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Two neutron removal in relativistic nucleus-nucleus reactions

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Significant discrepancies between theory and experiment have previously been noted for double neutron removal via electromagnetic processes in relativistic nucleus-nucleus collisions. The present work examines the cause of these discrepancies and systematically investigates whether the problem might be due to electromagnetic theory, nuclear contributions, or an underestimate of experimental error. Using cross-section systematics from other reactions it is found that the discrepancies can be resolved in a plausible manner.

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In recent studies [1–6] of electromagnetic (EM) dissociation in relativistic nucleus-nucleus collisions, the cross sections measured are total cross sections $\sigma_{\rm tot}$, which actually comprise both the nuclear $\sigma_{\rm nuc}$ and EM cross sections $\sigma_{\rm EM}$ via

$$\sigma_{\rm tot}=\sigma_{\rm nuc}+\sigma_{\rm EM} . \qquad (1)$$

Thus, in extracting $\sigma_{\rm nuc}$ (or $\sigma_{\rm EM}$) one has to know the EM (or nuclear) cross section.

The pioneering experimental work on separating nuclear and EM cross sections for one [1–5] and two [6] nucleon removal from nuclear beams was done by Hill, Wohn, and collaborators [1–6]. Their work has provided an extremely important and useful set of data with which to compare theoretical studies of EM processes in nuclear collisions [7]. They used the concept of limiting fragmentation [1–6] to estimate the nuclear cross section (denoted by $\sigma^F_{\rm nuc}$) and thereby deduced experimental values for the EM cross section (denoted by $\sigma^{\rm expt}_{\rm EM}$). It was found that significant discrepancies between theory and experiment occurred for these EM cross sections [1–6,8,9], particularly [9] for ^{197}Au. This discrepancy was interpreted by Benesh, Cook, and Vary (BCV) [10] (and confirmed in Ref. [11]) as being due to an underestimate of the $\sigma_{\rm nuc}$ contribution.

Hill, Wohn, and collaborators have recently extended their work on single neutron removal to a very interesting study of two neutron removal [16] from ^{59}Co and ^{197}Au targets. Their results [6] are reproduced in Tables I and II. It can be seen that they find a deviation between Weizsacker-Williams (WW) theory and experiment for ^{20}Ne, ^{40}Ar, and ^{139}La projectiles for two neutron removal from ^{197}Au targets (compare $\sigma^{\rm WW}_{\rm EM}$ with $\sigma^{\rm expt}_{\rm EM}$). This discrepancy was also noted in Ref. [9]. In Ref. [10] and [11] deviations between theory and experiment were studied only for *single* neutron removal. It is the aim of the present work to use the BCV methods [10] and cross-section systematics to study the above two neutron removal discrepancies.

When deviations between theory and experiment occur, the problem can be due to any of the cross sections in Eq. (1). (BCV have shown [10] that interference terms are negligible.) Hill, Wohn, and collaborators [1–6] have discussed possible problems with $\sigma_{\rm EM}$, in contrast to Refs. [10] and [11] that have investigated problems with $\sigma_{\rm nuc}$. Of course, the third possibility is problems with the experimental cross section $\sigma^{\rm exp}_{\rm tot}$. These three possibilities will be discussed below for the two neutron removal experiments [6].

Electromagnetic cross sections. In Ref. [6] it was suggested that the discrepancy between theory and experiment might be due to problems with the WW calculation. (This calculation is discussed extensively in Refs. [1–10] and will not be repeated here.) Possible problems in the use of WW theory might be (i) neglect of electric quadrupole excitations [7,12,13], (ii) large experimental errors [13] in the photonuclear cross sections used as input, (iii) neglect of Rutherford bending of the trajectory [14], (iv) multiple Coulomb excitations [15], (v) incorrect choice of the impact parameter [9,11], or (vi) finite-size effects [7]. All of these possibilities have been thoroughly studied [1–15], and most previous discrepancies have been resolved [13], leading one to the conclusion that WW theory should be an excellent approximation for the two neutron removal studies [6]. Furthermore, it is somewhat mysterious that all the ^{59}Co target cross sections, as well as the ^{12}C and ^{56}Fe projectiles for ^{197}Au targets, are in good agreement, yet ^{20}Ne, ^{40}Ar, and ^{139}La projectiles on ^{197}Au targets are in poor agreement. One might expect that, if there really is a problem, all of the ^{197}Au target cross sections would be problematic because the neutrons are being removed from the target. Thus, one is led to consider the possibility that the trouble might be elsewhere, and not with WW theory. This was the conclusion reached in Refs. [10–11] for the case of *one* neutron removal.

Nuclear cross sections. In Refs. [10] and [11] it was claimed that an optical model for one neutron removal $\sigma^{\rm opt}_{\rm nuc}$ provided better agreement between theory and experiment. In other words $\sigma^{\rm opt}_{\rm nuc}+\sigma^{\rm WW}_{\rm EM}$ provided better agreement with $\sigma^{\rm expt}_{\rm tot}$ than did $\sigma^F_{\rm nuc}+\sigma^{\rm WW}_{\rm EM}$, where $\sigma^F_{\rm nuc}$ is the nuclear contribution calculated by Hill, Wohn, and collaborators [1–6] from limiting fragmentation. Thus, it is natural to try the same explanation for the case of two neutron removal.

TABLE I. Cross sections for the ^{59}Co(P,X)^{57}Co and ^{59}Co(P,X)^{58}Co reactions, where P is the projectile and X is anything. Values listed are for two neutron removal, and values in parentheses are for one neutron removal [6,11]. Symbols are $\sigma_{\rm tot}^{\rm expt}$ (total experimental cross section), $\sigma_{\rm nuc}^{F}$ (nuclear cross section determined from factorization), $\sigma_{\rm EM}^{\rm expt}\equiv\sigma_{\rm tot}^{\rm expt}-\sigma_{\rm nuc}^{F}$, and $\sigma_{\rm EM}^{\rm WW}$ (theoretically calculated WW cross section). $\sigma_{\rm nuc}$ is the nuclear neutron removal cross section calculated as in the text. All cross sections are in units of mb and $T_{\rm lab}$ is in units of GeV/nucleon. * denotes that $P_{\rm esc}^{(2N)}$ was fitted to data.

Projectile	$T_{\rm lab}$	$\sigma_{\rm tot}^{\rm expt}$ [a]	$\sigma_{\rm nuc}^{F}$ [a]	$\sigma_{\rm EM}^{\rm expt}$ [a]	$\sigma_{\rm EM}^{\rm WW}$ [a]	$\sigma_{\rm nuc}$
^{12}C	2.1	46±3(89)	38±3(83)	6±4(6)	1.1(8.1)	45*(111)
^{20}Ne	2.1	49±3(132)	46±4(100)	3±5(32)	2.9(21)	49(121)
^{56}Fe	1.7	62±4(194)	49±4(106)	13±6(88)	14(111)	60(122)
^{139}La	1.26	110±11(450)	82±10(170)	32±16(280)	44(376)	72(142)

[a] Reference [6].

In Ref. [10] the single *nucleon* removal cross section was parametrized as

$$\sigma_G(1N)=2\pi(b_c-\tfrac{1}{2}\Delta b)\Delta b\ , \tag{2}$$

where b_c is the critical impact parameter [10] and $\Delta b\approx 0.5$ fm. Thus, one can write the two nucleon removal cross section as

$$\sigma_G(2N)=2\pi(b_c-\tfrac{3}{2}\Delta b)\Delta b\ . \tag{3}$$

The cross section for one *neutron* removal is

$$\sigma_{\rm nuc}^{1N}=\frac{N}{A}P_{\rm esc}^{(1N)}\sigma_G(1N)\ , \tag{4}$$

where N/A is the ratio of neutrons to nucleons and $P_{\rm esc}^{(1N)}$ is the escape probability for that neutron. In Ref. [11] it was noted that $P_{\rm esc}^{(1N)}$ is the most uncertain part of the calculation. For two neutron removal

$$\sigma_{\rm nuc}^{2N}=\left[\frac{N}{A}\right]^2 P_{\rm esc}^{(2N)}\sigma_G(2N)\ , \tag{5}$$

where $P_{\rm esc}^{(2N)}$ is the two neutron escape probability. Given the difficulties in determining this probability, the approach that we take here is to fit it to one experimental data point (e.g., for the ^{12}C projectile) by making sure that $\sigma_{\rm nuc}+\sigma_{\rm EM}^{\rm WW}$ fits the value $\sigma_{\rm tot}^{\rm expt}$ and then use that value for the calculation of the other reactions. (Such an approach also works very well for single nucleon removal, although the results are not presented here.) For ^{59}Co the fitted value of $P_{\rm esc}^{(2N)}$ is 0.71, whereas for ^{197}Au it is 0.58.

Final model cross sections are listed in Tables I and II in the column labeled $\sigma_{\rm nuc}$. (The single nucleon values are from Ref. [11].) It can be seen that, whereas for one neutron removal there existed significant differences between $\sigma_{\rm nuc}^{F}$ and $\sigma_{\rm nuc}$ (as discussed previously in Refs. [10] and [11]), the situation for two neutron removal seems to be quite acceptable. In other words, the present model calculation for the nuclear contribution seems to agree reasonably well with the cross section $\sigma_{\rm nuc}^{F}$ derived from the factorization by Hill, Wohn, and collaborators [6].

Given our reluctance to find fault with WW theory, and given the above good agreement between the nuclear cross section as determined from factorization [6] and the present calculation, one is led to consider a third alternative.

Total experimental cross sections. Quite apart from the above considerations, is there any other evidence to suggest that the discrepancies for ^{20}Ne, ^{40}Ar, and ^{139}La projectiles on ^{197}Au targets may be due to an underestimate of the experimental error bars?

First, note that the $\sigma_{\rm tot}^{\rm expt}$ for one and two neutron removal from ^{59}Co and for one neutron removal from ^{197}Au all increase as the mass of the projectile increases. (The exception is two neutron removal from ^{59}Co for ^{12}C and ^{20}Ne projectiles.) One would surely also expect this behavior for two neutron removal from ^{197}Au, yet a *drop* (or more accurately a constant value within experimental error) is observed from ^{40}Ar to ^{56}Fe. Given that the EM discrepancy (compare $\sigma_{\rm EM}^{\rm expt}$ with $\sigma_{\rm EM}^{\rm WW}$) for two neutron removal occurs for ^{40}Ar, one suspects that the ^{40}Ar value of $\sigma_{\rm tot}^{\rm expt}$ might be too large. This would explain why $\sigma_{\rm EM}^{\rm WW}$ is smaller than the experimental EM cross section $\sigma_{\rm EM}^{\rm expt}$.

Second, note that the $\sigma_{\rm tot}^{\rm expt}$ for two neutron removal from ^{59}Co are equal (within experimental error) for ^{12}C and ^{20}Ne projectiles. One should therefore also expect this to be the case for two neutron removal from ^{197}Au, yet the ^{20}Ne cross section is nearly *double* the ^{12}C cross

TABLE II. Same as Table I, except now the reactions are for ^{197}Au(P,X)^{195}Au and ^{197}Au(P,X)^{196}Au. $\sigma_{\rm EM}^{\rm rev}$ is the revised EM "experimental" cross section as explained in the text.

Projectile	$T_{\rm lab}$	$\sigma_{\rm tot}^{\rm expt}$ [a]	$\sigma_{\rm nuc}^{F}$ [a]	$\sigma_{\rm EM}^{\rm expt}$ [a]	$\sigma_{\rm EM}^{\rm WW}$ [a]	$\sigma_{\rm nuc}$	$\sigma_{\rm EM}^{\rm rev}$
^{12}C	2.1	67±15(178)	58±8(103)	9±17(75)	5(39)	62*(140)	
^{20}Ne	2.1	114±12(268)	65±9(115)	49±15(153)	14(103)	66(152)	19
^{40}Ar	1.8	141±15(463)	65±10(115)	76±18(348)	38(292)	73(149)	42
^{56}Fe	1.7	133±9(707)	60±9(106)	73±13(601)	73(569)	77(147)	
^{139}La	1.26	424±47(2130)	89±18(160)	335±49(1970)	238(2058)	89(167)	239

[a] Reference [6].

section. Again, given that the two neutron EM discrepancy occurs for ^{20}Ne, one suspects that the ^{20}Ne value of $\sigma_{\rm tot}^{\rm expt}$ might be too large. Again, this would explain why $\sigma_{\rm EM}^{\rm WW}$ is smaller than the $\sigma_{\rm EM}^{\rm expt}$ cross section.

Third, note that the $\sigma_{\rm tot}^{\rm expt}$ for two neutron removal from ^{59}Co are roughly doubled when one goes from ^{56}Fe to ^{139}La, but for two neutron removal from ^{197}Au the value is roughly quadrupled rather than doubled as one would expect. Again, this explains why $\sigma_{\rm EM}^{\rm WW}$ is smaller than experiment for ^{139}La.

The above considerations have led to the hypothesis that perhaps the two neutron $\sigma_{\rm tot}^{\rm expt}$ values for ^{20}Ne, ^{40}Ar, and ^{139}La projectiles on ^{197}Au targets are overestimated. Can one use $\sigma_{\rm EM}^{\rm expt}$ cross-section systematics on the remaining reactions to deduce "revised" values of $\sigma_{\rm EM}^{\rm expt}$ for the above three projectiles on ^{197}Au? Let us assume that the $\sigma_{\rm EM}^{\rm expt}$ values for *one* neutron removal from ^{197}Au are correct for all five projectiles. (In fact they are not quite correct [10,11], but their ratios, discussed below, do scale correctly.) Also assume that the two neutron values are correct for ^{12}C and ^{56}Fe on ^{197}Au. The two neutron values should scale exactly as the one neutron values. Thus, to determine the "revised" EM experimental value for two neutron removal from projectile P using one neutron values for projectiles P and ^{56}Fe, we write

$$\sigma_{\rm EM}^{\rm rev}(P)_{2N}=\sigma_{\rm EM}^{\rm expt}(P)_{1N}\frac{\sigma_{\rm EM}^{\rm expt}(^{56}{\rm Fe})_{2N}}{\sigma_{\rm EM}^{\rm expt}(^{56}{\rm Fe})_{1N}} . \tag{6}$$

Thus, for example, for the ^{20}Ne projectile we have $19=153\times73/601$. (^{56}Fe is used rather than ^{12}C because the relative experimental error is much smaller. Nevertheless, one obtains nearly identical results using ^{12}C. One could also use the theoretical $\sigma_{\rm EM}^{\rm WW}$ numbers. The results are not that different.) When these revised "experimental" values $\sigma_{\rm EM}^{\rm rev}$ are compared to $\sigma_{\rm EM}^{\rm WW}$ (see Table II) excellent agreement is found, thus providing a plausible explanation for the previous discrepancies.

The foregoing arguments do not prove absolutely that the experimental error bars are too small. They simply suggest that the discrepancies between theory and experiment for two neutron removal from ^{197}Au are not *necessarily* the fault of WW theory. The conclusion from this study is that cross-section systematics provide a possible explanation for previously observed discrepancies.

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[1] M. T. Mercier, J. C. Hill, F. K. Wohn, and A. R. Smith, Phys. Rev. Lett. **52**, 898 (1984).

[2] 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).

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

[4] A. R. Smith, J. C. Hill, J. A. Winger, and P. J. Karol, Phys. Rev. C **38**, 210 (1988).

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

[6] J. C. Hill, F. K. Wohn, J. A. Winger, M. Khayat, M. T. Mercier, and A. R. Smith, Phys. Rev. C **39**, 524 (1989).

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

[8] J. W. Norbury, Phys. Rev. C **39**, 2472 (1989); J. C. Hill and F. K. Wohn, *ibid.* **39**, 2474 (1989).

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

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

[11] J. W. Norbury and L. W. Townsend, Phys. Rev. C **42**, 1775 (1990).

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

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

[14] A. N. F. Aleixo and C. A. Bertulani, Nucl. Phys. **A505**, 448 (1982).

[15] W. J. Llope and P. Braun-Munzinger, Phys. Rev. C **41**, 2644 (1990).