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STUDY OF HIGH ENERGY GAMMA-RAYS IN HEAVY ION REACTIONS

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The gamma-spectra up to gamma-ray energy of 20 MeV in coincidence with KX-rays and fission fragments were measured. The reactions induced by ^{15}N, ^{22}Ne, ^{40}Ar ions with E/A = 5.5-10 MeV/nucleon leading to the formation of the Yb or Bi compound nuclei were studied. The ^{130}Te, ^{150}Nd, ^{153}Eu, ^{159}Tb, ^{181}Ta, and ^{192}Os targets were used. The gamma-rays were registered by a NaJ(Tl) scintillation detector with ϕ150x100 mm dimensions. The effective temperature of the gamma-ray spectrum has been determined in the 4 MeV < E < 12 MeV range and its dependence on the projectile mass has been established. Broad bumps have been observed in the E > 12 MeV energy region. The possible correspondence between these bumps and the gamma-decay of GDR's built on highly excited states of compound nuclei and projectiles is discussed.

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

Изучение жесткой компоненты гамма-излучения в реакциях с тяжелыми ионами

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Измерялись гамма-спектры до энергий 20 МэВ в совпадении с КХ-лучами и осколками деления. Изучались реакции с тяжелыми ионами ^{15}N, ^{22}Ne, ^{40}Ar при энергиях 5,5-10 МэВ/нуклон, приводящие к образованию составных ядер Yb или Bi. Использовались мишени ^{130}Te, ^{150}Nd, ^{153}Eu, ^{159}Tb, ^{181}Ta и ^{192}Os. Гамма-лучи регистрировались NaJ(Tl)-сцинтилляционным детектором размерами ϕ150x100 мм. Была определена эффективная температура гамма-спектров в области 4 МэВ < E_γ<12 МэВ и установлена ее зависимость от массы иона. Наблюдались широкие пики в области E >12 МэВ, обсуждается возможность соответствия этих пиков гамма-распаду ГДР, построенных на высоковозбужденных состояниях составного ядра и налетающей частицы.

Работа выполнена в Лаборатории ядерных реакций ОИЯИ.

1. *Introduction*

The intensive studies of the mechanism of fast neutron, proton and heavier particle emission in heavy ion reactions with $E/A < 10$ MeV/nucleon were carried out during the last few years in many laboratories. The characteristic parameters of fast particle emission, such as the effective temperature of the spectra, the cross sections, the angular distributions, etc., were shown to differ from the predictions of the statistical theory [1,2]. In some theoretical works [3,4] the emission of fast particles is supposed to be due to preequilibrium processes. Such preequilibrium processes can lead to the "preequilibrium" emission of gamma-rays, too [4,5]. However, no systematic studies of "preequilibrium" gamma-emission in heavy ion reactions have yet been carried out. The preequilibrium gamma-ray contribution computed in the work [4] makes the theoretical gamma-ray spectrum not so steep as in the case of the statistical decay of compound nucleus. Some indication of such behaviour is contained in the work [6]. The authors claim that for the reaction $^{124}Sn + ^{40}Ar$, the effective temperature of the gamma-ray spectrum is $T_{eff} \sim \sim 1$ MeV for $E_\gamma < 8$ MeV and $T_{eff} \sim 1.4$ MeV for $E_\gamma > 8$ MeV. The authors have observed a "bump" in the region of $E_\gamma > > 12$ MeV of the gamma-ray spectra. The energy of the bump was $E_b \sim 15$ MeV and its width was $\Gamma_b \sim 6$ MeV. The "bump" was interpreted as due to the gamma-decay of giant dipole resonances (GDR) built on highly excited states of the compound nucleus. They claim that the experimental yield of the "bump" is larger than that expected on the basis of the statistical theory. This fact may indicate the possible preequilibrium contribution to the experimental yield. Subsequently there have been observed some "bumps" in the region of $E_b \sim 15$ MeV in heavy ion reactions by many authors [8-11]. The main systematic disadvantage of many experiments in which these "bumps" have been studied, is the use of a gamma-multiplicity trigger for indicating the formation of a compound system [8-11]. The gamma-multiplicity trigger cannot provide the unambiguous identification of the reaction channel in the reactions of heavy ions with $E/A > 6$ MeV/nucleon leading to the formation of compound nuclei with $A > 200$. The observation of the characteristic KX-rays of the evaporation residues was recently shown to be a very effective method of their identification [12]. In the present paper we give the gamma-ray spectra observed in coincidence with characteristic KX-rays (X-channel) and with fission fragments (ff-channel), from which the reaction channel can be identified unambiguously. The reactions induced by ^{15}N, ^{22}Ne , ^{40}Ar ions with energies E/A=5.5-10 MeV/nucleon, leading to the formation of the Yb or Bi compound nuclei, have been studied.

2. *Experiment*

Experiments were carried out using an external beam from the U-300 cyclotron of the JINR Laboratory of Nuclear Reactions. A schematic view of the experimental set-up is shown in fig.1. The selfsupporting targets of ^{159}Tb and ^{181}Ta were used. The oxides of ^{153}Eu, ^{150}Nd , ^{130}Te, and ^{192}Os were deposited on 1 mg/cm ^{2} Al foils. The thickness of targets was 1-2 mg/cm , the isotope purity was better than 92%.

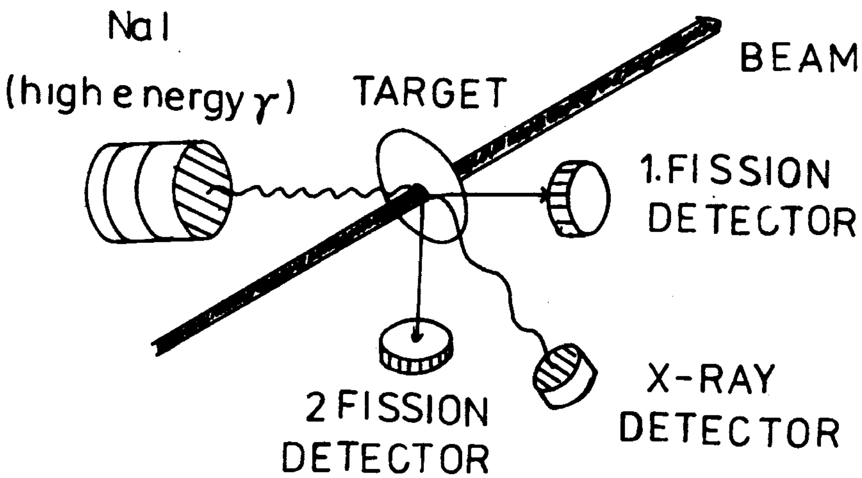

Fig.1. Schematic view of the experimental setup.

The gamma-rays were registered by a NaJ(Tl) scintillator detector. The NaI(Tl) crystal with dimensions of ∅150x100 mm was placed perpendicularly to the beam direction at a distance of 200 mm from the target. The shield against neutrons, which consisted of 150 mm of borated paraffin, was placed between the crystal and the target. The neutrons emitted by the target were substantially suppressed by this shield. The efficiency of protection againts neutrons was tested by a Pu(Be) neutron source. The NaI(Tl) crystal was surrounded by thin, 50 mm lead and 100 mm borated paraffin walls to protect it from the gamma and neutron background. The linearity of the energy

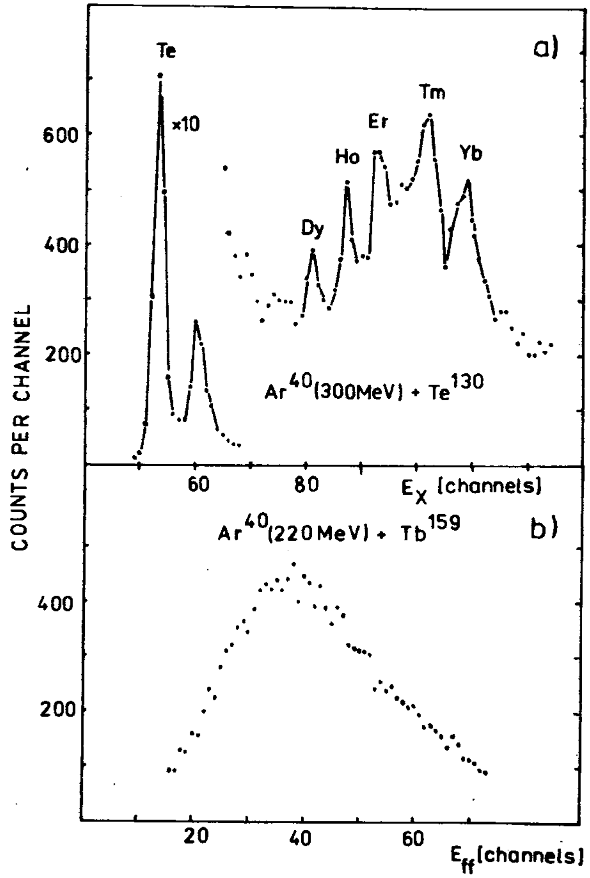

Fig.2. a) The X-ray spectrum measured in coincidence with gamma-rays at $E_\gamma >$ > 2 MeV. b) The spectrum of fission fragments measured in coincidence with gamma-rays at $E_\gamma >$ > 2 MeV.

response and the efficiency of the NaI(Tl) detector were determined in the reactions $^{19}F(p, \alpha\gamma)^{16}O$, $E_\gamma =$ $= 6.13$ MeV and $^{11}B(p,\gamma)^{12}C$, $E_\gamma =$ $= 4.43$ MeV, 12.8 MeV, 17.2 MeV. A proton beam from an electrostatic generator of the Nuclear Physics Research Institute of the Moscow State University was used. The energy calibration was done during the experiments according to gamma-transition at $E_\gamma = 4.43$ MeV from the Pu(Be) neutron source and according to gamma-transition at $E_\gamma =$ $= 2.22$ MeV, which corresponds to the capture of thermal neutrons by the hydrogen.

The characteristic KX-rays of evaporation residues were registered by a Ge(intrinsic) X-ray detector. Its full photopeak efficiency was 1% in the region of $E_X \sim$ $\sim$ 60–90 keV and its energy resolution was 600 eV in the same energy range. The typical spectrum of X-rays is demonstrated in figure 2a).

The fission channel plays an important role in the decay of the Bi compound nucleus formed in the reactions studied by us. The fission fragments were registered by 50 μm thick surface-barrier silicon detectors. The fission detector was situated on the line connecting the target and the gamma-detector (see fig.1). The typical spectrum measured by the fission fragment detector is shown in figure 2b).

An electronic setup allowed the measurement of the time coincidences of gamma-rays with KX-rays and fission fragments. The time resolution of the setup was better than 15 nsec for gamma-rays at $E > 2$ MeV. The parameters of the experimental setup were similar to those of the study [13]. The on-line data acquisition was performed using a SM-3 computer. All coincidence events at $E_\gamma > 7$ MeV were stored on magnetic tape for subsequent off-line sorting. The other coincident events were first scaled down to shorten the dead time of acquisition. The single spectra measured by the fission fragment detectors were stored in the CPU memory. These single spectra allowed us to determine the yield of gamma-rays per one fission fragment. Random coincidences were used to estimate the background in the usual way.

3. *Results*

The results of our experiments are shown in figures 3-5 and in the table. In the region of 4 MeV $< E_\gamma <$ 12 MeV the gamma-ray spectra can be described by the function $\exp(-E_\gamma/T_{eff})$. The values of the effective temperatures T_{eff} are presented in the table for each reaction studied and for the X-channel and the ff-channel separately. The main features of the T_{eff} values for the reactions which lead to the formation of the Bi compound nuclei, are the following ones:

a) the values of T_{eff} are the same in both channels of the ^{22}Ne (155 MeV) + Ta reaction;

b) the value of T_{eff} increases as the mass of the projectile decreases;

c) there is no correlation between the excitation energy of the compound nucleus and the value of T_{eff}.

The behaviour of T_{eff} in the X-channel of the reactions which lead to the formation of the Yb compound nuclei is similar. These facts may indicate the existence of the source of preequilibrium gamma-ray emission. The increase of T_{eff} with decreasing projectile mass is a typical feature of preequilibrium emission, as it has been stated in the case of neutrons [2].

The observed gamma-ray spectra rise considerably higher than the exponentially falling tail observed at energies above 12 MeV. The yields of these shoulders per one decay of compound nuclei are presented in the table. Their form is clearly seen in the X-channel and the ff-channel of the ^{22}Ne (155 MeV) + Ta reaction only, because of low statistics for the other reactions (see fig.5). The "A"

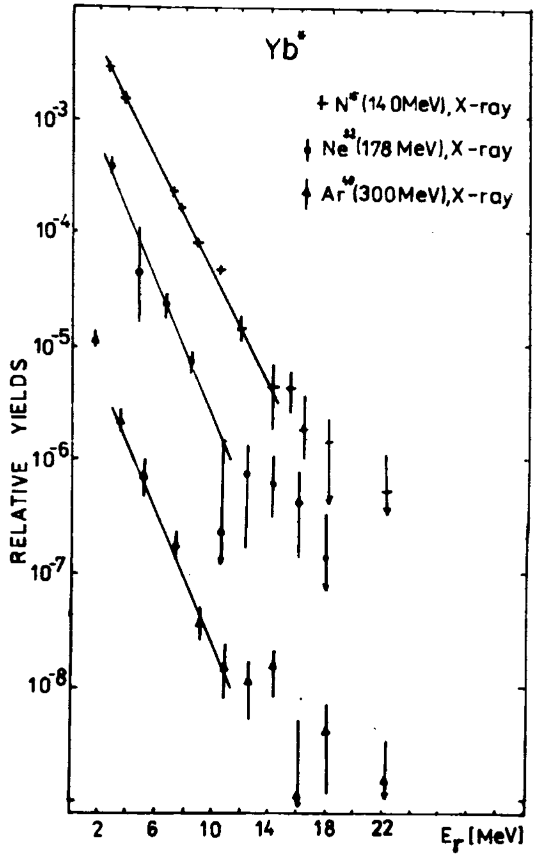

Fig.3. The gamma-ray spectra measured in coincidence with characteristic KX-rays of residual nuclei for the reactions leading to the formation of the Yb compound nuclei.

bump seen in the X-channel is characterised by an energy E_A = = 13±1 MeV and width Γ_A = 4-5 MeV. The "B" bump observed in the ff-channel, lies at an energy E_B = 20±1 MeV and has a width Γ_B = = 2-3 MeV. Let us suppose the correspondence between these bumps and the gamma-decay of GDR[8-11]. Then their energies must be correlated with the gamma-ray source mass[14]. The energies and the widths of the bumps for some possible gamma-ray sources are indicated by horizontal lines in figure 5. The energy of the "A" bump corresponds to the energy of the GDR of the Bi nucleus quite well. The energy of the "B" bump is higher than the value derived for GDR's of fission fragments taking into account the experimental fission fragment mass distribution[15]. The "B" bump shifts towards lower energies in the case of the ^{40}Ar + ^{159}Tb reaction, which leads to the formation of the same Bi compound nucleus (fig.5). The correlation between the energy of the "B" bump and the projectile mass is clearly seen.

We have also studied the reaction induced by the lighter ^{15}N projectile, which leads to the Bi compound nucleus (see fig.4). The energy of the GDR of ^{15}N is equal to about 27 MeV[14]. We failed to measure the gamma-ray spectrum up to so high energies. However, the non-observation of any resonance structure in the energy region up to E_γ = 19 MeV confirms the assumption concerning the correlation between the "B" bump energy and the projectile mass. The gamma-ray spectrum was not measured in the X-

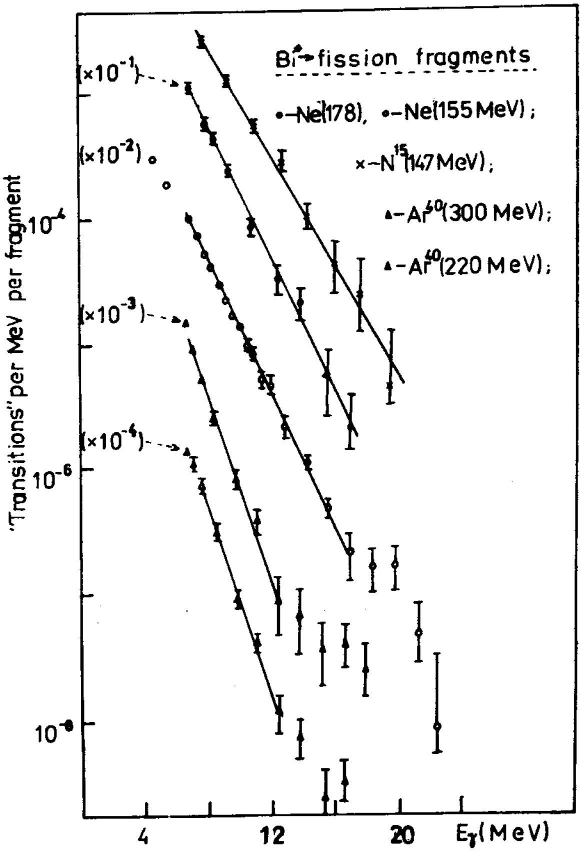

Fig.4. The gamma-ray spectra measured in coincidence with fission fragments from the Bi compound nucleus.

channel of the $^{40}Ar + ^{159}Tb$ reaction, because of the high fissionability of the Bi compound nucleus. The behaviour of the "A" bump was studied in the X-channel of reactions leading to the formation of the Yb compound nuclei. No significant correlation has been observed between the energy or yield of the "A" bump and the projectile mass or the excitation energy of the compound nucleus. Very puzzling is the disappearance of the "A" bump in the ff-channel of reactions leading to Bi compound nuclei. Because of low statistics for $E_\gamma >$ 15 MeV in the X-channel, we cannot draw any definite conclusion about the presence of the "B" bump in the X-channel. We can only mention a small shoulder at $E_\gamma \sim$ 18 MeV in the spectrum of the X-channel of the ^{40}Ar (300 MeV) + ^{130}Te reaction (see fig.3), which may be due to the "B" bump.

We measured the yield of high energy gamma-rays in the direction parallel and/or perpendicular to the spin orientation of the compound nuclei produced in the ^{40}Ar + + ^{159}Tb reactions. To determine the spin orientation we employ the correlation between the fission plane and the spin orientation of the fissioning nucleus [17]. The first fission fragment detector (see fig.1) registers fission fragments, which determine the spin orientation perpendicular to the emission of the detected gamma-rays and, the second fission detector records fission fragments, which

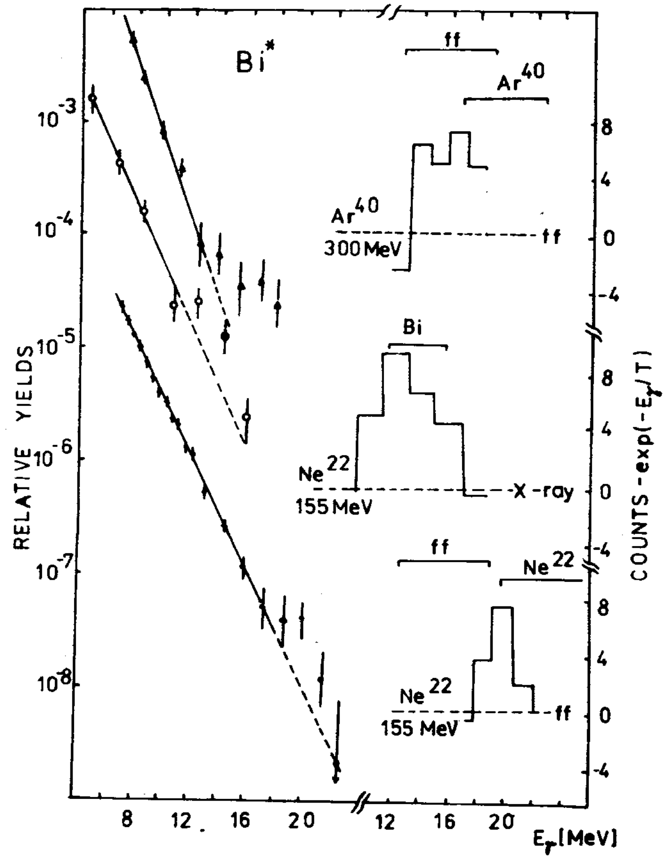

Fig.5. The gamma-ray spectra for the X-channel (open circles) and the ff-channels (closed circles and open triangles) of reactions leading to the formation of the Bi compound nuclei. The right-hand histograms indicate the difference between the experimental points and the exponentially falling tail in the region of the "A" and the "B" bumps.

correspond to the spin orientation parallel to the gamma-ray emission. Let us denote by Y_k the yield of coincident gamma-rays per fission fragment registered in the k-th detector. The maximum yield from the stretched dipole gamma-ray transition is known to lie along the spin direction/16/, which is equivalent to $R = Y_2/Y_1 < 1$.The ratio $R \sim 1$ is equivalent to isotropic gamma-ray emission. We compute the ratio $R = .56$ for dipole stretched transitions taking into account our experimental geometry and using known formulas/16/.The value obtained is close to

Table. Experimental results

Reaction	Excit.en. of CN, MeV	Proj.en. over c.b. per nucl.	T_{eff}	Yield of bump per CN
Compound nucleus Yb, X-channel				
$^{153}Eu+^{15}N$(140 MeV)	116	4.7	$1.9\pm.1$	
$^{150}Nd+^{22}Ne$(178 MeV)	132	3.7	$1.9\pm.4$	$(9\pm7)\cdot10^{-4}$
$^{130}Te+^{40}Ar$(300 MeV)	166	2.7	$1.5\pm.1$	$(9\pm3)\cdot10^{-4}$
Compound nucleus Bi, X-channel				
$^{192}Os+^{15}N$(147 MeV)	121	4.8	$2.0\pm.4$	
$^{181}Ta+^{22}Ne$(155 MeV)	103	2.4	$1.6\pm.1$	$(3\pm1)\cdot10^{-3}$
Compound nucleus Bi, ff-channel				
$^{192}Os+^{15}N$(147 MeV)	121	4.8	$2.2\pm.2$	
$^{181}Ta+^{22}Ne$(155 MeV)	103	2.4	$1.7\pm.1$	$(1.2\pm.6)\cdot10^{-5}$
$^{181}Ta+^{22}Ne$(178 MeV)	124	3.3	$1.7\pm.1$	
$^{159}Tb+^{40}Ar$(220 MeV)	93	1.1	$1.2\pm.1$	$(7\pm3)\cdot10^{-5}$
$^{159}Tb+^{40}Ar$(300 MeV)	153	2.7	$1.2\pm.1$	$(1.2\pm.6)\cdot10^{-4}$

the experimental ones for gamma-ray energies $E_\gamma > 12$ MeV and for two projectile energies: $R = .5 \pm .3$ (E_{Ar} = = 220 MeV) and $R = .5 \pm .3$ (E_{Ar} = 300 MeV). In the case of gamma-rays with energies of 8 MeV to 10 MeV these values are $R = .9 \pm .1$ and $R = 1.1 \pm .3$. These values indicate the isotropic emission of gamma-rays with energies 8 MeV $< E_\gamma <$ 10 MeV. The spin of the fissioning nucleus is not precisely perpendicular to the fission plane, however. The spin projection onto the fission axis K_0, increases as the excitation energy of the compound nucleus increases /17/. The small difference between the experimental and theoretical values of R indicates a weak influence of this effect on the experimentally observed anisotropy.

4. *Conclusions*

The method of identification of the reaction channel by detecting the KX-rays of residual nuclei (X-channel) and/or fission fragments (ff-channel) was shown to have sufficient efficiency to observe highly energetic gamma-rays, which correspond to the fusion of two heavy nuclei. By using this method the spectra of gamma-rays were studied, especially in the region of GDR energies. The effective temperature of the gamma-ray spectra was determined in the range 4 MeV $< E_\gamma <$ 12 MeV and its dependence on the projectile mass was established. The broad bumps have been observed in the energy region of $E_\gamma > 12$ MeV. The energies and yields of the "A" bumps, which have been observed in the X-channel of the studied reactions, agree quite well with results of other studies /6-11/. They probably correspond to the gamma-decay of GDR's built on highly excited states of compound nucleus /7/. The "B" bumps, which we have observed in the ff-channel of the same reactions, have significantly higher energies and lower yields comparing to the "A" bumps. The "A" bumps have not been seen in the gamma-ray spectra of the ff-channel. The dependence of the energies and the yields of the "B" bumps on the projectile mass has been established. The results of measuring the correlation between the yield of gamma-rays with energies $E_\gamma > 12$ MeV and the direction of the fission plane indicate the emission of stretched dipole gamma-rays in the ff-channel.

The correspondence of the energy of the "A" bump and that of GDR of the compound nucleus (Bi) cannot exclude the possible contribution from the target (Ta), because the GDR energy $E_G \sim 78 \times A^{-1/3}$ depends only weakly on the gamma-ray source mass A[14]. The drastic change in the width of GDR's with mass can be used in future experiments to resolve the target from the compound nucleus[14]. The study of the mechanism involved in the excitation and gamma-decay of giant resonances in the heavy ion reactions can lead to a better understanding of the mechanism of energy dissipation in heavy ion collisions[9,19].

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