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ELECTROMAGNETIC EXCITATION OF ONE- AND MULTIPHONON GIANT RESONANCE STATES WITH RELATIVISTIC HEAVY IONS

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1. INTRODUCTION

Relativistic Heavy Ion (RHI) accelerators exist already in some places of the world, and more of them are being built or planned. There is the BEVALAC (~ 1-2 GEV/A), Brookhaven (~ 15 GEV/A) and CERN (60 and 200 GEV/A). In Darmstadt, SIS/ESR will be built and a relativistic heavy ion collider, RHIC, is planned in the USA.The strong motivation for the investigation of RHI collisions is the study of nuclear matter under extreme conditions, of special interest is the study of the theoretically expected quark-gluon-plasma phase. RHI's provide a unique opportunity.

It is the aim of the present paper to show that, in addition to the central nuclear collisions, the distant collisions (see Fig.1) are also interesting.

It is the extremely short and strong pulse of electromagnetic radiation which leads to new effects. The investigation of electromagnetic properties of nuclei with Coulomb excitation at non-relativistic and sub-barrier energies and with electrons (Al-66, Al-75) is a very fruitful tool. The various probes complement each other in the study of electromagnetic properties. In non-relativistic Coulomb excitation one can ideally investigate low lying collective states, with heavy ions multiple excitation can be very strong. On the other hand, electron scattering can be well described by a one-photon exchange mechanism. Since the electrons do not interact strongly, they can penetrate the nucleus easily, and form-factors can be determined as a function of the three-momentum transfer $\vec{q}$ and excitation energy ω. Due to the condition that strongly interacting projectiles should not penetrate through each other in the Coulomb excitation process, one can only obtain information about the electromagnetic matrix-elements at the "photon point" ($|\vec{q}| = \omega$) in this case.

Apart from the interest in electromagnetic processes for their own sake, they can also be of more practical importance. E.g. the copious production of e^+e^- pairs in RHI collisions can serve to keep control of the beam luminosity in a RHI collider (An-87). On the other hand, it is also important to under-

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stand these electromagnetic processes with their large cross sections, because they can be a potential background in the investigations of the central nuclear collisions.

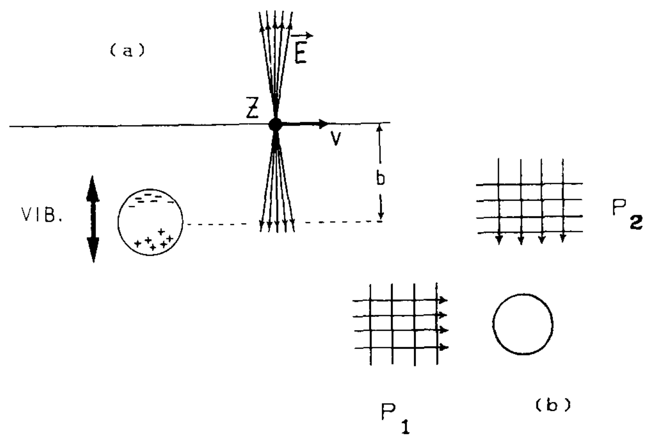

FIGURE 1:
(a) A relativistic charged projectile incident on a target with impact parameter larger than the strong interaction radius. A sketch of the electric field generated by it is also shown. One of the effects of this field is to induce collective vibrations of the nuclear charges.
(b) Two pulses of plane wave of light which produce the same effect on the target as the electromagnetic field created by the projectile's motion.

In chapter 2, a short description of the theoretical framework is given, quantal as well as semiclassical methods are discussed and compared with each other. In chapter 3, one- and multiphoton excitation of high lying collective states, mainly of the giant dipole resonance (GDR), is studied. RHI's seem to be a unique tool to investigate multiphoton processes with high energy (tens of MeV) equivalent photons. The investigation of multiphonon GDR states is of special interest. The possibilities of experimental investigation of these new states will be discussed. The following chapters will provide a "guided tour" to the literature in this field (see also Ba 85, Ba 86a, Ber 87a). In chapter 4 the so called Primakoff-effect is discussed. High energy physicists have, for some time already, made use of the virtual (equivalent) photons provided by a heavy nucleus to study photon interactions with (unstable) particles, like the Λ or the π^0. In chapter 5, we discuss lepton (mainly electron) pair production. This process can also be viewed as an interaction of two equivalent photons. We further discuss the possibility to investigate γ-γ collisions, especially in the MeV range, with RHI's. Conclusions and an outlook will be given in chapter 6.

2. SEMICALSSICAL AND QUANTAL THEORIES OF ELECTROMAGNETIC EXCITATION IN RHI COLLISIONS

The electromagnetic field of a highly relativistic particle with charge Z is equivalent to the field of photons which move in the direction of the particle. The spectrum of these "equivalent photons" is given in the Weizsäcker-Williams method (for a detailed and pedagogical account, see Ja-75; the method goes back to the work of Fermi (Fe 24)) by

$$n(\omega) = \frac{2}{\pi} Z^2 \alpha \ln \left(\frac{\delta}{\xi}\right) \qquad (1)$$

where $\alpha = \frac{e^2}{\hbar c} \simeq \frac{1}{137}$ and $\delta = 0.681\ldots$. The quantity ξ is defined by

$$\xi = \frac{\omega R}{\gamma v} \qquad (2)$$

where $\gamma = \frac{1}{\sqrt{1-(\frac{v}{c})^2}}$ is the Lorentz-factor and v the velocity of the particle.

The minimum impact parameter is given by R. In some cases (see Ja-75, and below) it has to be replaced by the Compton-wave-length $\lambda_C = \frac{\hbar}{m_e c}$ of the electron. In the limit of very large frequencies, i.e. $\omega \gg \frac{\gamma v}{R}$ an adiabatic cut-off sets in and we have, instead of eq. 1,

$$n(\omega) = \frac{Z^2 \alpha}{2} e^{-2\xi}. \qquad (3)$$

An improved theory is given by Wi-79. It is based on a classical straight-line motion of the projectile with an impact parameter b and constant velocity v (with an appropriate rescaling of b one can take recoil effects into account in an approximate way). The multipole decomposition of the electromagnetic field is given under the condition that the target and the projectile do not overlap. The cross section σ_C of an electromagnetic process can be expressed in terms of the equivalent photon number $n_{\pi\ell}$, for a given multipolarity $\pi\ell$, as (Wi 79, Ber-85)

$$\sigma_C = \sum_{\pi\ell} \int \frac{d\omega}{\omega} n_{\pi\ell}(\omega)\ \sigma_\gamma^{\pi\ell}(\omega) \qquad (4)$$

where $\sigma_\gamma^{\pi\ell}(\omega)$ denotes the corresponding photonuclear cross section for the multipolarity $\pi\ell$. In Ho-84 it was noted that the E1 photon spectrum corresponds exactly to the one given by the Weizsäcker-Williams method. Furthermore, it can be seen (Ber-86a) that in the limit $\gamma >> 1$ the photon numbers for all multipolarities approach the Weizsäcker-Williams limit. This seems physically obvious, since, due to the Lorentz-contraction, the electromagnetic field resembles more and more closely that of a superposition of plane wave photons, which contain all multipolarities with equal weight.

A quantal method, which is based on the eikonal approximation in the strong absorption limit, is given in Ber-85. The differential cross section is dependent on the momentum transfer $\vec{q}$; in the high energy limit, which is appropriate here, the longitudinal component is given by $q_l = \frac{\omega}{v}$ and the transverse momentum transfer is $q_t = \frac{E}{\hbar c}\left(\frac{v}{c}\right) \sin\theta$ where θ is the scattering angle. The T-matrix-element for a one-photon transition $|I_i M_i\rangle \rightarrow |I_f M_f\rangle$ can be expressed in terms of the electromagnetic multipole transition matrix-element as

$$T_{fi} = \frac{2\pi Ze}{\gamma} \sum_{\pi \ell m} i^m k^\ell \sqrt{2\ell+1}\, e^{-im\psi} \chi_m(q_t, R) G_{\pi \ell m}\left(\frac{c}{v}\right) \times \times \langle I_f M_f | M(\pi\ \ell, -m) | I_i M_i \rangle \tag{5}$$

where $k = \frac{\omega}{c}$, ψ is the azimuthal scattering angle and the functions χ_m and $G_{\pi \ell m}$ are given analytically in Ber-85 and Wi-79 respectively. As it is appropriate quite generally for the case of no penetration of the two interacting charge distributions, only the electromagnetic matrix-element appears, which is directly related to the photon transition between the two states. It was shown in Ber-85 that the total cross section (i.e. integrated over the scattering angles) calculated in the eikonal approximation, is equal to the total cross section as calculated in the semiclassical approximation (integrated from a minimum impact parameter R up to infinity).

The angular distribution of the scattered particle will be very forward peaked, which makes a direct measurement of the scattering angle difficult. Perhaps one can measure the recoil energy of the target in some cases? The angular distribution will either be dominated by the quantal diffraction effects, as described by eq. 5, with a characteristic angle θ_d or by the Coulomb repulsion with a characteristic angle θ_c. This depends on the product of the charges $Z_1 \cdot Z_2$, one obtains (see Ber-85)

$$\frac{\theta_c}{\theta_d} \simeq 2\alpha Z_1 Z_2 \tag{6}$$

The properties of the equivalent photon numbers are further discussed in Ber-85, and Ber-86a.

3. ELECTROMAGNETIC EXCITATION AND FRAGMENTATION OF HIGH LYING COLLECTIVE STATES

(a) One-photon exitation and fragmentation in peripheral collisions.

A theoretical study of these processes is given in Ber-86b and Ba-86b. Clear evidence of Coulomb fragmentation was given especially in experiments at the BEVALAC (see e.g. Me-84, Me-86). These were inclusive type of experiments. With the large excitation cross sections it may become possible to investigate experimentally the properties of giant resonances in more detail (like the photon decay to excited states). At present there is satisfactory agreement between theory and experiment. The experiments are and will be going on at Brookhaven, CERN and SIS (Darmstadt). Coincidence cross sections are theoretically studied in Ber-87b, where also Coulomb-nuclear interference is considered. An interesting possibility of further experimental improvement is the Projectile-Fragment-Separator at SIS (Ge-87). The production of relativistic radioactive beams (e.g.Ne^{19}, aβ^+ emitter) by means of Coulomb dissociation can be useful for radiation biophysics (Ge-87).

Furthermore, the Coulomb dissociation process can be used to obtain information on radiative capture processes of astrophysical interest (see Ba 86c and Ba 86d).

Loosely bound nuclei can easily be dissociated by the Coulomb force. Examples are the deuteron (see e.g. Ref. Ho-84 and further references therein) and more recently, Li^{11} (see Ha-87). In this case, Coulomb fragmentation is not dominated by the GDR excitation. A simple model is studied in Ber-87b. In the weak binding limit the Coulomb fragmentation cross section can be related directly to the mean square radius $\langle r^2\rangle$ of the ground state of the given nucleus as was stressed in Ha-87, i.e. the Coulomb fragmentation measures the size of the system. This result can also be obtained from the formalism discussed here by using closure over the final unobserved states (see e.g. Be-86 p 324); the non energy weighted sum over the B(E1, $i\to n$) values is given directly by $\langle r^2\rangle$.

(b) A forced harmonic oscillation of all neutrons against all protons.

In a harmonic oscillator model discussed by Brink (Br-57) the nuclear Hamiltonian can be split in the following way

$$H=H_{Zint} + H_{Nint} + H_{cm} + H_r \ . \tag{7a}$$

In this separation H_{Zint} and H_{Nint} contain only proton-proton and neutron-neutron relative coordinates respectively, they are independent of the center of mass coordinate $\vec{R} = \frac{1}{A}(Z\vec{R} + N\vec{R}_N)$ and the proton-neutron relative coordinate

$\vec{r}=\vec{R}_Z-\vec{R}_N$. Correspondingly, we can write the nuclear wave function in the factorized form (omitting the center of mass wave function)

$$\phi=\psi_{Zint}\ \chi_{Nint}\ \beta_0(\vec{r}) \tag{7b}$$

The dipole operator is given by $\vec{D}=\frac{NZ}{A}\vec{r}$, it acts only on the wave function of the relative motion of all protons against neutrons. In this case the giant dipole state corresponds to a Goldhaber-Teller collective excitation. If the amplitude of the neutron-proton relative motion is small enough the Hamiltonian H_r of the relative motion will be a harmonic oscillator

$$H_r=\frac{p^2}{2m}+\frac{1}{2}fr^2 \tag{8}.$$

where $m=\frac{NZ}{A}m_N$ is the reduced mass, m_N being the nucleon mass. The spring constant f can be determined from the empirically known-position of the GDR at $E_{GDR}=\hbar\omega=80\ A^{-1/3}$Mev as

$$f=m\omega^2\simeq 155\ \frac{NZ}{A^{5/3}}\ \text{MeV fm}^{-2} \tag{9}$$

The length parameter $L=\sqrt{\frac{\hbar}{m\omega}}\cong 0.7\ \frac{A^{2/3}}{(NZ)^{1/2}}$ fm defines a length scale for the separation of the neutrons against the protons. Of course, the model sketched here is a strong idealization of the actual situation, however, the results presented below are quite independent of the detailed nuclear dynamics (like a Goldhaber-Teller, or Steinwedel-Jensen, or a shell model approach). What enters into our calculations are only the electromagnetic moments between phonon states, which are given quite reliably by the Thomas-Reiche-Kuhn (TRK) sum rule and the known position of the GDR. Our main asumption is that the motion is harmonic.

Let us now study the excitation of this harmonic oscillator under the influence of the time depended electromagnetic field of the RHI. We describe the motion of the projectile cassically by a straight line with impact parameter b in the x-direction and a constant velocity v in the z-direction. The electric field acting on the target nucleus is decomposed into an x-component $E_x(t)$ and a z-component $E_z(t)$. As is well known, (see e.g. Ja-75) the z-component of the field is quite unimportant in the relativistic case and we can restrict ourselves for clarity of presentation to the x-component. This component is enhanced in strength by the Lorenz-factor γ . The time dependent Hamiltonian can now be written as

$$H(t) = H_r + V(t) \tag{10a}$$

with

$$V(t) = E_x(t) \cdot eZ \cdot \frac{N}{A} x = Z_p \frac{\gamma be^2}{(b^2 + (\gamma vt)^2)^{3/2}} \frac{NZ}{A} x \tag{10b}$$

where eZ denotes the charge and $\frac{N}{A}x$ is the elongation from the center of mass of the harmonically moving Z protons in the x-direction. (For sufficiently fast projectiles we can neglect the recoil of the nucleus as a whole). The problem given by eq.10, i.e. the motion of a one-dimensional harmonic oscillator under a time-dependent external perturbation, can be solved in closed form (see e.g. Me-70).

In the sudden approximation, which is appropriate for the present situation, we obtain for the excitation amplitude a_n $(t = +\infty)$ of a state $|n\rangle$ with n phonons

$$a_n = \langle n | e^{-\frac{i}{\hbar} \int_{-\infty}^{\infty} dt V(t)} | 0 \rangle \tag{11}$$

where we have assumed that the system is in the ground state $|0\rangle$ for $t \to -\infty$. (Actually it is not necessary to use the sudden approximation, the following results can be obtained exactly, see e.g. Me-70). The time integration in the exponent of eq. 11 can be done in closed form, and with $x = \frac{L}{\sqrt{2}}(a + a^+)$, where a^+ and a denote the creation and destructions operators of the phonons, one obtains the rather simple expression

$$a_n = \langle n | e^{-iu(a+a^+)} | 0 \rangle = \frac{(-iu)^n}{\sqrt{n!}} e^{-\frac{u^2}{2}} \tag{12}$$

Here we introduced the abbreviation

$$u = \frac{NZ}{A} \frac{L}{b} \sqrt{2} \frac{Z_p e^2}{\hbar v} \tag{13}$$

The operator identity $e^{A+B} = e^A e^B e^{-\frac{1}{2}[A,B]}$ was used, which is valid for two operators A and B for which the commutator is a c-number. The excitation probability P_n of an n-photon state is given by

$$P_n = |a_n|^2 = \frac{1}{n!} e^{-u^2} u^{2n}, \tag{14}$$

as was already obtained in Ba 86b and Ba 86e. It is of interest to note that the wave function $\psi(x,t) = \sum_n a_n \phi_n(x,t)$ of the system corresponds to a so called coherent state (Me-70). The probability distribution W(x,t) has the simple form

$$W(x,t) = |\Psi(x,t)|^2 = \frac{1}{\sqrt{\pi}\,L} e^{-\left(\frac{x}{L} - \sqrt{2}\,u \cos(\omega t + \frac{\pi}{2})\right)^2} \qquad (15)$$

i.e. we have a harmonic motion of a Gaussian distribution (of a width given by L) with an amplitude $x_0 = \sqrt{2}\,L \cdot u$ and a period ω. The amplitude x_0 can be expressed as

$$x_0 = \frac{Z_p e^2}{\hbar v} \frac{A^{1/3} \mathrm{fm}^2}{b} \qquad (16)$$

A maximum value can be achieved for two heavy nuclei (like U-U), it is of the order of $x_0 \simeq 0.4$ fm ($\frac{Z_p e^2}{\hbar v} \simeq 1, b \simeq 15$fm). The width L of the zero point motion is given by L = 0.23 fm in the case of ^{238}U.

(c) A dissipative quantum pendulum: decay of multiphonon GDR and experimental possibilities.

Relativistic heavy ions seem to be an ideally suited "electric dipole hammer" in order to probe charge oscillation in nuclei. The GDR is the prototype of a nuclear vibration, and it is a characteristic of a vibration that their phonons can be superimposed independently. Unfortunately, not too much is known about such nuclear multiphonon states. The GDR seems to be a good candidate for such investigations. Furthermore, the "Brink hypothesis" (see e.g. Sno-86), saying that a giant dipole resonance is built on every state, tells us that such multiphonon states should exist. The exploration of such states can tell us about collective nuclear structure at high excitation energies. From the theoretical point of view, it seems rather speculative at the moment to go beyond the predictions which can be made apart from those based directly on the harmonic motion. Especially, it will probably be very hard to make predictions about specific decay channels. This is even more so, since even for the one-phonon GDR the question of the mechanism of the width is not completely resolved (see Bo-75).

Indeed, there exist various proposals which aim at a study of such hitherto unknown nuclear states. In two of these proposals, projectile excitation will be studied. Coincidence studies are planned by H. Emling et al (Em-87) at the forthcoming SIS/ESR. Braun-Munzinger et al. (Br-85) investigate the fragmentation of ^{16}O and ^{32}S beams at an energy of 14.5 GeV/A at Brookhaven. It is planned to look for exotic fragments (like polyneutrons, and very proton- or neutron - rich nuclei). They could be a signature of multiphonon states which are characterized by a relatively large separation of proton and neutron nuclear matter.

Two proposals for SIS/ESR aim at a study of target excitations. The proposal by Hilscher et al. is quite speculative: they try to detect polyneutrons ^{N}n (the question of their existence is still open) by observing the reaction

$$^{N}n + p \rightarrow Nn+p \qquad (17)$$

taking place in their scintillation detector. In the other proposal (Fi-87), the study of γ - and particle decay of one- and multiphonon giant resonances is proposed. An important ingredient is a 4π-veto-detector for the central collisions. It would be interesting to investigate γ-γ correlations from the electromagnetic decay of the GDR states. In the harmonic approximation, the γ-width $\Gamma_\gamma^{(N)}$ of an N-phonon state is given by (see e.g. Bo-75)

$$\Gamma_\gamma^{(N)} = N \cdot \Gamma_\gamma^{(1)} \qquad (18)$$

where $\Gamma_\gamma^{(1)}$ is the γ-width of the usual GDR. In Ba-86a it was shown in a simple model that a relation analogous to eq. 18 holds also for the particle decay widths $\Gamma_{part}^{(N)}$:

$$\Gamma_{part}^{(N)} = N \cdot \Gamma_{part}^{(1)} \qquad (19)$$

This is expected from an independent decay of N bosons. The γ-width of the GDR can be directly calculated from the known electromagnetic dipole transition matrix-elements, one obtains

$$\Gamma_\gamma^{(1)} \simeq 10^{-2} A^{1/3} \text{ MeV} \qquad (20)$$

Since we know that the particle width of the GDR is of the order of several MeV (see e.g. Bo-75) a branching of about 1% is expected for the photon decay, independent of the number of phonons N. This rather large number will open the possibility to study γ-γ correlations of the decay of the multiphonon giant dipole states.

The γ-decay should show a rather simple angular distribution. The RHI will preferentially excite a dipole vibration along the x-axis with an angular distribution $\sim \sin^2 \Theta$, where Θ is the angle between the γ-ray and the x-axis. The angular distribution can also be used to investigate the multipolarities of the electromagnetic excitation (e.g. the E2 excitation, which is rather strong in the RHI excitation (see section 3a), and also possible E1-E2 interference).

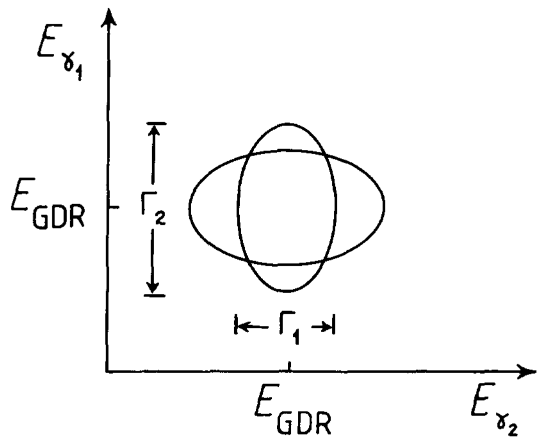

FIGURE 2:
Correlations of the two γ-energies in the two-photon decay of the N = 2 GDR. The widths Γ_1 and Γ_2 of the N=1 → N=0 and the N=2 → N=1 lines are also indicated.

To get an order of magnitude estimate, let us look at U-U collisions. The cross section for N=2 excitation in U is of the order of 1 barn (see Ba-86b, Ba-86e). With $\Gamma_\gamma/\Gamma_{part} \simeq 10^{-2}$ we obtain a cross section of the order of 100 μb for the γ-γ coincidence. A plot of E_{γ_1} vs. E_{γ_2} is sketched in Fig. 2. With this method one can determine the excitation energy and the width of the N=2 (and possibly also N > 2) multiphonon states. Furthermore, unharmonicities, splittings (due to spin, isospin, deformation) of these states could be investigated.

4. PRIMAKOFF EFFECT

High energy physicists have made use of the "equivalent" photons corresponding to the Coulomb field of nuclei in order to investigate the interaction of unstable particles with photons. Such a type of experiments, where highly relativistic particles interact with the Coulomb field of a target nucleus were suggested by Primakoff (Pr-51) and Pomeranchuck and Shmushkevich (Po-61).

In an experiment at CERN by Dydak et al. (Dy-77), a highly relativistic ($E_{lab} \simeq 20$ GeV) Λ beam was scattered on a nuclear target, where Σ^0 hyperons were produced at forward angles in the nuclear Coulomb field:

$$\Lambda + Z \rightarrow \Sigma^0 + Z. \qquad (21)$$

The Σ^0 were detected through their decay $\Sigma^0 \rightarrow \Lambda\gamma$, which is by far the dominant decay mode of the Σ^0 particle. The cross section for the Σ^0 Coulomb production can be expressed in terms of the magnetic transition moment $\mu_{\Lambda\Sigma^0}$ or the Σ^0 lifetime. This is specially interesting since it allows for a test of the $SU(3)_{flavor}$ properties of the strong and electromagnetic interactions. The $\Lambda\Sigma^0$ conversion cross section in the field of a nucleus was calculated by Dreitlein and Primakoff (Pr-62) and by Pomeranchuck and Shmushkevich (Po-61). In these calculations, the nuclear form factor and absorption are taken into account in a rather complicated way. We have shown (Ber86a) that their results can be obtained with the much simpler eikonal approach, as described in chapter 2, where nuclear absorption is included from the beginning, and no nuclear form factors enter any more.

The $\Lambda\Sigma^0$ conversion experiment has been recently (Pe-85, Pe-86) redone at Fermilab with a Λ beam of $p_\Lambda \approx 200$ GeV/c incident on nuclear targets with Z = 4,50, and 82. These experiments show the expected logarithmic increase of the electromagnetic cross section with energy. A comparison of their experimental data with the result of the present method was done in Ber-87a. The agreement is quite good, and the value for the lifetime of the Σ^0-particle remains practically the same as the one given before (AB-86).

There are also other examples, where the Primakoff effect is used to study the interaction of photons with unstable particles. Quite recently (Ant-87), the vertex $\gamma \rightarrow 3\pi$ has been investigated in the reaction of pion pair production by pions in the nuclear Coulomb field

$$\pi^- + Z \rightarrow \pi^- + \pi^0 + Z \qquad (22)$$

in the region of low-invariant-mass of the $\pi^-\pi^0$ system. A highly relativistic 40 GeV pion beam has been used. This is interesting in the context of the so-called chiral anomalies.

In a similar experiment the polarizability of the π^- has been measured (Ant-83, Ant-85). The Compton effect on a pion was studied in the reaction

$$\pi^- + Z \rightarrow \pi^- + \gamma + Z \qquad (23)$$

From this the cross section for the elastic π^- photon scattering was deduced; this in turn, could be related to the pion polarizability, and it was found that $\alpha_\pi = (6.8 \pm 1.4).10^{-43}$ cm^3. This quantity is of great interest in the study of hadron properties.

As another possibility we mention the study of the production of resonances in the interaction of real photons with the equivalent photons of the Coulomb field. At KEK (N. Sasao et al, Tsukuba, as mentioned in Ya-87) the production of axion-like particle is investigated in this manner. On the original suggestion of Primakoff (Pr-51) the π^0-lifetime was measured in the process $\gamma + Z \to \pi^0 + Z$ (Br-74).

5. LEPTON PAIR PRODUCTION AND 2γ-PROCESSES

Due to the high mass of the heavy ions, bremsstrahlung (see Ber-86b) and bremsstrahlung production of lepton pairs is of minor importance in RHI collisions. Rather, the lepton pair production cross section is dominated by the 2 photon graph. This mechanism was considered in 1934 by Landau and Lifshitz (La-34), where the semiclassical approximation was used. More detailed calculations along these lines were done recently by Bertulani and Baur (Ber-87a, Ber-87c and further references given there). The cross sections are very large. It is suggested (see An-87) to use the pair production cross section as a luminometer for the RHIC current.

The measurement of the Coulomb cross section for the production of direct electron-pairs by high energy heavy ions (^{16}O at 60 and 200 GeV/A) is in preparation at the CERN SPS (Pa-86). A main aim of this investigation is the test of the QED theory and the screening corrections (see also Ber-87c). This experiment should provide a firm foundation for a new method to determine the energies of heavy cosmic ray nuclei in the region of 10^{13} - 10^{16} eV/AMU by the measurement of these electron pairs. It is pointed out in Ber-87c that at very high energies and high charges the unitarity limit will be exceeded in a lowest order QED calculation. For the heaviest systems (like U-U) this will occur at γ-values of the order of 10^3, for lighter systems this will practically be not important (see Fig. 5 of Ber-87c).

Heavy lepton ($\mu^+\mu^-$, $\tau^+\tau^-$) pair production is rather unimportant, due to the strong limitation imposed by the adiabaticity condition. Total cross sections are calculated in Ba-87a and Ber-87c. On the other hand, e^+e^- pair production will be so copious that also the e^- atomic shell capture process

$$Z_1 + Z_2 \to (Z_1 + e^-)_{K,L,\ldots} + e^+ + Z_2 \tag{24}$$

is important. It is studied in Ber-87d and Be-87.

In addition to the production of e^+e^- pairs in the collision of two equivalent photons it will also be interesting to investigate other possible final states in the collisions of 2 photons (for more details, see Ba-87b). Two-photon-physics is extensively studied at e^+e^- colliders (see Lo-60 and AB-86). Due to the much higher charges of the heavy ions 2γ processes can also play a role in RHI collisions. It is shown in Ba-87b that one obtains in the heavy ion case

$$\sigma_C = \left(\frac{Z_1 Z_2 \alpha}{\pi}\right)^2 \int dx\, \sigma_{\gamma\gamma\to X}(x) I(x) \tag{25}$$

with

$$I(x) = \frac{16}{3x} \left(\ln \frac{\gamma c}{\sqrt{x} R_1 R_2}\right)^3 \tag{26}$$

where 4x corresponds to the square of the invariant mass of the 2γ-system. The radii of the 2 heavy ions are given by R_1 and R_2, respectively; the Lorentz factor γ (in a system where the two heavy ions collide with opposite velocities with each other) is related to the corresponding Lorentz-factor γ_p of the projectile for a fixed target machine by

$$\gamma_p = 2\gamma^2 - 1 \tag{27}$$

For the production of neutral, C = + 1 states R (like π^0, η, η_c,...) one obtains (Ba-87b)

$$\sigma_C = \frac{128}{3} (Z_1 Z_2 \alpha)^2 \frac{\Gamma(R\to\gamma\gamma)}{m_R^3} \left(\ln \frac{2\gamma}{m_R \sqrt{R_1 R_2}}\right)^3 \tag{28}$$

where $\Gamma(R\to\gamma\gamma)$ denotes the 2γ-width of the resonance R.

Due to the comparatively low values of γ in a RHI collision, it will not be possible to reach states of high mass (like the η_c). However, it could be possible to look for hitherto unknown resonances in the γ-γ system in the MeV region. This could also be of interest in connection with the appearance of positron peaks in the collision of low energy heavy ions (see Ki-86 for a review) where also speculations were made that this could have something to do with unknown particles, like axions. If such a particle were heavier than $2m_e c^2$, one could look for peaks in the invariant e^+e^- mass spectrum. This would also complement the search for resonances in e^+e^- collisions in the MeV region (Wi-87, Ma-87).

6. CONCLUSION AND OUTLOOK

Electromagnetic effects in relativistic nuclear collisions are very important and interesting. Electromagnetic processes with their copious production of hadrons, photons and lepton pairs may be a background which has to be well understood in the search for a quark-gluon plasma. We have discussed the theoretical framework to describe such processes. The method of equivalent photons has proven to be a very powerful and transparent tool to study these processes.

The large cross section for the electromagnetic excitation of giant resonances could open up new experimental possibilities, which are not possible e.g. with electrons. Of special interest is the excitation of multiphonon giant dipole resonances. These are hitherto unknown nuclear states with especially large separation of neutron and proton nuclear matter. The damping of this collective motion will have to be further investigated. Electromagnetic dissociation is also of more practical importance in the production of new and interesting isotopes (like e.g. ^{19}Ne, also with possible applications in medicine).

Furthermore, we have investigated the possibility of studying γ-γ-physics (the e^+e^- production has a very large cross section) with relativistic heavy ion collisions. Again, it is the very strong and short pulse of electromagnetic radiation which offers new possibilities.

REFERENCES

AB-86 M. Aguilar Benitez et al, Phys. Lett. 170B (1986) 1.

Al-66 K. Alder and A. Winther, Coulomb Excitation, (Academic, NY, 1966).

Al-75 K. Alder and A. Winther, Electromagnetic Excitation, (North Holland,Amsterdam, 1975).

An-87 R. Anholt and H. Gould, preprint LBL-20661, to be published as a chapter in Advances in Atomic and Molecular Physics, ed. by B. Bederson, (Academic, Orlando, 1987); see also H. Gould, Atomic Physics Aspects of a Relativistic Nuclear Collider, Lawrence Berkeley Laboratory, LBL 18593 UC-28.

Ant-83 Yu. M. Antipov et al., Phys. Lett. 121 B (1983) 445.

Ant-85 Yu. M. Antipov et al., Z. Phys. C26 (1985) 495.

Ant-87 Yu. M. Antipov et al., Phys. Rev. D36 (1987) 21.

Ba-85 G. Baur, invited talk at the 1985 Varna Int. Summer School on Nuclear Physics, September 22 - October 1, 1985.

Ba-86a G. Baur and C.A. Bertulani, Proc. Int. School of Heavy Ion Physics, 12-22 October 1986, Erice, Italy, Plenum Press, ed. by R.A. Broglia.

Ba-86b G. Baur and C.A. Bertulani, Phys. Rev. C34 (1986) 1654.

Ba-86c G. Baur, C.A. Bertulani and H. Rebel, Nucl. Phys. A458 (1986) 188.

Ba-86d G. Baur, C.A. Bertulani and H. Rebel, Proc. Int. Symp. on Weak and Electromagnetic Interactions in Nuclei, 1-5 July 1986, Heidelberg, Germany.

Ba-86e G. Baur and C.A. Bertulani, Phys. Lett. B174 (1986) 23.

Ba-87a G. Baur and C.A. Bertulani, Phys. Rev. C35 (1987) 836.

Ba-87b G. Baur and C.A. Bertulani, to be published.

Be-68 H.A. Bethe and R.W. Jackiw, Intermediate Quantum Mechanics, (Benjamim, NY, 1968).

Be-87 U. Becker, N. Grün and W. Scheid, Pair production with inner-shell capture, preprint, University Giessen, to be published in Journal of Physics B: At. Mol. Phys., 1987.

Ber-85 C.A. Bertulani and G. Baur, Nucl. Phys. A442 (1985) 739.

Ber-86a C.A. Bertulani and G. Baur, Phys. Rev. C33 (1986) 910.

Ber-86b C.A. Bertulani and G. Baur, Nucl. Phys. A458 (1986) 725.

Ber-87a C.A. Bertulani and G. Baur, to be published in Physics Reports.

Ber-87b C.A. Bertulani and G. Baur, to be published in Nucl.Phys.A.

Ber-87c C.A. Bertulani and G. Baur, submitted to Phys. Rev. C.

Ber-87d C.A. Bertulani and G. Baur, submitted to Phys. Rev. C.

Bo-75 A.G. Bohr and B. Mottelson, Nuclear Structure, vol. II, (Benjamim, Reading, MA, 1975).

Br-57 D. Brink, Nucl. Phys. 4 (1957) 215.

Br-74 A. Browman, J. Dewire, B. Gittelman, K.M. Hanson, D. Larson, E. Loh, and R. Lewis, Phys. Rev. Lett. 33 (1974) 1400.

Br-85 P. Braun-Munzinger et al., Proposal 814 submitted to the AGS Program Committee, SUNY at Stony Brook, accepted 1985 (unpublished).

Dr-62 J. Dreitlein and H. Primakoff, Phys. Rev. 125 (1962) 1671.

Dy-77 F. Dydak, F.L. Navarria, O.E. Overseth, P. Steffen, J. Steinberger, H. Wahl, E.G. Williams, F. Eisele, C. Geweniger, K. Kleinknecht, H. Taureg, and G. Zech, Nucl. Phys. B118 (1977)1.

Em-87 H. Emling et al., Proposal to the SIS Program Committee, GSI-Darmstadt, Germany, february 1987.

Fe-24 E. Fermi, Z. Phys. 29 (1924) 315.

Fi-87 R.D. Fischer et al., Proceedings of the Workshop on Experiments and Experimental Facilities at SIS/ESR, March 30 - April 1, 1987, GSI Darmstadt.

Ge-87 H. Geissel et al., Accepted proposal to the SIS-ESR Experimental Program, GSI-Darmstadt, February 1987.

Ha-87 P.G. Hansen and B. Jonson, Europhys. Lett. 4 (1987) 409.

Hi-87 D. Hilscher et al., Proceedings of the Workshop on Experiments and Experimental Facilities at SIS/ESR, GSI-Report, April 1987.

Ho-84 B. Hoffman and G. Baur, Phys. Rev. C30 (1984) 247.

Ja-75 J.D. Jackson, Classical Electrodynamics, (Wiley, NY, 1975).

Ki-86 P. Kienle, Ann. Rev. of Nucl. and Part. Science, Vol. 36 (1986) 605.

La-34 L.D. Landau and E.M. Lifshitz, Phys. Zs. Sowjet. 6 (1934) 244.

Lo-60 F.E. Low, Phys. Rev. 120 (1960) 582.

Ma-87 K. Maier et al., Z. Phys. A326 (1987) 527.

Me-70 E. Merzbacher, Quantum Mechanics, 2nd ed. (Wiley, NY, 1970).

Me-84 M.T. Mercier, J.C. Hill, F.K. Wohn, and A.R. Smith, Phys. Rev. Lett. 52 (1984) 898.

Me-86 M.T. Mercier, J.C. Hill, F.K. Wohn, C.M. McCullough, M.E. Nieland, J.A. Winger, C.B. Howard, S. Renwick, D.K. Matheis, and A.R. Smith, Phys. Rev. C33 (1986) 1655.

Pa-86 T.A. Parnell et al., IONS, in Experiments at CERN in 1986, p. 123.

Po-61 I.Y. Pomeranchuck and I.M. Shmushkevich, Nucl. Phys. 23 (1961) 452.

Pr-51 H. Primakoff, Phys. Rev. 31 (1951) 899.

Pe-85 P.C. Petersen, PhD thesis, Rutgers University , 1985, unpublished.

Pe-86 P.C. Petersen et al., Phys. Rev. Lett. 57 (1986) 949.

Sno-86 K.A. Snover, Ann. Rev. of Nucl. and Part. Science, Vol. 36 (1986) 545.

Wi-79 A. Winther and K. Alder, Nucl. Phys. A319 (1979) 518.

Wi-87 U. von Wimmersperg et al., Phys. Rev. Lett. 59 (1987) 266.

Ya-87 Y. Yamaguchi and H. Sato, Phys. Rev. C35 (1987) 2156.