Electromagnetic Dissociation for High-Z Projectiles and at Ultrarelativistic Energies

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Experiments to determine the characteristics of electromagnetic dissociation (ED) have been extended to high projectile charge and ultrarelativistic energies using ^{139}La and ^{16}O projectiles on ^{197}Au targets. The gross features are reproduced in a Weizsäcker-Williams calculation but significant systematic deviations appear. The results are used as a guide in extension of the calculations to the regime of energies and projectiles expected for planned heavy-ion colliders where ED effects should comprise a major fraction of the total cross section.

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A central goal of the study of nucleus-nucleus collisions at ultrarelativistic energies is to observe new forms of nuclear matter created at small impact parameters. However, in collisions involving impact parameters large enough so that no nuclear interaction occurs, extremely strong electromagnetic fields are produced for a short time at the nucleus. These electromagnetic pulses increase in strength with energy because of the Lorentz contraction. Such electromagnetic interactions could therefore produce, for high charges and ultrarelativistic energies, cross sections larger than the total nuclear cross section.

The process called electromagnetic dissociation (ED)[1] occurs when a virtual photon is exchanged between a target nucleus and the projectile. The usual result of this process is the excitation of a giant multipole resonance. For high-Z nuclei the mode of deexcitation is primarily by neutron emission. Charged-particle emission is hindered as a result of the Coulomb barrier, but can compete for low-Z nuclei. ED was first reported in projectile fragmentation of ^{12}C and ^{16}O by Heckman and Lindstrom.[2] Olson *et al.*[1] observed ED in the fragmentation of 1.7-GeV/nucleon ^{18}O. The effect was observed for the n, $2n$, and p decay modes. The largest ED cross section (σ_{ED}) measured was 0.14 b for the reaction U(^{18}O, ^{17}O)X.[1] Significantly larger σ_{ED} values were observed by Mercier and co-workers[3,4] in the fragmentation of ^{197}Au targets by various projectiles with a maximum value of σ_{ED} reaching 0.60 b for the reaction[4] ^{197}Au(^{56}Fe, X)^{196}Au with 1.7-GeV/nucleon ^{56}Fe projectiles.

Calculations[1-4] of σ_{ED} have been made with use of a virtual-photon spectrum obtained by the Weizsäcker-Williams (WW) method.[5] Agreement with measured cross sections has been satisfactory, but some discrepancies for the highest σ_{ED} values have been noted.[4] For the projectile energies of 100 GeV/nucleon expected for the planned relativistic heavy-ion collider (RHIC) at Brookhaven, recent calculations by Baur and Bertulani[6] for ^{238}U on ^{238}U and Mercier *et al.*[4] for ^{197}Au on ^{197}Au give σ_{ED} values that reach *40 and 24 b*, respectively, for stationary targets. These values are much larger than the corresponding geometric cross sections of 6.9 and 6.1 b, and indicate that at such ultrarelativistic energies the ED process is predicted to dominate the reaction.

For ultrarelativistic high-Z projectiles, ED processes are of great interest for a number of other reasons. Because of the strength of the electromagnetic field, it may be possible to produce (with significant cross sections) multiphonon giant dipole excitations which could break up into new exotic, very neutron-rich nuclei.[6-9] It has also been suggested[10] that ultrarelativistic heavy ions would be a convenient mechanism for the production of heavy leptons, but the sizes of the cross sections are in doubt.[11] In any case, both the production of e^+e^- pairs in the K shell[11,12] (with very large cross sections) and ED processes involving excitation of the nucleus will be the major factors[12] in the determination of the lifetime of stored beams in planned heavy-ion colliders such as RHIC.

It is not possible at present to measure σ_{ED} in the regime of both very large charge combinations and ultrarelativistic energies, but it is possible to study the above two parameters separately. We report in this Letter the first observation of σ_{ED} values above 1 b for the interaction of $^{139}_{57}$La projectiles with a $^{197}_{79}$Au target. We also report the first observation of ED at ultrarelativistic energies.

In one experiment Au targets were bombarded with 1.26-GeV/nucleon ^{139}La projectiles at the LBL Bevalac. The total number of ^{139}La projectiles was determined by our counting ^{11}C produced in polystyrene targets and comparing with accurately determined ^{12}C(^{139}La,X)^{11}C cross sections. (See, for example, Hill *et al.*[13]) In a

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separate experiment Au targets were bombarded with 60- and 200-GeV/nucleon ^{16}O projectiles from the CERN SPS accelerator. The total number of ^{16}O projectiles was obtained from data generated by the CERN experiment NA38 beam-monitor hodoscope. After irradiation, yields of various target fragments were determined by γ-ray spectroscopy with methods outlined in detail in Ref. 4. (Since the targets in the ^{16}O beam were only 5 mg/cm^2 in thickness, corrections for secondary reactions were negligible; however, corrections for recoil of fragments out of the target were estimated with the recoil properties for various fragments measured by Kaufman *et al.*[14] For fragments with masses near that of the target, the corrections were negligible.)

The nuclear contribution to the cross sections was deduced with use of the concept of factorization as described in Ref. 4 and references therein. Factorization implies that the yield of a particular fragment from the target due to nuclear interactions is independent of the beam except through a constant geometric factor.[1] Thus, for example, the ratio

$$R(\mathrm{RHI}) = \sigma(^{197}\mathrm{Au}(\mathrm{RHI},X)F_i)/\sigma(^{197}\mathrm{Au}(p,X)F_i)$$

should have a constant value for a particular relativistic heavy ion. F_i represents an arbitrary target fragment. We assume $\sigma_{\mathrm{ED}} = \sigma_{\mathrm{expt}} - \sigma_{\mathrm{nuc}}$ and estimate the nuclear part of the ^{197}Au(RHI,X)^{196}Au cross section by

$$\sigma_{\mathrm{nuc}}(^{197}\mathrm{Au}(\mathrm{RHI},X)^{196}\mathrm{Au}) = \left[\frac{\sigma(^{197}\mathrm{Au}(\mathrm{RHI},X)F_i)}{\sigma(^{197}\mathrm{Au}(p,X)F_i)}\right]_{\mathrm{av}} \sigma(^{197}\mathrm{Au}(p,X)^{196}\mathrm{Au}).$$

A $\sigma(^{197}\mathrm{Au}(p,X)^{196}\mathrm{Au})$ value of 62 ± 4 mb was used. The ratio $R(\mathrm{RHI})_{\mathrm{av}}$ in the above formula was deduced with the assumption of limiting fragmentation, which assumes that reaction cross sections are constant above a certain minimum energy. This has been shown to be true within experimental error for protons[15] above $\simeq 10$ GeV and heavy ions[16] above $\simeq 2$ GeV/nucleon. Values for $R(\mathrm{RHI})_{\mathrm{av}}$ of 2.58 ± 0.20 and 1.95 ± 0.25 were obtained for ^{139}La and ^{16}O projectiles, respectively. The ratios in both cases had a variance of 0.20 and no deviations as a function of the mass of F_i from the assumed constancy were noted. The fragment values were limited to the range $A = 89$ to 188. For the reaction ^{197}Au(^{139}La,X)^{196}Au our measurements gave a total cross section of 2.13 ± 12 b, resulting in $\sigma_{\mathrm{ED}} = 1.99 \pm 0.12$ b. The measured σ_{ED} values for the reaction ^{197}Au(^{16}O,X)^{196}Au were 0.28 ± 0.03 b and 0.44 ± 0.04 b at 60 and 200 GeV/nucleon, respectively, while the corresponding total cross sections were 0.40 ± 0.02 b and 0.56 ± 0.03 b, respectively. The details of these measurements and σ_{ED} determinations will be given in subsequent publications.

With use of a virtual-photon spectrum generated by the WW method,[5] calculated values of σ_{ED} are given by $\int_0^\infty N_\gamma(E_\gamma)\sigma_\gamma(E_\gamma)dE_\gamma$, where $N_\gamma(E_\gamma)dE_\gamma$ is the WW number of photons with energy between E_γ and $E_\gamma + dE_\gamma$. The ^{197}Au(γ,n)^{196}Au cross section $\sigma_\gamma(E_\gamma)$ was measured by Veyssiere *et al.*[17] The only adjustable parameter is the impact-parameter cutoff b_c which we choose to be of the form

$$b_c = r_0[A_p^{1/3} + A_t^{1/3} - X(A_p^{-1/3} + A_t^{-1/3})]$$

as suggested by Vary,[18] where $r_0 = 1.34$ fm and the curvature correction parameter $X = 0.75$. (See Ref. 4 for detailed discussion.) The photon number $N_\gamma(E_\gamma)$ is obtained by integration of $N_\gamma(E_\gamma, b)$ over all impact parameters from b_c to ∞. It varies as $\ln(1/b_c)$ at low photon energies but as e^{-b_c} at high energies. (See Ref. 5, pp. 722–723.)

The behavior of σ_{ED} as a function of projectile charge is shown in Fig. 1 for the reaction ^{197}Au(RHI,X)^{196}Au for projectiles ranging from 2.1-GeV/nucleon ^{12}C to 1.26-GeV/nucleon ^{139}La. In Fig. 2 the behavior of σ_{ED} as a function of projectile energy is shown for the reaction ^{197}Au(^{16}O,X)^{196}Au for 60- and 200-GeV/nucleon projectiles. As can be seen from Figs. 1 and 2, the WW calculation reflects the general trends of the observed increase of σ_{ED} with both projectile charge and projectile energy. However, our results imply that the WW calculation overestimates the ED effect for high charge projectiles (Fig. 1), but underestimates it for ultrarelativistic energies (Fig. 2). The reasons for these two types of

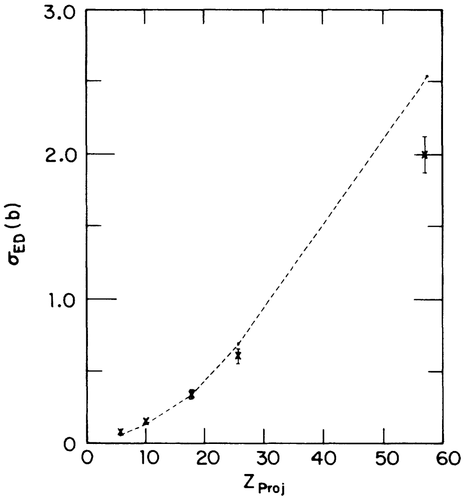

FIG. 1. σ_{ED} for the reaction ^{197}Au(RHI,X)^{196}Au at Bevalac energies as a function of projectile charge. The crosses are experimental σ_{ED} values. The corresponding values calculated with the WW method are indicated by small dots connected by dashed straight lines.

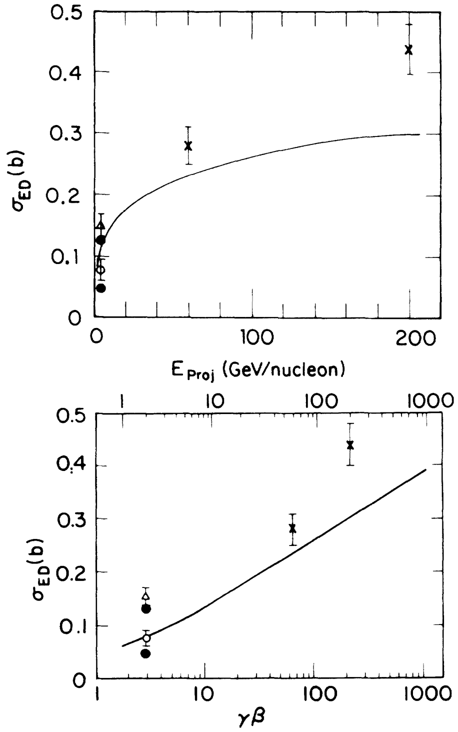

FIG. 2. (Top) σ_{ED} for the reaction $^{197}Au(^{16}O,X)^{196}Au$ as a function of projectile energy. The crosses are experimental σ_{ED} values. For comparison at low energies, σ_{ED} values for 2.1-GeV/nucleon ^{12}C and ^{20}Ne on ^{197}Au are shown as open circles and open triangles, respectively. The continuous line indicates the results of a WW calculation of σ_{ED} for ^{16}O projectiles, and the filled circles indicate the calculated ED cross sections for 2.1-GeV/nucleon ^{12}C and ^{20}Ne, respectively. (Bottom) The above results plotted as functions of $\beta\gamma$ to illustrate the approximate linear dependence of the WW cross section on $\ln(\beta\gamma)$.

discrepancies are not clear; therefore more work is needed to determine the nature of this problem.

It is also of interest to estimate σ_{ED} for colliding beams of ultrarelativistic heavy ions planned for future colliders. Using as an example 100-GeV/nucleon ^{197}Au on ^{197}Au projectiles, the WW calculation predicts σ_{ED} for the reaction $^{197}Au(^{197}Au,X)^{196}Au$ to be about 60 b, or about a factor of 10 larger than the nuclear cross section. The experimental results presented here imply that such a large cross section could be expected. However, the actual value could be considerably larger or smaller than 60 b as a result of the uncertainties discussed above. Future experiments planned with heavier projectiles at energies from 1 to 200 GeV/nucleon should help to explain the reasons for these deviations.

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