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Single nucleon emission in relativistic nucleus-nucleus reactions

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Significant discrepancies between theory and experiment have previously been noted for nucleon emission via electromagnetic processes in relativistic nucleus-nucleus collisions. The present work investigates the hypothesis that these discrepancies have arisen due to uncertainties about how to deduce the experimental electromagnetic cross section from the total measured cross section. An optical-model calculation of single neutron removal is added to electromagnetic cross sections and compared to the total experimental cross sections. Good agreement is found thereby resolving some of the earlier noted discrepancies. A detailed comparison to the recent work of Benesh, Cook, and Vary is made for both the impact parameter and the nuclear cross section. Good agreement is obtained giving an independent confirmation of the parametrized formulas developed by those authors.

Recently Hill *et al.*[1] made a very detailed experimental study of nucleon emission induced by electromagnetic (EM) processes in relativistic nucleus-nucleus reactions. They compared the measured cross sections with theoretical calculations based upon the Weizsäcker-Williams (WW) method[2] of virtual quanta. Initial comparisons indicated[1,3] that the WW method is in serious disagreement with experiment for some projectile-target combinations, particularly[3] for nucleon emission from ^{197}Au. However, Benesh, Cook, and Vary[4] (BCV) recently speculated that the problem is due to difficulties in determining the experimental values of the EM cross section and not in the WW method.

The cross sections actually measured in experiments[1] are the total nucleon removal cross sections σ_{tot} which consist of both the nuclear and EM cross sections, $\sigma_{\mathrm{nuc}}+\sigma_{\mathrm{EM}}$. One theoretically calculates σ_{nuc} and then the experimental EM cross section is defined as

$$\sigma_{\mathrm{EM}}\equiv\sigma_{\mathrm{tot}}-\sigma_{\mathrm{nuc}} . \qquad (1)$$

(Note that BCV have found interference effects[4] to be negligible.) Therefore, the reported σ_{EM} actually depends on the theory used to determine σ_{nuc}, which, if incorrect, will lead to an incorrect experimental EM cross section. Hill *et al.* used the concept of weak factorization[1] to calculate σ_{nuc}.

Benesh, Cook, and Vary[4] have recalculated σ_{nuc} using a very simple and convenient parametrization of a Glauber theory description of single nucleon removal. They added this to σ_{WW} and compared the sum to the originally measured σ_{tot}. In general they find excellent agreement with experiment which strongly indicates that the discrepancies noted earlier[1,3] have more to do with nuclear reaction theory than with the WW method. However, not all problems have disappeared. The BCV calculations[4] give rather poor agreement for neutron removal from ^{59}Co. In addition the discrepancies noted[1, at the higher energies of 60 and 200 GeV/nucleon wer not addressed.

An integral part of the BCV work[4] involved coming t grips with the problem of the impact parameter, b. I WW theory one must specify a *minimum* value $b_{\min}$ which is roughly the sum of the nuclear radii and then integrate from $b_{\min}$ to infinity. To unify the nuclear an WW theory, BCV determined the value of b necessary t remove one nucleon via the nuclear force and then use this same value as the input $b_{\min}$ to WW theory.

The present work has three aims: (1) to provide an independent study of whether or not the EM discrepancie between theory and experiment[1,3] are due to the way i which the nuclear contribution was subtracted from th total measured cross section; (2) to provide an independent estimate of the impact parameter for one nucleon removal which corresponds to the EM $b_{\min}$; and (3) to provide a detailed comparison to the recent BCV results.

The cross-section formalism, developed previously, has been used in an abrasion-ablation model of nuclea fragmentation. In the present work we use only th abrasion model cross section which is simply given by Glauber optical-model cross section for one nucleon removal but which also includes a Pauli correlation facto (neglected in the present work because it is negligible fo peripheral collisions[5]) and an energy-dependent finite range nuclear force term[5] (which *is* retained in th present work). In the absence of Pauli correlation effect and with a zero-range nuclear force, our expression fo the cross section becomes identical to the BCV result [E (1) of Ref. 4]. We have been very careful to use correc parametrizations of nuclear number densities, obtaine by an unfolding procedure[5] from the corresponding nuclear charge densities whose parameters are from the la

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est compilations.[6] To calculate the neutron production cross section we multiply the nucleon removal optical-model cross section by the neutron to nucleon ratio of the target nucleus and also by the final-state interaction (FSI) factor $P_{\rm esc}$ of BCV. Results are listed in Table I and will be discussed below.

In the above optical-model theory the cross section involves an integral over the impact parameter which is also true for the BCV optical theory.[4] Thus in order to determine $b_{\rm min}$ for the EM cross section, an independent method must be used to determine the most probable impact parameter for which a single nucleon is removed via the nuclear force. To calculate b we use a geometrical model based upon the methods of Ref. 7 which is described also in Ref. 8. The basic idea is that when the impact parameter takes on a certain small range of values, a

TABLE I. Impact parameters and cross sections for single neutron removal from various targets. σ represents the strong interaction nucleon removal cross section multiplied by the neutron to nucleon ratio of the target, $P_{\rm esc}$ is the escape probability and $\sigma_{\rm WW}$ is the Weiszäcker-Williams EM cross section. $\sigma P_{\rm esc}+\sigma_{\rm WW}$ is to be compared to the experimental cross section $\sigma_{\rm expt}$ (Ref. 1). For each projectile-target combination, the first row represents the present calculation (using $P_{\rm esc}$ and $\sigma_{\rm WW}$ from Ref. 4) and the second row is that of Ref. 4, which differs slightly from the values listed in that reference due to a small error (Ref. 9). Note also that for ^{20}Ne on ^{12}C the correct energy should be 1.05 GeV/nucleon (Ref. 1).

Projectile	Target	$T_{\rm lab}$ (GeV/nucleon)	b (fm)	σ (mb)	$P_{\rm esc}$	$\sigma P_{\rm esc}$ (mb)	$\sigma_{\rm WW}$ (mb)	$\sigma P_{\rm esc}+\sigma_{\rm WW}$ (mb)	$\sigma_{\rm expt}$ (mb)
^{12}C	^{238}U	2.1	10.7	252		165		189	173±22
			10.8	203	0.654	133	24	157	
^{20}Ne	^{238}U	2.1	11.2	273		177		240	192±16
			11.4	215	0.650	140	63	203	
^{12}C	^{197}Au	2.1	10.2	212		140		180	178±7
			10.3	188	0.659	124	40	164	
^{20}Ne	^{197}Au	2.1	10.7	234		153		257	268±11
			10.9	200	0.654	131	104	235	
^{40}Ar	^{197}Au	1.8	11.6	230		149		444	463±30
			11.9	220	0.648	143	295	438	
^{56}Fe	^{197}Au	1.7	12.1	228		147		716	707±52
			12.5	230	0.645	148	569	717	
^{139}La	^{197}Au	1.26	13.8	262		167		2225	2130±120
			14.4	266	0.636	169	2058	2227	
^{238}U	^{197}Au	0.96	15.1	325		205		4353	NA
			15.8	292	0.630	184	4148	4332	
^{16}O	^{197}Au	60	10.4	227		149	218	367	400±20
			10.6	195	0.656	128		346	
^{16}O	^{197}Au	200	10.4	227		149	281	430	560±30
			10.6	195	0.656	128		409	
^{12}C	^{89}Y	2.1	8.5	173		118		135	115±6
			8.4	144	0.682	98	17	115	
^{20}Ne	^{89}Y	2.1	9.0	191		129		171	160±7
			9.0	155	0.676	105	42	147	
^{40}Ar	^{89}Y	1.8	9.9	192		128		243	283±11
			10.0	173	0.668	116	115	231	
^{56}Fe	^{89}Y	1.7	10.4	192		127		349	353±14
			10.6	183	0.664	122	222	344	
^{12}C	^{59}Co	2.1	7.8	159		111		119	89±5
			7.6	125	0.695	87	8	95	
^{20}Ne	^{59}Co	2.1	8.3	176		121		142	132±7
			8.2	136	0.689	94	21	115	
^{56}Fe	^{59}Co	1.7	9.7	181		122		235	194±9
			9.8	163	0.675	110	113	223	
^{139}La	^{59}Co	1.26	11.4	214		142		518	450±30
			11.7	195	0.663	129	376	505	
^{12}C	^{12}C	2.1	5.7	116		88		89	60.9±0.6
			5.3	78	0.755	59	0.51	60	
^{20}Ne	^{12}C	1.05	6.3	130		97	1.0	98	78±2
			5.9	89	0.746	66		67	
^{56}Fe	^{12}C	1.7	7.6	141		103		110	94±2
			7.5	114	0.727	83	7	90	
^{139}La	^{12}C	1.26	9.4	173		123		147	148±2
			9.4	143	0.711	102	24	126	

single nucleon can be removed via the nuclear force. The *maximum* value of this impact parameter should correspond to the minimum value $b_{\min}$ used in the EM cross-section calculation. It is this maximum value which is listed in Table I. However, we wish to emphasize that this impact parameter is *not* used in our nuclear optical-model calculations. (We integrate over b.) It is calculated simply to provide an independent estimate of the appropriate value of $b_{\min}$ to be used for the EM calculations.

We now come to a detailed discussion of our results which are presented in Table I as the first row for each projectile-target combination. Also listed as the second row are the BCV results. (See Ref. 9 for an important comment.) First note the extremely good agreement between our impact parameters and those of BCV. Note that they are *both significantly different* from those obtained using the naive formula $1.2(A_p^{1/3}+A_T^{1/3})$ fm and thus we now strongly recommend that the BCV parametrization of $b_{\min}$ be used for future EM calculations. (This has always been used in the past by Hill *et al.*[1]) Second, note the comparison between our optical-model neutron removal cross section σ and that of BCV (fifth column of Table I). The agreement is good although generally our results are somewhat larger than BCV, especially for neutron emission from ^{12}C, perhaps due to the fact that we use realistic nuclear densities whereas BCV use a geometrical parametrization of their optical model. At this point we wish to emphasize that the good agreement between the present work and that of BCV for both b and σ was obtained *without* adjusting any parameters to force agreement. Finally we have used the FSI formula for P_{esc} and the EM cross sections of BCV to arrive at the cross section $\sigma P_{\text{esc}}+\sigma_{\text{WW}}$ which is to be compared to experiment. (BCV did not calculate σ_{WW} for ^{16}O and ^{197}Au at 60 and 200 GeV/nucleon and thus we include our own calculation in Table I.) It can be seen that both the present work and that of BCV give comparable good agreement with experiment. In particular, whereas previously the worst discrepancy between theory and experiment for the EM cross section[3] occurred for ^{197}Au, there is now excellent agreement except for the 200-GeV/nucleon data. This fact strongly supports the BCV hypothesis that the EM discrepancies have more to do with nuclear theory than with WW formulation. However, not all problems are solved and some new disagreements arise. Some reasons for these may be due to neglect of electric quadrupole excitations,[2,10] errors in the photonuclear data used as input to σ_{WW}, or uncertainties in the treatment of FSI. In our studies we noted that the calculated cross sections are *very* sensitive to the value of P_{esc} and we regard this as the major uncertainty in the BCV work. Another reasonable value[11] for P_{esc} such as 0.5 gives significantly different results which also generally agree with the experimental data.

In summary, the present work has resolved some of the earlier discrepancies between theory and experiment for EM cross sections by determining the nuclear cross section for one neutron removal, adding it to the EM cross section, and comparing the sum to the originally measured total cross section. Our conclusions are in agreement with those of Benesh, Cook, and Vary.[4] Furthermore, we have independently verified that the BCV impact parameter is the appropriate one to use in EM calculations.

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[1] 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).

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

[3] J. W. Norbury, Phys. Rev. C **40**, 2621 (1989).

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

[5] L. W. Townsend, J. W. Wilson, F. A. Cucinotta, and J. W. Norbury, Phys. Rev. C **34**, 1491 (1986); L. W. Townsend, Can. J. Phys. **61**, 93 (1983).

[6] H. De Vries, C. W. De Jager, and C. De Vries, At. Data Nucl. Data Tables **36**, 495 (1987); **14**, 479 (1974).

[7] J. Gosset, H. H. Gutbrod, W. G. Meyer, A. M. Poskanzer, A. Sandoval, R. Stock, and G. D. Westfall, Phys. Rev. C **16**, 629 (1977).

[8] J. W. Wilson, L. W. Townsend, and F. F. Badavi, Nucl. Instrum. Methods Phys. Res. B **18**, 225 (1987).

[9] J. P. Vary, private communication. The cross section in the second and fourth columns of Tables II–VII of Ref. 4 are slightly different from the numbers one obtains using the formulas of that reference due to a small error. The correct values are listed in Table I of the present work.

[10] J. W. Norbury, Phys. Rev. C **41**, 372 (1990); **42**, 711 (1990).

[11] L. F. Oliveira, R. Donangelo, and J. O. Rasmussen, Phys. Rev. C **19**, 826 (1979).

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Electric quadrupole excitations in relativistic nucleus-nucleus collisions

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Calculations are presented for electric quadrupole excitations in relativistic nucleus-nucleus collisions. The theoretical results are compared to an extensive data set and it is found that electric quadrupole effects provide substantial corrections to cross sections, especially for heavier nuclei.

I. INTRODUCTION

The search for a fundamentally new state of matter in the form of a quark-gluon plasma[1] has stimulated the production of very high-energy nuclear beams. The hope is to observe the quark-gluon plasma in a relativistic nucleus-nucleus collision. At the Berkeley Bevalac a variety of light nuclei such as ^{12}C, ^{16}O, and ^{20}Ne can be accelerated up to energies of 2.1 GeV/nucleon and heavier nuclei such as ^{139}La and ^{238}U can be accelerated to 1.26 and 0.96 GeV/nucleon, respectively. At the Brookhaven National Laboratory, ^{16}O and ^{28}Si beams are available at 14.6 GeV/nucleon and at the CERN Super Proton Synchrotron (SPS) in Geneva, beams of ^{16}O and ^{32}S are both produced at 60 and 200 GeV/nucleon. The relativistic heavy-ion collider (RHIC) is expected to produce two *colliding* beams at 100 GeV/nucleon to give a total *center-of-mass* energy of 200 GeV/nucleon, which corresponds to a single beam energy of 21 TeV/nucleon. Grabiak[2] has pointed out that nuclear beams of 3.5 and 8 TeV/nucleon may be possible at the CERN Large Hadron Collider (LHC) or the Superconducting Super Collider (SSC). By way of comparison, the majority of galactic rays have energies[3] of about 1 GeV/nucleon, with a range[3] typically from 10 MeV/nucleon to 1 TeV/nucleon. However, the JACEE (Japanese-American Cooperative Emulsion Experiment) collaboration[4] has made observations as high as 1000 TeV/nucleon.

Nucleus-nucleus reactions proceed mainly through either the strong or electromagnetic (EM) interactions. Historically, strong interaction processes have been the main object of study,[5] however, with the availability of the above high-energy nuclear beams there has been a resurgence of interest in EM interactions in relativistic nucleus-nucleus collisions.[6]

The primary theoretical tool for studying these relativistic EM processes has been via the Weizsäcker-Williams (WW) method[6,7] of virtual quanta. The nucleus-nucleus total EM reaction cross section is

$$\sigma=\int N_{\mathrm{WW}}(E_\gamma)\sigma(E_\gamma)dE_\gamma \ , \qquad (1)$$

where E_γ is the virtual photon energy, $N_{\mathrm{WW}}(E_\gamma)$ is the WW virtual photon spectrum, and $\sigma(E_\gamma)$ is the photonuclear reaction cross section. For high accuracy it is important to use experimental photonuclear data for $\sigma(E_\gamma)$. (For an excellent compilation of photoneutron data see Ref. 8.) However, a more exact formulation of σ involves a breakdown into the various EM multipolarities such as electric dipole ($E1$), electric quadrupole ($E2$), magnetic dipole ($M1$), etc. The most important contributions to σ are from $E1$ and $E2$ so that

$$\begin{aligned}\sigma&=\sigma_{E1}+\sigma_{E2}\\&=\int[N_{E1}(E_\gamma)\sigma_{E1}(E_\gamma)+N_{E2}(E_\gamma)\sigma_{E2}(E_\gamma)]dE_\gamma \ , \qquad (2\end{aligned}$$

where $N_{Ei}(E_\gamma)$ is the virtual photon spectrum of a particular multipolarity due to the projectile nucleus anc $\sigma_{Ei}(E_\gamma)$ is the photonuclear reaction cross section of the target nucleus. Bertulani and Baur[6] have derived expressions for $N_{Ei}(E_\gamma)$ and found that the electric dipole spectrum is the same as the WW spectrum, i.e. $N_{E1}(E_\gamma)=N_{\mathrm{WW}}(E_\gamma)$. Furthermore, at very high projectile energies *all* $N_{Ei}(E_\gamma)$ and $N_{Mi}(E_\gamma)$ are equal so tha Eq. (1) is seen to be a very high-energy approximation t all multipolarities included in Eq. (2). Bertulani anc Baur[6] have made a crude estimate of the EM cross section using Eq. (2) but they pulled $N_{E1}(E_\gamma)$ and $N_{E2}(E_\gamma$ outside the integral and evaluated them at a single energ and used sum rules to evaluate $\int\sigma_{Ei}(E_\gamma)dE_\gamma$. A mor accurate calculation can be performed if one uses experimental data for the photonuclear cross section and evaluates the full integral numerically without removing th energy dependence in the photon spectra. Thus I undertook a more exact study[9] leaving Eq. (2) as it stands an using experimental data for the photonuclear cross sections by defining

$$\sigma_{E1}(E_\gamma)\equiv\sigma_{\mathrm{expt}}(E_\gamma)-\sigma_{E2}(E_\gamma) \ , \qquad ($$

where $\sigma_{\mathrm{expt}}(E_\gamma)$ is the *experimentally* measured photonuclear cross section and $\sigma_{E2}(E_\gamma)$ is a *theoretical* calculation based on a Lorentzian shape for the electric giar quadrupole resonance (GQR). Details for this procedur can be found in Ref. 9. As was noted in that referenc the above procedure yields very accurate values for th sum $\sigma_{E1}+\sigma_{E2}$ (which is to be compared to nucleus nucleus reaction experiments) even though the GQR parameters are uncertain. The basic reason for this, as ca be seen from Eq. (3), is that an under (over) estimate i $\sigma_{E2}(E_\gamma)$ will give an over (under) estimate in $\sigma_{E1}(E_\gamma)$, s that the combined $\sigma_{E1}+\sigma_{E2}$ in Eq. (2) will not chang very much.

In Ref. 9 a detailed study of $E1$ and $E2$ was undertal en for the reaction ^{89}Y(RHI,X)^{88}Y, where RHI refers to various relativistic heavy ions and X is anything. It was found that the $E2$ effects account for a considerable fraction of the cross section, and that inclusion of $E2$ [via Eq. (2)] provides improved agreement with experiment over the WW method. Given this situation, it was decided to compare this theoretical approach to as much experimental data as possible. Thus, the present work involves a comparison to neutron emission from ^{89}Y, ^{197}Au, and ^{59}Co and neutron and proton emission from ^{12}C, ^{16}O, and ^{18}O which includes both electric dipole and quadrupole effects. This complements earlier work[7] which involved an extensive comparison of the WW theory to experiment.

II. CALCULATIONAL METHOD

The basic calculational method is outlined in Ref. 9 and the discussion will not be repeated here. Also, Ref. 7 includes a very detailed summary of which photonuclear data were used for $\sigma_{\text{expt}}(E_\gamma)$ in Eq. (3). The same data is used in the present work. All isoscalar GQR parameters were taken from the compilation of Refs. 10 and 21 and are listed in Table I. As mentioned in the Introduction, even though these parameters are somewhat uncertain, the total EM cross section $\sigma_{E1}+\sigma_{E2}$ is expected to be very accurate[9] due to the subtraction procedure of Eq. (3). The most inaccurate results would be expected for the ^{12}C, ^{16}O, and ^{18}O GQR parameters where the isoscalar GQR is fragmented into several components.[10] Only a single Lorentzian[9] was used in the present work. However, σ_{E2} is found to be quite small for these nuclei (see below) so that my conclusion that the calculated $\sigma_{E1}+\sigma_{E2}$ is accurate remains valid.

For the nuclei ^{12}C, ^{16}O, and ^{18}O, proton (p) emission occurs as well as neutron (n) emission. Thus, Eq. (3) needs to be modified to incorporate the branching ratio. I assume that the excited nucleus decays *only* by proton or neutron emission and that the (photon) energy-dependent neutron branching ratio is defined as

$$f_n(E_\gamma)\equiv\frac{\sigma_{\text{expt}}(E_\gamma,n)}{\sigma_{\text{expt}}(E_\gamma,n)+\sigma_{\text{expt}}(E_\gamma,p)} . \tag{4}$$

This is simply a statement that the fraction of neutrons emitted at a given energy is determined by dividing the experimental neutron cross section by the total cross section at the same energy. The total cross section is given as the sum of the neutron and proton cross sections. Thus,

$$\sigma_{E2}(E_\gamma,n)=f_n(E_\gamma)\sigma_{E2}(E_\gamma) , \tag{5}$$

where $\sigma_{E2}(E_\gamma)$ is the photonuclear GQR cross section. Thus, for proton and neutron emission Eq. (3) becomes

$$\sigma_{E1}(E_\gamma,n)=\sigma_{\text{expt}}(E_\gamma,n)-f_n(E_\gamma)\sigma_{E2}(E_\gamma) \tag{6a}$$

and

$$\sigma_{E1}(E_\gamma,p)=\sigma_{\text{expt}}(E_\gamma,p)-[1-f_n(E_\gamma)]\sigma_{E2}(E_\gamma) . \tag{6b}$$

Equations (4)–(6) were used for nucleon emission from ^{12}C, ^{16}O, and ^{18}O. For ^{59}Co, the (γ,p) cross section is not available and so a constant value of $f_n=0.7$ (suggested from Ref. 11) was used. For ^{89}Y and ^{197}Au I used $f_n=1.0$.

TABLE I. Isoscalar giant quadrupole resonance (GQR) parameters taken from the compilation of Refs. 10 and 21. E is the GQR resonance excitation energy, Γ is the full-width at half maximum, and f is the fractional depletion of the energy weighted sum rule. (The GQR of light nuclei are fragmented into several peaks, so that the parameters below represent an estimated average value.)

Nucleus	E (MeV)	Γ (MeV)	f
^{12}C	22.0[a]	6.0[a]	0.3[a]
^{16}O	22.0[b]	6.0[a]	0.4[c,d]
^{18}O	24.0[e]	6.0[a]	0.4[a]
^{59}Co	16.3[b]	5.6[b]	0.61[b]
^{89}Y	13.8[b]	3.2[b]	0.55[c]
^{197}Au	10.8[e]	2.9[b]	0.95[c]

[a] Estimate.

[b] Best value from Table 4 of Ref. 10.

[c] From Fig. 23 of Ref. 10.

[d] From Fig. 17 of Ref. 21.

[e] E is calculated from 63 $A^{-1/3}$.

III. RESULTS AND DISCUSSION

The calculated results are listed in Table II, along with the experimental results of various groups.[12-16] $\sigma_{E1}+\sigma_{E2}$ is the calculated result to be compared with the data σ_{expt}. Also listed are the results of WW calculations.[7] In all cases two theoretical cross sections are listed. The first is calculated using an expression for the minimum impact parameter as

$$b_{\min}=R_{0.1}(T)+R_{0.1}(P) , \tag{7}$$

where $R_{0.1}$ represents the 10% charge-density radius[7] of the target or projectile. The second theoretical cross section listed in parentheses in Table II uses $b_{\min}$ given by Hill *et al.*[14-16] as

$$b_{\min}=r_0[A_P^{1/3}+A_T^{1/3}-X(A_p^{-1/3}+A_T^{-1/3}] , \tag{8}$$

where $r_0=1.34$ fm and $X=0.75$. (Note that there is a small difference between some of my WW calculations and those of Hill *et al.*[14-16] due to a small term which they had inadvertently forgotten.[19,20])

There are several features readily apparent from Table II.

(i) $\sigma_{E1}+\sigma_{E2}$ is *always* larger than σ_{WW}. However, for nucleon emission from ^{12}C, ^{16}O, and ^{18}O this difference is never larger than about 4%, but for neutron emission from ^{59}Co, ^{89}Y, and ^{197}Au the difference is much larger varying between about 7–15 %.

(ii) For nucleon emission from ^{12}C and ^{16}O both $\sigma_{E1}+\sigma_{E2}$ and σ_{WW} agree with experiment for both choices of $b_{\min}$.

(iii) For nucleon emission from ^{18}O both $\sigma_{E1}+\sigma_{E2}$ and σ_{WW} disagree with experiment for both choices of $b_{\min}$. σ_{WW} actually gives slightly better agreement but not by a significant amount.

TABLE II. Calculated results, $\sigma_{E1}+\sigma_{E2}$ and σ_{WW}, compared to experiment (Refs. 12–16). Two theoretical cross sections are listed. The first set uses $b_{\min}$ given by Eq. (7) and the second set (in parentheses) uses $b_{\min}$ given by Eq. (8). All choices of experimental photonuclear data used as input follow Ref. 7.

Projectile	$R_{0.1}(P)$ (fm)	Target	$R_{0.1}(T)$ (fm)	Energy (GeV/nucleon)	Final state	σ_{expt} (mb)	σ_{WW} (mb)	σ_{E1} (mb)	σ_{E2} (mb)	$\sigma_{E1}+\sigma_{E2}$ (mb)
^{12}C	3.30	Pb	7.83	2.1	^{11}C	51±18	47 (51)	46 (50)	1 (1)	47 (51)
^{12}C	3.30	Pb	7.83	2.1	^{11}B	50±25	68 (74)	68 (73)	2 (2)	70 (75)
^{12}C	3.30	Pb	7.83	1.05	^{11}C	39±24	28 (31)	28 (31)	1 (1)	29 (32)
^{12}C	3.30	Pb	7.83	1.05	^{11}B	50±25	42 (47)	42 (46)	1 (2)	43 (48)
^{16}O	3.68	Pb	7.83	2.1	^{15}O	50±24	59 (64)	58 (63)	2 (2)	60 (65)
^{16}O	3.68	Pb	7.83	2.1	^{15}N	96±26	111 (120)	110 (119)	3 (4)	113 (123)
^{12}C	3.30	Ag	6.37	2.1	^{11}C	21±10	18 (20)	18 (20)	0 (0)	18 (20)
^{12}C	3.30	Ag	6.37	2.1	^{11}B	18±13	26 (29)	26 (29)	1 (1)	27 (30)
^{12}C	3.30	Ag	6.37	1.05	^{11}C	21±10	11 (13)	11 (13)	0 (0)	11 (13)
^{12}C	3.30	Ag	6.37	1.05	^{11}B	25±19	17 (20)	17 (19)	1 (1)	18 (20)
^{16}O	3.68	Ag	6.37	2.1	^{15}O	26±13	23 (25)	22 (25)	1 (1)	23 (26)
^{16}O	3.68	Ag	6.37	2.1	^{15}N	30±16	42 (46)	42 (46)	1 (2)	43 (48)
^{12}C	3.30	Cu	5.45	2.1	^{11}C	10±7	8 (9)	8 (9)	0 (0)	8 (9)
^{12}C	3.30	Cu	5.45	2.1	^{11}B	4±8	11 (12)	11 (12)	0 (0)	11 (12)
^{12}C	3.30	Cu	5.45	1.05	^{11}C	9±8	5 (6)	5 (6)	0 (0)	5 (6)
^{12}C	3.30	Cu	5.45	1.05	^{11}B	5±8	8 (9)	8 (9)	0 (0)	8 (9)
^{16}O	3.68	Cu	5.45	2.1	^{15}O	9±8	10 (11)	10 (11)	0 (0)	10 (11)
^{16}O	3.68	Cu	5.45	2.1	^{15}N	15±8	18 (20)	17 (19)	1 (1)	18 (20)
^{12}C	3.30	Al	4.09	2.1	^{11}C	0±5	2 (2)	2 (2)	0 (0)	2 (2)
^{12}C	3.30	Al	4.09	2.1	^{11}B	0±5	3 (3)	3 (3)	0 (0)	3 (3)
^{12}C	3.30	Al	4.09	1.05	^{11}C	1±6	1 (2)	1 (2)	0 (0)	1 (2)
^{12}C	3.30	Al	4.09	1.05	^{11}B	1±7	2 (2)	2 (2)	0 (0)	2 (2)
^{16}O	3.68	Al	4.09	2.1	^{15}O	0±5	2 (3)	2 (3)	0 (0)	2 (3)
^{16}O	3.68	Al	4.09	2.1	^{15}N	−1±9	4 (5)	4 (5)	0 (0)	4 (5)
^{12}C	3.30	C	3.30	2.1	^{11}C	−2±5	0.4 (0.5)	0.4 (0.5)	0 (0)	0.4 (0.5)
^{12}C	3.30	C	3.30	2.1	^{11}B	−1±4	0.6 (0.7)	0.6 (0.7)	0 (0)	0.6 (0.7)
^{12}C	3.30	C	3.30	1.05	^{11}C	−2±5	0.3 (0.4)	0.3 (0.4)	0 (0)	0.3 (0.4)
^{12}C	3.30	C	3.30	1.05	^{11}B	−2±5	0.5 (0.6)	0.5 (0.6)	0 (0)	0.5 (0.6)
^{16}O	3.68	C	3.30	2.1	^{15}O	−1±4	0.5 (0.6)	0.5 (0.6)	0 (0)	0.5 (0.6)
^{16}O	3.68	C	3.30	2.1	^{15}N	−1±4	1 (1)	1 (1)	0 (0)	1 (1)
^{18}O	3.78	Ti	5.00	1.7	^{17}O	8.7±2.7	15 (16)	15 (16)	0 (1)	15 (17)
^{18}O	3.78	Ti	5.00	1.7	^{17}N	−0.5±1.0	3 (3)	3 (3)	0 (0)	3 (3)
^{18}O	3.78	Pb	7.83	1.7	^{17}O	136±2.9	155 (165)	154 (164)	4 (4)	158 (168)
^{18}O	3.78	Pb	7.83	1.7	^{17}N	20.2±1.8	28 (31)	27 (30)	2 (2)	29 (32)
^{18}O	3.78	U	8.09	1.7	^{17}O	140.8±4.1	191 (202)	189 (200)	5 (5)	194 (205)
^{18}O	3.78	U	8.09	1.7	^{17}N	25.1±1.6	34 (37)	34 (36)	2 (2)	36 (38)
^{12}C	3.30	^{197}Au	7.56	2.1	^{196}Au	75±14	38 (40)	37 (38)	6 (7)	43 (45)
^{20}Ne	4.00	^{197}Au	7.56	2.1	^{196}Au	153±18	100 (105)	97 (101)	16 (18)	113 (119)

TABLE II. (*Continued*).

Projectile	$R_{0.1}(P)$ (fm)	Target	$R_{0.1}(T)$ (fm)	Energy (GeV/nucleon)	Final state	σ_{expt} (mb)	σ_{WW} (mb)	σ_{E1} (mb)	σ_{E2} (mb)	$\sigma_{E1}+\sigma_{E2}$ (mb)
^{40}Ar	4.72	^{197}Au	7.56	1.8	^{196}Au	348±34	289 (297)	280 (287)	46 (49)	326 (336)
^{56}Fe	5.24	^{197}Au	7.56	1.7	^{196}Au	601±54	565 (578)	547 (560)	90 (94)	637 (654)
^{139}La	6.89	^{197}Au	7.56	1.26	^{196}Au	1970±130	2076 (2089)	2006 (2009)	357 (361)	2363 (2380)
^{16}O	3.68	^{197}Au	7.56	60	^{196}Au	280±30	215 (218)	208 (211)	14 (15)	222 (226)
^{16}O	3.68	^{197}Au	7.56	200	^{196}Au	440±40	278 (281)	270 (273)	15 (16)	285 (289)
^{12}C	3.30	^{89}Y^{a}	6.02	2.1	^{88}Y	9±12	12 (13)	12 (13)	1 (1)	13 (14)
^{20}Ne	4.00	^{89}Y^{a}	6.02	2.1	^{88}Y	43±12	32 (35)	31 (34)	3 (4)	34 (38)
^{40}Ar	4.72	^{89}Y^{a}	6.02	1.8	^{88}Y	132±17	90 (96)	88 (94)	9 (10)	97 (104)
^{56}Fe	5.24	^{89}Y^{a}	6.02	1.7	^{88}Y	217±20	175 (185)	171 (181)	16 (18)	187 (199)
^{12}C	3.30	^{59}Co	5.33	2.1	^{58}Co	6±9	7 (8)	7 (7)	0 (1)	7 (8)
^{20}Ne	4.00	^{59}Co	5.33	2.1	^{58}Co	32±11	18 (20)	18 (20)	1 (1)	19 (21)
^{56}Fe	5.24	^{59}Co	5.33	1.7	^{58}Co	88±14	98 (105)	96 (104)	7 (7)	103 (111)
^{139}La	6.89	^{59}Co	5.33	1.26	^{58}Co	280±40	339 (358)	333 (352)	24 (26)	357 (378)

[a] For ^{89}Y calculations are presented using the photonuclear data of Lepretre (Ref. 17), multiplied by 0.82, as suggested, by Berman *et al.* (Ref. 18).

(iv) For neutron emission from ^{197}Au, $\sigma_{E1}+\sigma_{E2}$ is significantly closer to experimental values than σ_{WW} is, although for most cases it still lies outside the error bars. An exception, however, is a much poorer agreement for ^{139}La (see also Refs. 19 and 20). Significant discrepancies with ^{197}Au data have been noted previously for WW theory.[7]

(v) For neutron emission from ^{89}Y, $\sigma_{E1}+\sigma_{E2}$ is in much better agreement with experiment than σ_{WW} is. This is especially true for the ^{40}Ar and ^{56}Fe projectiles.

(vi) For ^{59}Co, $\sigma_{E1}+\sigma_{E2}$ is again better for ^{20}Ne, although slightly worse for ^{56}Fe. As above, the agreement for the ^{139}La projectile is significantly poorer.

Finally, the earlier results of Bertulani and Baur can be compared for single neutron emission from ^{59}Co, ^{89}Y, and ^{197}Au targets with ^{12}C, ^{20}Ne, ^{40}Ar, and ^{56}Fe projectiles (see Table II and Ref. 6). Surprisingly the results of Ref. 6 give better agreement with experiment than Table II for ^{12}C and ^{20}Ne on ^{197}Au and also for ^{40}Ar on ^{89}Y. However, for ^{40}Ar and ^{56}Fe on ^{197}Au and ^{56}Fe on ^{59}Co, Table II gives far superior agreement with experiment. Otherwise other comparisons are comparable. However, it should be emphasized that there are substantial differences between Ref. 6 and Table II. In particular, *all* dipole and quadrupole cross-section values are significantly larger than the present work.

IV. SUMMARY AND CONCLUSIONS

Calculations have been made for nucleon emission via EM dissociation in relativistic nucleus-nucleus collisions. Results are presented for the Weizsäcker-Williams theory and also for separate electric dipole and quadrupole components. The theories have been compared to an extensive data set. It is found that electric quadrupole ($E2$) effects are not significant for proton and neutron emission from ^{12}C, ^{16}O, or ^{18}O. However, $E2$ contributions are substantial for neutron emission from ^{59}Co, ^{89}Y, and ^{197}Au, generally leading to improved agreement between theory and experiment. Notable disagreements occur for ^{139}La projectiles (1.26 GeV/nucleon) where the theoretical $\sigma_{E1}+\sigma_{E2}$ are too big. Quadrupole effects improve the theoretical results for ^{16}O projectiles at 60 and 200 GeV/nucleon, although the theoretical cross sections are still too small.

In general, it has been found that electric quadrupole effects are an important component in nucleus-nucleus collisions and that these effects can be calculated accurately.

Note added in proof: Some additional references on electric quadrupoles are R. Fleischhauer and W. Scheid, Nucl. Phys. A **493**, 583 (1989); **504**, 855 (1989); A. Goldberg, *ibid.* **420**, 636 (1984). Also note that Eq. (4) of Ref. 9 should have E_{GQR} in the numerator instead of E.

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[1] K. Kajantie and L. McLerran, Annu. Rev. Nucl. Part. Sci. **37**, 293 (1987).

[2] M. Grabiak, B. Muller, W. Greiner, G. Soff, and P. Koch, J. Phys. G **15**, L25 (1989).

[3] J. A. Simpson, Annu. Rev. Nucl. Part. Sci. **33**, 323 (1983).

[4] W. V. Jones, Y. Takahashi, B. Wosiek, and O. Miyamura, Annu. Rev. Nucl. Part. Sci. **37**, 71 (1987); J. Wdowczyk and A. W. Wolfendale, *ibid.* **39**, 43 (1989).

[5] W. G. Lynch, Annu. Rev. Nucl. Part. Sci. **37**, 493 (1987).

[6] C. A. Bertulani and G. Baur, Phys. Rep. **163**, 299 (1988); G. Baur and C. A. Bertulani, Phys. Rev. C **34**, 1654 (1986).

[7] J. W. Norbury, Phys. Rev. C **40**, 2621 (1989). The last entry in column 5 of Table I should read 335±49 and not 73±13.

[8] S. S. Dietrich and B. L. Berman, At. Data Nucl. Data Tables **38**, 199 (1988).

[9] J. W. Norbury, Phys. Rev. C **41**, 372 (1990).

[10] F. E. Bertrand, Annu. Rev. Nucl. Sci. **26**, 457 (1976).

[11] J. W. Norbury, F. A. Cucinotta, L. W. Townsend, and F. F. Badavi, Nucl. Instrum. Methods Phys. Res. B **31**, 535 (1988).

[12] H. H. Heckman and P. J. Lindstrom, Phys. Rev. Lett. **37**, 56 (1976).

[13] D. L. Olson, B. L. Berman, D. E. Greiner, H. H. Heckman, P. J. Lindstrom, G. D. Westfall, and H. J. Crawford, Phys. Rev. C **24**, 1529 (1981).

[14] M. T. Mercier, J. C. Hill, F. K. Wohn, C. M. McCullough, M. E. Nieland, J. A. Winger, C. B. Howard, S. Renwick, D. K. Matheis, and A. R. Smith, Phys. Rev. C **33**, 1655 (1986).

[15] J. C. Hill, F. K. Wohn, J. A. Winger, and A. R. Smith, Phys. Rev. Lett. **60**, 999 (1988).

[16] J. C. Hill, F. K. Wohn, J. A. Winger, M. Khayat, K. Leininger, and A. R. Smith, Phys. Rev. C **38**, 1722 (1988).

[17] A. Lepretre, H. Beil, R. Bergere, P. Carlos, A. Veyssiere, and M. Sugawara, Nucl. Phys. **A175**, 609 (1971).

[18] B. L. Berman, R. E. Pywell, S. S. Dietrich, M. N. Thompson, K. G. McNeill, and J. W. Jury, Phys. Rev. C **36**, 1286 (1987).

[19] J. W. Norbury, Phys. Rev. C **39**, 2472 (1989).

[20] J. C. Hill and F. K. Wohn, Phys. Rev. C **39**, 2474 (1989).

[21] J. Speth and A. van der Woude, Rep. Prog. Phys. **44**, 46 (1981).