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COULOMB DISSOCIATION OF RELATIVISTIC
$^{12}\text{C}$ AND $^{16}\text{O}$ NUCLEI

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ABSTRACT

Cross sections for the dissociation of relativistic $^{12}\text{C}$ and $^{16}\text{O}$ nuclei by the Coulomb fields of target nuclei have been measured at the Bevatron. Coulomb contributions to the total fragmentation cross sections are interpreted by the Weizsäcker-Williams method. The minimum-impact parameters deduced from the measured cross sections are characterized by radial overlap distances comparable to the charge-skin thicknesses of the interacting nuclei, compatible with the effects of nuclear absorption.
We report in this Letter experimental evidence for the dissociation of Bevatron/Bevalac beams of $^{12}\text{C}$ and $^{16}\text{O}$ in the nuclear Coulomb fields of target nuclei. This evidence comes from experiments on the target dependence of the isotopic production cross sections for secondary nuclei produced by the fragmentation of $^{12}\text{C}$ and $^{16}\text{O}$ beam nuclei at energies $E=1.05$ GeV/n ($^{12}\text{C}$) and 2.1 GeV/n ($^{12}\text{C}$ and $^{16}\text{O}$). By use of photonuclear cross-section data and the Weizsacker-Williams (WW) method of virtual quanta, we are able to account for the measured cross sections and to determine the minimum impact parameters for Coulomb-dissociation of heavy-ion projectiles.

Lindstrom et al. have measured the isotopic production cross section $\sigma_{\text{BT}}^F$ for the single-particle inclusive reaction $B+T\rightarrow F+...$, where $B$, $T$, and $F$ are the beam, target, and fragment nuclei, respectively. Essential to our analysis is that the cross sections $\sigma_{\text{BT}}^F$ are factorable, i.e., $\sigma_{\text{BT}}^F = \gamma_B^F \gamma_T^F$, where $\gamma_B^F$ is dependent on $B$ and $F$ only, and $\gamma_T^F$ is the target factor. Given in Ref. 1 are the measured cross sections $\sigma_{\text{BT}}^F$ and the factored quantities $\gamma_B^F$ and $\gamma_T^F$ for all isotopes produced by the fragmentation of $^{12}\text{C}$ and $^{16}\text{O}$ projectiles in H, Be, C, Al, Cu, Ag, and Pb targets. Plotted in Fig. 1 are the target factors $\gamma_T^F = \sigma_{\text{BT}}^F / \gamma_B^F$ versus target mass $A_T$(AMU). For fragment nuclei with mass $A_F < A_B - 2$, i.e., at least two nucleons are removed from the beam projectile, all isotopic production cross sections, for a given target, are interrelated by a unique target factor, $\gamma_T^F$. Striking deviations of $\gamma_T^F$ from $\gamma_T^F$, up to 30 percent in Pb, are observed for those fragmentation cross sections...
that involve the loss of one nucleon from the projectile. The differences between the observed values of $\gamma_T$ and $\bar{\gamma}_T$ increase approximately as $Z_T^{-2}$ of the target, indicative of a Coulomb effect. We therefore attribute the target factors $\bar{\gamma}_T$ to nuclear fragmentation and the $Z_T$-dependent differences between $\gamma_T$ and $\bar{\gamma}_T$ for fragments with mass $A_F = A_B - 1$ to Coulomb dissociation. The experimental Coulomb-dissociation cross sections are therefore defined as $\sigma_{\text{WW}}(\text{exp}) = \sigma_{\text{BT}} - \bar{\gamma}_B \gamma_T$, the difference between the measured and factored cross sections.

Jackson presents a classical development of the Weizsacker-Williams method of virtual quanta for point charges moving at relativistic velocities. Jakke and Pilkuhn have extended the validity of the Weizsacker-Williams formula to nonrelativistic energies, and have incorporated nuclear absorption and charge form factors in the theory. The present analysis refines the work of Artru and Yodh, who applied Jackson's treatment of the Weizsacker-Williams method to estimate the cross sections for Coulomb dissociation of relativistic nuclei.

To the extent that $N(\omega)$, the equivalent number of virtual photons per MeV, is the same for all electric and magnetic multipoles, the Weizsacker-Williams cross section for the dissociation of a nucleus, at velocity $\beta$, by the Coulomb field of a target nucleus, atomic number $Z$, is given by

$$\sigma_{\text{WW}} = \int_{\omega_0}^{\infty} \sigma_\gamma(\omega) N(\omega) \, d\omega,$$

where $\sigma_\gamma(\omega)$ is the measured photonuclear cross section at photon energy $\omega$. 
The number density of virtual photons has the functional form
\[ N(\omega) = \frac{(Z^2/\omega^2)}{F(\beta, \omega b_{\text{min}}/\beta)} \], where \( b_{\text{min}} \), the minimum-impact parameter, is the only adjustable parameter in \( N(\omega) \).

References to the photoneutron and photoproton cross sections we used to compute \( a_{\text{WW}} \) are, for \(^{12}\text{C} \): \( \sigma(\gamma,n) \) \( \), \( \sigma(\gamma,p) \), \( \) \( \) and for \(^{16}\text{O} \): \( \sigma(\gamma,n) \), \( \) \( \sigma(\gamma,p) \). The cross section \( \sigma(\gamma,p) \) for \(^{12}\text{C} \) was obtained from the difference between \( \sigma(\gamma,\text{total}) \) and \( \sigma(\gamma,n) \). The cross-section data given in Refs. 10-14 were used to extrapolate \( \sigma_\nu(\omega) \) to higher values of \( \omega_{\text{max}} \) (to 65 MeV for \(^{12}\text{C} \), 62 MeV for \(^{16}\text{O} \)). Because the shape of the high-energy tail of \( \sigma_\nu(\omega) \) has little effect on \( a_{\text{WW}} \), we have taken the extrapolated values of the cross sections to be constant.

The giant dipole resonance dominates the photonuclear reaction in the photon-energy interval from about 15 MeV (threshold) to 30 MeV. The photo-dissociation of \(^{12}\text{C} \) and \(^{16}\text{O} \) proceeds mainly by single-nucleon emission. Furthermore, contributions to \( a_{\text{WW}} \) from the higher-threshold multinucleon-loss photoreactions are suppressed by the \( \omega^{-1} \) weighting [from \( N(\omega) \)] of \( \sigma_\nu(\omega) \) in Eq. (1). The experimental observation that only the single-nucleon-loss fragmentation cross sections exhibit significant deviations from strict factorization in high-Z targets is thus in accord with the process of Coulomb excitation and dissociation.

By equating \( a_{\text{WW}}(\text{exp}) \) to \( a_{\text{WW}} \), Eq. (1) we have determined the impact parameter \( b_{\text{min}} \) appropriate for each cross section. The minimum-impact parameter is defined by the relation \( b_{\text{min}} = r_{B,0.1} + r_{T,0.1} - d \), where the \( r_{0.1} \)'s are the 10 percent charge-density radii of the beam and target.
nuclei, and \( d \) is the radial-overlap distance. The values of \( b_{\text{min}} \) obtained in this experiment are, to within the accuracy of the data, confined to a limited range in \( d \). Presented in Fig. 2ab, then, are histograms of the overlap-distances \( d \) that account for the experimental cross sections \( \sigma_{\text{ww}}(\text{exp}) \) for \( ^{12}\text{C} \) and \( ^{16}\text{O} \) projectiles in Ag and Pb targets. Because of the differences in the theory for the spectra of virtual quanta, we present two distributions for \( d \), each based upon the expressions for \( N(\omega) \), hence \( \sigma_{\text{ww}} \), given by a) Jackson and b) Jackle and Pilkuhn.

The standard deviations of the \( d \)-distributions are compatible with the statistical errors in \( \sigma_{\text{ww}}(\text{exp}) \). Systematic variations in \( \sigma_{\text{ww}}(\text{exp}) \) are expected to be small, since the cross sections are obtained from quantities that are insensitive to errors in beam monitoring, background, focusing corrections, etc. Possible systematic errors in \( d(b_{\text{min}}) \), other than those from the theoretical differences in \( \sigma_{\text{ww}} \), are the photonuclear cross sections \( \sigma_{\nu}(\omega) \) and those inherent in the method used to extract \( \sigma_{\text{ww}}(\text{exp}) \) from \( \sigma_{\text{BT}}^F \). On the average, a 12 percent change in \( \sigma_{\nu}(\omega) \), a typical uncertainty in the photonuclear cross-section data, leads to a 1-fm change in \( d(b_{\text{min}}) \).

The unweighted mean (and its statistical error) of the \( d \)-distributions are \( d=0.4\pm0.8 \) fm (Jackson) and \( 3.0\pm0.6 \) fm (Jackle and Pilkuhn). These mean values are shown in Fig. 2. Also included in this figure is the interval of overlap distances bounded by \( 0 \leq d \leq t_B + t_T \), where \( t_B \) and \( t_T \) are the charge-skin thicknesses of the beam and target nuclei, which, in this experiment, range from 1.9 to 2.3 fm.

Fig. 3 presents the cross-section data from this experiment, \( \sigma_{\text{ww}}(\text{exp}) = \sigma_{\text{BT}}^F \gamma_B \gamma_T \), plotted as a function of target mass. Superimposed on the data are curves of the computed cross sections \( \sigma_{\text{ww}} \) (Jackle and Pilkuhn) evaluated for a constant overlap distance \( \overline{d}=3.0 \) fm. [Curves of \( \sigma_{\text{ww}} \) (Jackson)
versus $A_T$ evaluated for $\bar{d}=0.4$ fm are indistinguishable from those shown.]

Following Lindstrom et al.,\(^1\) we find that $\gamma_T \propto (A_B^{1/3} + A_T^{1/3})^{-0.8}$ gives an excellent fit to the target factors of $\sigma_{BT}^F$ for $A_T > 12$, as illustrated in Fig. 1. When expressed in terms of $r_{0.1}$, the target factor has the form of an impact parameter, $\gamma_T \propto (r_{0.1} + r_{0.1} - 2.0)$, where $r_{0.1} = r_{0.5} + t/2$ and $r_{0.5} = 1.18 A^{1/3} - 0.48$.\(^{15}\) Thus, we find that the effective overlap distance in $\gamma_T$ is $d=2.0$ fm, a value that agrees well with the $d$'s (0.4 and 3.0 fm) obtained in this analysis.

To summarize our results, all the salient features of $\sigma_{WW}(exp)$ are attributable to the fragmentation of projectile nuclei by the Coulomb field of the target nucleus. Irrespective of the theoretical model,\(^2\),\(^3\) use of the Weizsacker-Williams method to interpret $\sigma_{WW}(exp)$ correctly accounts for: i) the identification of those isotope-production cross sections that are significantly enhanced by Coulomb dissociation, ii) the target dependence of $\sigma_{WW}(exp)$, and iii) the magnitudes of $\sigma_{WW}(exp)$. The values of $b_{min}$ derived from $\sigma_{WW}(exp)$ limit the radial overlap, $d$, of the colliding nuclei to distances comparable to their charge-skin thicknesses $t$, a manifestation of the effects of nuclear absorption. The Coulomb and nuclear fragmentation processes are related by the result that $\bar{d} \approx d'$, which shows that the maximum overlap distance that accounts for Coulomb dissociation is, in essence, tantamount to the nuclear overlap distance required to account for nuclear (direct-interaction) fragmentation.

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FOOTNOTES AND REFERENCES

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5. Jäckle and Pilkuhn, who give equations for $N(\omega)$ for the $E_1$ and $M_1$ transitions, write the integrand of Eq. (1) as $\sigma_{E1}(\omega) N_{E1}(\omega) + \sigma_{M1}(\omega) N_{M1}(\omega)$. Because $N_{M1}(\omega) \approx N_{E1}(\omega)$, to within 10% for our experiment, we can express the integrand as given in Eq. (1), where $\sigma(\omega) = \sigma_{E1}(\omega) + \sigma_{M1}(\omega)$ is the photo-disintegration cross section, and $N(\omega) \approx N_{E1}(\omega)$. In Jackson's treatment of the Weizsäcker-Williams effect, the $N(\omega)$ for all electric and magnetic multipoles are, in fact, equal.


FIGURE CAPTIONS

Fig. 1. Target factors $\gamma_T$ plotted versus target mass $A_T(\text{AMU})$, from Lindstrom et al. \textsuperscript{1} Individual values of $\gamma_T$ are shown for the single-nucleon-loss cross sections indicated. The curve $\gamma_T = A_B^{1/3} + A_T^{1/3} - 0.8$ is drawn through the mean target factors, shown with error bars, for all cross sections $\sigma_F$, where $A_F < A_B - 2$.

Fig. 2. Distributions of overlap distances $d(b_{\text{min}})$, and their means, derived from $\sigma_{WW}(\text{exp})$ when fitted to the Weizsacker-Williams cross sections $\sigma_{WW}'$, as given by a) Jackson\textsuperscript{2} and b) Jackle and Pilkuhn.\textsuperscript{3} The dark horizontal bar delineates the overlap region bounded by $0 \leq d < t_B + t_T$, the sum of the charge-skin thicknesses of the beam and target nuclei.

Fig. 3. Target dependence of the measured cross sections $\sigma_{WW}(\text{exp})$ for the Coulomb dissociation reactions indicated. The curves are computed using the Jackle and Pilkuhn form of $\sigma_{WW}$ with $d=3.0 \text{ fm}$. 
Fig. 1

\[ \overline{\gamma_T} \propto A_B^{1/3} + A_T^{1/3} - 0.8 \]

-16O, 15N, 2.1 GeV/n
-12C, 11B, 2.1
-12C, 11C, 1.05"
Fig. 2

\[ A^z \rightarrow (A-1)^z \]
\[ A^z \rightarrow (A-1)^{z-1} \]
Fig. 3
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