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FINITE P_T CONTRIBUTION TO RELATIVISTIC COULOMB EXCITATION: A POSSIBLE EXPLANATION FOR THE CLEAN FISSION PUZZLE

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ABSTRACT

We study the quantum relativistic Coulomb excitation process including recoil effects in the plane wave Born approximation. Quantum and relativistic recoil effects allow for relatively large transverse momentum transfers, usually neglected(1,6). This specific feature is shown to modify the angular distribution of Coulomb induced fission fragmentation in an essential manner. In contrast with usual treatments we find that our results compare favourably with recent data(7).

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Recent studies of relativistic Uranium beam in emulsions reveal that approximately 700 mb of the total cross section corresponds to the so called clean fission events, i.e., events in which only two heavy fragment are observed(7). A natural explanation for these events is the Coulomb excitation of the projectile. Recent calculations(8) using the conventional semiclassical theories underestimate the experimental cross section by a factor of seven. However, the most intriguing fact with respect to this data is the angular distribution, which exhibits a peak at zero degree in the Uranium rest frame. This also cannot be reproduced by the available theories(2). Based on such calculations(8), it has been suggested that some new unknown mechanism could be responsible for the observed clean fission phenomena.

To our knowledge, every treatment of the Coulomb excitation mechanism (quantum as well as semiclassical(1-6)) neglects recoil effects. In this letter, we derive the relativistic quantum Coulomb excitation cross section including recoil effects. The exchange of a virtual photon together with recoil effects drastically alter the clean fission angular distribution and quantitatively modify its total cross section as compared to those without recoil. Our result seems to be compatible with experiment.

We consider the excitation mechanism indicated in fig. 1. The corresponding amplitude reads

$$S_{f \to i} = i \int dx \int dy \, \langle A' P_A' | j^\mu(x) | A P_A \rangle D_F(x-y) \langle B' P_B' | j_\mu(y) | B P_B \rangle \quad (1)$$

and $j_\mu(x)$ is the nuclear current operator, where $D_F(x-y)$ is the Feynman propagator for the electromagnetic field. In general it is a rather difficult and delicate problem to define the nuclear state $|A P_A\rangle$ when P_A is relativistic. This is because the nucleus is an extended object and the relativistic boost involves intrinsically the dynamical response of the nucleus. However, for the case of the Coulomb scattering process, we may assume that the momentum transfer $\Delta P = P' - P$ is always non-relativistic. In such a case, from the Lorentz invariance of the theory, we can express the current matrix element in terms of well established non-relativistic nuclear physics terminology. Let $\Lambda(P_A)$ be the Lorentz transformation matrix from the rest frame of A to the system with momentum P_A

$$\langle A' P_A' | j^\mu(x) | A P_A \rangle = \Lambda^\mu_{\ \nu}(P_A) \langle A' \overline{\Delta P_A} | j^\nu(\Lambda^{-1}(P_A)x) | A\, 0 \rangle \quad (2)$$

where

$$\overline{\Delta P_A} = \Lambda^{-1}(P_A)(P_A' - P_A) \quad (3)$$

is the momentum transfer as seen by an observer in the rest frame of A. With the help of the Fourier decomposition of the Feynman propagator and assuming that the nuclear current is a sum of local operators we get, after separating the center of mass coordinate

$$S_{i \to f} = \frac{(2\pi)^4}{V^2} \delta^4(P_A' + P_B' - P_A - P_B) \frac{e^2 Z_A Z_B}{(P_A' - P_A)^2} F_{B\mu}(\bar{q}_B) \, .$$

$$\Lambda^\mu_{\ \sigma}(P_A) \Lambda^\sigma_{\ \nu}(P_B) F_A^\nu(\bar{q}_A) \quad (4)$$

where

$$F_A^\nu(\bar{q}_A) = \frac{1}{e Z_A} \int d^3\xi \, \langle E_A^* | e^{i \bar{q}_A \cdot \xi} j^\nu(\xi) | E_A^{gs} \rangle \quad (5)$$

the kets $|E_A^*\rangle$, $|E_A^{gs}\rangle$ correspond to the intrinsic excited and ground state of nucleus A respectively, $\overline{q_A}$ is given by the spatial part of eq. (3), V is the normalization volume in eq. (4).

Collecting all factors and integrating the energy momentum conserving δ-function, we get for the Coulomb excitation cross section in the limit of small excitation energies

$$\frac{d\sigma}{d\Omega} = 4(\alpha Z_A Z_B)^2 \left(\frac{M_A M_B}{\sqrt{s}}\right)^2 \int dE^* \rho(E^*) \frac{|M|^2}{q^4} |F(\bar{q}_B)|^2 \quad (6)$$

where

$$M = \left(\gamma - \beta\gamma \frac{q_z^A E^*}{|\vec{q}_A|^2}\right) \int d\vec{\xi} \langle E^* | \rho(\vec{q}_A) | G.S.\rangle \, e^{i\vec{q}\cdot\vec{\xi}} - \beta\gamma \hat{e}_z (1 - \hat{q}_A \hat{q}_A^T) \int d\vec{\xi} \langle E^* | \vec{j} \, | G.S.\rangle \, e^{i\vec{q}\cdot\vec{\xi}} \tag{7}$$

and

$$q^2 = (\delta E)^2 - (\vec{p}_A\,' - \vec{p}_A)^2 = (\delta E)^2 - \left[(p_A + \delta p_A)^2 + p_A^2 - 2p_A(p_A + \delta p_A)\cos\theta\right] \tag{8}$$

$$|\vec{q}_A|^2 = \frac{(1+\eta^2)E^* + 2p_A(p_A+\delta p_A)(1-\cos\theta)}{1 - E^*/M_A} \quad ; \quad \eta = \frac{1}{(\beta\gamma)_B}\left(\frac{M_A}{\sqrt{s}}\right) \tag{9}$$

with

$$\delta p = -\left(\frac{M_A E_b}{\sqrt{s}\; p_A}\right) E^* \tag{10}$$

$$\delta E = \frac{M_A}{\sqrt{s}} E^* \tag{11}$$

and γ is the Lorentz factor of the incident nucleus with velocity β.

Expression (6) is the main result of this letter. The first thing to note is the limit of no excitation when it becomes a simple matter to check that the Rutherford cross section is recovered. It is worthwhile to discuss at this point some essential differences with the semiclassical expression for the Coulomb excitation mechanism at relativistic energies[1,5]:

a) In the cases where excitations are important, one can still recover the factorized semiclassical expression from eq. (6) provided

$$1 - \cos\theta \gg \left|\frac{\delta E^2 - \delta p^2}{2p(p+\delta p)}\right| \approx \left(\frac{E^*}{E_{CM}}\right)^2 \tag{12}$$

In non-relativistic Coulomb excitation processes this condition is easily satisfied, since most of the contribution to the cross section will come from finite deflection angles. However, in the relativistic limit, this will not be the case, for

$$1 - \cos\theta \simeq \left(\frac{p_T}{p}\right)^2 \tag{13}$$

and this is of the same order as $\left(\frac{E^*}{E_{CM}}\right)^2$, showing thus that the factorization assumption becomes a delicate matter for these deflection angles.

b) The angular distribution of the clean fission fragments will be completely different from the one obtained neglecting recoil effects ($\delta p = 0$): the first term on the r.h.s. of eq. (7) involves the transition operator given by the Fourier transform of the charge density. This excites the nuclear state $|E_A^*\rangle$ in the direction of $\vec{q}_A$. When δp is set to zero $\vec{q}_A$ is almost perpendicular to the incident beam direction so that the excited state should also fission in this direction. On the other hand if we include recoil effects $\delta p \sim 10$ MeV the momentum transfer for small angle scattering will be almost parallel to the beam direction (see Fig. 2a), yielding the opposite result. When the momentum transfer becomes large with respect to δp, the main contribution will come from the second term on the r.h.s. of eq. (7), as will be shown later. In this case the nuclear excitation is induced by the transverse component of the current density with respect to $\vec{q}_A$. Therefore the polarization is perpendicular to $\vec{q}_A$ (see Fig. 2b), yielding again fission fragments parallel to the beam direction. This explains the experimental angular distribution[7].

c) In the semiclassical calculations, due to the on shell nature of the trajectories, the transverse momentum transfer (P_T) is always limited to very small values and therefore neglected. In this quantum treatment, there is no such a restriction. In particular relatively large (~ 200 MeV/c) transverse momentum transfers can contribute to the observed clean fission events. This fact invalidates the usual simple estimates using a multipole expansion and related sum rules.

In order to compare our results for the total cross section to the ones obtained in ref. (8) we consider small momentum transfers ($P_T \lesssim 60$ MeV/c) where the second term can be safely neglected. We calculate the contributions from dipole

and quadrupole transitions using Tassie's model[9], assuming for simplicity a spherical nucleus where the radial derivative of the density distribution $\frac{d\rho}{dr}$ is approximately by a Gaussian of width $a = 1$ fm centered at the nuclear radius R. We get

$$\sigma^D = 8\pi\,(\alpha Z_p Z_T)^2 \frac{1}{Z_p^2}\,\frac{3}{R^2}\,B(E1)\,\frac{(M_A M_B)^2}{(\sqrt{s})^2}\,\gamma_{A\to B}^2 \times$$

$$\int_{1-\Delta x}^{1} dx \left[\frac{1}{\eta + \zeta(1-x)}\right]^2 e^{-q^2\frac{a^2}{2}} \left| j_1(qR) + \frac{1}{2}\left(\frac{a}{R}\right)^2 \sin qR \right|^2 \quad (14)$$

$$\sigma^Q = 8\pi\,(\alpha Z_p Z_T)^2 \frac{1}{Z_p^2}\,\frac{45}{4R^4}\,B(E2)\,\frac{(M_A M_B)^2}{(\sqrt{s})^2}\,\gamma_{A\to B}^2 \times$$

$$\int_{1-\Delta x}^{1} dx \left[\frac{1}{\eta + \zeta(1-x)}\right]^2 e^{-q^2\frac{a^2}{2}} \cdot$$

$$\left| j_2(qR) + \frac{3}{2}\,qR\left(\frac{a}{R}\right)^2 j_1(qR) + \frac{1}{4}\,qa\left(\frac{a}{R}\right)^3 \sin qR \right|^2 \quad (15)$$

where

$$q^2 = E^{*2} + \eta + \zeta(1-x)$$

$$B(E1) = 66.4\ \mathrm{fm}^2$$

$$B(E2) = 2.54 \times 10^4\ \mathrm{fm}^2$$

$$\gamma_{A\to B} = \frac{M_A + T_L}{M_A}$$

and T_L is the laboratory kinetic energy of the projectile.

The factors B(E1) and B(E2) appear as a consequence of the normalization of the transition densities to the respective sum rule for low momentum transfers. The angular integration limit is essentially connected to the maximum allowed transverse momentum transfer involved in the process,

$$\Delta x \cong \frac{1}{2}\left(\frac{P_{T\,max}}{P}\right)^2 \tag{16}$$

The total cross section for clean fission events in emulsion is given by an average of equations (14) and (15) over the various target nuclei multiplied by a fission branching ratio Γ_f/Γ which we assume to be 0.25. In fig. 3 we plot the calculated total cross section of the events in the emulsion as a function of P_T. For values of P_T up to 60 MeV/c, the total cross section is increased by a factor of 3 at least as compared to the corresponding values in ref. 8. Note the saturation of the calculated contribution at $P_T \sim 60$ MeV/c. Therefore after this value the main contribution comes from the second term. Our estimate is certainly conservative: in the most favourable experimental conditions, the coplanarity claimed in the measurement of the clean fission events cannot rule out P_T as large as several hundred MeV/c. For such high values of P_T, excitation mechanisms leading to fission other than the dipole or quadrupole excitations should be taken into account,

as, e.g. the photoabsorption by a correlated neutron-proton pair. In this region the fission branching ratio should also be increased.

For heavy ion collisions, it might be important to study the higher order correction in $(\alpha Z_1 Z_2)$. A straightforward generalization of the usual field theoretical eikonal approximation[11] to include nuclear excitations allows for a derivation of a closed form expression for the cases when only one transition matrix element is involved[12], as illustrated in Fig. 4. This corresponds to a DWBA type of treatment and therefore is not expected to change the present result quantitatively. Higher order corrections with respect to transition matrix elements for collective modes should decrease as $(\frac{\delta\rho}{\rho})^n$, where $\delta\rho$ is the amplitude of the collective density oscillation.

The mechanism proposed in this letter gives a natural explanation for highly asymmetric events in heavy ion collisions, which have actually been observed. This could occur via the transfer of high momenta induced by the virtual photon. It is interesting to note that this asymmetric events have a close analogy with diffractive dissociation processes observed in high energy hadron-hadron collisions. We might therefore classify the highly asymmetric heavy ion events as Coulomb diffractive dissociations. Work along these lines is in progress.

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REFERENCES

(1) D.L. Olson et al., Phys. Rev. C24 (1981) 1529.

(2) A. Winther and K. Alder, Nucl. Phys. A319 (1979) 518.

(3) B. Hoffmann and G. Baur, Phys. Rev. C30 (1984) 247.

(4) A. Goldberg, Nucl. Phys. A420 (1984) 636.

(5) R. Jäckle and H. Pilkuhn, Nucl. Phys. A247 (1975) 521.

(6) C.A. Bertulani and G. Baur, Nucl. Phys. A442 (1975) 739.

(7) P.C. Jain et al., Phys. Rev. Lett. 52 (1984) 1763.

(8) L.F. Canto, R. Donangelo, L.F. Oliveira and J.O. Rasmussen, LBL-19897 Preprint.

(9) L.J. Tassie, Aust. J. Phys. 9 (1956) 407.

(10) H.H. Heckman, D.E. Greiner, P.J. Lindstrom and D.D. Tuple, "An Atlas of Heavy Ion Fragmentation Topology", unpublished.

(11) M. Levy and J. Sucher, Phys. Rev. 186 (1969) 1656.

(12) D. Galetti, T. Kodama and M.C. Nemes, to be published.

FIGURE CAPTIONS

Fig. 1 - Feynman diagram for the first order relativistic Coulomb escitation.

Fig. 2 - Schematic illustration of the momentum transfer direction. a) The case $\delta p \gtrsim P_T$. b) The case $\delta p \ll P_T$.

Fig. 3 - Total cross section for clean fission events in nuclear emulsion plates due to Coulomb excitation. $P_{T_{max}}$ is the maximum value for the transverse momentum transfer.

Fig. 4 - Higher order elastic correction, where the nuclear excitation takes place at only one of the vertices.

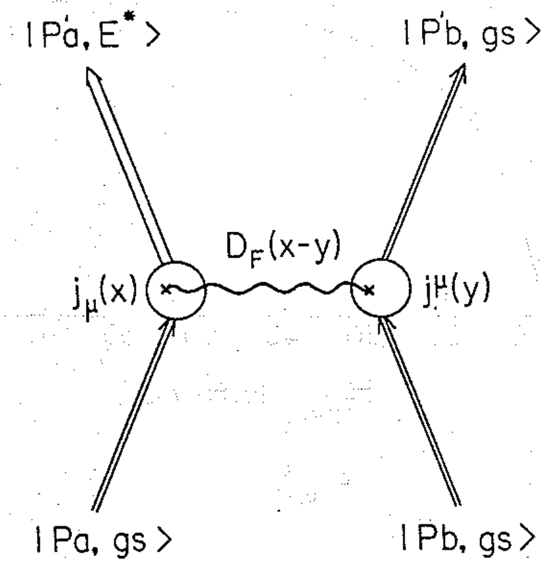


Fig 1

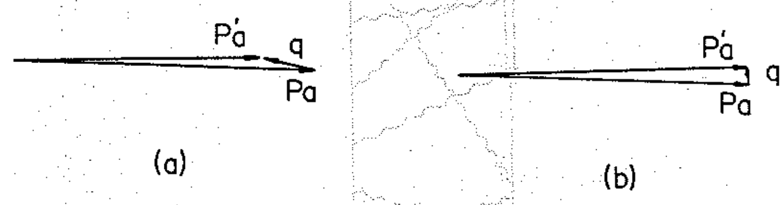
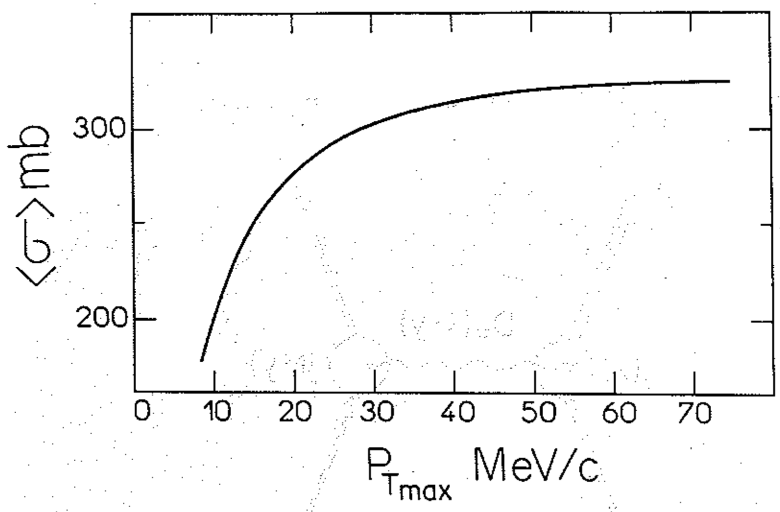
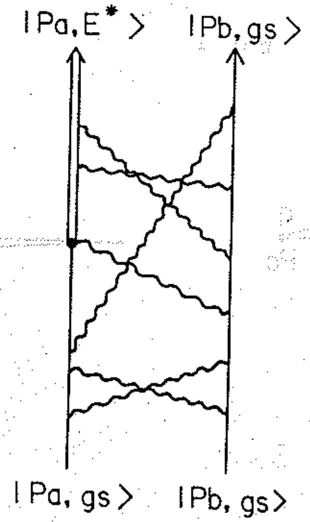


Fig 2



300
200
$\langle\sigma\rangle$mb
0
10
20
30
40
50
60
70
$P_{T_{max}}$ MeV/c

Fig 3



$|Pa, E^*\rangle$
$|Pb, gs\rangle$
$|Pa, gs\rangle$
$|Pb, gs\rangle$

Fig 4