a sharp-cutoff initial exciton distribution. The dashed lines represent master equation calculations using the quantum bremsstrahlung cross sections of Neuheuser and Koonin (26).

semiclassical radiation expession are not in good agreement with the newer (p,nucleus)γ data. Quantal radiation results due to Neuheuser and Koonin,[24] based on the pioneering work of V. Brown,[25,26] give results which are in much better agreement with the data; the difference between the two sets of results is mainly due to the inclusion of the meson exchange currents in the quantal theory. What is still needed is a good experimental verification of the quantal theory via measurements of either p(d,γ) or n(p,γ) spectra at a range of projectile energies.

4. Energetic γ-rays from heavy ion collisions

In Figs. 3 and 4 we show comparisons of experimental and calculated spectra from ^{14}N and ^{12}C induced reactions at energies of 20-84 MeV/nucleon.[27-29] It appears that the quantal radiation result, when incorporated into the BME, is capable of reproducing all measured spectra. The semi-classical dependence, which (if the quantal result is more nearly correct) has an incorrect energy dependence, shows discrepancies which systematically increase with increasing bombarding energy. We therefore believe that the energetic photons may be understood in terms of the elementary n,pγ process, and illustrate once again the importance of Fermi momentum coupling in these reactions. A final conclusion requires experimental data with which to confirm the correctness of the theoretical npγ spectra used as input to the calculations presented herein.

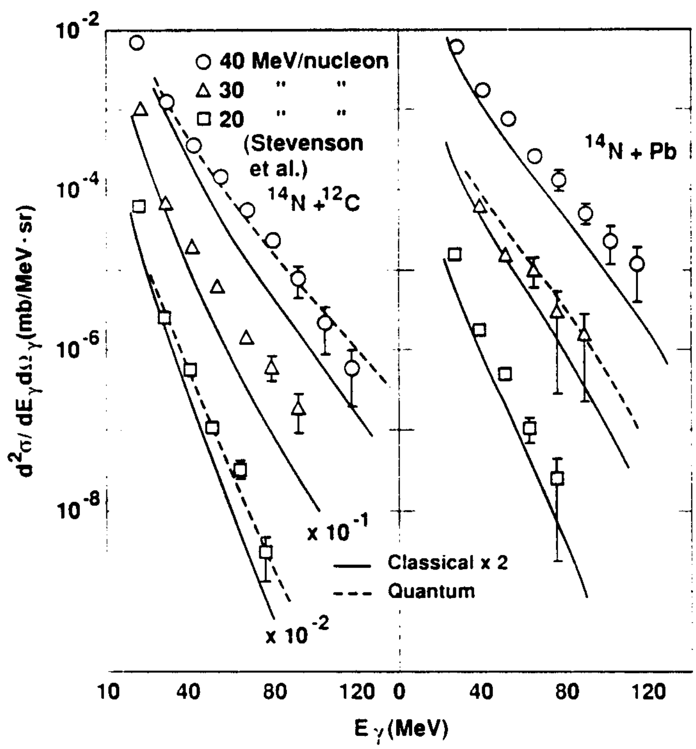


Fig. 4. The γ-ray data of Stevenson (27,29) are shown for $^{14}N+^{12}C$ (left side) and for $^{14}N+Pb$ (right side) at 20, 30 and 40 MeV/nucleon. The solid lines correspond to the BME calculation using the semi-classical bremsstrahlung cross sections multiplied times 2 in Eq. 1 while the dashed lines correspond to quantum bremsstrahlung cross section of Ref. (24). The results of Stevenson et al. have been plotted to include the recent detector calibration results (29).

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