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SUBTHRESHOLD PHOTONS IN HEAVY-ION REACTIONS AT INTERMEDIATE ENERGIES *

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In the present talk, I discuss about the properties of the energetic photons produced in heavy-ion reactions. I show that they are sensitive to the maximum density reached in the first stage of the nuclear reaction. Then, the existence of a thermal contribution to the photon differential cross-section is discussed. These photons are sensitive to the properties of the Equation-of-State, to the dynamics of the reaction and represent a new thermometer of heated nuclear matter. I finally describe the future experiments planified at KVI and GANIL.

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1. Introduction

The creation of particles like photons, mesons, di-lepton and anti-baryons below the free NN threshold energy provides today the best observable to study hot and dense nuclear matter [1] created in heavy-ion (HI) reactions. Subthreshold particles are mainly created during the high energy and baryon density phase of the reaction probing well defined states of the dynamical evolution of nuclear matter in HI collisions. A major part of their energy is provided by the excited nuclear medium giving information about the phase space occupancy of nucleons at intermediate energies (20–200A MeV) [2] and about the chemical composition at relativistic energies (500–2000 A MeV) [3].

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TABLE I

Threshold energies for the production of particles in free nucleon-nucleon collisions

Particle	$E_{NN}^{\rm thr}$(MeV)
photon 30 MeV	60
π°	280
$\pi^{+,-}$	290
η	1256
K^{+}	1580

Subthreshold hard photons ($E_\gamma > E_{\rm beam}/2$) have the additional advantage, as an electromagnetic probe, that they weakly interact with the surrounding nuclear medium. In this respect information carried on by these photons is easier to decode since the photon freeze-out and photon production occur in the same phase of the nuclear reaction. Unfortunately, subthreshold photons can only be detected at intermediate energies, $10A$ MeV to $\sim 200A$ MeV, since the high yield of neutral mesons at relativistic energies makes impossible the detection of direct energetic photons from the nuclear reaction. In intermediate energy HI reactions hard photons are mainly produced during the first stage in first-chance np (*direct photons*), but a second contribution is observed at photon energies between 20 to 50 MeV (*thermal photons*). In this talk, I will show that subthreshold photon production represents a good observable to measure the compression in the initial phase of the reaction. Then I discuss the experimental evidences of a contribution to the hard photon spectrum from second-chance pn collisions. These photons could be produced in later stages of the nuclear reaction from a thermalizing source, carrying on information the EoS and being sensitive to the temperature of nuclear matter well before than the freeze-out phase of the source is reached.

2. The photon spectrum in HI reactions at intermediate energies

The, par excellence, photon spectrum in HI reactions at intermediate energies was measured at GANIL with the photon spectrometer TAPS [4] for the system Kr+Ni at $60A$ MeV (see Fig. 1). Photon energies from 1 to 300 MeV were measured, covering more than ten orders of magnitude of the differential cross-section. Traditionally, the photon spectrum has been

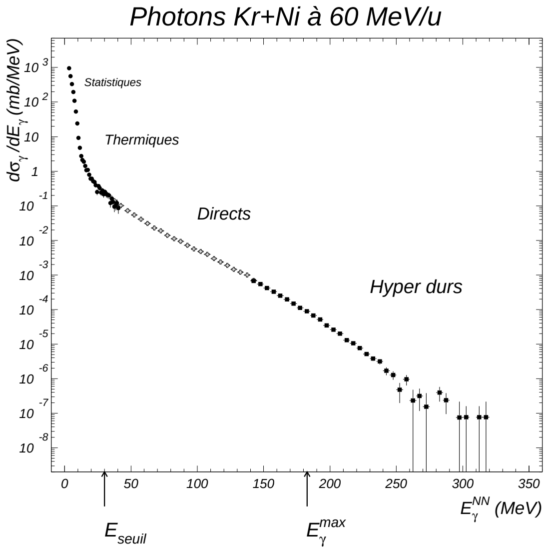

Fig. 1. The measured photon spectrum in the nucleon-nucleon center of mass frame in the reaction Kr+Ni at 60A MeV.

divided in three regions according to the main mechanism involved in their production. First we observe the emission of photons from 1 to 15 MeV energy. They are produced by the statistical decay of hot fragments produced in the final stage of the nuclear reaction. The intermediate region from 15 to 25 MeV is believed to be populated by the decay of the giant resonance states of the projectile-like fragment, target like fragment and intermediate mass fragments of the reaction as it has been observed at lower beam energies ($\sim 20A$ MeV). The last contribution is from hard photons ($E_\gamma > 30$ MeV) produced by individual proton-neutron bremsstrahlung which takes place in the first stage of the reaction [1,5]. I do not consider the trivial contribution to the photon spectrum due to the neutral pion decay. This contribution can be neglected for beam energies below $50A$ MeV, and for higher beam energies this contribution can be measured studying the production of neutral pions in coincidence with the photon production [6].

Recent measurements with the TAPS photon spectrometer TAPS have brought to light new aspects of the photon production in HI reaction at intermediate energies. These measurements have enable to study the photon production in detail, by measuring the double-differential cross-section [6], exclusive photon production [7–9], very energetic photons [10] and the photon correlation function (see contribution of F.M.Marqués at this conference). Today, the photon spectrum can be divided in four regions as:

1. Statistical photons are dominate in the region from 1 to 15 MeV and are produced by the statistical decay of hot fragments.
2. In the region from 20 to 50 MeV we shall see that two contributions are present: (*i*) the bremsstrahlung photons from first chance proton-neutron (*direct photons*) and (*ii*) a softer photon emission that we explain in terms of a bremsstrahlung emission from a thermalizing source (*thermal photons*).
3. The region from 50 to 150 MeV photon energy dominated by the direct photons.
4. The very energetic photons ($E_\gamma > 150$ MeV) [11] (see Fig. 1) which have revealed a new tool for the study of collective properties of the dense and excited nuclear medium. The crucial question is how a mesoscopic system of interacting fermions is able to concentrate a significant fraction of the total available energy in the creation of a massive or energetic particle. In particular, since the intrinsic momentum is not high enough, new mechanisms should be considered like secondary processes [10] or many-body effects (high order correlations, three-body collisions, off-shell nucleons...).

2.1. Direct photons

The production of hard photons in HI reactions at beam energies from 10 to 100A MeV have been largely studied during the last ten years [1, 5]. Summarizing, it has been found that:

1. The photon production scales with the geometrical number of nucleon-nucleon collisions in the overlap region [12].
2. Assuming that photon angular distribution is almost isotropic from a moving source, the velocity of the source is half of the beam velocity and is weakly dependent on the size of the system [1].
3. The angular photon distribution of photons in the moving source frame exhibits a contribution of dipolar radiation.
4. Photon multiplicity increases with the centrality of the reaction [7, 13, 14].
5. Photon spectrum exhibits an exponential shape from 40 to 150 MeV photon energy. The slope of this spectrum E_0 is almost independent on the size of the system and linearly increases with the beam energy E_l [1, 15, 16]. The following parameterization of the hard photon slope has been found: $E_0[\mathrm{MeV}] = 0.68(E_l[\mathrm{MeV}])^{0.83}$ [15].

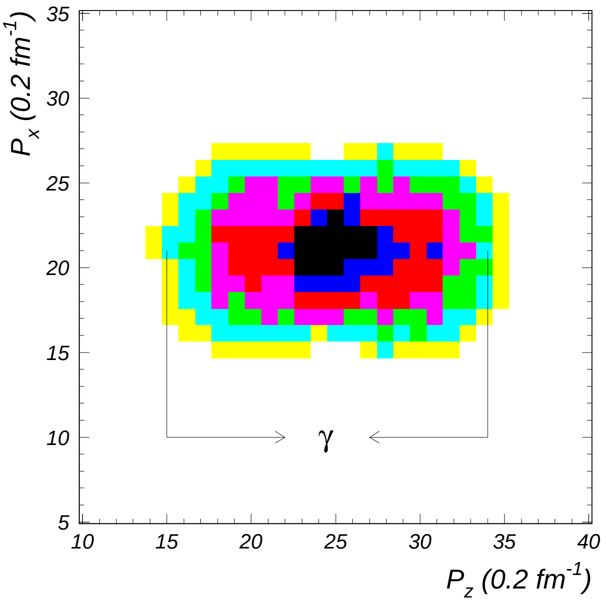

Fig. 2. Density distribution of pseudo-particles in the momentum space given by BUU [1] when the maximum rate of photon production is reached for the system Xe+Sn at 50A MeV.

These experimental facts suggest that hard photons in HI reactions are produced by individual proton-neutron bremsstrahlung. This interpretation is in agreement with the measured source velocities and with the participant-number scaling. The presence of a dipolar term suggest that photons are mainly emitted in the first-chance *pn* collision.

Models of the production of energetic photons in HI reactions based on the folding of the beam momentum of nucleons, the elementary *pn* bremsstrahlung cross-section and the intrinsic momentum of nucleons in the interaction zone successfully explain the properties of the photon production. The density of nucleons in the momentum space in the first stage of the reaction (see Fig. 2) has been calculated with a BUU simulation. We observe that only proton-neutron collisions with high relative momentum (see Fig. 2) are able to concentrate the energy necessary for the creation of a hard photon. Thus the shape of the photon spectrum explores the momentum density of nucleons with the highest intrinsic momentum and during the compression phase of the reaction.

The dependence of the exponential slope of the photon spectrum with the centrality of the reaction was exhaustively studied for the system Kr+Ni at 60A MeV [7, 15] (see Fig. 3). We observe a strong decrease when one goes from central collisions to peripheral ones. Since the photon spectrum

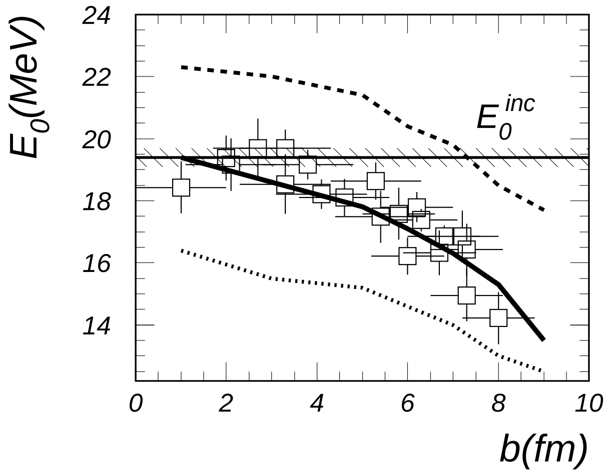

Fig. 3. Variation of the slope parameter E_0 of the hard photon spectra with the impact parameter in the reaction Kr+Ni at 60A MeV.

shape reflects the initial beam momentum and the momentum distribution of nucleons within participant zone, the observed change in the slope results from a variation of the maximum intrinsic momentum of nucleons in the participant zone with the centrality of the collision.

We can extend the previous parameterization of the hard photon slope with the beam energy and include the dependence with centrality the reaction [2, 15]:

$$E_0(p_l, b) = A(p_l + 2\Delta p_i(b))^B\,, \tag{1}$$

where p_l is the laboratory beam momentum per nucleon and Δp_i de variation of the intrinsic momentum when one goes from central reactions to peripheral ones. Parameters A and B are obtained by fitting the existing systematics of the hard photon slope as a function of the laboratory beam momentum. Parameterization of Eq. (2) allows to measure the variation of the intrinsic momentum of nucleons as a function of the centrality of the reaction. Furthermore, the density of the participant zone can be calculated assuming the local Thomas–Fermi relation and normalizing the highest impact parameter value (compression effects should be negligible in peripheral reactions) to the maximum density given by a BUU calculation at the same impact parameter (see Fig. 4). We observe a good agreement of the increase of the maximum density going from peripheral reactions to the central ones with the densities obtained from BUU calculations. Maximun densities of $1.5\rho_0$ are reached in central reactions.

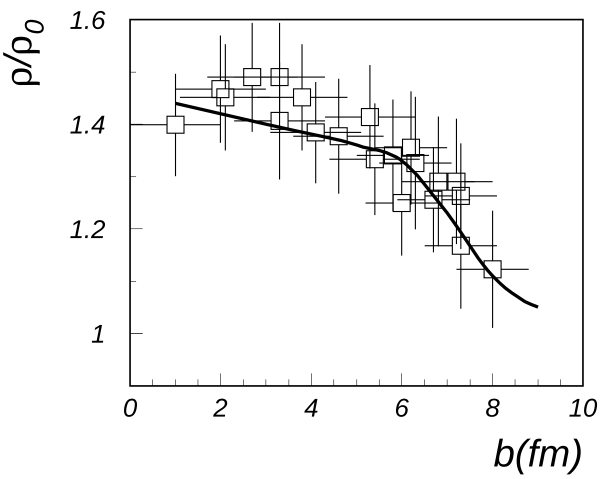

Fig. 4. Relative density reached in the overlap region in the reaction Kr+Ni at 60A MeV. Experimental values have been normalized to the density $\rho = 1.1\rho_0$ for the highest impact parameter. The solid line represent a BUU calculation of maximum density reached in the participant zone.

2.2. Thermal photons

Can the full photon spectrum be explained in terms of first-chance nucleon-nucleon bremsstrahlung or should other mechanisms be taken into account? In order to answer this question we will compare the two interpretations of the photon production in HI reactions given in the following references [17, 18] (see Fig. 5 and 6).

One of the first measured spectrum of hard photons was in the reaction N+C and N+Pb at 20, 30 and 40A MeV [17] (the present discussion will be centered on the highest beam energy, see Fig. 5). We observe that the spectrum for the lightest system shows an exponential behaviour from 20 to 100 MeV, however a deviation from this behaviour is observed at photon energies between 20 to 50 MeV in the heaviest system. In this article the photon production is explained in terms of thermal bremsstrahlung emission in energetic pn collisions which take place in a thermalized fireball. We observe that the calculated photon spectra has an exponential shape and underestimate the photon differential cross-section for photon energies larger than 50 MeV.

More recently, the photon production has been studied in the reaction N+Ag at 35A MeV [18] (see Fig. 6). In this case, the photon spectrum is understood in terms of bremsstrahlung emission in first-chance pn collisions. Reacting nuclei are considered to be Fermi gases of nucleons. The nucleons are transferred from target (projectile) to the projectile (target) during the

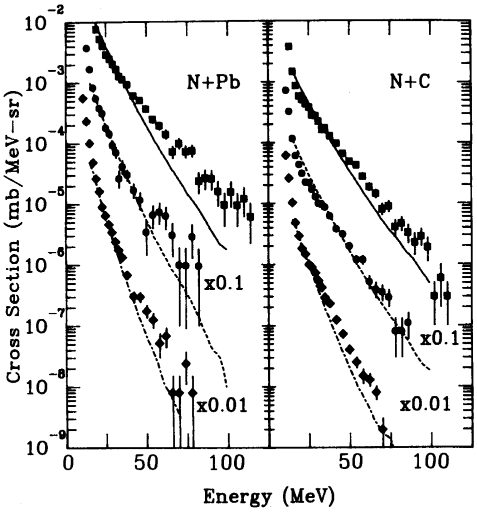

Fig. 5. Photon spectra measured at 90° in the reaction N+C and N+Pb at 20(square), 30(circle) and 40A MeV(diamond). Theoretical prediction of a thermal bremsstrahlung model are compared to the experimental data.

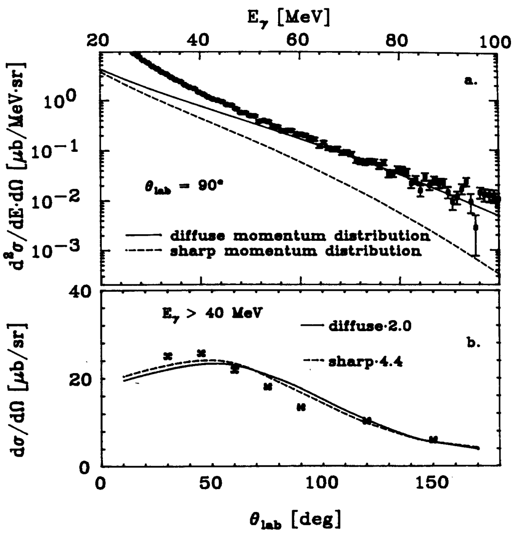

Fig. 6. a — Photon spectrum measure at 90° in the reaction n+Ag at 35 A MeV. The solid line is the result of the calculation of the yield of hard photons photons using the incoherent bremsstrahlung in NN collision boosted by a diffuse momentum distribution of nucleons. b — Angular distribution of photons above 40 MeV energy.

formation of a neck. Transferred nucleons from target (projectile) collide with the nucleons in the projectile (target). The present calculation reproduces quite well the photon spectrum for energies larger than 50 MeV but underestimates the photon yield below this energy.

Combining both measurements and interpretations, we should conclude that the hard photon production can be fully explained as an emission of bremsstrahlung photons in the first-chance nucleon-nucleon collisions, followed on an emission of thermal bremsstrahlung photons from a thermalizing source. The thermal contribution is seen as a deviation of the exponential behaviour at low energies ($E_\gamma < 50$ MeV). This thermal contribution is not seen for the lightest system (N+C).

As we have seen in Fig. 1, the last generation of experiments with new photon arrays like TAPS [4] have allowed to measure the exclusive photon spectra up to very high energies. These measurements allow to properly determine the contribution of the first-chance *pn* bremsstrahlung which mainly populates the energetic part of the spectrum. We assume, as it is suggested by most of models of photon production based on incoherent bremsstrahlung emission from individual *pn* collision boosted by the Fermi momenta [1,5,18], that the photon spectrum exhibits an exponential behaviour in the NN center of mass frame. The direct photon contribution is determined fitting the hard photon spectrum from 50 to 150 MeV photon energy (see Fig. 7). After subtraction of the direct and statistical photon contributions (see Fig. 8) the remaining photon spectrum exhibits an exponential behaviour, with a

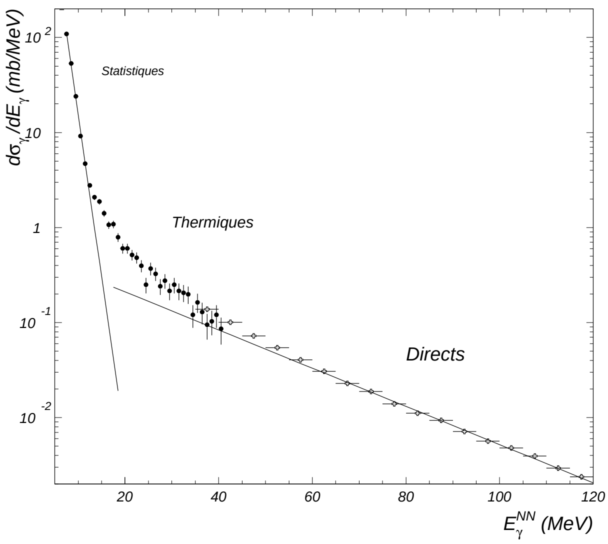

Fig. 7. Inclusive photon spectrum for the system Kr+Ni at 60A MeV.

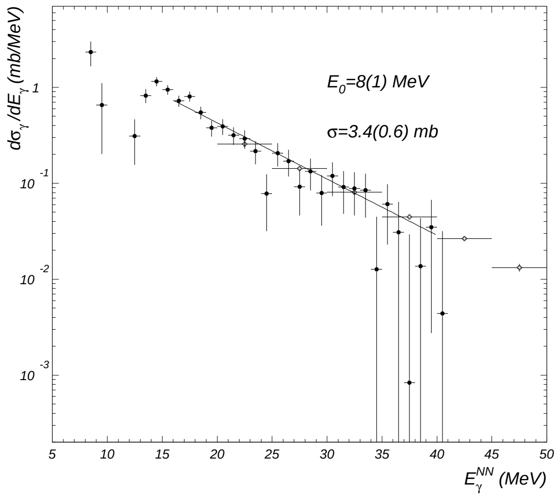

Fig. 8. Inclusive photon spectrum for the system Kr+Ni at 60A MeV after subtraction of the direct and statistical photons.

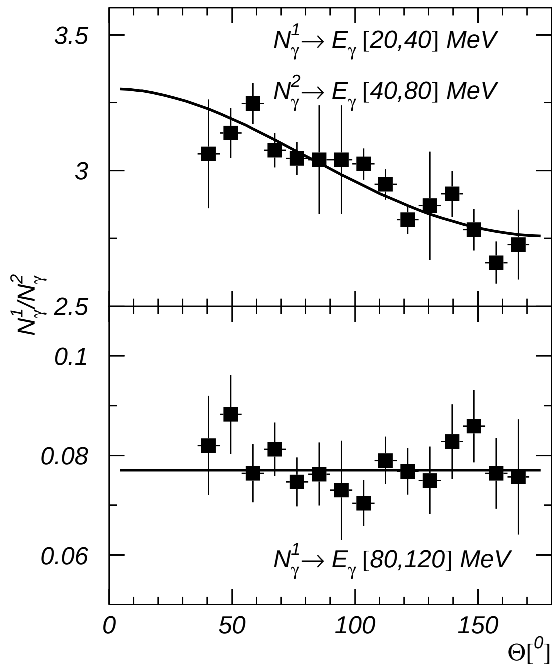

Fig. 9. The ratio of angular distributions measured for hard photons in different energy ranges in the reaction Kr+Ni at 60A MeV.

slope half of the slope of the direct photon contribution, $E_0 = 8(1)$ MeV and an integrated cross-section $E_\gamma > 20$ MeV of 3.4(0.6) mb. It should be noticed that no contribution from the statistical decay of the giant dipole resonance states is observed. We conclude that, at this beam energy, the GDR contribution is fully masked by the bremsstrahlung photons. In addition, the study of the relative angular distribution of hard photons for different energy ranges [2] (see Fig. 9) indicates that a fraction of photons in the energy range from 20 to 40 MeV are produced in a frame with a velocity compatible with the one of the nucleus-nucleus center-of-mass. Whereas more energetic photons are produced by a moving source with the velocity of the nucleon–nucleon center-of-mass.

3. Interpretation

The Boltzmann–Ühling–Uhlenbeck transport equation [1] provides a good description of the photon production in HI reactions. The basics of this model are clearly described in references [1, 19]. Photon spectrum is calculated as the incoherent sum of the individual *pn* bremsstrahlung. Calculations for the system Mo+Mo at $20A$ MeV [1] showed that most of photons are produced in the first stage of the reaction due to first-chance *np* collisions, but a second emission of photons from a thermalizing source is observed which represents 20% of the total yield. At higher beam energies ($\sim 50A$ MeV) a dense system is formed ($\rho = 1.4\rho_0$) in the first stage of the reaction which then expands until the attractive part of the nuclear force is strong enough to drive a second compression of the system. Direct photons are produced from the dense nuclear matter in the first 70 fm/c of the reaction while thermal photons are produced in the later stage when hot nuclear matter is formed [8]. The formation of the source of thermal bremsstrahlung has a strong consequences in the study of nuclear matter properties:

1. Thermal photons are produced from a thermalizing source, they thus represent a new thermometer of nuclear matter much earlier than the freeze-out phase charge for fragments emission. We have applied the thermal bremsstrahlung emission model proposed by Neuhauser and Koonin [20] to reproduce the thermal component of the photon spectra [8]. The elementary *pn* bremsstrahlung is given by the parameterization of Ref. [21]. We obtain that the thermal contribution of the photon spectrum for the system Kr+Ni at $60A$ MeV, gives a temperature of 6.3(1.0) MeV. For semi-central reactions, the temperature increases up to 7.5(1.0) MeV. It should be noticed that these temperature are much lower that the ones obtained when the full photon spectrum is explained in terms of thermal emission [20].

2. The ratio of direct photon cross-section to thermal photon one is very sensitive to the incompressibility modulus of the nuclear matter [2,8]. A value of K=290(50) MeV is deduced.

4. Near future experiments

We have seen that subthreshold photon production is a promising probe to study the properties of nuclear matter and dynamics of the HI reaction at intermediate beam energies. In near future, new experiments programmed at KVI(Groningen, The Netherlands) and GANIL(Caen, France) will be performed. The main goals of these experiments are to elucidate the origin of the "thermal component" of the photon spectrum and study more in detail the properties of the EoS. For this purpose, the photon spectrum will be studied for a symmetric and asymmetric systems in coincidence with most of the fragments emitted in the reaction. The detection of nuclear fragments allows for the selection of specific classes of reactions. Special interest is to measure the photon production in central and semi-central reactions when the multifragment channel is opened.

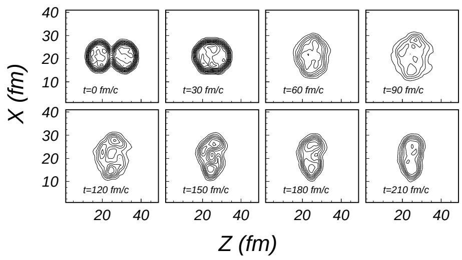

Fig. 10. Spatial evolution of a central collision in the AA center of mass frame obtained with BUU simulations.

Two experiments have been programmed with different systems: Ar+Au at $60A$ MeV at KVI and Xe+Sn at $50A$ MeV at GANIL. Most of fragments of the reaction will be detected by the Dwarf-Ball 4π multidetector system [22] from the Washington University in St.Louis. The Dwarf Ball consists of 64 CsI(Tl) plastic phoswich detectors covering polar angles from 30° to 160°. These phoswiches are able to identify the light charged particles and the intermediate mass fragments. The fragment emission at forward angles will be detected by the Forward Wall multidetector system from KVI [23]. It consists of 92 plastic phoswiches of fast scintillator NE102A and slow scintillator NE115. In the GANIL experiment, an additional detection system will be used for the detection of the projectile-like fragment and intermediate mass fragments at forward angles. This system consists of a telescope of two strip silicon detectors. The photon production will be measured with

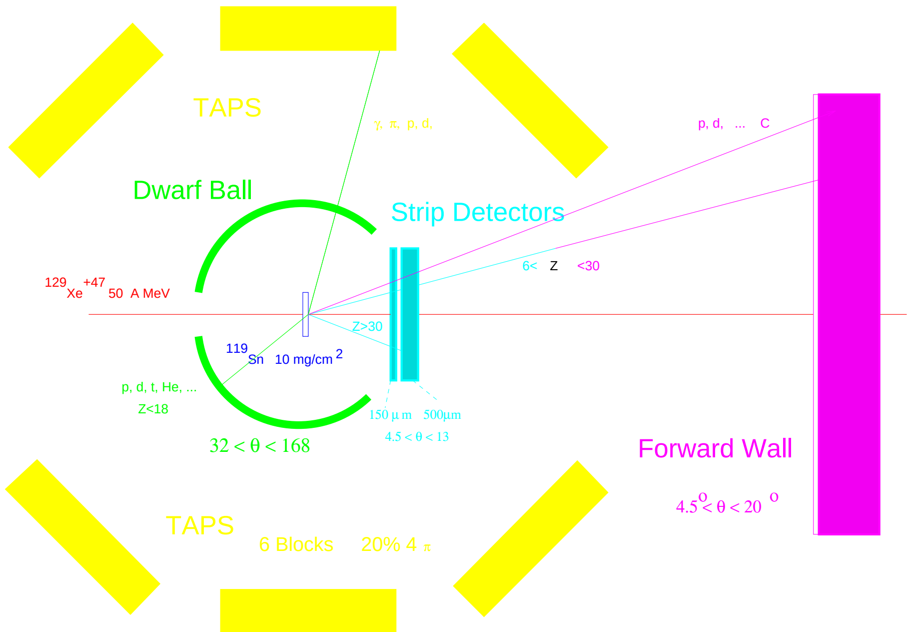

Fig. 11. View of the detection system TAPS, Dwarf-Ball, Forward-Wall and Silicon Strip Telescope for the programmed experiments at GANIL and KVI.

TAPS photon spectrometer [4]. It is a modular detector system of 384 BaF_2 crystals. A NE102A plastic scitillator is positioned in front of each crystal as a veto of charged particles. The 384 modules (BaF_2+Veto) will be assembled in 6 blocks of 64 elements each one, covering 20% of the full solid angle.

5. Concluding remarks

We have shown that energetic photons produced in HI reaction at intermediate energies are a powerful observable to study both, the dynamics of the nuclear collision and the collective properties of dense and hot nuclear matter. We have seen that the variation of the slope of the photon spectrum with the centrality of the reaction is related with the variation of the maximum density reached within the participant zone. The existence of a thermal bremsstrahlung component in the photon differential cross-section has been discussed. This component is detected as an excess of photon differential cross-section in the energy range from 20 to 50 MeV with respect to a pure exponential like spectrum. In addition, thermal photons are emitted from a moving source with the velocity of the nucleus-nucleus center-of-mass. The

BUU transport equation is able to provide a consistent description the the photon production in HI reactions. In particular the emission of thermal photons is show to take place in a later stage of the reaction from a thermalizing source, created after an oscillation of nuclear matter density. From the characteristics of the photon production, we have then deduced an incompressibility modulus of 290(50) MeV. Thermal photon spectrum is used to measure the temperature of this source in the system Kr+Ni at 60A MeV. A temperature of 6.3(1.0) MeV is obtained for the inclusive measurement and 7.5(1.0) MeV for semi central reactions. The photon thermometer has the advantage to measure the temperature at high density, much earlier than the freeze-out of hadrons occurs.

At the end of this talk, one of the comments concerned the formation of the thermalizing source. A. Faessler pointed out that the BUU simulations of the nuclear reaction are not reliable for long times, since they do not contain density fluctuations due to high order correlations which may play an important role when low densities are reached. He proposed to calculate the photon production in HI reaction using Quantum Molecular Dynamics model. In relation with this point, I would like to add that recent TDHF calculations of an expanded gold nucleus shows that during second expansion drives the system to lower densities [24]. This result qualitatively agrees with the formation of a second thermalizing source which fragments after a more violent second expansion.

More exclusive experiments of photon production in HI reactions have been programmed at KVI and at GANIL, which, I hope, will generate more surprises for a new contribution to the next Mazurian Lakes School of Physics.

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