Two-neutron emission from electromagnetic dissociation of ^{59}Co and ^{197}Au targets by relativistic heavy ions

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Electromagnetic dissociation of ^{59}Co and ^{197}Au target nuclei and their subsequent deexcitation by two-neutron emission was observed. Beams of relativistic ^{12}C, ^{20}Ne, ^{40}Ar, ^{56}Fe, and ^{139}La ions were used. The measured electromagnetic dissociation cross sections become large for high-Z targets and projectiles, reaching 335 mb for the ^{197}Au(^{139}La,X)^{195}Au reaction with 1.26 GeV/nucleon ^{139}La projectiles. The experimental cross sections in excess of the estimated nuclear contributions are in reasonable agreement with a calculation of the electromagnetic dissociation contribution using the Weizsäcker-Williams method for estimating the virtual photon spectrum.

I. INTRODUCTION

Dissociation of nuclei by the nuclear Coulomb field, called electromagnetic dissociation (ED), was first reported for fragmentation of projectiles accelerated at the Bevalac by Heckman and Lindstrom[1] and for target fragmentation by Mercier *et al.*[2] Earlier the same effect had been observed in absorption of cosmic rays by W nuclei.[3] Olson *et al.*[4] observed two-neutron emission from ED of 1.7 GeV/nucleon ^{18}O projectiles interacting with targets ranging from Be to U. The measured ED cross section for two-neutron emission ranged from 6.3 mb for a Ti target to 74.3 mb for a U target.

ED can be pictured as a purely electromagnetic process which occurs when relativistic heavy ions (RHI's) pass near a high-Z target nucleus but outside the range of the nuclear force. A virtual photon from the Coulomb field is absorbed by either the target or the projectile, resulting in an excitation, usually to a giant multipole resonance, which subsequently deexcites by particle emission. ED can occur over a large range of impact parameters, thus under conditions where both projectile and target have high-Z, cross sections in the barn range can be realized. ED cross sections have been calculated[1,2,4–6] from a virtual photon spectrum obtained using the Weizsäcker-Williams (WW) procedure.[7] Although agreement is satisfactory, discrepancies for the largest σ_{ED} values have been observed.[5,6]

Baur and Bertulani[8] have suggested that due to the strong pulsed electromagnetic field generated in ED processes, it may be possible to produce multiphonon giant dipole excitations. Due to the higher excitation energy, the net effect of this process could be enhancement of the two-neutron removal relative to the one-neutron removal reaction, but little is known about such processes, so that the signature is a matter of conjecture.

For intermediate- and heavy-mass targets, cross sections for ED leading to two-neutron emission are expected to be roughly an order of magnitude smaller than those leading to one-neutron emission. There are two reasons for this. First, the $(\gamma,2n)$ process generally has a threshold near or above the peak of the giant $E1$ resonance. Second, the intensity of the virtual photons that drive ED decreases rapidly with increasing photon energy. This is illustrated in Fig. 1 for the example of 1.26

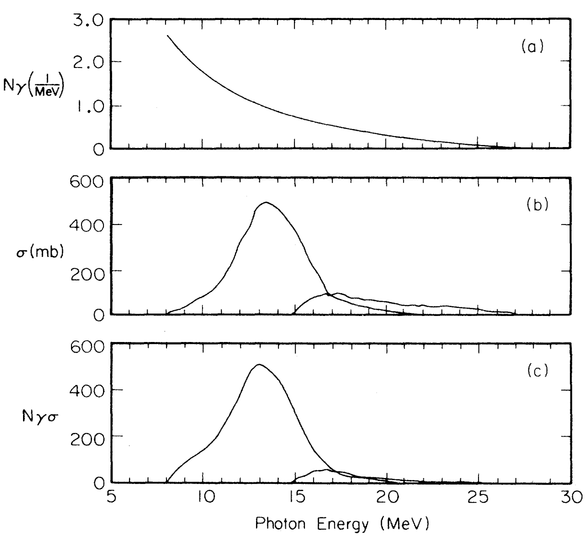

FIG. 1. Components necessary for calculation of the electromagnetic dissociation cross section σ_{ED} from the one- and two-neutron removal processes are shown. The ^{197}Au(^{139}La,X)^{196}Au and ^{197}Au(^{139}La,X)^{195}Au reactions initiated by 1.26 GeV/nucleon ^{139}La projectiles are used as examples. Part (a) shows the virtual-photon spectrum N_γ for 1.26 GeV/nucleon ^{139}La projectiles calculated using the Weizsäcker-Williams method. Part (b) shows the ^{197}Au$(\gamma,n)^{196}$Au and ^{197}Au$(\gamma,2n)^{195}$Au photonuclear cross sections taken from Refs. 17 and 18. Part (c) shows the product of (a) and (b) that is integrated over photon energy to obtain σ_{ED} for the two above-mentioned reactions.

GeV/nucleon ^{139}La projectiles on a ^{197}Au target. In this case the one-neutron removal cross section is calculated to be 2.06 b, whereas the two-neutron removal cross section is calculated to be only 0.24 b.

ED resulting from target fragmentation has been studied by Mercier *et al.*[5] for ^{59}Co, ^{89}Y, and ^{197}Au targets using RHI's ranging from 2.1 GeV/nucleon ^{12}C to 1.7 GeV/nucleon ^{56}Fe. Even though definitive evidence was observed for ED leading to the one-neutron removal process, evidence for ED leading to two-neutron removal was inconclusive and, for target fragmentation, has not been reported. Recently these experiments have been extended to higher Z using 1.26 GeV/nucleon ^{139}La projectiles,[6] and more definitive information on the two-neutron emission reaction was obtained. In this paper the first observation, in target fragmentation, of two-neutron emission from ED is reported. The effect was observed for both the ^{59}Co(RHI,X)^{57}Co and ^{197}Au(RHI,X)^{195}Au reactions. Part of these results have been reported orally in preliminary form.[9]

II. EXPERIMENTAL METHOD

The bombardments of ^{59}Co and ^{197}Au targets were carried out in the external beam at the Lawrence Berkeley Laboratory Bevalac accelerator using projectiles ranging from 2.1 GeV/nucleon ^{12}C to 1.26 GeV/nucleon ^{139}La. These experiments also allowed the determination of ED cross sections for the one-neutron emission process. Those results and the experimental techniques employed have been extensively discussed[5,10] (for ^{12}C, ^{20}Ne, ^{40}Ar, ^{56}Fe, and ^{139}La projectiles) and will not be repeated in detail here.

The targets consisted of foils of the monoisotopic elements Co and Au. Three different thicknesses of each target foil were bombarded simultaneously in order to obtain the correction for secondary reactions. The number of beam particles was determined[5,10] by counting the ^{7}Be activity from a thick polystyrene block located at the end of the target string. The ^{7}Be activity was then related to the yield of ^{11}C in the ^{12}C(RHI,X)^{11}C reaction in a 0.159 cm polystyrene target that was bombarded for a short period of time.

After irradiation all metal targets were shipped by air to the Ames Laboratory at Iowa State University for counting of the appropriate residual γ-ray activities. The finite spread of the beam on the target was determined by counting the ^{24}Na activity in a 0.038 mm Al foil on the upstream side of each of the targets, and the information was used to make geometry corrections for the γ-ray detectors. It was also necessary to make corrections for geometry-dependent coincidence summing.

The experimental cross sections were determined from the expression

$$\sigma(\text{cm}^2)=\frac{N(\text{atoms/sec})M(\text{g/mole})}{f(\text{proj/sec})\rho(\text{g/cm}^2)N_a(\text{atoms/mole})} \ .$$

The target density ρ was determined by weighing the targets on an analytical balance, and the total beam flux f was determined from the ^{11}C measurements. N, the disintegration rate at saturation, was determined from the γ-ray count rate by

$$N(\text{atoms/sec})=\frac{n(\text{counts/sec})}{\lambda\epsilon bGB} \ ,$$

where n refers to counts per second at saturation and ϵ, b, G, and B represent absolute detector efficiency, γ-ray branching ratio, γ-ray absorption in the target, and correction for finite beam width, respectively. λ is the radioactive decay constant in sec^{-1}.

III. CALCULATION OF THE ELECTROMAGNETIC DISSOCIATION CROSS SECTION

In order to calculate cross sections for the ED process, the product of the virtual photon spectrum $N_\gamma(E_\gamma)$ and the appropriate photonuclear cross section $\sigma_\gamma(E_\gamma)$ was integrated to give σ_{ED},

$$\sigma_{\text{ED}}=\int_0^\infty N_\gamma(E_\gamma)\sigma_\gamma(E_\gamma)dE_\gamma \ .$$

The term $N_\gamma(E_\gamma)$ was calculated using the Weizsäcker-Williams (WW) method for virtual photons and a modification of a computer code by Cook.[11] The procedure and its limitations have been discussed in previous papers.[5,10] The only adjustable parameter in the calculation is the minimum impact parameter b_{min}. Rather than letting it vary arbitrarily, we have chosen it to be of the form

$$b_c=r_0[A_p^{1/3}+A_t^{1/3}-X(A_p^{-1/3}+A_t^{-1/3})]$$

as suggested by Vary,[12] where the A's refer to the projectile and target, respectively, and b_c is a lower limit for the ED process. In the expression for b_c, the term $r_0(A_p^{1/3}+A_t^{1/3})$ can be thought of as a "touching radius" for the two nuclei. The term $X(A_p^{-1/3}+A_t^{-1/3})$ is a curvature correction. The constants r_0 and X were determined[12] to be 1.34 fm and 0.75 fm, respectively. The functional form of b_c is suggested from Glauber theory[13] and the values for r_0 and X were from fits[12] to nucleon-nucleus and nucleus-nucleus calculations[14] and densities from electron scattering data.[15]

The term $\sigma_\gamma(E_\gamma)$ is the experimentally measured photonuclear cross section for the $(\gamma,2n)$ reaction. The photonuclear cross section ^{59}Co$(\gamma,2n)^{57}$Co used for the ^{59}Co targets was that measured by Alvarez *et al.*[16] The photonuclear cross section ^{197}Au$(\gamma,2n)^{195}$Au used for the ^{197}Au targets was that given by Vessiere *et al.*[17] but multiplied by a factor of 0.93 to conform to recent measurements by Berman *et al.*[18]

IV. CROSS-SECTION RESULTS

A. Two-neutron removal cross sections

The independent yield of ^{57}Co ($T_{1/2}=272$ d) was determined by following the decay of the 122 keV γ ray which is 85.9% abundant.[19] The nucleus ^{57}Fe is stable but ^{57}Ni ($T_{1/2}=35.6$ h) can be produced from a ^{59}Co target by secondary protons or α particles and subsequently decay into ^{57}Co. A similar problem exists for ^{195}Au ($T_{1/2}=183$ d). Its independent yield was determined by following

TABLE I. Cross sections for two-neutron removal reactions by RHI's on Co and Au targets.

Target	Projectile	Energy (GeV/nucleon)	Beam intensity (particles)	Cross section (mb)
^{59}Co	p	28	3.0×10^{14}	18±1
^{59}Co	^{12}C	2.1	1.8×10^{11}	46±3
^{59}Co	^{20}Ne	2.1	2.0×10^{12}	49±3
^{59}Co	^{56}Fe	1.7	5.3×10^{10}	62±4
^{59}Co	^{139}La	1.26	1.0×10^{10}	114±12
^{197}Au	p	28	2.8×10^{14}	35±3
^{197}Au	^{12}C	2.1	1.6×10^{11}	64±20
^{197}Au	^{20}Ne	2.1	9.2×10^{11}	109±11
^{197}Au	^{40}Ar	1.8	6.2×10^{11}	118±18
^{197}Au	^{56}Fe	1.7	2.2×10^{11}	122±11
^{197}Au	^{139}La	1.26	4.0×10^{10}	424±46

the decay of the 98.9 keV γ ray which is 10.9% abundant.[20] The nucleus ^{195}Pt is stable but ^{195}Hg ($T_{1/2}$=9.9,41.6 h) can be produced by secondary particles.

Since the two-neutron removal product can be produced directly by secondary processes as well as indirectly by secondary processes leading to its β decay parent, correction for such processes must be carefully considered. A search was made in spectra recorded about one day after bombardment for ^{57}Ni in the ^{57}Co target and ^{195}Hg in the ^{197}Au target, but neither were observed. Nevertheless, the runs were not optimized for these nuclides, so their contributions could be significant. It was assumed that ^{57}Ni and ^{195}Hg could only be produced by secondary processes in relativistic heavy-ion reactions since the momentum mismatch between projectile and target is too great for significant stripping to occur. This results in the reasonable assumption that all effects of secondary production of ^{57}Ni and ^{195}Hg can be corrected by applying the measured secondary correction to the ^{57}Co and ^{195}Au daughters. The resulting cross sections for the two-neutron removal products ^{57}Co and ^{195}Au for various projectiles are given in Table I.

B. Nuclear contribution to the two-neutron removal cross sections

In order to estimate the nuclear contribution to the total cross section, use is made of the concept of factorization[21] of the nuclear cross section. This assumes $\sigma_{TP}^{F}=\gamma_T^F\gamma_P^T$, where F, T, and P indicate dependencies on target fragment, target, and projectile, respectively. This notation is similar to that of Heckman and Lindstrom,[1] but with the roles of P and T reversed. In addition, use is made of the hypothesis of limiting fragmentation which states that for sufficiently high projectile energies the cross section for production of the fragment F_i is independent of energy.

The concept of factorization has been tested for a variety of targets using a number of relativistic heavy ions. This includes low-mass[22] Cu and high-mass[23] Au targets. Factorization was found to be approximately true. A more detailed discussion[5,10] of these results as applied to the estimation of ED cross sections was given earlier. The concept of limiting fragmentation has been thoroughly studied for Au target fragmentation by Kaufman and co-workers.[23–25] The use of the concept was discussed[5,10] in detail earlier and will not be repeated here. Thus limiting fragmentation is assumed to be a valid concept for the RHI's used in this experiment.

We estimate the nuclear part of the two-neutron removal reaction from ratios such as

$$\sigma[^{197}\mathrm{Au}(^{139}\mathrm{La},X)F_i]\sigma[^{197}\mathrm{Au}(p,X)F_i]$$

taken as a function of the fragment mass. Since the limiting fragmentation region for protons is not reached for deep spallation products until at least 10 GeV, the proton

TABLE II. Nuclear cross sections for two-neutron removal products from Co targets.

RHI	Number of ratios	Ratio mass range (A)	$\left[\frac{\sigma[^{59}\mathrm{Co}(\mathrm{RHI},X)F_i]}{\sigma[^{59}\mathrm{Co}(p,X)F_i]}\right]_{\mathrm{avg}}^{\mathrm{a}}$	Nuclear cross section[b] $\sigma[^{59}\mathrm{Co}(\mathrm{RHI},X)^{57}\mathrm{Co}]$ (mb)
^{12}C	9	44–56	2.13±0.13	38±3
^{20}Ne	10	43–56	2.57±0.17	46±4
^{56}Fe	8	44–56	2.71±0.19	49±4
^{139}La	4	44–52	4.54±0.50	82±10

[a]Ratios for ^{12}C, ^{20}Ne, and ^{56}Fe from Ref. 5.
[b]Nuclear cross sections based on a measured value of 18±1 mb for the ^{59}Co$(p,X)^{57}$Co reaction using 28 GeV protons.

TABLE III. Nuclear cross sections of two-neutron removal products from Au targets.

RHI	Number of ratios	Ratio mass range (A)	$\left[\frac{\sigma[^{197}\mathrm{Au(RHI},X)F_i]}{\sigma[^{197}\mathrm{Au}(p,X)F_i]}\right]^{a}_{\mathrm{avg}}$	Nuclear cross section[b] $\sigma[^{197}\mathrm{Au(RHI},X)^{195}\mathrm{Au}]$ (mb)
^{12}C	11	87–181	1.66±0.17	58±8
^{20}Ne	18	83–190	1.86±0.21	65±9
^{40}Ar	17	83–188	1.85±0.22	65±10
^{56}Fe	11	83–181	1.71±0.21	60±9
^{139}La	11	89–188	2.55±0.45	89±18

[a]Ratios for ^{12}C, ^{20}Ne, ^{40}Ar, and ^{56}Fe from Ref. 5.
[b]Nuclear cross sections based on a measured value of 35±3 mb for the $^{197}\mathrm{Au}(p,X)^{195}\mathrm{Au}$ reaction using 28 GeV protons.

cross sections measured by us at 28 GeV at the AGS were used. These cross sections are consistent with the measurements by Kaufman *et al.*[25] at 11.5 and 300 GeV. Assuming, for example, factorization for the nuclear part of the $^{197}\mathrm{Au}(^{139}\mathrm{La},X)^{195}\mathrm{Au}$ cross section, then

$$\sigma_{\mathrm{nucl}}(^{139}\mathrm{La},{}^{195}\mathrm{Au})=\left[\frac{\sigma(^{139}\mathrm{La},F_i)}{\sigma(p,F_i)}\right]_{\mathrm{avg}}\sigma(p,{}^{195}\mathrm{Au}) .$$

The averages of ratios of the type shown in the above equation have been measured for ^{12}C, ^{20}Ne, ^{40}Ar, and ^{56}Fe projectiles[5] and ^{139}La projectiles. The numerical averages are given in Tables II and III along with the number of ratios used in each case to calculate the average and the corresponding ratio mass range. The uncertainty of the average ratios include both statistical factors, uncertainties due to the deviation of the data from strict factorization, and uncertainties in the ^{11}C monitor cross sections. Also given in Tables II and III are our estimates of the nuclear contribution to the cross section for the two-neutron removal product. In estimating this quantity we use a cross section of 18±1 mb and 35±3 mb, respectively, for the $^{59}\mathrm{Co}(p,2n)^{57}\mathrm{Co}$ and $^{197}\mathrm{Au}(p,2n)^{195}\mathrm{Au}$ reactions.

C. ED cross sections from Weizsäcker-Williams calculations

The Weizsäcker-Williams method for virtual photons[7] was used to calculate the ED portion of the appropriate two-neutron removal cross sections. The procedure is discussed in Sec. III of this paper. The results of the ED calculations are given in Tables IV and V for the two-neutron removal products studied in this work. Also given in parentheses, for comparison, are the corresponding (most recent) calculated ED cross sections for the one-neutron removal products. As can be seen from the tables, the two-neutron removal cross sections are roughly an order of magnitude smaller than the corresponding one-neutron removal cross sections for the reasons discussed above.

D. Experimentally measured ED cross sections for the two-neutron removal process

We define the "measured" ED cross section to be the two-neutron removal cross section measured in this experiment minus the empirically determined nuclear cross section for the two-neutron removal process already described. The results are given in Tables IV and V and plotted as a function of projectile Z in Figs. 2 and 3. The uncertainties for the measured ED cross sections include uncertainties from both the total and nuclear cross sections. Also given in parentheses, for comparison, are the corresponding cross sections for the one-neutron removal process.

V. DISCUSSION

To summarize, the first observation of electromagnetic dissociation in target fragmentation leading to two-neutron emission is reported here. The effect was observed for both light (^{59}Co) and heavy (^{197}Au) targets using relativistic heavy ions ranging from ^{12}C to ^{139}La. The ED effect for two-neutron emission was observed to increase with the Z of both the target and projectile, as predicted by calculations, but to be roughly an order of mag-

TABLE IV. ED cross sections for two-neutron removal products from Co targets.

RHI	Energy (GeV/nucleon)	Total σ (mb)	Measured ED σ^{a} (mb)	Calculated[d] ED σ (mb)
^{12}C	2.1	46±3	6±4 (6)[b]	1.1 (8.1)
^{20}Ne	2.1	49±3	3±5 (32)[b]	2.9 (21)
^{56}Fe	1.7	62±4	13±6 (88)[b]	14 (111)
^{139}La	1.26	110±11	32±16 (280)[c]	44 (376)

[a]We assume measured ED cross section for protons to be zero. Our ED calculation gives 0.03 mb.
[b]Values in parentheses are one-neutron removal cross sections taken from Ref. 5.
[c]Values in parentheses are one-neutron removal cross sections taken from Ref. 10.
[d]Values in parentheses are calculated one-neutron removal cross sections.

TABLE V. ED cross sections for two-neutron removal products from Au targets.

RHI	Energy (GeV/nucleon)	Total σ (mb)	Measured ED σ^a (mb)	Calculated[d] ED σ (mb)
^{12}C	2.1	67±15	9±17 (75)[b]	5 (39)
^{20}Ne	2.1	114±12	49±15 (153)[b]	14 (103)
^{40}Ar	1.8	141±15	76±18 (348)[b]	38 (292)
^{56}Fe	1.7	133±9	73±13 (601)[b]	73 (569)
^{139}La	1.26	424±47	335±49 (1970)[c]	238 (2058)

[a]We assume measured ED cross section for protons to be zero. Our ED calculation gives 0.18 mb.
[b]Values in parentheses are one-neutron removal cross sections taken from Ref. 5. The values from Ref. 5 have been multiplied by a factor of 0.93 as recommended in Ref. 18.
[c]Values in parentheses are one-neutron removal cross sections taken from Ref. 10.
[d]Values in parentheses are calculated one-neutron removal cross sections.

nitude smaller in cross section than the corresponding process leading to one-neutron emission.

The two-neutron removal cross sections can be describe by an empirically determined nuclear part using the concept of factorization plus an ED part which is determined by folding a virtual photon spectrum determined by the Weizsäcker-Williams (WW) method with the appropriate measured $(\gamma,2n)$ cross section. As can be seen from Figs. 2 and 3, the agreement between the measured and calculated ED cross sections is satisfactory. There is some indication that the measured ED cross sections for the ^{197}Au(RHI,X)^{195}Au reaction are systematically high, but due to the large experimental uncertainties and difficulties peculiar to measurement of the two-neutron removal process, it cannot be said with confidence that a definite deviation from theory is present.

In view of the above-mentioned possible deviation of the experimental ED cross section from theory, it would be of interest to measure the corresponding two-neutron removal cross section for ^{238}U projectiles. Our WW calculation gives a value of 446 mb for the ^{197}Au(^{238}U,X)^{195}Au reaction using 1.0 GeV/nucleon ^{238}U projectiles. A similar calculation for the ^{59}Co(^{238}U,X)^{57}Co reaction gives an ED cross section of 76 mb.

Calculations using the WW method indicate that ED cross sections become very large at ultrarelativistic ener-

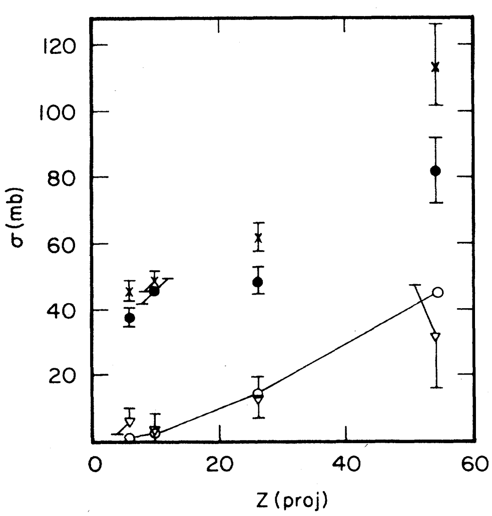

FIG. 2. Various cross sections for the ^{59}Co(RHI,X)^{57}Co reaction as a function of projectile charge. The cross sections are measured total (×), empirical nuclear (●), calculated ED (○), and measured ED (▽). The calculated ED points are connected by straight lines to guide the eye.

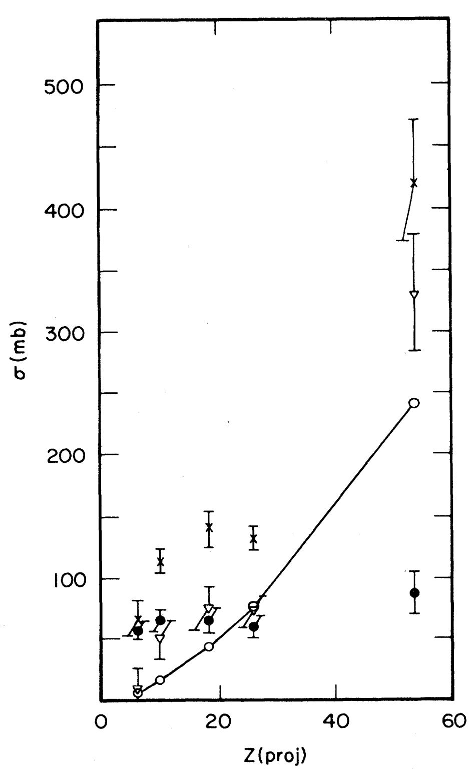

FIG. 3. Various cross sections for the ^{197}Au(RHI,X)^{195}Au reaction as a function of projectile charge. The cross sections are measured total (×), empirical nuclear (●), calculated ED (○), and measured ED (▽). The calculated ED points are connected by straight lines to guide the eye.

gies such as those expected for the RHI collider. For the case of 100 GeV/nucleon ^{197}Au projectiles on stationary targets, the calculated ^{59}Co(^{197}Au,X)^{57}Co cross section is 0.74 b and the ^{197}Au(^{197}Au,X)^{195}Au cross section is 3.7 b. The latter value is more than half of the total hadronic cross section and indicates that even the weaker branches of the ED process will be major factors in backgrounds encountered in experiments with high-Z ultrarelativistic heavy ions.

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