MULTIPLE ELECTROMAGNETIC EXCITATION OF GIANT DIPOLE PHONONS IN RELATIVISTIC HEAVY ION COLLISIONS

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Multiple electromagnetic excitation of giant dipole multiphonon states is studied in a harmonic vibrational model The cross sections are found to be quite large for very heavy nuclei, thus relativistic heavy ion collisions provide a unique tool to study new nuclear states by means of multiphonon excitation and produce new nuclei with unusual N/Z-ratios

The passage of a relativistic heavy ion (RHI) by a nuclear target provides an electromagnetic pulse of a short time duration $t_{coll} \simeq b/\gamma c$, where b is the impact parameter and $\gamma = [1 - (v/c)^2]^{-1/2}$. In such a collision virtual photons of energy up to

$$E_{\gamma}^{max} = \hbar/\tau_{coll} \simeq (\hbar c/b)\gamma \qquad (1)$$

are present [1]. Such photons can be sufficiently energetic to excite the giant dipole resonance (GDR) (and other high-lying multipole resonances) in RHI collisions. Such excitations have been observed [2] through the subsequent particle decay of the GDR (in the target as well as in the projectile). The strength of the electromagnetic multipole excitation of order Eλ can be measured [3] in terms of the strength parameter

$$\chi_{1\to f}^{(\lambda)} = Ze \langle f|M(E\lambda)|1\rangle/\hbar v b^{\lambda} , \qquad (2)$$

where Z is the charge number of the projectile and $\langle f|M(E\lambda)|1\rangle$ the electromagnetic multipole moment of the corresponding transition in the target nucleus.

In the case of non-relativistic Coulomb excitation where $v \ll c$, the strength parameter $\chi_{1\to f}^{(\lambda)}$ can be quite large, providing the possibility of multiple Coulomb excitation, especially by means of heavy ions. For RHI on the other hand, this strength parameter will not exceed the value of one, not even for very high Z.

The multipole matrix element $\langle f|M(E\lambda)|1\rangle$ is of the order of eR^{λ}, where R denotes the nuclear radius, therefore $\chi_{1\to f}^{(\lambda)} \simeq Z(e^2/\hbar c)(R/b)^{\lambda}$ which will be less than one ($Ze^2/\hbar c = Z\alpha < 1$), since the impact parameter b has to be chosen larger than R in order to obtain a pure electromagnetic excitation process. Therefore the first-order semiclassical theory [3] and its quantal versions [4,5], like the PWBA (modified by a cylindrical hole cut-off), will generally account well for electromagnetic excitation effects in RHI collisions.

It has been observed in ref. [4] that the absolute values of the semiclassical excitation amplitudes a_{f1} for the excitation of the GDR in very heavy nuclei by very heavy relativistic nuclei (like in U–U collisions) will approach unit magnitude. In such a situation the assumed first-order perturbation theory can no longer be accurate and higher-order effects must be taken into account.

Instead of giving a general theory of multiple excitation in RHI collisions (by means of e.g. semiclassical coupled channels or Glauber theories) we consider the problem of multiple excitation of a pure harmonic oscillator. We note that this problem can be solved (to all orders) in closed form [6,7]. The multiple excitation amplitude can be directly expressed in terms of the first-order amplitudes, which have already been calculated [3,4].

Since it cannot be studied with non-relativistic heavy ions due to the adiabaticity condition, the ex-

citation of two (and more) GDR phonons is of special interest. To our knowledge, nothing is known experimentally about such states (they would e.g. not be seen in photoabsorption, since a two-photon absorption mechanism would be required to excite such states; in atomic physics such kinds of excitations are of course widely achieved nowadays with lasers). In such a situation we therefore try to use the simplest possible model, the collective oscillation of all neutrons against all protons in terms of (undamped) harmonic vibrations. The usual GDR is a one-photon state of angular momentum 1 (assuming a spin zero nuclear ground state $|0\rangle$)

$$|1,1\mu\rangle = a^\dagger_\mu |0\rangle , \qquad (3)$$

where $a^\dagger_\mu$ denotes the creation operator for a GDR photon with angular momentum projection μ. The operators $a^\dagger_\mu$ and a_μ satisfy the usual boson commutation relations. The two phonon states $|2,IM\rangle$, coupled to good angular momentum I, M with $I = 0$ and 2, are given explicitly by (see e.g. ref. [7])

$$|2,IM\rangle = (1/\sqrt{2}) \sum_{\mu\mu'} \langle 1\mu 1\mu'|IM\rangle a^\dagger_\mu a^\dagger_{\mu'}|0\rangle . \qquad (4)$$

The dipole transition matrix elements are obtained from the TRK sum rule

$$\int \sigma^{E1}_\gamma (E_\gamma)\, dE_\gamma \simeq 60NZ/A \text{ MeV mb} , \qquad (5a)$$

and the experimentally known energy position of the GDR

$$E_{GDR} = 80 \text{ MeV}/A^{1/3} , \qquad (5b)$$

assuming that the GDR exhausts the sum rule, eq. (5a). This is a reasonable assumption for our purposes. With these numbers we calculate [3,4,8] the first-order excitation amplitude $a^m_{0\to1}$, where m denotes the angular-momentum transfer in the beam direction. One obtains for the excitation of a nucleus (N_2, Z_2) by a nucleus with charge Z_1

$$|a^{m=0}_{0\to1}| = 0.41\alpha\, [Z_1 (N_2 Z_2)^{1/2}/A^{2/3}_2]\,(c/\gamma v)^2 K_0(\xi) , \qquad (6a)$$

and

$$|a^{m=\pm1}_{0\to1}|$$

$$= 0.29\alpha\, [Z_1 (N_2 Z_2)^{1/2}/A^{2/3}_2]\,(c/v)^2 (1/\gamma) K_1(\xi) , \qquad (6b)$$

where the adiabaticity parameter ξ is given by

$$\xi = E_\gamma b/\hbar v\gamma . \qquad (6c)$$

The total excitation probability of the one-phonon GDR is given, in first-order perturbation theory, by

$$P^{(first\ order)}_1 = \sum^{1}_{m=-1} |a^m_{0\to1}|^2 \equiv |\chi(b)|^2 , \qquad (7)$$

where we have introduced a parameter $|\chi(b)|^2$. In the exact theory of multiple Coulomb excitation of a harmonic oscillator [6,7] one obtains a Poisson distribution for the excitation probability P_N of an N-phonon state

$$P_N = (1/N!)|\chi(b)|^{2N} \exp[-|\chi(b)|^2] , \qquad (8)$$

where $|\chi(b)|^2$ is given in eq. (7). In refs. [6,7] the theory was developed for nonrelativistic Coulomb excitation, the same arguments apply also to the relativistic case.

From eq. (6) it is seen directly that the largest excitation amplitudes are obtained the larger the projectile and the target area. Therefore we study the example of ^{238}U + ^{238}U collisions. In fig. 1 the impact parameter dependent excitation probabilities P_N given by eq. (8) using eqs. (7) and (6) are shown. The probabilities for $N = 1$ decrease essentially like $1/b^2$ until
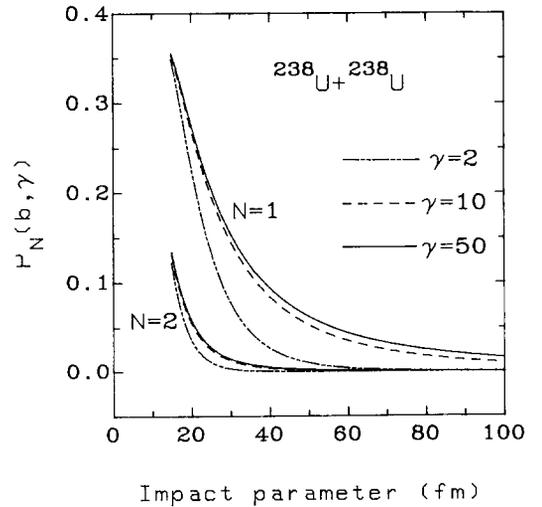

Fig. 1 The excitation probability P_N of N-phonon GDR states is shown as a function of the impact parameter b for ^{238}U + ^{238}U RHI collisions.
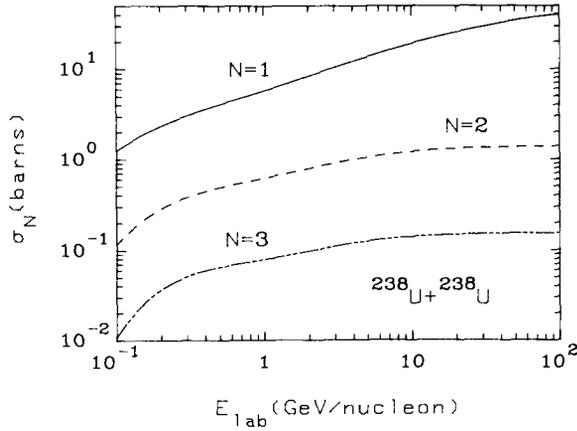
Fig 2 The total cross section σ_N for the excitation of N-phonon GDR states in ^{238}U $-^{238}$U RHI collisions as a function of the incident energy E_{lab} (GeV/nucleon)

the adiabatic cut-off [see eq. (1)] is reached. The probabilities for $N > 1$ decrease faster ($\sim 1/b^{2N}$) and are of smaller magnitude, as it is expected. However, their values are still quite appreciable. In fig. 2 the total cross sections σ_N for the excitation of N-phonon GDR states

$$\sigma_N = 2\pi \int\limits_{R_1+R_2}^{\infty} b \, db \, P_N(b) \qquad (9)$$

are given. The minimum impact parameter is given by $R_1 + R_2$, where $R_i = 1.2 A_i^{1/3}$ fm ($i = 1,2$). It can be seen that the cross section for $N = 1$ is larger than the geometrical cross section for $E_{lab} \gtrsim 2$ GeV/nucleon. It increases logarithmically with γ. The cross sections for $N \geqslant 2$ are smaller, however still large as compared to nuclear fragmentation cross sections. They tend to a constant value as $\gamma \to \infty$, as can be directly shown from the behaviour of $|a_{0 \to 1}(b)|^2$ [eqs (6), (8)].

The one-phonon GDR excitations in RHI collisions have been observed experimentally (see e.g. ref. [2]) with the theoretically expected large cross sections The experimental signature of that process was the observation of fragments which have lost one or two nucleons (mainly neutrons) by the decay of the GDR. Since this particle decay is very fast (the GDR is a strongly damped collective motion) it may be asked whether a two- or more-phonon excitation is possible at all. The decay time of GDR corresponding to a

width of $\Gamma = 5$ MeV is given by

$$\tau_{\text{decay}} = \hbar/\Gamma \simeq 10^{-22} \text{ s} . \qquad (10)$$

This time has to be compared to the passage time $t_{\text{coll}} \simeq b/\gamma c \sim (5/\gamma) \times 10^{-23}$ s for $b = 15$ fm. Thus we will have $\tau_{\text{decay}} > \tau_{\text{coll}}$ even for moderately high values of γ and multiple excitation will be possible in principle. Nothing is known about the widths of the higher ($N \geqslant 2$) phonon states, if the widths of these states would become larger than the level spacing E_{GDR} [see eq. (5b), ~ 13 MeV for $A = 238$] then the observation of such states would become difficult. The experimental detection of such two- (or more-) phonon GDR states is a challenge, the signature could be fragments where quite a few neutrons have been removed in this giant oscillation of neutrons against protons ("cold fragmentation", see Kienle [9]). This electromagnetic excitation process can therefore be a promising method to produce beams of new nuclei with unusual N/Z-ratios, this can lead to further interesting studies.

The two-phonon multiplet contains angular momentum states $I = 0$ and 2. These states are explicitly given by [see eq (4)]

$$|2,00\rangle = (1/\sqrt{6})(2a_1^\dagger a_{-1}^\dagger - a_0^\dagger a_0^\dagger)|0\rangle$$

$$= \sqrt{2/3}|1,0,1\rangle - (1/\sqrt{3})|0,2,0\rangle ,$$

$$|2,20\rangle = (1/\sqrt{3})(a_0^\dagger a_0^\dagger + a_1^\dagger a_{-1}^\dagger)|0\rangle$$

$$= \sqrt{2/3}|0,2,0\rangle + (1/\sqrt{3})|1,0,1\rangle ,$$

$$|2,21\rangle = a_1^\dagger a_0^\dagger|0\rangle = |0,1,1\rangle ,$$

$$|2,22\rangle = (1/\sqrt{2})a_1^\dagger a_1^\dagger |0\rangle = |0,0,2\rangle , \qquad (11)$$

and similarly for $M = -1$ and -2. Here we have introduced the uncoupled normalized states $|n_{-1},n_0,n_1\rangle$, where n_μ denotes the number of phonons with angular momentum projection μ. For $\gamma \gg 1$, the $m = \pm 1$ excitation amplitude completely dominates over the $m = 0$ excitation (see e.g. ref. [1]). Neglecting $|a_{0 \to 1}^{m=0}|$ [eq. (6a)] as compared to $|a_{0 \to 1}^{m=\pm 1}| \equiv x$ [eq. (6b)] we obtain a simple and realistic result for the excitation of the angular momentum states. In terms of x we obtain for the excitation probability $P_{n_{-1}n_0n_1}$ of the uncoupled states $|n_{-1},n_0,n_1\rangle$ (see ref. [7], p. 199ff)

$$P_{101} = x^4 \exp(-2x^2) ,$$

$$P_{002} = P_{200} = \tfrac{1}{2} x^4 \exp(-2x^2) . \tag{12}$$

The other combinations give only a negligible contribution. From eq. (11) we obtain for the excitation probability $P_{2,IM}$ of the angular momentum coupled states $|2, IM\rangle$

$$P_{2,22} = P_{2,2-2} = \tfrac{1}{2} x^4 \exp(-2x^2) ,$$

$$P_{2,21} = P_{2,2-1} = 0 ,$$

$$P_{2,20} = \tfrac{1}{3} x^4 \exp(-2x^2) ,$$

$$P_{2,00} = \tfrac{2}{3} x^4 \exp(-2x^2) . \tag{13}$$

The total $N = 2$ excitation probability adds of course up to the value $P_{N=2}$ which has already been obtained above [eq. (8) with $2x^2 = |\chi(b)|^2$]. The ratio of excitation of 0^+ and 2^+ states is $1:2$.

In conclusion, the use of RHI offers a unique method to study multiphonon GDR states, nuclear collective states very high up in the continuum hitherto unexplored. The multinucleon decay of these states offers a new method to produce nuclei with very unusual N/Z-ratios. Our simple model should give a fairly reliable estimate of the cross sections.

They are found to be quite appreciable. However it remains to be seen in new experiments with RHI what the properties of these new and exotic nuclear states really are, especially what their particle decay widths are, their anharmonicities, and how the strong damping of the giant dipole oscillation will affect these states.

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