APPENDIX I

Fragmentation Cross Sections of $^{16}$O Between 0.9 and 200 GeV/Nucleon

by

S. E. Hirzebruch, W. Heinrich, K. D. Tolstov, A. D. Kovalenko
and E. V. Benton
Fragmentation cross sections of $^{16}$O between 0.9 and 200 GeV/nucleon

S. E. Hirzebruch,¹¹ W. Heinrich,¹¹ K. D. Tolstov,² A. D. Kovalenko,¹² and E. V. Benton¹³

¹¹University of Siegen, Department of Physics, Adolf-Reichweinstr. 2, 5900 Siegen, Germany
²Laboratory of High Energies, Joint Institute for Nuclear Research, Dubna, Russia
¹³University of San Francisco, Department of Physics, San Francisco, California 94117 *

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Inclusive cross sections for high energy interactions at 0.9, 2.3, 3.6, and 13.5 GeV/nucleon of $^{16}$O with C, CR-39 (C$_{12}$H$_{16}$O$_{7}$), CH$_2$, Al, Cu, Ag, and Pb targets were measured. The total charge-changing cross sections and partial charge-changing cross sections for the production of fragments with charge $Z=6$ and $Z=7$ are compared to previous experiments at 60 and 200 GeV/nucleon. The contributions of Coulomb dissociation to the total cross sections are calculated. Using factorization rules the partial electromagnetic cross sections are separated from the nuclear components. Energy dependence of both components are investigated and discussed.

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I. INTRODUCTION

A. General

Depending on the impact parameter between the colliding nuclei, the type of reaction differs. For an impact parameter smaller than the sum of the projectile's and target's radii, the interaction is dominated by the strong force. For impact parameters which are too large for an overlap of target and projectile nuclei, the interaction is purely electromagnetic. For high projectile energies and strong electromagnetic fields (i.e., high-Z targets), the probability increases that this interaction leads to a fragmentation of the projectile or target nucleus. This effect, which is called electromagnetic dissociation (ED), has become the subject of systematic studies over the last years. Several groups report experimental results for the measurement of ED for different projectile [1-13] and target [14-17] fragmentation reactions. Recently, Olson et al. [18] reported direct observation of the giant dipole resonance of $^{16}$O via electromagnetic dissociation.

During the last years, we have been measuring fragmentation cross sections for high-energy heavy-ion reactions. In this paper we present our results for $^{16}$O projectiles at beam energies of 0.9 GeV/nucleon for H, CH$_2$, C, and Pb targets and at 2.3, 3.6, and 13.5 GeV/nucleon for H, CH$_2$, CR-39, C, Al, Cu, Ag, and Pb targets. Cross sections for the hydrogen target were calculated with the subtraction method using the CH$_2$/C data. We performed the 13.5-GeV/nucleon (14.5-GeV/c momentum) experiment at the Alternating Gradient Synchrotron (AGS) facility at Brookhaven National Laboratory (BNL). The 0.9-, 2.3-, and 3.6-GeV/nucleon experiments were carried out at the Synchrophasotron in Dubna (Russia).

In combination with the earlier published data for $^{16}$O at 60 and 200 GeV/nucleon [9], we are now able to analyze the energy dependence of nuclear and electromagnetic cross sections in the energy range from 1 to 200 GeV/nucleon. Our interest is focused on the following points: (a) The process of electromagnetic dissociation contributes significantly to the total charge-changing cross sections for heavy targets within the investigated energy range. With the complete set of our $^{16}$O data, we are able to determine the energy dependence of the ED contribution of different targets to the total charge-changing cross sections. (b) Cross sections for the hydrogen target are important input data for astrophysical calculations which describe the propagation of cosmic-ray nuclei through interstellar space. The energy dependence of hydrogen partial cross sections, which we have observed beyond 1 GeV/nucleon [19,20], can be analyzed in more detail. (c) The validity of factorization rules for partial elemental cross sections for the heavier targets is tested.

B. Experimental setup

We used stacks of CR-39 (C$_{12}$H$_{16}$O$_{7}$) plastic nuclear track detectors, which were mounted up and downstream of the target. One stack consists typically of five sheets of CR-39. The CR-39 used was produced by American Acrylics and has a unique charge resolution. The detection threshold lies near the energy loss for relativistic boron ($Z=5$) ions. The detectors were etched in 6N NaOH at 70 °C for 36 or 48 h. After this procedure etch cones of relativistic nuclei with charges $Z=5-8$ could be detected. Using the advanced Siegen automatic measuring system, we scanned all detector surfaces, which contained typically 70,000 tracks each (1.4×10⁶ objects for 1 target and energy). Further detailed information about the experimental setup and the automatic measuring system can be found in [21,22]. Since etch cones for particles with charge 5 were detected with a reduced efficiency, we could only determine partial cross sections for charges 6 and 7.

C. Nuclear and ED total cross sections

The total nuclear cross section is generally parametrized by overlap formulas, which have the form

\[ \sigma_{\text{total}} = \sigma_{\text{nuclear}} + \sigma_{\text{ED}} \]

where $\sigma_{\text{total}}$ is the total cross section, $\sigma_{\text{nuclear}}$ is the nuclear cross section, and $\sigma_{\text{ED}}$ is the ED cross section.
\[ \sigma_{\text{tot}}^{(P,T)} = \pi(R_T + R_P - \delta_{PT})^2, \]  
where \(R_T\) and \(R_P\) are the radii of target and projectile nucleus and \(\delta_{PT}\) takes into account the drop of the nuclear density in the nucleus sphere. Since none of common cross-section formulas [23-26,38] take the ED effect into account (most of them are not even energy dependent), all of them give constant cross-section values for energies greater than 2 GeV/nucleon. This is expected to be correct for the nuclear component of the cross section because of the concept of limiting fragmentation.

For a theoretical description of the ED effect, Bertulani and Baur [27-29] have derived spectra of virtual photons, which are equivalent to the electromagnetic pulse a projectile suffers while passing a target nucleus (or vice versa). The intensity of the photon-number spectra \(dN/dE_{\gamma}\) is approximately proportional to \(Z_f^2 \ln y/E_{\gamma}\), where \(Z_f\) is the target charge, \(y\) is the Lorentz factor of the projectile in the laboratory frame, and \(E_{\gamma}\) is the energy of an absorbed photon. The nucleus absorbs the photon by giant resonances, by the quasideuteron effect [30], or by resonances which lie in higher-photon-energy regimes (e.g., \(\Delta\) resonances). The deexcitation of these excited modes can easily lead to the emission of protons or alpha particles or may even cause a severe destruction of the nucleus [10]. For high energies the relativistic contracted field of the target seen by the passing projectile is nearly a plane wave which contains all photon multipoles with the same strength. In this case the total charge-changing ED cross section can be calculated by

\[ \sigma_{\text{tot}}^{(P,T)} = \sum_{\text{all multipolarities}} \sigma_{\gamma E^2}(E_{\gamma}) dE_{\gamma}, \]  

where \(n(E_{\gamma})\) is the virtual-photon spectrum and \(\sigma_{\gamma E^2}(E_{\gamma})\) is the photonuclear charge-changing cross section for \(^{16}\text{O}\), respectively. This is equivalent to the method used by Weizsäcker [31] and Williams [32].

For smaller projectile energies, the strengths of the different multipoles differ very much, especially in the photon-energy region of the \(^{16}\text{O}\) giant resonance. For that reason electrical dipole \((E1)\) absorption has to be distinguished from the electrical quadrupole \((E2)\) absorption process. The total charge-changing ED cross section can then be calculated by evaluating (3):

\[ \sigma_{\text{tot}}^{(P,T)} = \int n(E_{\gamma}) \sigma_{\gamma E^2}(E_{\gamma}) dE_{\gamma}, \]  

where \(n(E_{\gamma})\) is the virtual-photon spectrum and \(\sigma_{\gamma E^2}(E_{\gamma})\) is the photonuclear charge-changing cross section for \(^{16}\text{O}\), respectively. This is equivalent to the method used by Weizsäcker [31] and Williams [32].

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\[ \sigma_{\text{tot}}^{(P,T)} = \int [n(E_{\gamma}) \sigma_{\gamma E^1}(E_{\gamma}) + n(E_{\gamma}) \sigma_{\gamma E^2}(E_{\gamma})] dE_{\gamma}. \]  

Since photonuclear cross sections measured with real photon beams contain all absorption modes, separation of the \(E1\) and \(E2\) contributions has to be performed using several assumptions. In previous calculations of Norbury [33-35], \(E2\) contributions were obtained using a Lorentzian distribution as an approximation of the quadrupole excitation cross section in combination with sum rules and empirical formulas for the position of the resonances. This method may be adequate for heavy nuclei. However, for light nuclei such as \(^{16}\text{O}\), for which the \(E2\) photon cross section is fragmented in energy, this procedure is possibly incorrect.

In a recent theoretical paper by Fleischhauer and Scheid [36], \((\gamma,n)\) and \((\gamma,p)\) \(E2\) cross sections for \(^{16}\text{O}\) were calculated. In order to determine the charge-changing ED cross section, we use their cross sections \(\sigma_{\gamma E^2}\) to calculate \(\sigma_{\gamma E^2}\). In addition to the \((\gamma,p)\) process, the \((\gamma,\alpha)\) process plays an important role in the \(E2\) absorption process. We use experimental data compiled by Fuller [37] to determine the contribution of the \(\alpha\) channel to \(\sigma_{\gamma E^2}\) and estimate \(\sigma_{\gamma E^2}\) by multiplying the given experimental \((\gamma,\alpha)\) cross sections by the ratio of the relevant sum-rule values \(\sigma_0\) in the photon-energy interval from 9 to 29 MeV [37]:

\[ \sigma_{\gamma E^2} = \sigma_{\gamma E^2}(\gamma,\alpha) \frac{\sigma_{\gamma}(E2)}{\sigma_{\gamma}(E1) + \sigma_{\gamma}(E2)}, \)  

\[ \sigma_{\gamma E^2} = \sigma_{\gamma E^2}(\gamma,\alpha) \frac{\sigma_{\gamma}(E2)}{\sigma_{\gamma}(E1) + \sigma_{\gamma}(E2)}, \]  

\[ \sigma_{\gamma E^2} = \sigma_{\gamma E^2}(\gamma,\alpha) \frac{\sigma_{\gamma}(E2)}{\sigma_{\gamma}(E1) + \sigma_{\gamma}(E2)}. \]  

The charge-changing \(E2\) cross section is then calculated with help of (5):

\[ \sigma_{\gamma E^2} = \sigma_{\gamma E^2}(\gamma,\alpha) \sigma_{\gamma}(E2). \]  

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\[ \sigma_{\gamma E^2} = \sigma_{\gamma E^2}(\gamma,\alpha) \sigma_{\gamma}(E2). \]  

The total charge-changing ED cross sections were calculated inserting (5) and (6) into (3) and using the virtual-photon spectra derived from Bertulani and Baur [27]. This method is effectively equivalent to using \(n = 0.978 \sigma_{\gamma E^2} + 0.022 \sigma_{\gamma E^2}\) for the virtual-photon spectra in the whole \(\gamma\)-energy regime of the giant resonance. This effective weighting differs from the weighting of \(n = 0.96 \sigma_{\gamma E^2} + 0.04 \sigma_{\gamma E^2}\), which we have used in [9]. The consequences of the different weighting, however, have a negligible influence on the calculated ED cross sections at CERN energies. At lower energies the calculated ED cross sections are about 3% smaller ( Pb target, 2.3 GeV) than those using the method described in [9]. More details about the photonuclear data used can be found in [9].

The only adjustable parameter in our calculation of the total charge-changing ED cross section is \(b_{\text{min}}\), which is the minimum impact parameter giving the maximum range of the strong force. For our calculations we used the overlap formula of Lindstrom et al. [23], which gives total nuclear cross sections \(\sigma_{\gamma}\). This parametrization is a fit to the data obtained with \(^{12}\text{C}\) and \(^{16}\text{O}\) projectiles at low Bevalac energies and is in good agreement with different experimental data, which we have compiled in [9]. We calculate the minimum impact parameter setting \(b_{\text{min}} = (\sigma_{\gamma}/\pi)^{1/2}\).

To determine the error of our calculation, we consider contributions by the error of the measured photonuclear cross section, the different weighting of the photon spectra, and the selection of \(b_{\text{min}}\): (i) The error of the photonuclear data is estimated to be about 6% (after averaging where possible over several experimentalists data) [9].

The influence of \(b_{\text{min}}\) on
TABLE I. Measured cross sections for 16O projectiles. All cross sections are given in mb.

<table>
<thead>
<tr>
<th>Target</th>
<th>0.9 GeV/nucleon</th>
<th>2.3 GeV/nucleon</th>
<th>3.6 GeV/nucleon</th>
<th>13.5 GeV/nucleon</th>
<th>60 GeV/nucleon</th>
<th>200 GeV/nucleon</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>302.6±22.7</td>
<td>67.5±4.8</td>
<td>67.3±5.7</td>
<td>88.3±2.0</td>
<td>301.9±15.8</td>
<td>299.6±18.0</td>
</tr>
<tr>
<td>CH₂</td>
<td>580.3±9.6</td>
<td>81.5±1.9</td>
<td>101.5±3.9</td>
<td>120.1±4.7</td>
<td>121.1±4.7</td>
<td>121.4±4.7</td>
</tr>
<tr>
<td>C</td>
<td>895.8±35.1</td>
<td>109.3±3.9</td>
<td>142.5±5.8</td>
<td>181.5±9.0</td>
<td>216.1±11.3</td>
<td>216.1±11.3</td>
</tr>
<tr>
<td>Pb</td>
<td>3426.0±204.7</td>
<td>277.8±15.1</td>
<td>309.1±15.8</td>
<td>626.2±21.6</td>
<td>67.3±4.8</td>
<td>677.9±15.8</td>
</tr>
</tbody>
</table>

Assuming independence of the error sources, we obtain a total error of \( \sigma_{\text{tot}}^{16} \text{O} \) of 10.3%, 7.6%, 7.5%, 6.6%, 6.2%, and 6.1% for the 0.9-, 2.3-, 3.6-, 13.5-, 60-, and 200-GeV/nucleon data, respectively. A further error source is multiple-photon excitation. Lipo and Braun-Munziger [39] have shown that the contribution of multiple-photon excitation for 28Si interacting with a Pb target accounts about 1% to the total ED cross section, almost independent of projectile energy. For the 16O projectile, this effect should be even smaller than for 28Si. According to the calculations of Lipo and Braun-Munziger for 16O and 238U target [39], higher-order excitation contributes only 0.83% to the total ED cross section at 100 GeV/nucleon. An effect of this strength can be neglected in our case since the other errors discussed are considerably larger. For other projectile, target, and energy combinations, however, the contribution of multiple-photon excitation can be more significant [39,40].

II. RESULTS

The obtained experimental total and partial cross sections for charges 6 and 7 for the 0.9-, 2.3-, 3.6-, and 13.5-GeV/nucleon experiments are listed in Table I. The cross sections for the hydrogen target were calculated using the cross sections for CH₂ and C targets.

A. Total charge-changing cross sections

The calculated total charge-changing ED cross sections are given in Table II. The determined total ED cross sections were subtracted from the measured total ones to derive the pure nuclear component. In Fig. 1 we show measured total cross sections (solid squares), calculated ED cross sections (solid triangles), and difference cross sections (open squares) for Pb, Ag, and Cu targets. The horizontal lines give the average value of the difference cross section for the five energies (six for the lead target). The nuclear fragmentation cross sections obviously are constant at high energies. This means that the method we use succeeded in estimating the energy dependence of the ED contribution to the total reaction cross section.

The difference cross sections for the light targets H, C, and Al where the ED contribution is small are shown in Fig. 2. For these targets the total charge-changing cross sections are also constant in the whole energy regime from 2.3 to 200 GeV/nucleon.

The averaged nuclear cross sections for the five heavier targets and all energies are compared with results which

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The table below shows the calculated total ED cross sections for 16O.

<table>
<thead>
<tr>
<th>Target</th>
<th>2.3</th>
<th>3.6</th>
<th>13.5</th>
<th>60</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>2.0±0.1</td>
<td>2.4±0.2</td>
<td>4.5±0.3</td>
<td>8.3±0.5</td>
<td>12±0.7</td>
</tr>
<tr>
<td>Al</td>
<td>7.8±0.6</td>
<td>9.7±0.7</td>
<td>19.0±1.3</td>
<td>36.1±2.2</td>
<td>53.6±3.3</td>
</tr>
<tr>
<td>Cu</td>
<td>32.7±2.5</td>
<td>41.6±3.1</td>
<td>84.9±5.6</td>
<td>166.8±10.3</td>
<td>251.7±15.4</td>
</tr>
<tr>
<td>Ag</td>
<td>76.0±5.8</td>
<td>98.5±7.4</td>
<td>207.4±13.7</td>
<td>416.6±25.8</td>
<td>636.6±38.8</td>
</tr>
<tr>
<td>Pb</td>
<td>194.4±14.8</td>
<td>259.4±19.5</td>
<td>573.0±37.8</td>
<td>1184.7±73.5</td>
<td>1841.2±112.3</td>
</tr>
</tbody>
</table>
all energies. The solid squares show the measured change in cross sections, which include errors from measured and calculated cross sections, are given by the open squares. The horizontal line represents the average value of difference cross sections for all energies.

FIG. 1. Energy dependence of $^{16}$O charge-changing cross-section data for Pb (top), Ag (middle), and Cu (bottom) targets. The solid squares show the measured reaction cross sections, while the open triangles represent the calculated charge-changing electromagnetic cross sections. The difference cross sections, which include errors from measured and calculated cross sections, are given by the open squares. The horizontal line represents the average value of difference cross sections for all energies.

FIG. 2. Energy dependence of $^{16}$O cross-section data for the light targets H (results are calculated from C and CH$_2$ targets), C, and Al after subtraction of the ED component. The horizontal line represents the average value of our cross-section data for all energies.

are obtained from empirical formulas. The empirical estimations of Westfall et al. [24] and Binns et al. [26] give total charge-changing cross sections as measured in our experiment. The formulas of Lindstrom et al. [23], Benesh, Cook, and Vary [38], and Kox et al. [25] give the total nuclear reaction cross sections. In order to compare our data with the results of these formulas, we have to estimate the contribution of the $\sigma (Z=8\rightarrow 8)$ neutron-emission channel. This contribution is obtained by using the data of Olson et al. [41] from a similar experiment ($^{16}$O projectile fragmentation at 2.1 GeV/nucleon), which allows the calculation of this contribution with the help of factorization rules. As can be seen in Table III, the measured cross sections agree with the total charge- and mass-changing cross sections derived from different formulas. Only the value for the lead target is overestimated by some formulas. (All formulas are energy independent above 2 GeV/nucleon and do not take into account the ED contribution.)

B. Partial charge-changing cross sections

Partial nuclear cross sections can be described by the factorization rule expressed as

TABLE III. Total nuclear cross sections in comparison to results of different cross section formulas. The first column gives the averaged value of the nuclear cross sections for our experiments at five energies. The next two columns include charge-changing cross sections derived from empirical formulas. In the fourth column, the average total cross sections including the neutron-emission channel are given. The contribution of this channel was estimated using data of Olson et al. [41]. These cross sections are compared with the results of four empirical formulas. All cross sections are given in mb.

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Delta Z &gt; 0$</td>
<td>$\Delta A &gt; 0$</td>
<td>$\Delta Z &gt; 0$</td>
<td>$\Delta A &gt; 0$</td>
<td>$\Delta Z &gt; 0$</td>
<td>$\Delta A &gt; 0$</td>
<td>$\Delta Z &gt; 0$</td>
<td>$\Delta A &gt; 0$</td>
</tr>
<tr>
<td>C</td>
<td>883.4±9.7</td>
<td>906.6</td>
<td>992.9</td>
<td>927.2±9.8</td>
<td>924.0</td>
<td>898.3</td>
<td>987.5</td>
<td>999.3</td>
</tr>
<tr>
<td>Al</td>
<td>1271.5±11.9</td>
<td>1259.3</td>
<td>1314.4</td>
<td>1326.8±12.1</td>
<td>1314.2</td>
<td>1290.2</td>
<td>1394.6</td>
<td>1438.5</td>
</tr>
<tr>
<td>Cu</td>
<td>1908.5±21.1</td>
<td>1853.6</td>
<td>1811.3</td>
<td>1972.5±21.2</td>
<td>1979.5</td>
<td>1861.9</td>
<td>2054.3</td>
<td>2125.0</td>
</tr>
<tr>
<td>Ag</td>
<td>2444.6±31.0</td>
<td>2383.5</td>
<td>2234.0</td>
<td>2515.8±31.2</td>
<td>2577.7</td>
<td>2367.9</td>
<td>2629.1</td>
<td>2699.1</td>
</tr>
<tr>
<td>Pb</td>
<td>3313.9±69.7</td>
<td>3311.7</td>
<td>2949.2</td>
<td>3393.0±69.8</td>
<td>3632.9</td>
<td>3249.0</td>
<td>3620.1</td>
<td>3649.2</td>
</tr>
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</table>
The relative probabilities of producing different projectile fragments in interactions depend only on the species of projectile and target, while the absolute value of the probability to produce a fragment depends on the species of projectile and fragment, while \( \gamma_{PT} \) depends only on the species of projectile and target [41].

We found that in a similar way it is also possible to determine partial electromagnetic cross sections [10]. The photon spectra for different targets at constant beam energies do not change significantly in shape, but only in intensity. Therefore the relative probabilities for the production of different projectile fragments in interactions with different targets should be independent of the target. We introduce a factor \( \varepsilon_F \), which is proportional to the probability to produce a fragment \( F \) by ED in a collision of projectile \( P \) with an arbitrary target. At a given energy, the absolute value of the partial ED cross section into a given channel is expected to scale with the intensities of the photon spectra associated with each target. We use the target factors \( \gamma_{PT} \) and \( \varepsilon_{PT} \), defined separately for each energy as

\[
\gamma_{PT} = \sqrt{\sigma_{nuc}(P, T, F)} / \sigma_{nuc}(P, T = C)
\]

and

\[
\varepsilon_{PT} = \sigma_{em}(P, T) / \sigma_{em}(P, T = C),
\]

where \( \sigma_{nuc}(P, T) \) is the total nuclear cross section for the target \( T \) obtained by subtracting the calculated total charge-changing ED cross sections \( \sigma_{em}(P, T) \) from the measured data. The scaling on the \( C \) target is arbitrary, and so scaling to a different target does not lead to any difference in the separated cross sections.

The partial ED cross section is written as

\[
\sigma_{em}(P, T, F) = \gamma_{PT} \gamma_F + \varepsilon_{PT} \varepsilon_F.
\]

For the measured partial cross sections \( \sigma_{meas}(P, T, F) \), we can write

\[
\sigma_{meas}(P, T, F) = \gamma_{PT} \gamma_F + \varepsilon_{PT} \varepsilon_F.
\]

The fragment factors \( \gamma_F \) and \( \varepsilon_F \) are evaluated for all energies and fragments by minimizing the expression

\[
\sum_T \left[ \frac{\gamma_{PT} \gamma_F + \varepsilon_{PT} \varepsilon_F - \sigma_{meas}(P, T, F)}{\Delta \sigma_{meas}(P, T, F)} \right]^2 \rightarrow \text{minimum},
\]

where \( \Delta \sigma_{meas}(P, T, F) \) is the error of the measured partial cross section \( \sigma_{meas}(P, T, F) \).

Nuclear and electromagnetic target factors determined by this procedure are given in Table IV for all five energies. The fragment factors determined by our fit procedure are shown in Table V. Using (7) and (10), the pure nuclear and pure electromagnetic components were determined. In Fig. 3 the partial charge-changing nuclear cross sections \( \Delta Z = 1 \) and 2 are shown together with data of Olson et al. at 2.1 GeV/nucleon [41]. In general, our partial nuclear cross sections are constant in the whole energy range and agree with the data of Olson et al. It should be noted that all cross sections belong to one fixed energy scale with one fragment factor and its error. For that reason all cross sections for a certain energy but different targets are smaller or bigger than the average for all energies (for example, the 13.5-GeV/nucleon data for \( \Delta Z = 1 \) are significantly larger than the average).

Figure 4 shows the energy dependence of the partial electromagnetic cross sections for the lead target. The cross section \( \sigma(Z = 8 \rightarrow Z \leq 5) \) was calculated by sub-

<table>
<thead>
<tr>
<th>Target</th>
<th>( \gamma_{PT} )</th>
<th>( \varepsilon_{PT} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>Al</td>
<td>1.216</td>
<td>1.200</td>
</tr>
<tr>
<td>Cu</td>
<td>1.487</td>
<td>1.485</td>
</tr>
<tr>
<td>Ag</td>
<td>1.669</td>
<td>1.678</td>
</tr>
<tr>
<td>Pb</td>
<td>1.944</td>
<td>1.953</td>
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<table>
<thead>
<tr>
<th>Kinetic energy (GeV/nucleon)</th>
<th>2.3</th>
<th>3.6</th>
<th>13.5</th>
<th>60</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma_F ) (( Z = 7 ))</td>
<td>97.50±2.79</td>
<td>99.02±2.65</td>
<td>107.76±2.76</td>
<td>105.01±2.99</td>
<td>105.94±3.96</td>
</tr>
<tr>
<td>( \varepsilon_F ) (( Z = 7 ))</td>
<td>1.24±0.17</td>
<td>1.70±0.15</td>
<td>2.94±0.16</td>
<td>5.44±0.21</td>
<td>6.75±0.27</td>
</tr>
<tr>
<td>( \gamma_F ) (( Z = 6 ))</td>
<td>116.89±3.25</td>
<td>119.72±3.06</td>
<td>113.72±2.86</td>
<td>122.28±3.16</td>
<td>124.75±4.26</td>
</tr>
<tr>
<td>( \varepsilon_F ) (( Z = 6 ))</td>
<td>0.66±0.19</td>
<td>0.45±0.18</td>
<td>0.88±0.14</td>
<td>1.62±0.20</td>
<td>1.98±0.26</td>
</tr>
</tbody>
</table>
based on factorization rules. The data include cross sections to the total ED cross sections derived from our experiments (solid squares) based on factorization rules. The data include cross sections from [41] at 2.1 GeV/nucleon (open squares). The horizontal line represents the average value of our cross-section data for all energies.

FIG. 3. Partial nuclear cross sections \( \Delta Z = 1 \) (top) and \( \Delta Z = 2 \) (bottom) for the reaction of \(^{16}\text{O}\) with targets C, Al, Cu, Ag, and Pb determined from our experiments (solid squares) based on factorization rules. The data include cross sections from [41] at 2.1 GeV/nucleon (open squares). The horizontal line represents the average value of our cross-section data for all energies.

tracting the two partial ED cross sections from the calculated total one. The relative abundance of the ED partial cross sections to the total ED cross sections derived from the data for all targets is shown in Fig. 5. From both figures it can be seen that the partial cross sections for \( \Delta Z = 1 \) and 2 are the dominant electromagnetic interactions. These interactions are induced by proton or alpha emission from the giant resonance of the \(^{16}\text{O}\) projectile. With higher energies the virtual-photon spectra become harder and the excitation of a delta resonance becomes more likely. The excitation of a delta resonance within the projectile nucleus can lead to an intranuclear cascade and can cause a more complete destruction of the projectile nucleus. That is the reason why the \( \Delta Z \geq 3 \) channel exceeds the \( \Delta Z = 2 \) channel at 200 GeV/nucleon. This fact was also observed for \(^{32}\text{S}\) data at 200 GeV/nucleon [10].

C. Cross sections for light targets

The cross sections of the three light targets CH\(_2\), CR-39, and C were used for the determination of the hydrogen-target cross sections. The energy dependence of the total charge-changing cross sections together with cross-section data of Webber, Kish, and Schrier [42,43] are shown in Fig. 6. It turns out that the data of Webber, Kish, and Schrier match our data at 2 GeV/nucleon.
FIG. 7. Energy dependence of partial cross sections for \( \Delta Z = 1 \) (top) and \( \Delta Z = 2 \) (bottom) reaction of \( ^{16}\text{O} \) with hydrogen. Data from Webber, Kish, and Schrier [42,43] (open triangles) and Lindstrom et al. [23] (open circles) are also included.

Our partial cross sections for the carbon target in comparison to other data are shown in Fig. 8. The partial cross sections for \( \Delta Z = 1 \) and 2 are constant between 2 and 200 GeV/nucleon. In contradiction to the data of Webber, Kish, and Schrier, we only observe a slight decrease from 1 to 2 GeV/nucleon. Our data point at 2.3 GeV/nucleon is consistent with the data point of Lindstrom et al. at 2.1 GeV/nucleon [23]. A surprising point is that for low energies the two partial cross sections \( \Delta Z = 1 \) and 2 for the C target of Webber, Kish, and Schrier [43] show nearly no odd/even effect which is present at higher energies.

The fact that the partial hydrogen target cross sections are smaller at energies of some GeV/nucleon than expected implies a change of parameters for astrophysical models for propagation of cosmic-ray heavy ions from the sources to the Earth. These calculations relate measured nuclear abundances near the Earth to source compositions. The thickness of penetrated matter and the probabilities of the nuclei escaping our Galaxy are obtained in these calculations. A reduced partial fragmentation cross section \( \Delta Z = 1 \) \( ^{16}\text{O} \rightarrow \text{N} \), which must be put into these calculations to reproduce the experimental data, e.g., for the measured N/O ratio, affects the escape probabilities [45].

FIG. 8. Energy dependence of partial cross sections \( \Delta Z = 1 \) (top) and \( \Delta Z = 2 \) (bottom) for reaction of \( ^{16}\text{O} \) with carbon. Data from Webber, Kish, and Schrier [42,43] (triangles) and Lindstrom et al. [23] (inverted triangles) are also included.

III. CONCLUSION

Fragmentation cross sections for \( ^{16}\text{O} \) were measured for a set of targets in the energy range from 0.9 to 200 GeV/nucleon. The rise of the total charge-changing cross sections with energy, especially for heavy targets caused by the ED effect, was observed. The contribution of the ED process was calculated using virtual-photon spectra and photonuclear data. Subtracting this ED contribution from the measured total cross sections, we obtained the pure nuclear component of the cross sections. The total nuclear cross sections for all targets show no energy dependence, as is expected by the concept of limiting fragmentation. Fit procedures enabled us to separate nuclear and ED components also for the partial cross sections. The partial nuclear cross sections for heavier targets are almost energy independent and agree quite well with other data. The partial ED cross sections show that with high energies ( \( > 100 \) GeV/nucleon) the ED process cannot lead to the emission of nucleons and \( \alpha \) particles only, but can result in a much more complete destruction of the projectile nucleus. The data for the H target may influence the output of astrophysical model calculations.

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[44] P. Kozma (private communication).