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Relativistic Coulomb fission

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Nuclear fission reactions induced by the electromagnetic field of relativistic nuclei are studied for energies relevant to present and future relativistic heavy-ion accelerators. Cross sections are calculated for ^{238}U and ^{239}Pu fission induced by ^{12}C, ^{28}Si, ^{197}Au, and ^{238}U projectiles. It is found that some of the cross sections can exceed 10 b.

Considerable interest in the use of electromagnetic (em) probes to study nuclear fission in recent years can be found by discussions of photofission by Bohr and Mottleson,[1] Huizenga and Britt,[2] and Berman and co-workers.[3,4]

In a detailed study of photofission in the actinide region using monoenergenic photon beams, Berman and co-workers[3,4] find that the photofission cross section in the region of the giant dipole resonance (GDR) is of a magnitude comparable to the photoneutron cross section.

Complementary em studies also have been made using electron beams. For example Arruda-Neto *et al.*[5] have made detailed studies of electrofission in which they separate out effects due to separate em multipolarities such as electric dipole ($E1$), quadrupole ($E2$), and magnetic dipole ($M1$). They relate the electrofission cross section $\sigma_{e,F}$ to the photofission cross section $\sigma_{\gamma,F}$ via

$$\sigma_{e,F}=\sum_{\lambda L}\int \sigma_{\gamma,F}^{\lambda L}(\omega)N^{\lambda L}(\omega)\frac{d\omega}{\omega}\,, \tag{1}$$

where λL refers to a particular em multipolarity (such as $E2$), and $N^{\lambda L}(\omega)$ is the number spectrum of virtual photons of frequency ω radiated by the electron. The total photofission cross section $\sigma_{\gamma,F}(\omega)$ is the sum of all multipolarities

$$\sigma_{\gamma,F}(\omega)=\sum_{\lambda L}\sigma_{\gamma,F}^{\lambda L}(\omega)\,. \tag{2}$$

The third type of em probe that has been used in fission studies are heavy ions which have the advantage of being able to carry a very large charge, thus giving rise to large cross sections. This is often referred to as *Coulomb fission* and has been reviewed by Oberacker, Pinkston, and Kruse[6] and also briefly discussed by Eisenberg and Greiner.[7] As with much of the early work on Coulomb excitations,[8] the studies of Coulomb fission have been limited to low energies near the Coulomb barrier.[6,7]

It is the aim of the present work to broaden the study of Coulomb fission to include *relativistic* nucleus-nucleus collisions. At relativistic energies the Weizsäcker-Williams (WW) equivalent-photon method[9,10] is a very good approximation where one replaces the incident nucleus with its equivalent virtual photon field given by[10]

$$N_{WW}(\omega)=\frac{2}{\pi}Z^2\alpha\left[\frac{c}{v}\right]^2\left[\xi K_0K_1-\frac{v^2\xi^2}{2c^2}(K_1^2-K_0^2)\right]\,, \tag{3}$$

where α is the fine-structure constant, ω is the photon frequency, v is the speed of the nucleus, and Z is the charge. K_1 and K_0 are modified Bessel functions which are both functions of ξ defined as

$$\xi=\frac{\omega b_{\min}}{\gamma v}\,, \tag{4}$$

where γ is the usual relativistic factor and $b_{\min}$ is the minimum impact parameter, below which the reaction proceeds via the hadronic interaction,

$$b_{\min}=1.2(A_T^{1/3}+A_P^{1/3})\text{ fm}\,, \tag{5}$$

where A_T and A_P are the target and projectile nucleon numbers. The total relativistic nuclear (N) Coulomb fission cross section is then given by

$$\sigma_{N,F}=\int \sigma_{\gamma,F}(\omega)N_{WW}(\omega)\frac{d\omega}{\omega}\,. \tag{6}$$

Bertulani and Baur[11,12] have shown that the WW photon spectrum is the same as the $E1$ spectrum. Also, when $v=c$, they have shown that the spectrum of *all* multipolarities is the same as WW. Thus, Eqs. (1) and (6) are identical in the high-energy limit. Clearly Eq. (6) is simpler to use because one does not need to breakup the photofission cross section into its individual multipoles, (which become important at low energy[11,12]). In Ref. 13 some detailed studies were made of the effects of electric quadrupole ($E2$) excitations for single nucleon emission and for a more exact form of $b_{\min}$. $E2$ effects on fission cross sections have not yet been examined but it is expected[13] that they would be negligible at high energies and would produce *at most* a 3% change in the cross section near 14 GeV/nucleon. $E2$ and $b_{\min}$ differences are neglected in the present work to keep the analysis simple and because they do not contribute *large* differences. Their effects will be included in later work. The use of Eq. (6) enables accurate calculations of relativistic Coulomb fission to be made because one can simply insert *experimental* photofission cross sections[3,4] for $\sigma_{\gamma,F}(\omega)$.

Berman and co-workers[3,4] have provided some very nice photofission data in the GDR region for actinides ^{232}Th, ^{233}U, ^{234}U, ^{235}U, ^{236}U, ^{238}U, ^{237}Np, and ^{239}Pu. Given the exploratory nature of the present work, calculations are presented for relativistic Coulomb fission only from ^{238}U and ^{239}Pu targets. The projectiles used are ^{12}C, ^{28}Si, ^{197}Au, and ^{238}U at a range of energies relevant to relativistic heavy-ion accelerators. These are the Bevalac at Berkeley ($T_{\text{lab}}=2.1$ GeV/nucleon), the Alternating Gra-

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dient Synchrotron (AGS) at Brookhaven ($E_{\rm lab}=14.6$ GeV/nucleon), and the Super Proton Synchrotron (SPS) at the European Center for Nuclear Research (CERN) ($E_{\rm lab}=60$ and 200 GeV/nucleon). Results are also presented for the Relativistic Heavy Ion Collider (RHIC) to be built at Brookhaven ($E_{\rm c.m.}=100$ GeV/nucleon per beam, corresponding to a single beam energy $T_{\rm lab}=21$ TeV/nucleon).

The calculated cross sections are presented in Figs. 1 and 2 for the above projectiles, targets, and energies. It can be seen that many of the cross sections are enormous. For instance for ^{239}Pu fission with a ^{197}Au projectile the cross section is about 10 b for the AGS energies growing to about 50 b for RHIC energies. These large values suggest that experimental studies of relativistic Coulomb fission may be possible. For instance at the AGS one could use a ^{197}Au projectile on a ^{238}U or ^{239}Pu target.

Given the large cross sections a question arises as to whether beams would live long enough for a RHIC experiment. For definiteness consider a U-U colliding-beam experiment at RHIC with an energy per beam of 100 GeV/nucleon, corresponding to a $T_{\rm lab}$ of 21 TeV/nucleon (cf. Figs. 1 and 2). The fission cross section is 33 b. However the em interaction also can cause the excited ^{238}U nucleus to emit a neutron (n) or two neutrons ($2n$). Using the same technique as the present paper (see also Ref. 14) one obtains cross sections of 48 and 31 b, respectively, giving a total em cross section (fission$+n+2n$) of 112 b, which agrees well with the estimate of Baur and Bertulani,[15] who also calculate the $U+U\to(U+e^-)+e^++U$ cross section as 80 b. These processes provide the dominant beam ion cross section which is discussed in Refs. 15 and 16 (see pages 130–136).

The ^{197}Au beam parameters[16] (which would not be too different from a ^{238}U beam) for RHIC are the following: number of beam intersections $k=6$; number of particles per bunch $N_B=1.1\times10^9$; number of bunches $B=57$; and initial luminosity $L_0=9.2\times10^{26}$ cm^{-2}sec^{-1}.

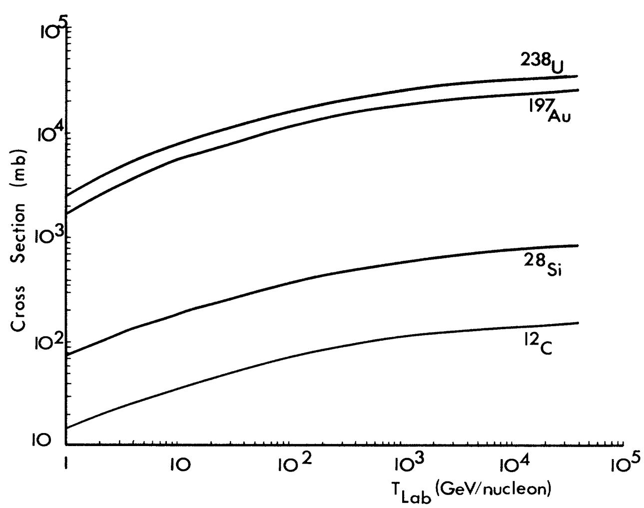

FIG. 1. Relativistic Coulomb fission cross sections as a function of laboratory kinetic energy for ^{238}U targets. The projectiles are ^{12}C, ^{28}Si, ^{197}Au, and ^{238}U.

The reaction rate is[16]

$$\lambda=-\frac{1}{I}\frac{dI}{dt}\,, \tag{7}$$

where I is the beam intensity, with the total beam initial half-life given by[16]

$$\tau=\frac{0.693}{\Sigma_i\lambda_i}\,, \tag{8}$$

where λ_i are the reaction rates due to various processes which are given in Ref. 16 as beam-gas nuclear reaction λ_1, beam-beam nuclear reaction λ_2, beam-beam Coulomb dissociation λ_3, and beam-beam bremstrahlung electron pair production λ_4. Only λ_3 and λ_4 contribute significantly for U-U collisions at RHIC. For the 80 b cross section[15,16] listed above λ_4 is 31.6×10^{-3} h^{-1}. For Coulomb dissociation[16]

$$\lambda_3=\frac{kL_0\sigma}{BN_B}=35.5\times10^{-3}\,h^{-1} \tag{9}$$

for $\sigma=112$ b. Thus the total initial half-file of the beam is 10 h. As mentioned in Ref. 16, the beam lifetime will actually be somewhat larger due to dilution of the phase-space density of the bunch since the beam lifetime depends on the beam dimensions. Thus U-U beams installed in RHIC appear to live long enough for fission and other measurements to be carried out.

Finally, it is of interest to consider how one might distinguish Coulomb fission from fission induced by nuclear forces. From Eq. (3) one can see the characteristic Z^2 dependence of the Coulomb cross section, although, as pointed out in the second paper of Ref. 13, this dependence becomes modified at lower energies. Nevertheless for energies greater than about 10 GeV/nucleon the dependence for all nuclei should remain as Z^2. Such a dependence would provide a clear signature for Coulomb versus nuclear processes.

A brief summary is now given. (i) The first calculations for *relativistic* Coulomb fission are presented herein. The calculations are performed using the Weizsäcker-

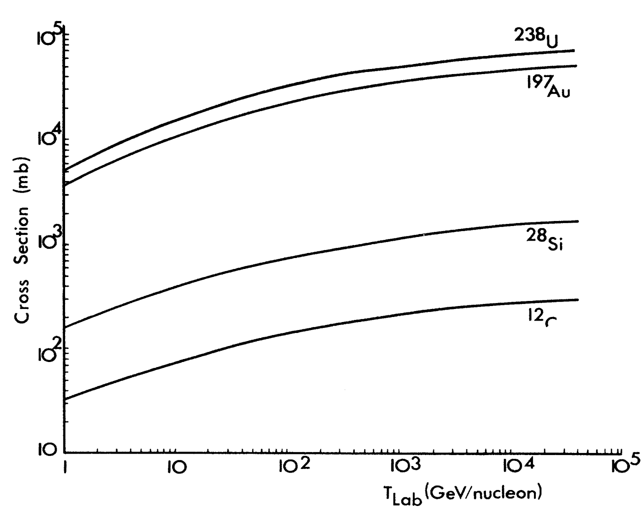

FIG. 2. Same as Fig. 1 except for ^{239}Pu targets.

Williams method of virtual quanta. (ii) The cross sections are very large and indicate that experiments may be feasible at fixed target accelerators such as the AGS. (iii) Even though the cross sections are large, it still appears that ^{238}U ions installed at RHIC would live long enough to make a useful beam. (iv) For energies greater than 10 GeV/nucleon, the Coulomb cross section will vary as Z^2 providing a clear separation from nuclear processes.

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