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Explanation of recent observations of very large electromagnetic dissociation cross sections. II. Higher order corrections

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Hill, Wohn, Schwellenbach, and Smith have recently measured very large electromagnetic dissociation cross sections in the collisions of very heavy nuclei. Weizsacker-Williams (WW) theory predicts that these cross sections should be even larger. It has recently been shown that WW theory fails for these reactions because the associated probabilities are too large. However, WW theory is based on first order perturbation theory and an electric dipole approximation. Calculations are presented which show that for those cases where WW theory and experiment disagree, higher order perturbation plus electric quadrupole corrections improve the agreement between theory and experiment. These corrections also imply that multiple electromagnetic excitations occur.

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I. INTRODUCTION

Coulomb excitation has recently provided a very powerful tool for the study of exotic nuclei, such as ^{11}Li, far from the limits of normal nuclear stability [1]. This has proven to be one of the most exciting new areas of nuclear physics and has provided evidence for the existence of neutron halos.

Another new area that may blossom in future years is the study of multiple electromagnetic (EM) excitations [2–8] whereby the nucleus is excited not by a single photon (as in photonuclear or electron-nucleus reactions) but is excited simultaneously by two or more photons. These processes are expected to involve nuclear excitations never observed before, like double giant dipole resonances at high excitation energies and with exotic decay modes [2–8] such as the formation of polyneutrons. The most dominant excitation mechanism [3] in high-energy EM reactions between nuclei is the single photon excitation of the giant dipole resonance (GDR). The most likely reaction in which one might observe multiple EM processes is the collision of two heavy nuclei [2–8] where the probability of simultaneous emission of two or more virtual photons is high. Indeed Ritman *et al.* [6] have observed the Coulomb-excited double giant dipole resonance in ^{208}Pb from the collision with ^{209}Bi at 1 GeV/nucleon by studying the two-γ decay channel. Aslo Schmidt *et al.* [7] have observed the double GDR in ^{136}Xe from the collision with Pb at 0.7 GeV/nucleon by studying the neutron decay channel. Both studies [6,7] observe a cross-section peak at twice the normal energy of the giant dipole resonance and with a substantially larger decay width.

Hill *et al.* [9] have recently observed very large electromagnetic dissociation (EMD) cross sections for one-neutron removal in the reaction $^{238}\mathrm{U}+{}^{197}\mathrm{Au}\rightarrow{}^{196}\mathrm{Au}+\mathrm{X}$ at 0.96 GeV/nucleon. They reported a cross section of 3160±230 mb which represents the *largest EMD cross section ever observed.* However, the Weizsacker-Williams (WW) theory predicted [10] that the cross section should be even larger, i.e., 4205 mb. The corresponding WW probability has also been calculated [10] and was found to have the relatively large value of 0.4 at the minimum impact parameter value. Norbury [10] has analyzed the entire EMD data set (about 70 different reactions) and has come to the conclusion that all the data can be explained with WW theory and reasonable modifications (such as inclusion of quadrupole excitations etc.) *except* for those few reactions which have a large probability value at the minimum impact parameter. These few reactions also involve very heavy nuclei such as ^{197}Au, ^{139}La, and ^{238}U and have the largest observed experimental EMD cross sections. In these cases WW theory also predicts that the cross sections should be even substantially larger. Simple modifications to WW theory are unable to account for the experimentally observed cross sections [10].

A possible explanation may involve multiple electromagnetic processes, in which the excitation of the single photon GDR is depleted by multiple higher-order EM processes. This provides a natural explanation as to why the WW calculation is bigger than the experimental value, because the WW calculation assumes that all of the photons excite the single GDR state. Indeed Baur and Bertulani [2,3] have shown that multiple EM cross sections will be significant only if the WW probability is large. The present paper explores this idea quantitatively and is an extension of previous work on this subject [10].

II. THEORY

The WW virtual photon spectrum has been shown to be identical to the electric dipole ($E1$) spectrum and is given by [2,3]

$$N_{\mathrm{WW}}(\omega,b)=N_{E1}(\omega,b)$$

$$=\frac{Z_T^2\alpha}{\pi^2}\left[\frac{\omega}{\gamma v}\right]^2\left[\frac{c}{v}\right]^2\left[K_1^2(x)+\frac{1}{\gamma^2}K_0^2(x)\right]. \tag{1}$$

Z_T is the charge of the target nucleus (which is supplying the virtual photons) and the modified Bessel functions K_1 and K_0 are functions of the parameter

$$x=\frac{\omega b}{\gamma v}, \tag{2}$$

where ω is the frequency of the virtual photon, b is the impact parameter, and v is the speed of the projectile. The first-order probability is given by [2,3]

$$\Phi(b)=\int N_{\mathrm{WW}}(\omega,b)\sigma(\omega)\frac{d\omega}{\omega}, \tag{3}$$

where $\sigma(\omega)$ is the experimental photonuclear cross section and the WW cross section by [3]

$$\sigma_{\mathrm{WW}}=2\pi\int_{b_{\min}}^{\infty}\Phi(b)b\,db, \tag{4}$$

where $b_{\min}$ is the minimum impact parameter below which the reaction proceeds mainly via the strong force. [The integral in Eq. (4) is evaluated numerically using Gaussian quadrature. In order to ensure convergence for all reactions studied herein 100 Gauss points were used.]

The harmonic vibrator model has been discussed by Baur and Bertulani [2,3]. The present calculations differ significantly from Refs. [2,3] in that experimental photonuclear cross-section data will be used as input to the calculations whereas references [2,3] used a dipole model to calculate this cross section. Also the present work will use the parametrization of $b_{\min}$ as advocated by Benesh, and co-workers [14,15]. Also we will include quadrupole effects.

The probability to excite an N-phonon state is given by the Poisson probability [3]

$$P_N(b)=\frac{1}{N!}\Phi^N e^{-\Phi}, \tag{5}$$

with Φ given by Eq. (3). Thus the higher-order EM cross section is

$$\sigma_N=2\pi\int_{b_{\min}}^{\infty}P_N(b)b\,db. \tag{6}$$

Clearly this equation reduces to the WW Eq. (4) when $N=1$ and Φ is small. We shall refer to Eqs. (5) and (6) as the *higher-order dipole approximation* because it incorporates higher orders of perturbation theory [see Eq. (5)] but still relies on the electric dipole approximation to the virtual photon spectrum, just as the WW approximation does.

It has been well established that electric quadrupole ($E2$) corrections are very significant in the collisions of heavy nuclei [3,12–15]. Therefore, in order to provide a meaningful comparison to experiment, these must be included. The impact parameter dependent $E2$ virtual photon spectrum can be derived from the equations of Ref. [3] with the result that

$$N_{E2}(\omega,b)=\frac{Z_T^2\alpha}{\pi^2}\left[\frac{\omega}{\gamma v}\right]^2\left[\frac{c}{v}\right]^4\left\{\frac{1}{\gamma^2}K_2^2(x)+\frac{3}{\gamma^2}K_0^2(x)+\left[\frac{v}{c}\right]^4\left[2\left[\frac{c}{v}\right]^2-1\right]^2K_1^2(x)\right\}. \tag{7}$$

Thus the first-order probabilities can be written as

$$\Phi_{E1}(b)=\int N_{E1}(\omega,b)\sigma_{E1}(\omega)\frac{d\omega}{\omega} \tag{8}$$

and

$$\Phi_{E2}(b)=\int N_{E2}(\omega,b)\sigma_{E2}(\omega)\frac{d\omega}{\omega} \tag{9}$$

and the corresponding higher-order probabilities are

$$P_N^{E1}(b)=\frac{1}{N!}\Phi_{E1}^N e^{-\Phi_{E1}} \tag{10}$$

and

$$P_N^{E2}(b)=\frac{1}{N!}\Phi_{E2}^N e^{-\Phi_{E2}}. \tag{11}$$

Thus the cross sections become

$$\sigma_N=\sigma_N^{E1}+\sigma_N^{E2}$$

$$=2\pi\int_{b_{\min}}^{\infty}[P_N^{E1}(b)+P_N^{E2}(b)]b\,db. \tag{12}$$

This is substituted into Eq. (5) and upon calculating the resultant cross section from Eq. (6) one obtains the *higher-order EM cross section complete with dipole and quadrupole effects.* Note that the $E1$ and $E2$ photonuclear cross sections $\sigma_{E1}(\omega)$ and $\sigma_{E2}(\omega)$ appear in Eq. (8). If at all possible, however, one would still like to be able to use experimental photonuclear data as input for these cross sections. A method for doing this was developed in Ref. [12] and we shall follow the same method herein.

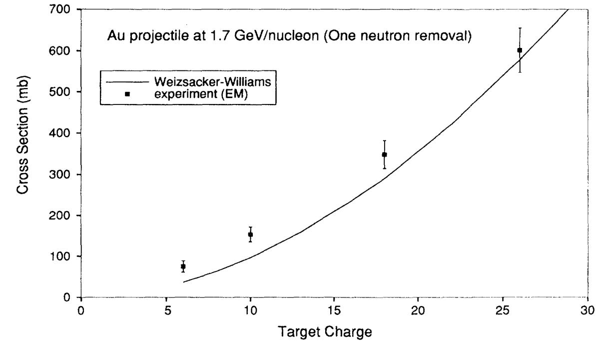

FIG. 1. Weizsacker-Williams theory compared to experiment for single neutron removal. The theory is calculated at 1.7 GeV/nucleon, but the experimental energy varies somewhat as given in Tables I and II.

TABLE I. WW cross sections compared to experiment. $\sigma_{\rm em}^{\rm expt}$ is the experimental electromagnetic cross section from Refs. [9,11]. $\sigma_{\rm WW}$ is the cross section calculated using the WW (first-order dipole) approximation [given in Eq. (4)] and $\Phi(b=b_{\rm min})$ is the minimum impact parameter probability, both of which are from Ref. [10]. The higher-order cross section σ' is calculated from Eq. (6). Reactions which have a sizable probability and hence higher-order EM cross section are highlighted in bold face. All cross sections are in units of millibarns.

Projectile	Target	$T_{\rm lab}$ (GeV/nucl)	Final state	$\sigma_{\rm em}^{\rm expt}$	$\sigma_{\rm WW}$	$\Phi(b=b_{\rm min})$	σ'
^{12}C	^{197}Au	2.1	^{196}Au	75±14	40	0.004	40
^{20}Ne	^{197}Au	2.1	^{196}Au	153±18	105	0.01	105
^{40}Ar	^{197}Au	1.8	^{196}Au	348±34	297	0.03	294
^{56}Fe	^{197}Au	1.7	^{196}Au	601±54	578	0.05	568
^{139}La	**^{197}Au**	**1.26**	**^{196}Au**	**1970±130**	**2 089**	**0.2**	**1 960**
^{139}La	**^{197}Au**	**0.15**	**^{196}Au**	**447**	**666**	**0.2**	**621**
^{197}Au	**^{197}Au**	**11.0**	**^{196}Au**		**11 072**	**0.35**	**10 332**
^{238}U	**^{197}Au**	**0.96**	**^{196}Au**	**3160±230**	**4 205**	**0.4**	**3 671**
^{16}O	^{197}Au	60	^{196}Au	280±30	218	0.007	217
^{16}O	^{197}Au	200	^{196}Au	440±40	281	0.007	281
^{32}S	^{197}Au	200	^{196}Au	1120±160	1 104	0.03	1 104

III. COMPARISON BETWEEN THEORY AND EXPERIMENT

Calculations based on Eqs. (6) and (12) are presented herein. These will be compared to the calculations of Ref. [10]. Of the 70 reactions which make up the complete EMD data set [10], about 15 of these reactions involve nucleon removal from a ^{197}Au target. The higher-order EM cross sections have been calculated for the entire EMD data set and it was found that only those higher-order cross sections involving ^{197}Au provide a significant correction to the first-order calculation. Thus calculational results will only be shown for the ^{197}Au data set.

Calculations for $\sigma_{\rm WW}$ and $\Phi(b=b_{\rm min})$ from Ref. [10] are shown in Table I and Fig. 1. A clear disagreement with experiment is evident. The calculations for the higher-order corrections σ' to the WW calculation are also shown in Table I. It is clear that the higher-order corrections are only significant for reactions with a large probability. There are many corrections that one can reasonably apply to the first-order WW calculation and these have been extensively described previously [3,10,12–15]. As discussed in Ref. [10] these corrections resolve the discrepancies between theory and experiment for the entire EMD data set except for reactions with a large value of $\Phi(b=b_{\rm min})$. This is shown quantitatively in Table II and Fig. 2 where the corrections of Ref. [13] are applied. These corrections involve considerations of quadrupole excitations, nuclear interaction contributions to the total measured cross section, Rutherford bending, and uncertainties in the input photonuclear cross sections and quadrupole parameters. By comparing the sum of electric dipole, quadrupole, and nuclear cross sections, $\sigma_{E1}+\sigma_{E2}+\sigma_{\rm nuclear}$ with $\sigma_{\rm tot}^{\rm expt}$ one can see from Table II and Fig. 2 that these corrections now provide better agreement between theory and experiment *except* for the large probability reactions (bold face). This shows the

TABLE II. $\sigma_{\rm tot}^{\rm expt}$ is the experimental total (electromagnetic plus nuclear) cross section from Refs. [9,11]. $\sigma_{E1+E2}+\sigma_{\rm nuclear}$ is from Ref. [13], where σ_{E1+E2} is the first-order EM dipole plus quadrupole cross section and $\sigma_{\rm nuclear}$ is the nuclear cross section. The theoretical uncertainties come from uncertainties in the input photonuclear data and the quadrupole parameters [13]. σ'' is the higher-order EM dipole plus quadrupole cross section discussed in the text. Other notational conventions are the same as in Table I.

Projectile	Target	$T_{\rm lab}$ (GeV/nucl)	Final state	$\sigma_{\rm tot}^{\rm expt}$	$\sigma_{\rm nuclear}$	$\sigma_{E1+E2}+\sigma_{\rm nuclear}$	$\sigma''+\sigma_{\rm nuclear}$
^{12}C	^{197}Au	2.1	^{196}Au	178±7	128	173±8	173±8
^{20}Ne	^{197}Au	2.1	^{196}Au	268±11	136	255±14	254±14
^{40}Ar	^{197}Au	1.8	^{196}Au	463±30	149	483±34	481±34
^{56}Fe	^{197}Au	1.7	^{196}Au	707±52	156	807±66	798±65
^{139}La	**^{197}Au**	**1.26**	**^{196}Au**	**2130±120**	**180**	**2545±237**	**2419±224**
^{139}La	**^{197}Au**	**0.15**	**^{196}Au**	**765±48**	**180**	**1320±114**	**1260±108**
^{197}Au	**^{197}Au**	**11.0**	**^{196}Au**		**192**	**11 664±1147**	**10 952±1076**
^{238}U	**^{197}Au**	**0.96**	**^{196}Au**	**3440±210**	**198**	**5023±483**	**4504±431**
^{16}O	^{197}Au	60	^{196}Au	400±20	132	358±24	358±24
^{16}O	^{197}Au	200	^{196}Au	560±30	132	422±30	422±30
^{32}S	^{197}Au	200	^{196}Au		144	1277±114	1277±114

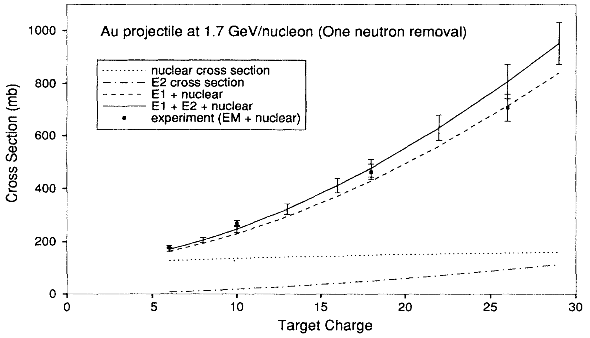

FIG. 2. Corrected theory compared to experiment for single neutron removal. The theory is calculated at 1.7 GeV/nucleon, but the experimental energy varies somewhat as given in Tables I and II. The error bars attached to the solid curve come from uncertainties in the input values used in the calculation.

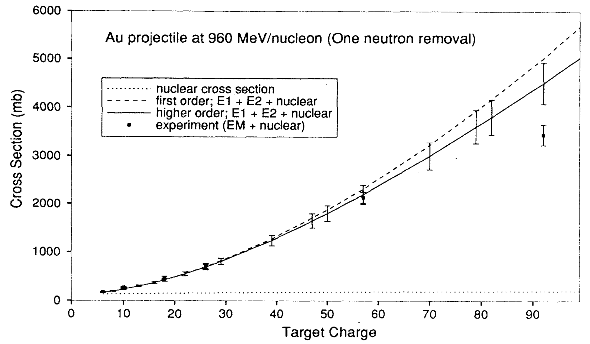

FIG. 3. Higher-order corrected theory compared to experiment for single neutron removal. The theory is calculated at 960 MeV/nucleon, but the experimental energy varies somewhat as given in Tables I and II. The error bars attached to the solid curve come from uncertainties in the input values used in the calculation.

need to incorporate higher-order corrections for these reactions.

The new calculations of the present work concern the higher-order corrections to WW theory and also higher-order $E1$ and $E2$ contributions as discussed in Sec. II. Calculations for these higher-order processes are shown in Table II and Fig. 3. One can see that the corrections are only significant for exactly those high probability reactions where theory and experiment disagree. Even though the discrepancies between theory and experiment are not completely resolved for the high Z reactions, nevertheless it can be seen that the higher-order corrections definitely improve the agreement between theory and experiment particularly for the recently measured [9] reaction $^{197}\mathrm{Au}+{}^{238}\mathrm{U}\rightarrow{}^{196}\mathrm{Au}+X$ at 960 MeV/nucleon. This clearly establishes the fact that one must include higher-order corrections in order to obtain a complete understanding of the high Z data.

Note added in proof. In the meantime T. Aumann *et al.* [Phys. Rev. C **47**, 1728 (1993)] reported additional measurements at high Z. Our conclusions remain the same.

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[1] I. Tanihata, Nucl. Phys. **A522**, 275c (1991).

[2] G. Baur and C. A. Bertulani, Phys. Lett. B **174**, 23 (1986); Phys. Rev. C **34**, 1654 (1986); Nucl. Phys. **A482**, 313c (1988); G. Baur, Z. Phys. A **332**, 203 (1989).

[3] C. A. Bertulani and G. Baur, Phys. Rep. **163**, 299 (1988).

[4] P. Braun-Munzinger *et al.*, Proposal 814 submitted to the AGS program committee, SUNY Stony Brook, 1985 (unpublished).

[5] W. J. Llope and P. Braun-Munzinger, Phys. Rev. C **41**, 2644 (1990); **45**, 799 (1992).

[6] J. Ritman, F. D. Berg, W. Kuhn, V. Metag, R. Novotny, M. Notheisen, P. Paul, M. Pfeiffer, O. Schwalb, H. Lohner, L. Venema, A. Gobbi, N. Herrmann, K. D. Hildenbrand, J. Mosner, R. S. Simon, K. Teh, J. P. Wessels, and T. Wienold, Phys. Rev. Lett. **70**, 533 (1993).

[7] R. Schmidt, Th. Blaich, Th. W. Elze, H. Emling, H. Freiesleben, K. Grimm, W. Henning, R. Holzmann, J. G. Keller, H. Klingler, R. Kulessa, J. V. Kratz, D. Lambrecht, J. S. Lange, Y. Leifels, E. Lubkiewicz, E. F. Moore, E. Wajda, W. Prokopowicz, Ch. Schutter, H. Spies, K. Stelzer, J. Stroth, W. Walus, H. J. Wollersheim, M. Zinser, and E. Zude, Phys. Rev. Lett. **70**, 1767 (1993).

[8] H. Emling, Nucl. Phys. **A553**, 493c (1993).

[9] J. C. Hill, F. K. Wohn, D. D. Schwellenbach, and A. R. Smith, Phys. Lett. B **273**, 371 (1991).

[10] J. W. Norbury, Phys. Rev. C **47**, 406 (1993).

[11] J. C. Hill, F. K. Wohn, J. A. Winger, and A. R. Smith, Phys. Rev. Lett. **60**, 999 (1988); J. C. Hill, F. K. Wohn, J. A. Winger, M. Khayat, K. Leininger, and A. R. Smith, Phys. Rev. C **38**, 1722 (1988); A. R. Smith, J. C. Hill, J. A. Winger, and P. J. Karol, *ibid.* **38**, 210 (1988); M. T. Mercier, J. C. Hill, F. K. Wohn, C. M. McCullough, M. E. Nieland, J. A. Winger, C. B. Howard, S. Renwick, and D. K. Matheis, *ibid.* **33**, 1655 (1986); J. C. Hill, in *Current Issues in Hadron Physics,* edited by J. Tran Thanh Van (Editions Frontières, Gif-sur-Yvette, France, 1988); see also AGS Users Newsletter, Brookhaven National Laboratory, April-June 1990; W. Loveland, Z. Xu, C. Casey, K. Aleklett, J. O. Liljenzin, D. Lee, and G. T. Seaborg, Phys. Rev. C **38**, 2094 (1988).

[12] J. W. Norbury, Phys. Rev. C **40**, 2621 (1989); **41**, 372 (1990); **42**, 711 (1990); **45**, 3024 (1992); J. W. Norbury and L. W. Townsend, *ibid.* **42**, 1775 (1990).

[13] J. W. Norbury, Phys. Rev. C **42**, 2259 (1990); **46**, 819 (1992).

[14] C. J. Benesh, B. C. Cook, and J. P. Vary, Phys. Rev. C **40**, 1198 (1989).

[15] C. J. Benesh and J. L. Friar, Los Alamos National Laboratory Report No. LA-UR-93-0076 (unpublished).