Explanation of recent observations of very large electromagnetic dissociation cross sections

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(Received 5 February 1992; revised manuscript received 5 May 1992)

The very large electromagnetic dissociation (EMD) cross section recently observed by Hill, Wohn, Schwellenbach, and Smith do not agree with Weizsacker-Williams (WW) theory or any simple modification thereof. Calculations are presented for the reaction probabilities for this experiment and the entire single and double nucleon removal EMD data set. It is found that for those few reactions where theory and experiment disagree, the probabilities are exceptionally large. This indicates that WW theory is not valid for these reactions and that one must consider higher order corrections and perhaps even a nonperturbative approach to quantum electrodynamics.

PACS number(s): 25.75.+r, 12.20.Ds

In nucleus-nucleus collisions when the impact parameter is larger than the sum of the nuclear radii the interaction proceeds via the electromagnetic (EM) force. Measurements of electromagnetic dissociation (EMD) cross sections have been carried out for many years [1–6]. The main theoretical tool employed in the interpretation of this data has been the Weizsacker-Williams (WW) method [7–9] of virtual quanta in which one replaces the incident nucleus by an equivalent photon field $n_{\mathrm{WW}}(E)$ which specifies the number spectrum of photons with energies E. To obtain the EMD nucleus-nucleus cross section σ_{WW} one integrates this photon spectrum over the photonuclear cross section $\sigma(E)$ of the nucleus in which particles are emitted as in [1–13]

$$\sigma_{\mathrm{WW}}=\int n_{\mathrm{WW}}(E)\sigma(E)\frac{dE}{E} \ . \tag{1}$$

$n_{\mathrm{WW}}(E)$ is given in Ref. [7] and includes an integral over the impact parameter from $b_{\min}$ to infinity where $b_{\min}$ is the value below which the reaction proceeds via the nuclear force, and is approximately the sum of the nuclear radii. The parametrization of Refs. [3,4,10] is used herein.

The WW method has been applied to EM processes in relativistic nuclear collisions involving such diverse topics as beam lifetime limitations [14], relativistic Coulomb fission [15], measuring the W boson magnetic moment [16] and EM properties of the τ lepton [17], exotic neutron rich nuclei [18,19], production of radioactive beams [18,19], measurement of astrophysically relevant cross sections [20], photonuclear physics [21], and production of Higgs bosons [22,23], lepton pairs [23], intermediate vector bosons [24], supersymmetric particles [25] and toponium [26], and in two-photon processes in e^+e^- reactions [9,27]. Clearly then it is important to understand the regions of applicability of the WW method.

Comparison of WW theory to experiment.—There has been very little effort devoted to a systematic experimental test of the validity of the WW method in nuclear collisions. Such tests are crucial if the theoretical calculations are to be believed. The most thorough investigations of the WW method for nucleon removal in nuclear collisions has been carried out by Hill and Wohn and others [3,4]. Their data and that of other authors [1–6] is presented in Table I.

The theoretical cross sections σ_{WW} listed in Table I were calculated by numerically integrating Eq. (1) using *experimental* photonuclear data for $\sigma(E)$. (Details are described in Refs [11,12].) There are some large differences between theory and experiment (highlighted in boldface in Table I) as first noted in Ref. [11]. These differences have been extensively studied [3,10–13] and most of them can be plausibly explained if one takes into account the following six items: (1) The experimental EM cross section is actually derived from the total measured cross section by subtracting off the nuclear component. Some differences are accounted for by using a more realistic model for the nuclear contribution [10,13]. (2) The WW virtual photon spectrum assumes that all of the radiation is electric dipole in character [7]. When including the effect of electric quadrupole contributions [7,12,13] better agreement with experiment is obtained. (3) The WW calculations assume a straight-line trajectory for the incident nucleus. One should also include Rutherford bending [13,28] of the orbit. (4) The experimental error in the photonuclear cross section $\sigma(E)$ used as input to the WW calculations must be considered as well as uncertainties in the quadrupole parameters. (5) The value used for $b_{\min}$ may need modification. (6) For the case of double nucleon removal it has been found that discrepancies can be plausibly resolved using cross-section systematics from other reactions [29]. Therefore in Table I the "revised" experimental numbers from Ref. [29] are quoted. (For extra clarification again note that the WW values listed in Table I represent the simple WW calculations discussed in Refs. [11,12]. The values quoted in the text are WW values calculated by including the six correction items discussed above.)

Consider how these effects account for the single nucleon removal discrepancies of Table I. $\mathbf{^{18}O+target\rightarrow{}^{17}O}$: The calculations of σ_{WW} in Table I use $b_{\min}$ from Refs. [3,4,10] which was derived [10] for single-nucleon removal from stable nuclei such as ^{16}O. There is no guarantee that this form should work for ^{18}O which has two valence neutrons. In fact, when discussing the original data, Olson *et al.* [1] used a much larger value of

TABLE I. Electromagnetic (EM) cross sections for single- and double-nucleon removal. σ_{expt} are the experimental EM cross sections from Refs. [1–6]. Where σ_{expt} for double-nucleon removal is given without experimental error it means that the "revised" experimental numbers from Ref. [29] are quoted. σ_{WW} is the theoretical cross section and $P(b=b_{min})$ is the probability calculated at the minimum impact parameter. Large discrepancies between σ_{expt} and σ_{WW} are shown in boldface. (σ_{WW} for double-nucleon removal is slightly different to the values in Ref. [29] which listed the calculations of Hill *et al.* [3]).

Projectile	Target	T_{lab} (GeV/nucl)	Final State	σ_{expt} (mb)	σ_{WW} (mb)	$P(b=b_{min})$
^{12}C	Pb	2.1	^{11}C	51±18	51	0.008
^{12}C	Pb	2.1	^{11}B	50±25	74	0.01
^{12}C	Pb	1.05	^{11}C	39±24	31	0.008
^{12}C	Pb	1.05	^{11}B	50±25	47	0.01
^{16}O	Pb	2.1	^{15}O	50±24	64	0.01
^{16}O	Pb	2.1	^{15}N	96±26	120	0.02
^{12}C	Ag	2.1	^{11}C	21±10	20	0.004
^{12}C	Ag	2.1	^{11}B	18±13	29	0.006
^{12}C	Ag	1.05	^{11}C	21±10	13	0.004
^{12}C	Ag	1.05	^{11}B	25±19	20	0.006
^{16}O	Ag	2.1	^{15}O	26±13	25	0.005
^{16}O	Ag	2.1	^{15}O	30±16	46	0.008
^{12}C	Cu	2.1	^{11}C	10±7	9	0.002
^{12}C	Cu	2.1	^{11}B	4±8	12	0.003
^{12}C	Cu	1.05	^{11}C	9±8	6	0.002
^{12}C	Cu	1.05	^{11}B	5±8	9	0.003
^{16}O	Cu	2.1	^{15}O	9±8	11	0.003
^{16}O	Cu	2.1	^{15}O	15±8	20	0.004
^{12}C	Al	2.1	^{11}C	0±5	2	0.0007
^{12}C	Al	2.1	^{11}B	0±5	3	0.0009
^{12}C	Al	1.05	^{11}C	1±6	2	0.0007
^{12}C	Al	1.05	^{11}B	1±7	2	0.0009
^{16}O	Al	2.1	^{15}O	0±5	3	0.0008
^{16}O	Al	2.1	^{15}N	−1±9	5	0.001
^{12}C	C	2.1	^{11}C	−2±5	1	0.0002
^{12}C	C	2.1	^{11}B	−1±4	1	0.0003
^{12}C	C	1.05	^{11}C	−2±5	0	0.0002
^{12}C	C	1.05	^{11}B	−2±5	1	0.0003
^{16}O	C	2.1	^{15}O	−1±4	1	0.0002
^{16}O	C	2.1	^{15}N	−1±4	1	0.0004
^{18}O	**Ti**	**1.7**	**^{17}O**	**8.7±2.7**	**16**	**0.004**
^{18}O	Ti	1.7	^{17}N	−0.5±1.0	3	0.001
^{18}O	**Pb**	**1.7**	**^{17}O**	**136±2.9**	**165**	**0.02**
^{18}O	**Pb**	**1.7**	**^{17}N**	**20.2±1.8**	**31**	**0.006**
^{18}O	**U**	**1.7**	**^{17}O**	**140.8±4.1**	**202**	**0.03**
^{18}O	**U**	**1.7**	**^{17}N**	**25.1±1.6**	**37**	**0.006**
^{28}Si	^{27}Al	13.7	1*p*	37±5	24	0.003
^{28}Si	^{27}Al	13.7	1*n*	15±4	9	0.001
^{28}Si	^{120}Sn	13.7	1*p*	313±4	317	0.02
^{28}Si	^{120}Sn	13.7	1*n*	136±6	118	0.008
^{28}Si	^{208}Pb	13.7	1*p*	743±27	806	0.04
^{28}Si	^{208}Pb	13.7	1*n*	347±18	301	0.02
^{12}C	**^{197}Au**	**2.1**	**^{196}Au**	**75±14**	**40**	**0.004**
^{12}C	^{197}Au	2.1	^{195}Au	9±17	6	0.0008
^{20}Ne	^{197}Au	2.1	^{196}Au	153±18	105	0.01
^{20}Ne	^{197}Au	2.1	^{195}Au	19	15	0.002
^{40}Ar	^{197}Au	1.8	^{196}Au	348±34	297	0.03
^{40}Ar	^{197}Au	1.8	^{195}Au	42	42	0.005
^{56}Fe	^{197}Au	1.7	^{196}Au	601±54	578	0.05
^{56}Fe	^{197}Au	1.7	^{195}Au	73±13	80	0.01
^{139}La	^{197}Au	1.26	^{196}Au	1970±130	2089	0.2
^{139}La	^{197}Au	1.26	^{195}Au	239	260	0.03
^{139}La	**^{197}Au**	**0.15**	**^{196}Au**	**447±28**	**666**	**0.2**
^{238}U	**^{197}Au**	**0.96**	**^{196}Au**	**3160±230**	**4205**	**0.4**
^{16}O	**^{197}Au**	**60**	**^{196}Au**	**280±30**	**218**	**0.007**
^{16}O	**^{197}Au**	**200**	**^{196}Au**	**440±40**	**281**	**0.007**
^{32}S	^{197}Au	200	^{196}Au	1120±160	1104	0.03
^{12}C	^{89}Y	2.1	^{88}Y	9±12	13	0.002
^{20}Ne	^{89}Y	2.1	^{88}Y	43±12	35	0.006
^{40}Ar	^{89}Y	1.8	^{88}Y	132±17	96	0.01
^{56}Fe	^{89}Y	1.7	^{88}Y	217±20	185	0.03

TABLE I. (*Continued*).

Projectile	Target	T_{lab} (GeV/nucl)	Final State	σ_{expt} (mb)	σ_{WW} (mb)	$P(b=b_{min})$
^{12}C	^{59}Co	2.1	^{58}Co	6±9	8	0.002
^{12}C	^{59}Co	2.1	^{57}Co	6±4	1	0.0003
^{20}Ne	^{59}Co	2.1	^{58}Co	32±11	20	0.004
^{20}Ne	^{59}Co	2.1	^{57}Co	3±5	3	0.0006
^{56}Fe	^{59}Co	1.7	^{58}Co	88±14	105	0.02
^{56}Fe	^{59}Co	1.7	^{57}Co	13±6	13	0.003
^{139}La	**^{59}Co**	**1.26**	**^{58}Co**	**280±40**	**358**	**0.05**
^{139}La	^{59}Co	1.26	^{57}Co	32±16	39	0.007

b_{min} and were able to obtain satisfactory agreement with all of the ^{18}O data [item (5) above]. **^{12}C + ^{197}Au → ^{196}Au; ^{16}O + ^{197}Au → ^{196}Au (60 GeV/nucleon); ^{139}La + ^{59}Co → ^{58}Co**: As discussed in Ref. [13] these reactions are satisfactorily explained if one considers items (1), (2), and (4) above. **^{16}O + ^{197}Au → ^{196}Au (200 GeV/nucleon)**: including the six items above one still does not obtain agreement between theory and experiment for this reaction [13]. Nevertheless, if one simply replaces the ^{16}O projectile with ^{32}S then agreement occurs (see Table I). Thus, there might be a problem with the experimental error bars. **^{139}La + ^{197}Au → ^{196}Au (150 MeV/nucleon)**: As pointed out in Ref. [13] this reaction cannot be explained even with the inclusion of all six items. **^{238}U + ^{197}Au → ^{196}Au**: This is the recent data of Hill *et al.* [4] who report the largest EMD cross section ever observed. Calculating the cross section including items (2), (3), and (4) above one obtains a theoretical value of 4.8±0.5 b. This gives even worse disagreement with the experimental value of 3.16±0.23 b. Considering the effect of item (1) the experimental total cross section [4] was reported as 3.44±0.21 b compared to the present calculated value of 5.0±0.5 b.

In conclusion so far, the reactions ^{139}La + ^{197}Au → ^{196}Au at 150 MeV/nucleon (measured by Loveland *et al.* [5]) and ^{238}U + ^{197}Au → ^{196}Au at 960 MeV/nucleon (measured by Hill *et al.* [4]) cannot be accounted for by the six simple modifications. These reactions show a genuine discrepancy between WW theory and experiment.

Probabilities—The present paper aims to explain the above failure of WW theory. In calculations of e^+e^- production [29] unitarity violation occurs for small impact parameters thus indicating that WW theory is not valid. It is natural to see if a similar unitarity violation occurs for the single-nucleon removal cross sections. The probability of interaction $P(b)$ is related to the cross section [7] via

$$\sigma_{WW} = \int_{b_{min}}^{\infty} 2\pi b P(b) db \ . \tag{2}$$

Equating this with Eq. (1) implies that

$$P(b) = \int N_{WW}(E,b)\sigma(E)\frac{dE}{E} \ . \tag{3}$$

$N_{WW}(E,b)$ is the photon spectrum [7] dependent on impact parameter.

The probabilities have been calculated by numerically integrating Eq. (3) using experimental data [11] for the photonuclear cross section $\sigma(E)$. It is found that the probability $P(b)$ is a maximum when $b=b_{min}$ and then drops steadily for larger b. This probability function was numerically integrated a second time according to Eq. (2) to check that the results from Eq. (1) were obtained. Bertulani and Baur have previously calculated some probabilities [7], but *this is the first time that probabilities have been calculated using experimental photonuclear data as input and the first time that these probabilities have been directly compared to the entire emd data set. Also it is the first time that both single and double nucleon probabilities have been calculated and compared.*

The place to look for unitarity violation is the (maximum) value of the probability $P(b=b_{min})$. Referring to Table I, unitarity is clearly *not* violated for any of these reactions. Thus, in contrast to e^+e^- production [30], unitarity violation is not the cause for the failure of WW theory as applied to single nucleon removal. However, note the remarkable result in which the probabilities are *small* for all reactions *except* the very reactions mentioned above where genuine discrepancies between theory and experiment occur. The experiment of Hill *et al.* [4] where the discrepancy is worst has the largest probability of 0.4.

Budnev *et al.* [9] have shown that the WW approximation results from the first-order Feynman amplitude when the mass of the virtual photon can be neglected. Therefore the large value of the calculated probability indicates that higher-order diagrams cannot be neglected and this suggests the reason for the failure of WW theory in predicting the recent data [4]. (See the footnote[1] below for an important comment.) In EM nucleus-nucleus reactions the coupling constant is $Z/137$ which for light nuclei is still small enough for the first-order diagram to be dominant. However, for virtual photons emanating from ^{238}U the coupling $Z/137$ is about 0.7 indicating that many diagrams or even a nonperturbative approach might be needed. Thus the recent data [4] lie somewhere between the perturbative and nonperturbative regime and

[1]One may think that the apparently good agreement between theory and experiment for ^{139}La + ^{197}Au → ^{196}Au at 1.26 GeV/nucleon (Table I) also with a large probability value of 0.2 invalidates this hypothesis. As mentioned, a more correct calculation incorporates the six items above. This is done in Ref. [13] where the total (nuclear plus EM) theoretical value is 2534±237 mb compared with the total experimental value of 2130±120 mb. Despite the large error bars, this more accurate calculation indicates that this large probability reaction also has the theoretical value larger than the experimental number.

the complete data set in Table I is significant because by varying Z it provides experimental evidence of the transition from perturbative towards nonperturbative QED.

Finally note the very interesting behavior of the double nucleon removal probabilities and cross sections. (Final states in Table I are ^{195}Au and ^{57}Co.) Based on the statements above one would guess that WW theory should also fail for double-nucleon removal in the $^{139}\mathrm{La}+^{197}\mathrm{Au}\rightarrow^{195}\mathrm{Au}$ reaction because the coupling $Z/137$ is 0.4 and WW theory does not work for the single-nucleon reaction. However, looking at Table I good agreement is obtained. It is surprising that WW theory does work for this large coupling reaction! However, the minimum impact parameter probability is 0.03 compared to 0.2 for the single-nucleon case and this is seen to be the explanation as to why WW theory works for double-nucleon removal and not for single-nucleon removal despite the coupling being the same for both reactions. Clearly, the probability is a much more reliable indicator of the validity of WW theory than is the coupling $Z/137$ alone.

Hill and Wohn [31] are planning to measure the $^{197}\mathrm{Au}+^{197}\mathrm{Au}$ reaction at 11 GeV/nucleon. Using the WW theory, I have calculated the minimum impact parameter probabilities (and cross sections) as 0.35 (11 b) and 0.07 (1.8 b) for one- and two-neutron removal, respectively. I therefore predict that when these measurements are made the two-neutron removal cross section will agree with my WW calculation but that the experimental one-neutron cross section will be considerably smaller than the WW calculation. This is in spite of the fact that the coupling $Z/137$ is the same for both reactions.

I am very grateful to Dr. Mirek Fatyga (Brookhaven) and Dr. Wang Cheung (University of Wisconsin) for useful discussions. This work was supported in part by NASA Grant No. NAG-1-1457.

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