Title
COULOMB DISSOCIATION OF RELATIVISTIC l2C and 16O NUCLEI

Author
Heckman, Harry H.

Publication Date
1976-03-01

Submitted to Physical Review Letters

LBL-4380
Preprint c.1

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

Harry H. Heckman and Peter J. Lindstrom

March 1976

Prepared for the U.S. Energy Research and Development Administration under Contract W-7405-ENG-48

DISCLAIMER

COULOMB DISSOCIATION OF RELATIVISTIC ^{12}C AND ^{16}O NUCLEI*

Harry H. Heckman and Peter J. Lindstrom

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

March 1976

ABSTRACT

Cross sections for the dissociation of relativistic ^{12}C and ^{16}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}C and ^{16}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}C and ^{16}O beam nuclei at energies E=1.05 GeV/n (^{12}C) and 2.1 GeV/n (^{12}C and ^{16}O).[1] By use of photonuclear cross-section data and the Weizsäcker-Williams (WW) method of virtual quanta,[2,3] 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.[1] have measured the isotopic production cross section σ_{BT}^{F} for the single-particle inclusive reaction $B+T \rightarrow F+\ldots$, where B, T, and F are the beam, target, and fragment nuclei, respectively. Essential to our analysis is that the cross sections σ_{BT}^{F} are factorable, i.e., $\sigma_{BT}^{F}=\gamma_{B}^{F}\,\bar{\gamma}_{T}$, where γ_{B}^{F} is dependent on B and F only, and $\bar{\gamma}_{T}$ is the target factor. Given in Ref. 1 are the measured cross sections σ_{BT}^{F} and the factored quantities γ_{B}^{F} and $\bar{\gamma}_{T}$ for all isotopes produced by the fragmentation of ^{12}C and ^{16}O projectiles in H, Be, C, Al, Cu, Ag, and Pb targets. Plotted in Fig. 1 are the target factors $\gamma_{T}=\sigma_{BT}^{F}/\gamma_{B}^{F}$ versus target mass A_T(AMU). For fragment nuclei with mass $A_F \leq A_B-2$, 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, $\bar{\gamma}_{T}$. Striking deviations of γ_T from $\bar{\gamma}_{T}$, 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 γ_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 γ_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 $\sigma_{WW}(\exp)=\sigma_{BT}^F-\gamma_B^F\,\bar{\gamma}_T$, the difference between the measured and factored cross sections.

Jackson[2] presents a classical development of the Weizsäcker-Williams method of virtual quanta for point charges moving at relativistic velocities. Jäckle and Pilkuhn[3] have extended the validity of the Weizsäcker-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,[4] who applied Jackson's treatment of the Weizsäcker-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,[5] the Weizsäcker-Williams cross section for the dissociation of a nucleus, at velocity β, by the Coulomb field of a target nucleus, atomic number Z, is given by

$$\sigma_{WW} = \int_{\omega_0} \sigma_\nu(\omega)\ N\ (\omega)\ d\omega\ , \qquad (1)$$

where $\sigma_\nu(\omega)$ is the measured photonuclear cross section at photon energy ω.

The number density of virtual photons has the functional form $N(\omega)=(Z^2/\omega\beta^2)F(\beta,\omega b_{min}/\beta\gamma)$, where b_{min}, the minimum-impact parameter, is the only adjustable parameter in σ_{WW}.

References to the photoneutron and photoproton cross sections we used to compute σ_{WW} are, for ^{12}C: $\sigma(\gamma,n)$,[6] $\sigma(\gamma,p)$,[6,7] and for ^{16}O: $\sigma(\gamma,n)$,[8] $\sigma(\gamma,p)$.[9] The cross section $\sigma(\gamma,p)$ for ^{12}C was obtained from the difference between $\sigma(\gamma,\text{total})$[7] and $\sigma(\gamma,n)$.[6] The cross-section data given in Refs. 10-14 were used to extrapolate $\sigma_\nu(\omega)$ to higher values of ω_{max} (to 65 MeV for ^{12}C, 62 MeV for ^{16}O). Because the shape of the high-energy tail of $\sigma_\nu(\omega)$ has little effect on σ_{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}C and ^{16}O proceeds mainly by single-nucleon emission. Furthermore, contributions to σ_{WW} from the higher-threshold multinucleon-loss photoreactions are suppressed by the ω^{-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 $\sigma_{WW}(\text{exp})$ to σ_{WW}, Eq. (1) we have determined the impact parameter b_{min} appropriate for each cross section. The minimum-impact parameter is defined by the relation $b_{min}=r^B_{0.1}+r^T_{0.1}-d$, where the $r_{0.1}$'s are the 10 percent charge-density radii of the beam and target

nuclei,[15] and d is the radial-overlap distance. The values of b_{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 $\sigma_{WW}(exp)$ for ^{12}C and ^{16}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 σ_{WW}, given by a) Jackson[2] and b) Jäckle and Pilkuhn.[3]

The standard deviations of the d-distributions are compatible with the statistical errors in $\sigma_{WW}(exp)$. Systematic variations in σ_{WW} (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 $d(b_{min})$, other than those from the theoretical differences in σ_{WW}, are the photonuclear cross sections $\sigma_{\nu}(\omega)$ and those inherent in the method used to extract $\sigma_{WW}(exp)$ from σ_{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 $d(b_{min})$.

The unweighted mean (and its statistical error) of the d-distributions are $\bar{d}=0.4\pm0.8$ fm (Jackson) and 3.0 ± 0.6 fm (Jäckle 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.[15]

Fig. 3 presents the cross-section data from this experiment, $\sigma_{WW}(exp)= \sigma_{BT}^{F}-\gamma_B^F\bar{\gamma}_T$, plotted as a function of target mass. Superimposed on the data are curves of the computed cross sections σ_{WW} (Jäckle and Pilkuhn) evaluated for a constant overlap distance $\bar{d}=3.0$ fm. [Curves of σ_{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 $\bar{\gamma}_T \propto (A_B^{1/3}+A_T^{1/3}-0.8)$ gives an excellent fit to the target factors of σ_{BT}^F for $A_T \geq 12$, as illustrated in Fig. 1. When expressed in terms of $r_{0.1}$, the target factor has the form of an impact parameter, $\bar{\gamma}_T \propto (r_{0.1}^B+r_{0.1}^T-2.0)$, 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 $\bar{\gamma}_T$ is d'=2.0 fm, a value that agrees well with the $\bar{d}$'s (0.4 and 3.0 fm) obtained in this analysis.

To summarize our results, all the saliant features of σ_{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 Weizsäcker-Williams method to interpret σ_{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 σ_{WW}(exp), and iii) the magnitudes of σ_{WW}(exp). The values of b_{min} derived from σ_{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.

The authors greatly appreciate the knowledgeable helpful comments unstintingly given us by Dr. B. L. Berman and Prof. J. D. Jackson on this work.

FOOTNOTES AND REFERENCES

*Work performed under auspices of the U. S. Energy Research and Development Administration and the National Aeronautics and Space Administration, Grant No. NGR 05-003-513.

1. P. J. Lindstrom, D. E. Greiner, H. H. Heckman, Bruce Cork, and F. S. Bieser, Lawrence Berkeley Laboratory Report No. LBL-3650, Feb. 1975.

2. J. D. Jackson, Classical Electrodynamics, (Wiley, New York, 1975), 2nd ed., p.719.

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

4. X. Artru and G. B. Yodh, Phys. Lett. 40B, 43 (1972).

5. Jäckle and Pilkuhn[3], who give equations for $N(\omega)$ for the E1 and M1 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 $\sigma_{\nu}(\omega)=\sigma_{E1}(\omega)+\sigma_{M1}(\omega)$ is the photodisintegration cross section, and $N(\omega) \approx N_{E1}(\omega)$. In Jackson's treatment of the Weizsäcker-Williams effect,[2] the $N(\omega)$ for all electric and magnetic multipoles are, in fact, equal.

6. W. A. Lochstet and W. E. Stephens, Phys. Rev. 141, 1002 (1966).

7. J. Ahrens, H. B. Eppler, H. Grimm, H. Gundrum, P. Riehn, G. Sita Ram, A. Zieger, and B. Ziegler, in Proceedings of the International Conference on Photonuclear Reactions and Applications, Pacific Grove, California, 1973, edited by B. L. Berman, (Lawrence Livermore Laboratory) p.23.

8. R. L. Bramblett, J. T. Caldwell, R. R. Harvey, and S. C. Fultz, Phys. Rev. 133, B869 (1964).

9. R. C. Morrison, J. R. Stewart, and J. S. O'Connell, Phys. Rev. Lett. 15, 367 (1965).

10. S. C. Fultz, J. T. Caldwell, B. L. Berman, R. L. Bramblett, and R. R. Harvey, Phys. Rev. 143, 790 (1966).

11. B. C. Cook, J. E. E. Baglin, J. N. Bradford, and J. E. Griffen, Phys. Rev. 143-3, 724 (1966).

12. G. G. Taran and A. N. Gorbunov, Sov. Phys.-JETP 19, 1010 (1964).

13. B. C. Cook, J. E. E. Baglin, J. N. Bradford, and J. E. Griffen, Phys. Rev. 143-3, 712 (1966).

14. A. N. Gorbunov and V. A. Osipova, Sov. Phys.-JETP 16, 27 (1963).

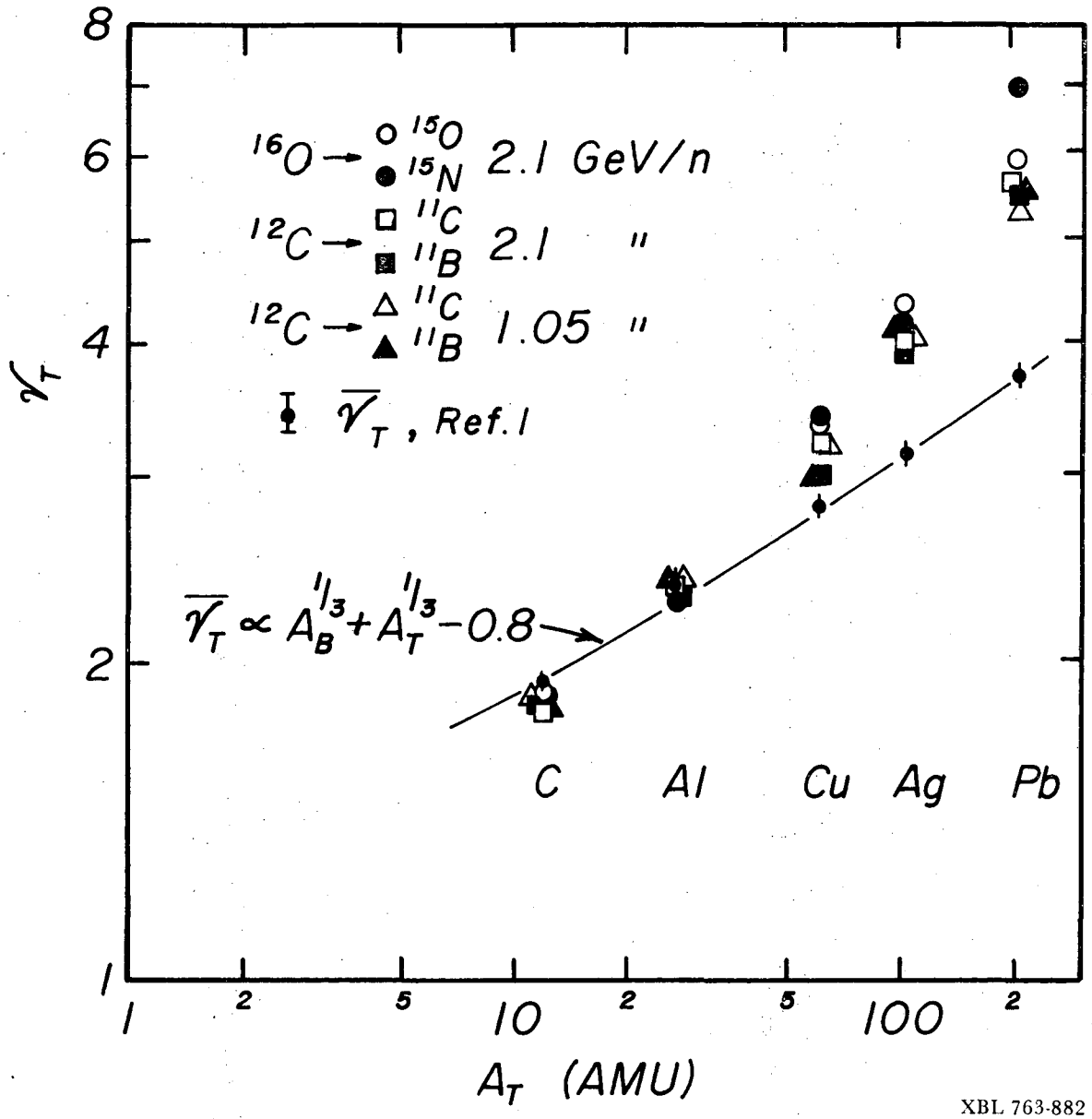
15. R. Hofstadter and H. R. Collard, in Numerical data and functional relationships in science and technology, Landolt-Börstein, edited by H. Schopper (Springer-Verlag) I/2, 21(1967).

FIGURE CAPTIONS

Fig. 1. Target factors γ_T plotted versus target mass A_T(AMU), from Lindstrom et al.[1] Individual values of γ_T are shown for the single-nucleon-loss cross sections indicated. The curve $\bar{\gamma}_T \propto A_B^{1/3}+A_T^{1/3}-0.8$ is drawn through the mean target factors, shown with error bars, for all cross sections σ_{BT}^F, where $A_F \leq A_B-2$.

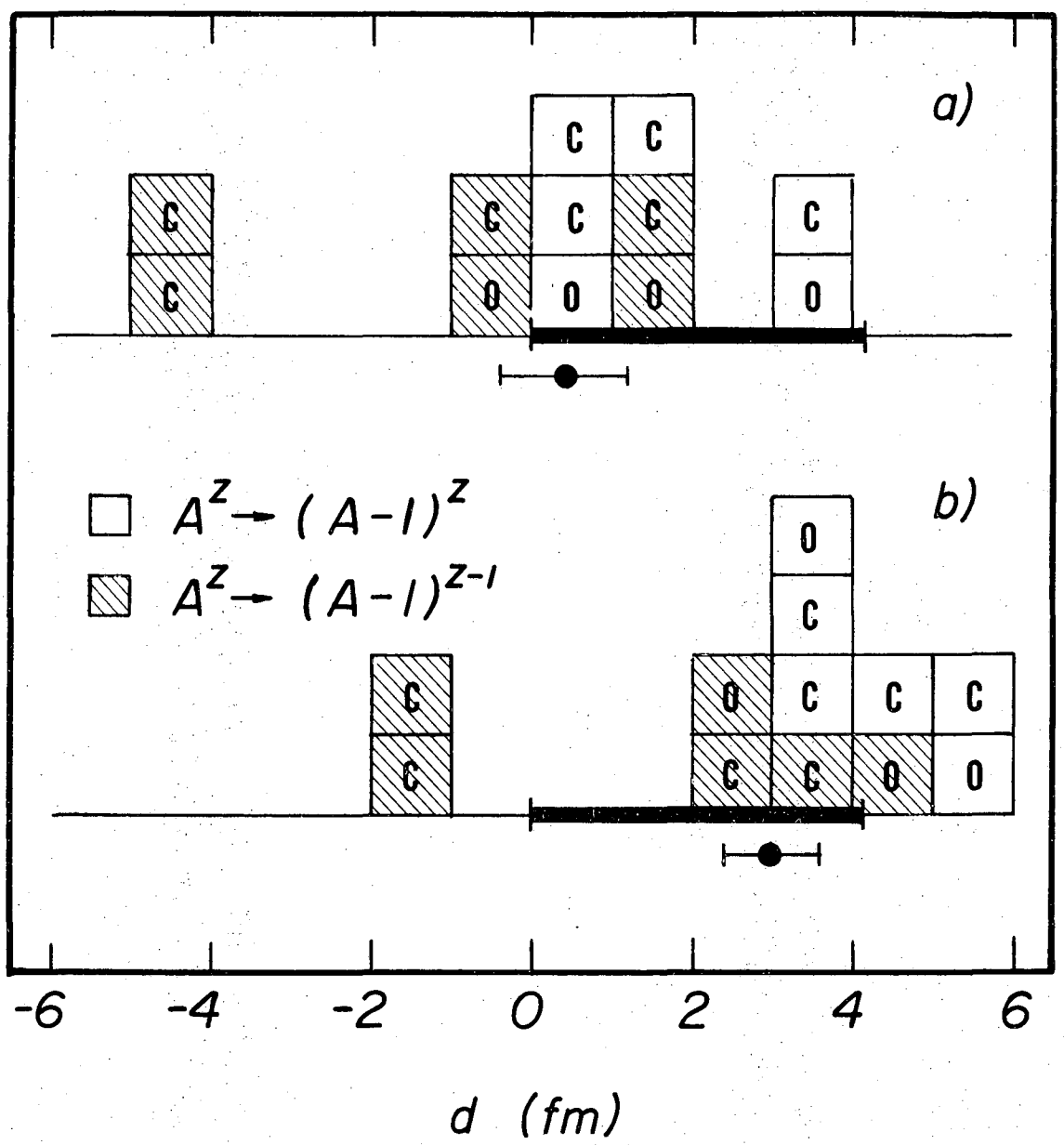
Fig. 2. Distributions of overlap distances $d(b_{min})$, and their means, derived from σ_{WW}(exp) when fitted to the Weizsäcker-Williams cross sections σ_{WW}, as given by a) Jackson[2] and b) Jäckle and Pilkuhn.[3] The dark horizontal bar delineates the overlap region bounded by $0 \leq d \leq t_B+t_T$,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

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



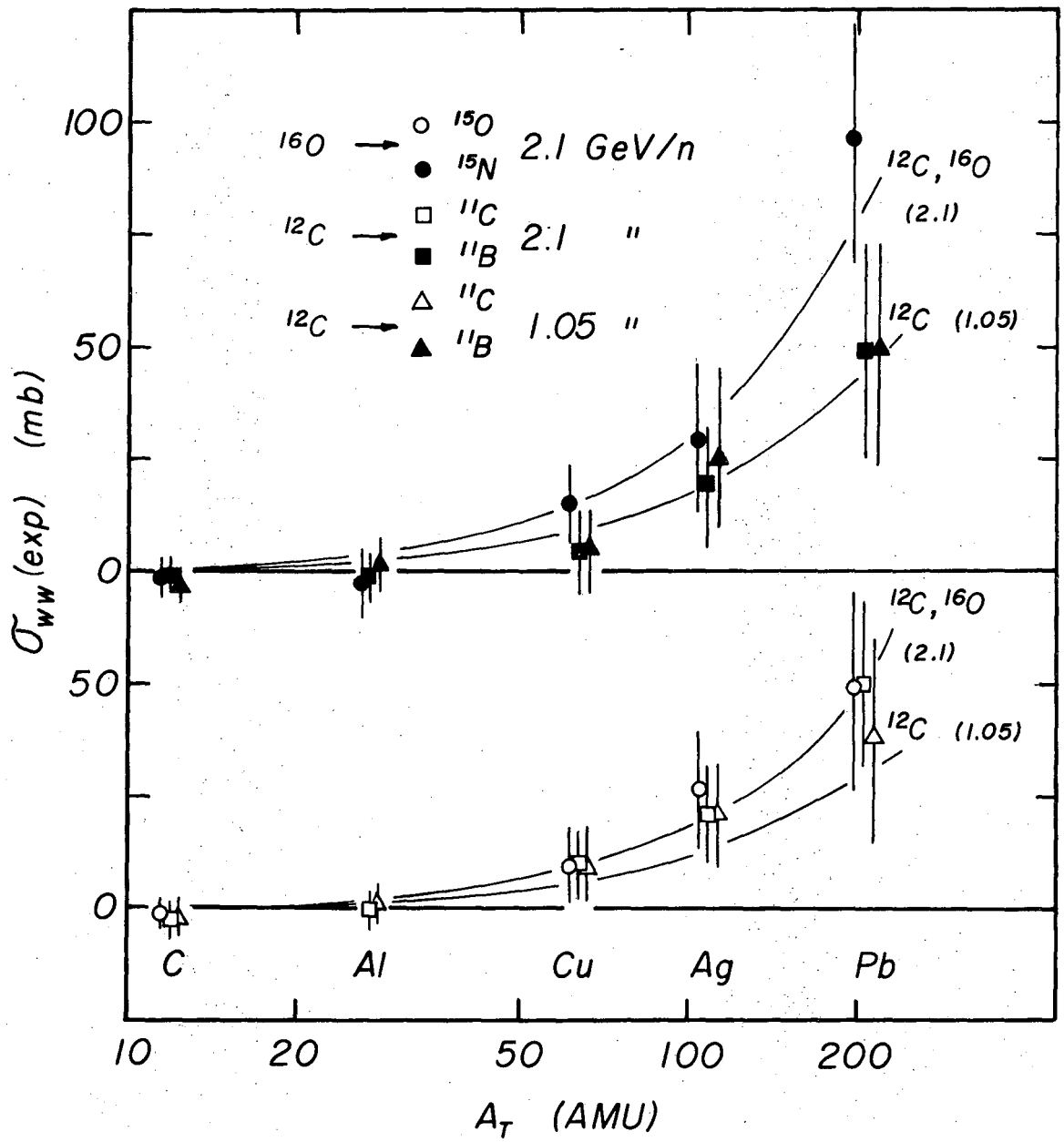
XBL 763-882

Fig. 1



XBL 763-881

Fig. 2



XBL 763-883

Fig. 3

TECHNICAL INFORMATION DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720