Electromagnetic Dissociation of ^{197}Au by Relativistic Heavy Ions

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Electromagnetic dissociation of ^{197}Au target nuclei by the Coulomb field of relativistic heavy ions (RHI) was inferred from measurements of $^{197}\mathrm{Au}(\mathrm{RHI},X)^{196}\mathrm{Au}$ cross sections. RHI represents 2.1-GeV/nucleon p, ^{12}C, or ^{20}Ne, 1.8-GeV/nucleon ^{40}Ar, or 1.7-GeV/nucleon ^{56}Fe projectiles. The experimental cross sections in excess of the estimated nuclear contributions are well described by use of the Weizsäcker-Williams method for calculating the electromagnetic dissociation contributions. Electromagnetic-dissociation calculations are given for ^{197}Au projectiles at energies expected for the new generation of heavy-ion colliders.

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Dissociation of relativistic heavy ions (RHI) by Coulomb fields of target nuclei, i.e., electromagnetic dissociation (ED), was first reported by Heckman and Lindstrom[1] for 2.1-GeV/nucleon ^{12}C and ^{16}O. Subsequently ED was observed[2,3] for 1.88-GeV/nucleon ^{56}Fe and 1.7-GeV/nucleon ^{18}O projectiles. This can be pictured as a process occurring when RHI pass near a high-Z target nucleus but outside the range of the nuclear force. A virtual photon from the Coulomb field is absorbed by the projectile resulting in the excitation of a giant multipole resonance. A similar process can occur in target nuclei. The resultant cross section σ_{ED} has been calculated[1-3] by the Weizsäcker-Williams (WW) method for virtual photons[4] and the method of Jäckle and Pilkuhn.[5] Winther and Alder[6] calculated σ_{ED} for both projectile and target excitation. Baur and Hoffman[7,8] have calculated σ_{ED} for ^{56}Fe projectile and ^{197}Au target fragmentation. ED has not been observed in target fragmentation but would be expected for sufficiently high-Z projectiles. For heavy nuclei such as Au it is expected that deexcitation following ED would occur primarily through neutron channels because of the large Coulomb barrier for charged-particle emission.

Recent calculations[9] indicate that σ_{ED} can become very large for sufficiently heavy target-projectile combinations. Calculations[9] of ^{197}Au fragmentation by 2.0-GeV/nucleon ^{56}Fe and ^{136}Xe give σ_{ED} of 0.6 and 2.3 b, respectively. Observed cross sections of 234.0 mb (Ref. 3) for $\mathrm{U}(^{18}\mathrm{O},{}^{17}\mathrm{O})X$ and 646 mb (Ref. 2) for $\mathrm{U}(^{56}\mathrm{Fe},\mathrm{Mn})X$ give an indication that such large cross sections may indeed occur. For ^{56}Fe fragmentation only the Mn elemental cross section was measured, and so the magnitude of the ED contribution is not clear. We report here experimental evidence for ED of ^{197}Au target nuclei. We measured cross sections for the production of various residues from ^{197}Au targets bombarded by 2.1-GeV/nucleon p, ^{12}C, and ^{20}Ne, and newly developed high-intensity 1.8-GeV/nucleon ^{40}Ar and 1.7-GeV/nucleon ^{56}Fe Bevalac beams.

In our experiments Au foil targets with thicknesses of 50, 90, and 240 mg/cm^2 were each separated by 30 cm and irradiated simultaneously by RHI for periods of a few hours. Beam intensities for projectiles with $Z \leqslant 10$ were determined by counting of ^{11}C produced in polystyrene targets and comparison with accurately determined $^{12}\mathrm{C}(\mathrm{RHI},X)^{11}\mathrm{C}$ cross sections (see, for example, Smith *et al.*[10]). Beam intensities for ^{40}Ar and ^{56}Fe were determined in a similar manner with use of extrapolated cross sections for the $^{12}\mathrm{C}(\mathrm{RHI},X)^{11}\mathrm{C}$ reaction. Various simple functional forms were compared to the $^{12}\mathrm{C}(\mathrm{RHI},X)^{11}\mathrm{C}$ data. The form used in Ref. 1, $\bar{\gamma}_T = A_p^{1/3} + A_T^{1/3} - C$, with C a constant, was found to be unsatisfactory since the ratio $\sigma/\bar{\gamma}_T$ increases significantly with A_p. However, the parametrization $\sigma = \sigma_0 b_c(1 + aA_p^{2/3})$, with σ_0 and a constants, reproduced the ^{11}C data quite well. {In Ref. 9, the total Glauber cross section is expressed as πb_c^2, where

$$b_c = 1.34[A_p^{1/3} + A_T^{1/3} - 0.75(A_p^{-1/3} + A_T^{1/3})]\ \mathrm{fm}$$

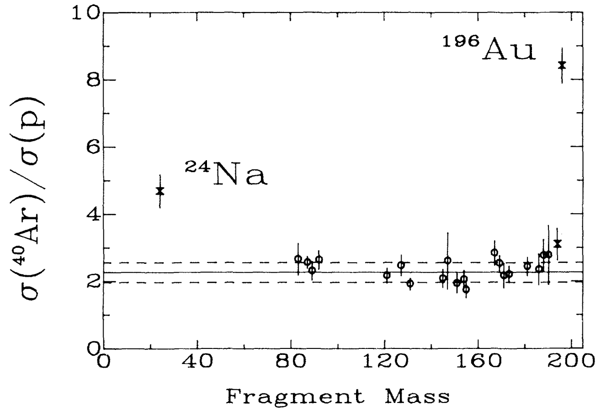

FIG. 1. Ratios of cross sections for 1.8-GeV/nucleon ^{40}Ar projectiles to 28-GeV protons for various reaction products. The solid line is the weighted average for all points shown as open circles. The dotted lines indicate the uncertainty in this average.

is the sum of the radii of projectile and target minus a curvature correction.} The term $aA_p^{2/3}$ can be regarded an an empirical correction for interactions of more than one nucleon in the projectile with a single target nucleon. For the known cross sections for p, α, ^{12}C and ^{20}Ne on ^{12}C, the form $\sigma = \sigma_0 b_c \times (1 + aA_p^{2/3})$ reproduced the experimental cross sections with an average deviation of 1.4 mb and a maximum deviation of 2.2 mb. Using this form, we estimate total cross sections of 111 ± 20 mb for the reactions $^{12}\mathrm{C}(\mathrm{RHI},X)^{11}\mathrm{C}$ with ^{40}Ar and ^{56}Fe, respectively. These extrapolated values were used in normalizing our beam intensities for the ^{40}Ar and ^{56}Fe measurements.

After irradiation, yields of various fragments were determined by γ-ray spectroscopy. Target spectra were recorded frequently for approximately 6 months. By comparison of the yields from three targets of differing thickness, corrections for secondary reactions were found to be at most 8% for ^{196}Au and were negligible for products with $A \leqslant 180$. Yields were corrected for extended source geometry, coincidence summing, target thickness, and counting dead time, as well as growth and decay. Details of the experimental setup and treatment of data will be given in a future publication.

The nuclear contribution to the cross section can be estimated with the concept of factorization of the nuclear cross section.[1, 11] This assumes $\sigma_{TP}^{F} = \gamma_T^F \gamma_P^T$, where F, T, and P indicate target fragment, target, and projectile, respectively. This notation is similiar to that of Heckman and Lindstrom[1] with roles of P and T reversed. For a given target T the cross section for producing fragment F is $\sigma(P,F) = \sigma_{\mathrm{nucl}}(P,F) + \sigma_{\mathrm{ED}}(P,F)$, which assumes no interference[3] between nuclear and electromagnetic processes. Factorization implies that the yield of a particular fragment from the target due to nuclear interactions will be independent of the beam except through the geometric factor γ_P^T. Thus for example the ratio

$$\frac{\sigma(^{197}\mathrm{Au}(^{20}\mathrm{Ne},X)F_i)}{\sigma(^{197}\mathrm{Au}(p,X)F_i)}$$

should have a constant value $\gamma_{\mathrm{Ne}}^{\mathrm{Au}}/\gamma_p^{\mathrm{Au}}$ for any fragment F_i. We also use the hypothesis of limiting fragmentation which states that for sufficiently high projectile energies the cross section for production of the fragment F_i is independent of energy.

We estimate the nuclear part of the one-neutron removal channel from the ratios

$$\frac{\sigma(^{197}\mathrm{Au}(\mathrm{RHI},X)F_i)}{\sigma(^{197}\mathrm{Au}(p,X)F_i)}.$$

Since the limiting fragmentation region for protons is not reached[12] for deep spallation products at least until 10 GeV, we used 28-GeV proton cross sections measured by us at the alternating-gradient synchroton which are consistent with measurements[12] at 11.5 and 300 GeV. On the other hand, limiting fragmentation is essentially correct[13] for RHI for energies $\gtrsim 1$ GeV/nucleon. Kaufman *et al.*[13] observed factorization for target fragmentation of ^{197}Au by 4.8- and 25-GeV ^{12}C (which is in reasonable agreement with our ^{12}C data) and 7.6-GeV ^{20}Ne projectiles to be approximately valid for fragments with $A > 40$. For $A < 40$ the enhancement in yields for RHI is attributed[13, 14] to collisions at low impact parameters. Figure 1 shows our results for the ratio

$$\frac{\sigma(^{197}\mathrm{Au}(^{40}\mathrm{Ar},X)F_i)}{\sigma(^{197}\mathrm{Au}(p,X)F_i)},$$

which would be constant if factorization were strictly true, versus the mass of the fragment. Clearly factorization is violated for RHI for the one-neutron removal process. If we attribute the excess ^{196}Au cross section to ED, then $\sigma_{\mathrm{ED}} = \sigma_{\mathrm{exp}} - \sigma_{\mathrm{nucl}}$. Using factorization to estimate the nuclear part of the $^{197}\mathrm{Au}(\mathrm{RHI},X)^{196}\mathrm{Au}$ cross section, we obtain

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

The average cross-section ratio was calculated for fragments F_i with $83 \leqslant A \leqslant 190$, with $A \geqslant 83$ to

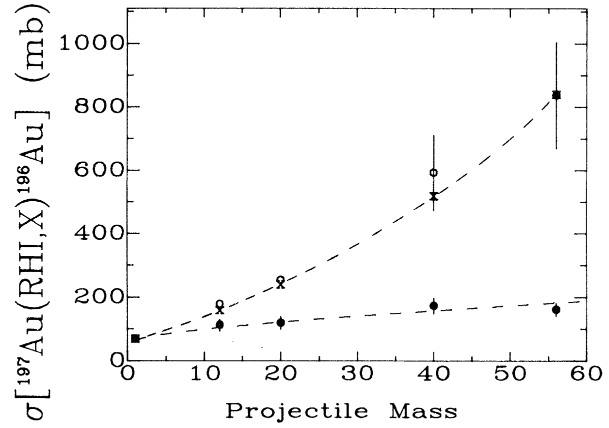

FIG. 2. One-neutron removal cross sections for ^{197}Au target. Open circles are the total experimental cross sections. Filled circles represent the nuclear contribution to the cross section. [The lower dashed curve is a fit to the nuclear cross section of the form $\sigma_0 b_c(1+aA_p^{2/3})$ with the same a as found for the ^{11}C data.] The × 's are the sums of the experimental nuclear cross sections and the WW estimates of σ_{ED}.

exclude effects of central collisions and $A \leq 190$ to exclude ED effects. In Fig. 2 the total $^{197}\mathrm{Au(RHI},X)^{196}\mathrm{Au}$ cross section is plotted as a function of projectile mass. The cross section for the reaction $^{197}\mathrm{Au}(p,X)^{196}\mathrm{Au}$ shown in Fig. 2 was measured at 2.1 GeV. The data are also summarized in Table I.

The WW method was used to calculate the σ_{ED} for the one-neutron removal process.[4] It is of the form $\sigma_{\mathrm{ED}} = \int_0^\infty N_\gamma(E_\gamma)\sigma_\gamma(E_\gamma)dE_\gamma$. $N_\gamma(E_\gamma)dE_\gamma$ is the WW number of photons with energy between E_γ and $E_\gamma + dE_\gamma$. The $^{197}\mathrm{Au}(\gamma,n)^{196}\mathrm{Au}$ cross section $\sigma_\gamma(E_\gamma)$ was from the National Bureau of Standards Digital DATA Library.[15] The minimum impact parameter was assumed[9] to be b_c. Calculated and experimental values of σ_{ED} are given in Table I. Good agreement between the calculation and experiment is obtained, implying that the ED process can readily account for the excess cross section observed for the one-neutron removal process.

To summarize, we report here the first observation both of ED for a heavy nucleus and of ED in target fragmentation. The large cross sections (590 and 840 mb for ^{40}Ar and ^{56}Fe projectiles, respectively) for one-neutron removal from a gold target are well described by an empirically determined nuclear part (which uses the concept of factorization) plus an ED part which is well described with use of the WW formalism. The deduced σ_{ED} of 680 mb for ^{56}Fe projectiles is the largest yet observed. The major uncertainty in the ^{40}Ar and ^{56}Fe cross sections, arising from the extrapolation of the $^{12}\mathrm{C(RHI},X)^{11}\mathrm{C}$ monitor cross sections, will be removed once measurements of these cross sections (see Ref. 10) are extended to higher-mass RHI.

The fact that σ_{ED} is large for only moderately heavy projectiles makes possible the future detailed study of the ED process for medium-weight and heavy nuclei. Determinations of $\sigma(^{197}\mathrm{Au(RHI},X)^{195}\mathrm{Au})$, which should also have an ED contribution, are in progress. Although activation type studies of target fragmentation such as those reported here have limitations (i.e., the need for relatively high beam intensities and insensitivity to fragment kinetic energy), they have the advantage that the one-neutron-removal product can be readily distinguished from the target nuclei or the two-neutron-removal products by γ-ray spectroscopy. The distinction between adjacent masses has in the past been possible in projectile fragmentation only for light RHI.

Recently it has been pointed out[16] that σ_{ED}, if

TABLE I. $\sigma(^{197}\mathrm{Au(RHI},X)^{196}\mathrm{Au})$ in millibarns.

Projectile (energy in GeV/nucleon)	Measured cross sections σ_{exp}	σ_{nucl}	σ_{ED}	Calculated (WW) σ_{ED}
p(2.1)	67 ± 4	67 ± 4	(0)[a]	1.5
^{12}C(2.1)	177 ± 7	111 ± 19	66 ± 20	46
^{20}Ne(2.1)	254 ± 7	118 ± 20	136 ± 21	121
^{40}Ar(1.8)	590 ± 110	170 ± 40	420 ± 120	346
^{56}Fe(1.7)	840 ± 150	160 ± 40	680 ± 160	678

[a] σ_{ED} for $^{197}\mathrm{Au}(p,X)^{196}\mathrm{Au}$ assumed to be zero.

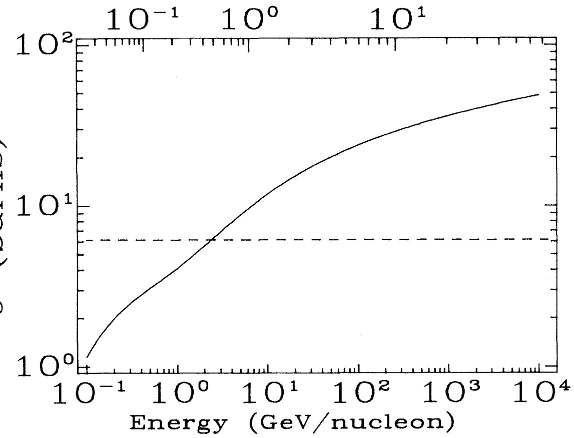

FIG. 3. Extrapolation of WW calculation to ultrarelativistic energies for ^{197}Au on ^{197}Au. The horizontal line is the geometric cross section. The lower and upper energy scales apply to fixed-target and colliding-beam arrangements, respectively.

sufficiently large, might be a constraint on the storage time of very relativistic heavy-ion beams. We extrapolate our WW calculations to the higher energies proposed for future heavy-ion colliding-beam accelerators. For ^{197}Au projectiles on stationary ^{197}Au targets σ_{ED} becomes greater than geometric at 2.3 GeV/nucleon. The results for ^{197}Au colliding beams are shown in Fig. 3. Our calculation gives the large value of 40 b for σ_{ED} for a single neutron removed from a ^{197}Au nucleus in 30-GeV/nucleon colliding beams.

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