Electromagnetic Dissociation Effects in Galactic Heavy-Ion Fragmentation

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SUMMARY

Methods for calculating cross sections for the breakup of galactic heavy ions by the Coulomb fields of the interacting nuclei are presented. With the Weizsäcker-Williams method of virtual quanta, estimates of electromagnetic dissociation cross sections for a variety of reactions applicable to galactic cosmic ray shielding studies are presented and compared with other predictions and with available experimental data.

INTRODUCTION

As the Space Station era approaches, concern is mounting over the need to provide adequate protection for astronauts from galactic and solar cosmic rays. Although 98 percent of cosmic radiation consists of particles lighter than lithium (ref. 1), the relativistic nucleus component of galactic cosmic rays will be of major radiobiological significance for extended stays or repeated journeys into space. When interacting with tissue, these relativistic nuclei cause unique biological damage in the form of microlesions (ref. 2). Further, it is known that high LET (linear energy transfer) particles, which compose galactic cosmic rays, are highly carcinogenic, especially for chronic low exposures (ref. 3), and produce residual damage in skin many years after exposure (ref. 4).

In previous work (refs. 5 to 17), a comprehensive nuclear interaction theory capable of describing absorption, total, and fragmentation cross sections at a large variety of energies has been developed for use as input to a radiation transport theory under concurrent development (refs. 18 to 21). This transport theory is needed for reliable analyses of self-shielding factors, as well as for determinations of personal and bulk shielding requirements.

It has recently been found (refs. 22 to 30) that the dissociation of projectile nuclei by the virtual photon field of target nuclei has cross sections which are a sizable fraction of the nuclear projectile fragmentation cross sections. A similar situation also occurs for target fragmentation (ref. 29). Consequently, when comparing a theory with inclusive data, one must include, as a minimum, both the nuclear fragmentation process and the electromagnetic or Coulomb dissociation process. (These two exclusive channels may exhaust the inclusive data; although, in principle, one should consider other possible channels.) Thus, it is of crucial importance when the Coulomb dissociation cross section is a considerable fraction of the inclusive cross section which is true for few-nucleon removal.

In figures 1 through 6 we have presented some simple pictures to help visualize the differences between dissociation due to the nuclear field and dissociation due to the electromagnetic field. Figure 5 shows the virtual photon field of the target nucleus interacting electromagnetically with the projectile to cause projectile excitation (and eventual breakup). Note that this process is exactly analogous to the excitation of light nuclei induced by the electromagnetic field of an electron (fig. 7 and ref. 31), which will be extensively studied at the 4-GeV Continuous Electron Beam Accelerator Facility (CEBAF) to be built in Newport News near the Langley Research Center. In the present investigation, the virtual photon spectrum of a target nucleus interacts with the nucleon constituents in the projectile nucleus, whereas at
CEBAF the virtual photons of an electron will interact with the quark constituents of nucleons and nuclei. The energy of the virtual photons causing nuclear dissociation is typically on the order of 20 MeV, whereas the virtual photons at CEBAF will have energies up to 4 GeV (ref. 31).

Because of the importance of nuclear electromagnetic dissociation, it is of great use to supplement the previously developed nuclear fragmentation theory (refs. 5 to 17) with calculations of the Coulomb dissociation cross section. Thus the present report represents an initial effort at estimating Coulomb dissociation cross sections. Given such a beginning effort, the methods employed here are rather simplistic and the resultant cross sections should be considered only as reasonable estimates. Specific suggestions are made as to how to improve future calculations.

The total photodissociation cross section for removal of a particular species X is designated as \( \sigma_{EM}(X) \). The symbol X corresponds to that defined in reference 17 as the ablated particle in nuclear fragmentation. In general, photons, neutrons, deuterons, tritons, alphas, dineutrons, and so forth, will decay from a photo-excited nucleus; however, for the present work X is considered to be protons and neutrons only (i.e., one-nucleon removal). The cross section is evaluated (ref. 27) as

\[
\sigma_{EM}(X) = \int_{E_0(X)} \sigma_{\nu}(E,X) N(E) \, dE
\]

where \( E_0(X) \) is the photonuclear threshold which actually depends on X, \( \sigma_{\nu}(E,X) \) is the total photonuclear reaction cross section for production of X, and \( N(E) \) is the virtual photon number spectrum. The calculation of \( N(E) \) and \( \sigma_{\nu}(E,X) \) is now considered. The symbols used in this paper are defined on pages 18 through 20.

VIRTUAL PHOTON NUMBER SPECTRUM

The classic Weizsäcker-Williams (WW) method of virtual quanta (ref. 32) is used in this report. (Short discussions of this method appear in refs. 33 and 34.) Jackson (ref. 35) has an excellent account of this method and it is Jackson's treatment that we follow. Before proceeding, however, note that an alternative treatment for calculating the virtual photon spectrum of a nucleus has been presented by Jäckle and Pilkuhn (JP) and appears in references 22, 24, and 25. The advantage of the JP method is that it predicts virtual photon spectra for individual multipoles, such as E1 and M1, whereas the WW method does not. Furthermore, the JP method accounts for the finite extent of the charge distribution, whereas the WW method assumes a point charge. Olson et al. (ref. 28) provide a very clear and presentable discussion of the differences between the WW and the JP spectra. They note that the discrepancy between these two methods is not understood and must certainly be resolved if further progress is to be made in this area. The minimum impact parameter \( b_{min} \) used in calculation of the virtual photon spectra is given by

\[
b_{min} = R_{0.1}(P) + R_{0.1}(T) - d
\]

where \( R_{0.1}(P) \) and \( R_{0.1}(T) \) are the 10-percent-charge density radii of the projectile and target nuclei, respectively (refs. 26 through 28) and \( d \) is the overlap.
distance treated as an arbitrary parameter. Olson et al. (ref. 28) find good agree-
ment with experimentally determined electromagnetic dissociation cross sections by
setting $d$ equal to 1.5 fm for the JP spectrum and to -1.5 fm for the WW spectrum.
In fact with these values of $d$, one finds from table IV of reference 28 that the WW
predictions are just as accurate, if not slightly better, than the JP prediction.
The very similar results of these two methods is the reason for using the WW method
in the present work. However, if one wishes to use the JP method, it is a simple
matter to substitute the WW spectrum for the JP spectrum given on page 1531 of
reference 28.

The WW virtual photon number spectrum is given by

$$N(E) = \frac{2}{\pi} \frac{Z_t^2}{E} \left\{ x \frac{1}{\beta^2} \left[ K_0(x) K_1(x) - \frac{1}{2} \beta^2 [K_1^2(x) - K_0^2(x)] \right] \right\}$$

(3)

where $N(E)$ is the number of virtual photons per unit energy $E$, $Z_t$ is the number
of protons in the target nucleus, $\beta$ is the velocity of the target in units of $c$,
and $\alpha$ is the electromagnetic fine structure constant given by

$$\alpha = \frac{e^2}{\hbar c}$$

(4)

and the parameter $x$ in equation (3) is defined as

$$x = \frac{E b_{\text{min}}}{\gamma \beta (\hbar c)}$$

(5)

where $\gamma$ is the usual relativistic factor, and $K_0(x)$ and $K_1(x)$ are modified
Bessel functions of the second kind (refs. 36 and 37). The relation between the fre-
quency spectrum $dI/dE$ and the number spectrum is simply (ref. 35)

$$N(E) = \frac{1}{E} \frac{dI}{dE}$$

(6)

The frequency and number spectra are shown in figures 8 and 9 and are seen to be
comparable to figure 15.8 of Jackson (ref. 35) and figure 2(a) of Olson et al.
(ref. 28), respectively.

As a minor technical point concerning evaluation of the Bessel functions, a gen-
eral analytic expression for them does not exist. Jackson (ref. 35) does provide ap-
proximate expressions for them in both the low and high frequency limits; however, in
the present applications, these limits are not generally applicable and Jackson's ap-
proximations fail badly. Thus, the very good polynomial approximations of Abramowitz
and Stegun (ref. 37, pp. 378-379) are actually used here to reliably calculate the
spectra for any frequency.
PHOTONUCLEAR CROSS SECTIONS

In principle, one should really use the experimentally determined photonuclear reaction cross sections, as in reference 28. (Two excellent reviews of photonuclear reactions are given in refs. 38 and 39.) For the sake of both simplicity and generality, however, the present work uses the parameterization of the total photo-absorption cross section $\sigma_{abs}$ as developed by Westfall et al. (ref. 27). The branching ratio $g_X$ is defined by

$$\sigma_{y}(E,X) = g_X \sigma_{abs}(E)$$

and $g_X$ will be taken from experiment. Following Westfall et al. (ref. 27), it is assumed that $\sigma_{abs}$ is dominated by the electric giant dipole resonance (E1 GDR) (refs. 38 through 42) so that the present work will take $\sigma_{abs}$ to be the E1 GDR absorption cross section. (This would only be approximately true (refs. 38 and 39) if one actually used experimental cross sections.) The absorption cross section is therefore given by (ref. 27)

$$\sigma_{abs}(E) = \frac{m}{1 + \left(\frac{E^2 - E_{GDR}^2}{\Gamma^2}\right)^2}$$

where $E_{GDR}$ is the energy of the peak in the GDR cross section, $\Gamma$ is the width of the E1 GDR, and

$$\sigma_m = \frac{\sigma_{TRK}}{\pi \Gamma/2}$$

with the Thomas-Reiche-Kuhn cross section (ref. 43) given by

$$\sigma_{TRK} = \frac{60N_tZ_t}{A_t} \text{MeV-mb}$$

where $N_t$ and $A_t$ are the target neutron and mass numbers. The GDR energy is given by (ref. 27)

$$E_{GDR} = \frac{\hbar c}{\sqrt{m^*c^2R^2 \alpha \left(1 + u - \frac{1 + \epsilon + 3u}{1 + \epsilon + u} \frac{\epsilon}{\epsilon}\right)^{1/2}}}$$
with

\[ u = \frac{3J}{Q'} \frac{1}{A_t^{1/3}} \]  

and

\[ R_0 = r_0 A_t^{1/3} \]  

where \( \epsilon = 0.0768 \), \( Q' = 17 \text{ MeV} \), \( J = 36.8 \text{ MeV} \), \( r_0 = 1.18 \text{ fm} \), and \( m^* \) is \( 7/10 \) of the nucleon mass. The main uncertainties in this cross section are the values of the branching ratios \( g_X \) and the width \( \Gamma \), which can vary from 3 to 10 MeV. The widths \( \Gamma \) are smallest for closed shell nuclei and largest for nonspherical nuclei (ref. 38). Attempts to parameterize \( \Gamma \) have not been very successful (ref. 39). Similarly for the branching ratios, where calculation, for instance, may involve knowledge of direct and statistical components as well as energy level densities of neighboring nuclei (refs. 40 through 42).

Because of the uncertainties in the widths and branching ratios we have performed a detailed study by comparing theoretical cross sections with experiment as presented in figures 10 through 22. The aim of this comparison to experiment was to try to formulate an overall prescription (method) for determining \( \Gamma \) and \( g_X \) which could be applied to systems where data do not exist. In figures 10 through 13, we present data and calculations for \((\gamma,n)\) reactions on \(^{12}\text{C}\), \(^{16}\text{O}\), \(^{28}\text{Si}\), and \(^{58}\text{Ni}\). The widths fitted were 8 MeV for \(^{12}\text{C}\) and 10 MeV for the other three nuclei. A branching ratio \( g_n = 0.5 \) (suggested from equation (A7) of Westfall et al. (ref. 27)) was found to be sufficient. For the \((\gamma,n)\) reactions on \(^{90}\text{Zr}\), \(^{160}\text{Gd}\), \(^{197}\text{Au}\), and \(^{208}\text{Pb}\) (figs. 14 through 17), the widths given in figure 46 of Berman and Fultz (ref. 39) were sufficient as were branching ratios obtained from Weinstock and Halpern (ref. 44) again suggested from equation (A7) of Westfall et al. (ref. 27). For \(^{238}\text{U}(\gamma,n)\) a fit of \( \Gamma = 5 \text{ MeV} \) was required (fig. 18).

These isotopes all have a large relative abundance and we have found a general variation of the width with mass number also in accord with Berman and Fultz (ref. 39). (Note however that fig. 46 of ref. 39 is only appropriate for heavier nuclei which have GDR energies below a value of 18 MeV. Lighter nuclei, such as \(^{16}\text{O}\), have values above this.) Thus, for naturally abundant isotopes, we feel it is safe to interpolate and use width values appropriate to certain mass regions as found in figures 10 through 18; this is done in table 1.

The branching ratios in figures 10 through 18 are all described by what shall henceforth be called the branching ratio equations (BRE) defined as

\[ g_p = \text{Min} \left( \frac{Z_p}{A_p, \text{WH}} \right) \]  

(14)
and

\[ g_n = 1 - g_p \]

where equation (14) refers to the minimum value of either \( \frac{Z_p}{A_p} \) or the value given by Weinstock and Halpern in reference 44 (denoted as \( \text{WH} \) in eq. (14)). The BRE is suggested from equation (A7) of Westfall et al. (ref. 27) but note that their equation is only valid in the Fe region. The BRE fits the data in figures 10 through 18 very well.

We warn, however, that these prescriptions for the width and branching ratios are not appropriate for "nonabundant" nuclei such as \(^{18}\text{O}\) and \(^{54}\text{Fe}\) as shown in figures 19 through 22 where both \((\gamma,n)\) and \((\gamma,p)\) cross sections are given. (Experimental data for these figures are from refs. 45 and 42.) Clearly the widths are abnormal (to be suspected from ideas of the shell model) and the fitted branching ratios are quite different to those given by the BRE. The latter point should be obvious. Clearly \(^{18}\text{O}\) would prefer to decay through neutron emission and \(^{54}\text{Fe}\) through proton emission.

To summarize this comparison with the data (table I) for "abundant" nuclei, values of \( \Gamma \) can be obtained from neighboring nuclei, and branching ratios can be determined from the BRE. For "nonabundant" nuclei, values must be obtained directly from experiment.

This prescription is followed for the calculations for \(^{20}\text{Ne}, 40\text{Ar}, 40\text{Ca}, 56\text{Fe}, 64\text{Cu},\) and \(^{108}\text{Ag}\) presented in figures 23 through 28. These nuclei were chosen for present and future calculations of electromagnetic dissociation cross sections. Variations of the photoreaction cross sections with width \( \Gamma \) are shown in figures 23 through 28. The actual values to be used in calculations are given in table I and follow the prescription of the preceding paragraph.

Finally, in retrospect, one sees that the theory presented here for calculating \((\gamma,n)\) and \((\gamma,p)\) cross sections fits extremely well with the data (figs. 10 through 18), given the very large mass range considered.

ELECTROMAGNETIC DISSOCIATION CROSS SECTIONS

As noted by Olson et al. (ref. 28), the product of the number spectrum with the photoreaction cross section forms a differential electromagnetic dissociation cross section. This cross section can be defined as

\[ \frac{d\sigma_{EM}(X,E)}{dE} = \sigma_2(E,X) N(E) \]
This differential cross section is finally integrated, as prescribed in equation (1), to produce the total electromagnetic dissociation cross section. Note that because $g_X$ is assumed to be energy independent, we can also write

$$\sigma_{EM}(X) = g_X \int_{E_o(X)} \sigma_{abs}(E) N(E) \, dE$$

$$= g_X \sigma_{EM-abs}(X)$$

with

$$\sigma_{EM-abs}(X) = \int_{E_o(X)} \sigma_{abs}(E) N(E) \, dE$$

being the electromagnetic absorption cross section not to be confused with the photonuclear absorption cross section $\sigma_{abs}(E)$.

As input to the calculations, one needs the proton and neutron threshold energies $E_o(p)$ and $E_o(n)$ as discussed in appendix A and listed in table 2. One also needs the 10-percent-charge radii discussed in appendix B and listed in table 3. The complete computer code listing with sample output is listed in appendix C.

Finally one calculates the electromagnetic dissociation cross sections as listed in tables 4 through 7. The total (proton plus neutron) absorption cross sections for $^{56}$Fe at 1.88 GeV/N are given in table 4 for both $d = -1.5$ and 0 fm (see eq. (2)) and compared with the calculations of Westfall et al. (ref. 27) who assumed $d = 0$. The reason that the present values are slightly larger than those of reference 27 is because they used a slightly smaller relativistic factor $\gamma$ to account for slowing down of the projectile in the target material. In table 5, comparisons are made with experimental values for $^{12}$C and $^{16}$O incident upon various targets (ref. 26). Overall, one finds outstanding agreement between theory and experiment. Further, both values of $d$ give comparable results.

Unfortunately such is not the case for $^{18}$O as shown in table 6. The value of $g_p = 0.4$ obtained by use of figures 19 and 20 is good but is better replaced by $g_p = 0.2$ for $d = -1.5$ fm and by $g_p = 0.3$ for $d = 0$ fm. The unusual structure in the $^{18}$O($\gamma$,n) cross section (fig. 20) may account for this discrepancy.

Target fragmentation of $^{197}$Au has also been studied as shown in table 7. Here again agreement is not as good as one would like, although the agreement is reasonable and better for $d = 0$ fm.

In conclusion, we have been able to obtain reasonable agreement with a wide range of experimental results. It is suggested that a value of $d = 0$ fm be used in present and future studies. Table 8 provides a compilation of electromagnetic dissociation cross sections for use in a general fragmentation theory. Note that the cross section for $^{238}$U on heavy targets is enormous. In order to improve the Coulomb dissociation theory, the most significant advance would be to always use the experimental photonuclear cross sections (both photoneutron and photoproton) rather than
calculating them as done herein. The present work has only considered neutron and proton removal. It would be very useful to have cross sections also for few-nucleon removal such as deuterons, tritons, alphas, diprotons, and dineutrons. Again experimental cross sections would be best to use. Concerning the frequency spectrum, it should be decided whether the WW or the JP spectrum should be used (or some other form) and finally the most correct value of $d$ should be determined.

CONCLUDING REMARKS

Methods for calculating cross sections for the breakup of galactic heavy ions by the Coulomb fields of the interacting nuclei are presented. By using the Weizsäcker-Williams method of virtual quanta, estimates of electromagnetic dissociation cross sections for a variety of reactions applicable to galactic cosmic ray shielding studies are presented and compared with other predictions and with available experimental data.

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THRESHOLD ENERGIES

For the reaction

\[ M_p + M_t + M_3 + M_4 \] (A1)

where \( M_p \) and \( M_t \) refer to the projectile and target masses, respectively, the projectile threshold kinetic energy for production of \( M_3 \) and \( M_4 \) is given by

\[ T_{th} = \frac{(M_3 + M_4)^2 - (M_p + M_t)^2}{2M_t} \] (A2)

Defining the \( Q \)-value as

\[ Q = (M_p + M_t) - (M_3 + M_4) \] (A3)

equation (A2) may be written as

\[ T_{th} = \frac{-Q(M_p + M_t + M_3 + M_4)}{2M_t} \] (A4)

For photonuclear reactions

\[ M_p = 0 \] (A5)

and, therefore, for reactions like \( ^{54}\text{Fe}(\gamma,n) \) and \( ^{32}\text{S}(\gamma,d) \),

\[ T_{th} = -Q \] (A6)

to a very good approximation. Note that \( Q \) is always negative for reactions because all reactions are endothermic, whereas decays, being exothermic, have positive values of \( Q \).
For more bodies in the final state, such as

\[ M_D + M_t + M_3 + M_4 + M_5 + M_6 + \ldots + M_N \]  \hspace{1cm} (A7)

we simply have

\[ T_{th} = \frac{(M_3 + M_4 + M_5 + M_6 + \ldots + M_N)^2 - (M_D + M_t)^2}{2M_t} \]

\[ = \frac{-Q(M_D + M_t + M_3 + M_4 + M_5 + \ldots + M_N)}{2M_t} \]  \hspace{1cm} (A8)
APPENDIX B

10-PERCENT-CHARGE DENSITY RADII

As input to the electromagnetic dissociation cross sections one requires the 10-percent-charge density radii. De Jager et al. (ref. 46) list half-density radii (C) and diffuseness (z) parameters for input to density parameterizations. The parameterizations considered herein are the Harmonic-oscillator (HO) model,

$$\rho(r) = \rho_0 [1 + z(r/C)^2] \exp[-(r/C)^2] \quad (B1)$$

the 2-parameter Fermi (2pF) model,

$$\rho(r) = \frac{\rho_0}{1 + \exp[(r - C)/z]} \quad (B2)$$

the 3-parameter Fermi (3pF) model,

$$\rho(r) = \frac{\rho_0 [1 + w(r^2/C^2)]}{1 + \exp[(r - C)/z]} \quad (B3)$$

and the 3-parameter Gaussian (3pG) model

$$\rho(r) = \frac{\rho_0 [1 + w(r^2/C^2)]}{1 + \exp[r^2 - C^2]/z^2} \quad (B4)$$

For the 2pF model one can calculate the 10-percent-charge density radius by

$$R_{0.1} = C + 2.2z \quad (B5)$$

However, such a simple analytic form is not available for the other models. Thus, the general method was simply to plot the various densities and determine $R_{0.1}$ graphically. Resultant values are listed in table 3.
APPENDIX C

COMPUTER CODE

A computer program which calculates total electromagnetic dissociation cross sections for neutron and proton removal is given in this appendix. Required as input are the mass excesses of the nucleus $^{A}_Z$ in question and also the mass excesses of $^{A-1}_Z$ and $^{A-1}_{Z-1}$ in order to calculate proton and neutron thresholds. Further, the 10-percent-charge density radii, the GDR width, and the proton branching ratio are also required. Other inputs such as proton and mass numbers should cause no problem. At the end of the program is included a sample output.
PROGRAM LISTING

10 REM COULOM
20 REM
30 REM
40 REM
50 REM FIXED 2
60 REM
70 REM
80 REM NUMERICAL INTEGRATION WILL BE PERFORMED USING THE TRAPEZOIDAL RULE
90 REM
100 REM

DIM E photon(900)
DIM Sigman(900)
DIM Ne(900)

140 REM
150 REM
160 REM Fsc = Fine Structure Constant
170 Fsc=1/137.03604
180 Hbarc=197.32856
190 Mncsq=938.95
200 Mneutron=939.5731
210 Mproton=938.2796
220 Amu=931.5016
230 Mstar=7*Mncsq
240 J=36.8
250 O=17
260 Epsilon=.0768
270 INPUT "ENTER GDR WIDTH (MeV)" , Width
280 INPUT "ENTER Z OF TARGET" , Zt
290 INPUT "ENTER A OF TARGET" , At
300 Nt=At-Zt
310 INPUT "ENTER Z OF PROJECTILE" , Zp
320 INPUT "ENTER A OF PROJECTILE" , Ap
330 Np=Ap-Zp
340 INPUT "INPUT PROTON BRANCHING RATIO" , Fracproton
350 INPUT "INPUT 10 percent CHARGE DENSITY RADIUS OF TARGET (fm)" , R10t
360 INPUT "INPUT 10 percent CHARGE DENSITY RADIUS OF PROJECTILE (fm)" , R10p
370 INPUT "INPUT Dee (overlap distance) (fm)" , Dee
380 Min=R10t+R10p Dee
390 INPUT "INPUT MASSE EXCESS OF PROJECTILE FOR <gamma,n> REACTION (MeV) : use correct sign" , Mexcessp
400 PRINT "<gamma,n) REACTION HAS NUCLEUS IN FINAL STATE WITH Z = ", Zp
410 PRINT "<gamma,n) REACTION HAS NUCLEUS IN FINAL STATE WITH A = ", Ap-1
420 PRINT
430 PRINT "<gamma,p) REACTION HAS NUCLEUS IN FINAL STATE WITH Z = ", Zp-1
440 PRINT "<gamma,p) REACTION HAS NUCLEUS IN FINAL STATE WITH A = ", Ap-1
450 PRINT
460 PRINT
470 PRINT
480 INPUT "INPUT MASSE EXCESS OF FINAL NUCLEUS FOR <gamma,n> REACTION (MeV) :" , Mexcessgn
490 INPUT "INPUT MASSE EXCESS OF FINAL NUCLEUS FOR <gamma,p) REACTION (MeV) :" , Mexcessgn
500 Mexcessp=Mexcessgn+Ap Amu
510 Mexcessgn=Mexcessgn+(Ap-1) Amu
520 Mexcessgp=Mexcessgp+(Ap-1) Amu
530 Ethresgn=( (Mexcessgn+Mneutron)^2-Mproj^2)/(2 Mproj)
540 Ethresgp=( (Mexcessgp+Mproton)^2-Mproj^2)/(2 Mproj)
550 INPUT "WHAT IS K/E/H OF PROJECTILE (MeV/N) ?", Tlab
560 Gamma=1+Tlab/Mncsq
570 Vel=1/SQR(1-1/Gamma^2)
580 REM Gamma IS THE RELATIVISTIC GAMMA FACTOR OF PROJ
590 REM Vel IS VELOCITY OF PROJ IN UNITS OF c (RELATIVISTIC BETA FACTOR)
600 Sigman=120*Hbarc^2/(PI*Amu^Width)
610 Ro=1.19*Ap/(1/3)
620 \( U = \frac{3 \cdot J \cdot R}{J} \cdot \frac{-1/3}{Q} \)
630 \( \text{Egdr} = \sqrt{R \cdot (0.01 \cdot J \cdot H_{\text{barc}})^2 / (M_{\text{star}} \cdot R_o)^2} \cdot 1 / (1 + U \cdot (-E_{\text{epi}} + 3 \cdot U \cdot E_{\text{epi}} / (1 + E_{\text{epi}} + U))) \)
640 REM
650 REM NUMERICAL INTEGRATION OR PLOT
660 REM
670 PRINT "neutron THRESHOLD ENERGY IS (MeV)";E_thresh
680 PRINT "proton THRESHOLD ENERGY IS (MeV)";E_thresh
690 PRINT
700 PRINT
710 PRINT
720 IF E_thresh < E_thresh THEN E_photon = E_thresh
730 IF E_thresh > E_thresh THEN E_photon = E_thresh
740 INPUT "ENTER ENERGY UPPER LIMIT FOR NUMERICAL INTEGRATION OR PLOT (MeV)";EPhotonMax
750 INPUT "ENTER NUMBER OF INTEGRATION OR PLOT INTERVALS";NPoints
760 REM
770 REM Eint is defined as the integration or plot interval
780 REM
790 Eint = (EPhotonMax - E_photon(1)) / (Npoints - 1)
800 Sum = 0
810 Sum = 0
820 Sum = 0
830 REM
840 REM
850 REM
860 FOR I = 1 TO Npoints
870 E_photon = E_photon(I) + (I - 1) * Eint
880 E_photon(I) = E_photon
890 Sigmanu = Sigmanu / (1 + E_photon^2 - Egdr^2) / (E_photon^2 * Width^2)
900 Sigmanu(I) = Sigmanu
910 Ecutoff = Hbarc * Gamma * Vel / E_min
920 G = E_photon / Ecutoff
930 CALL BesselI(G, K0, K1)
940 Ne = 2 * Zt / 2 * Fac / E_photon * PI / Vel^2 * (G / K0 * K1 - 5 * Vel / 2 * G + K1 * 2 - K0 * 2)
950 Ne(I) = Ne
960 Function = Sigmanu * He
970 IF I = 1 THEN Function = 0.5 * Function
980 IF I = Npoints THEN Function = 0.5 * Function
990 Sum = Sum + Function
1000 Function = Frac_prot + Function
1010 Function = (1 - Frac_prot) * Function
1020 IF E_photon < E_thresh THEN Function = 0
1030 IF E_photon < E_thresh THEN Function = 0
1040 Sum = Sum + Function
1050 Sum = Sum + Function
1060 NEXT I
1070 REM
1080 REM
1090 REM
1100 Integralp = Eint * Sum
1110 Integral = Integralp + Integraln
1120 PRINT
1130 PRINT
1140 PRINT "Width (MeV)"; Width
1150 PRINT "Zt", Zt
1160 PRINT "At", At
1170 PRINT "Zp", Zp
1180 PRINT "R", R
1190 PRINT "KE/N (MeV/N)"; Tab
1200 PRINT "PHOTON ENERGY (MeV)"; E_photon
1210 PRINT
1220 PRINT
1230 PRINT
1240 PRINT
1250 PRINT "Lower limit of integration (MeV)"; E_photon(1)
1260 PRINT "Upper limit of integration (MeV)", E photonmax
1270 PRINT "Number of integration intervals is", Npts
1280 PRINT "Value of integration interval width (MeV)", E int
1290 PRINT
1300 PRINT
1310 PRINT "S gmanu (mb)", S gmanu
1320 PRINT "Sigmam (mb)", Sigmam
1330 PRINT "Ro (fm)", Ro
1340 PRINT "U", U
1350 PRINT "GDR Energy (MeV)", E gdr
1360 PRINT
1370 PRINT
1380 PRINT PROJ VELOCITY (=Beta factor)-units of c", Vel
1390 PRINT RELATIVISTIC GAMMA FACTOR OF PROJ (MeV/N)", Gamma
1400 PRINT ECutoff (MeV)", E cutoff
1410 PRINT "10 percent charge radius of target (fm) ", R10t
1420 PRINT "10 percent charge radius of projectile (fm)", R10p
1430 PRINT "Dee", Dee
1440 PRINT "Bmin (fm)", Bmin
1450 PRINT "N(E) (1/MeV)", Ne
1460 PRINT "Sigma(gamma,p) (mb)", Integralp
1470 PRINT "Sigma(gamma,n) (mb)", Integraln
1480 STOP
1490 END
1500 SUB Bessel(G,K0,K1)
1510 A1=3.5156229
1520 A2=3.0899424
1530 A3=1.2967492
1540 A4=2.6579732
1550 A5=0.3687690
1560 A6=0.045913
1570 A7=3.9894228
1580 A8=0.13285592
1590 A9=0.00225319
1600 A10=0.01575655
1610 A11=0.00916281
1620 A12=0.02057706
1630 A13=0.02635537
1640 A14=0.01647633
1650 A15=0.0092377
1660 A16=0.87680594
1670 A17=0.5148869
1680 A18=0.15084934
1690 A19=0.02658733
1700 A20=0.0031532
1710 A21=0.0092411
1720 A22=0.39894228
1730 A23=0.0399024
1740 A24=0.00362018
1750 A25=0.00163801
1760 A26=0.0181555
1770 A27=0.02292967
1780 A28=0.02695312
1790 A29=0.0177654
1800 A30=0.00420059
1810 B1=0.57721566
1820 B2=0.42278420
Note: The large array of numbers listed in the subroutine are parameters for determining the Bessel functions as given in reference 37.
SAMPLE OUTPUT

Width (MeV) 5.00
Zt 82.00
At 208.00
Zp 26.00
Rp 56.00
KE/N (MeV/N) 1800.00
PHOTON ENERGY (MeV) 50.00

Lower limit of integration (MeV) 9.37
Upper limit of integration (MeV) 50.00
Number of integration intervals is 100.00
Value of integration interval width (MeV) .41

Sigma nu (mb) 1.40
Sigma m (mb) 106.41
R0 (fm) 4.51
U 1.70
GDR Energy (MeV) 18.40

PROJ VELOCITY (=Beta factor)-units of c .94
RELATIVISTIC GAMMA FACTOR OF PROJ (MeV/N) 3.68
E cutoff (MeV) 42.61
10 percent charge radius of target (fm) 7.63
10 percent charge radius of projectile (fm) 5.28
De/ 0.00
Ein (fm) 13.11
N(E) (1/MeV) .00

Mass excess of projectile (MeV) -60.60
Mass excess of (proj - neutron) (MeV) -57.48
Mass excess of (proj - proton) (MeV) -57.71

COULOMB DISSOCIATION CROSS SECTION (Sigma nu) (mb) 902.37
Sigma(gamma,p) (mb) 258.37
Sigma(gamma,n) (mb) 644.00
SYMBOLS

A \quad \text{nucleon number}

A_p \quad \text{nucleon number of projectile}

A_t \quad \text{nucleon number of target}

BRE \quad \text{branching ratio equations}

b_{\text{min}} \quad \text{minimum impact parameter, fm}

C \quad \text{half-density radius, fm}

c \quad \text{speed of light, } 3 \times 10^8 \text{ m/sec}

d \quad \text{overlap distance, fm}

E \quad \text{energy, MeV}

E_0(X) \quad \text{threshold energy, MeV}

E_{\text{GDR}} \quad \text{giant dipole resonance energy, MeV}

e \quad \text{electronic charge, } 1.6 \times 10^{-19} \text{ coul}

GDR \quad \text{giant dipole resonance}

g_n \quad \text{neutron branching ratio}

g_p \quad \text{proton branching ratio}

g_x \quad \text{branching ratio}

\hbar \quad \text{Planck's constant, } 6.58 \times 10^{-22} \text{ MeV-sec}

I \quad \text{intensity}

J \quad \text{nuclear liquid drop parameter, } 36.8 \text{ MeV}

K_0, K_1 \quad \text{modified Bessel functions of second kind}

M \quad \text{mass, MeV/c}^2

m^* \quad 7/10 \text{ nucleon mass, } 657 \text{ MeV/c}^2

N(E) \quad \text{virtual photon number spectrum, MeV}^{-1}

N_p \quad \text{neutron number of projectile}

N_t \quad \text{neutron number of target}

n \quad \text{neutron}

P \quad \text{projectile}
P'  prefragment
p  proton
Q  Q-value, MeV
Q'  nuclear liquid drop parameter, 17 MeV
q  momentum transfer
R_o  nuclear radius, r_oA^{1/3}, fm
R_{0.1}  10-percent-charge density radius, fm
r  distance, fm
r_o  radius parameter, 1.18 fm
T  target
T'  excited target
T_{th}  threshold energy, MeV
u  nuclear liquid drop parameter
v  speed
w  nuclear density parameter
X  ablated particles
x  energy parameter
Z  proton number
Z_p  proton number of projectile
Z_t  proton number of target
z  diffuseness, fm
\alpha  electromagnetic fine structure constant, 1/137
\beta  velocity in units of c
\Gamma  GDR width, MeV
\gamma  relativistic factor
\varepsilon  nuclear liquid drop parameter, 0.0768
\rho(r)  nuclear density, fm^{-3}
\rho_o  nuclear central density, fm^{-3}
\( \sigma \) cross section, mb

\( \sigma_{\text{abs}} \) absorption cross section, mb

\( \sigma_{\text{EM}} \) electromagnetic dissociation cross section, mb

\( \sigma_{\text{EM-abs}} \) electromagnetic absorption cross section, mb

\( \sigma_m \) cross section parameter, mb

\( \sigma_{\text{TRK}} \) Thomas-Reiche-Kuhn cross section, mb

\( \sigma_\nu \) photonuclear cross section, mb
REFERENCES


23
TABLE 1.- RESONANCE WIDTHS AND PARTICLE BRANCHING RATIOS

[Numbers to left of column have been confronted with experiment, numbers to right are our estimates used in present calculations]

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$\Gamma$, MeV</th>
<th>$g_p$</th>
<th>$g_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^7$Li</td>
<td>$^9$Be</td>
<td>$^9$Be</td>
<td>$^9$Be</td>
</tr>
<tr>
<td>$^{12}$C</td>
<td>$^{16}$O</td>
<td>$^{18}$O</td>
<td>$^{20}$Ne</td>
</tr>
<tr>
<td>a8.0</td>
<td>a9.0</td>
<td>a8.0</td>
<td>c10.0</td>
</tr>
<tr>
<td>a0.4</td>
<td>b0.5</td>
<td>b0.5</td>
<td>b0.5</td>
</tr>
</tbody>
</table>

aFitted to data.
bObtained from the BRE.
cEstimate.
dTaken from Berman and Fultz (ref. 39).
TABLE 2.— GIANT DIPOLE RESONANCE ENERGIES AND PARTICLE THRESHOLDS

[ Energies were calculated by equation (1); thresholds calculated by equation (A2) ]

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>GDR energy, MeV</th>
<th>Proton threshold, MeV</th>
<th>Neutron threshold, MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}$C</td>
<td>25.6</td>
<td>15.46</td>
<td>18.74</td>
</tr>
<tr>
<td>$^{16}$O</td>
<td>24.1</td>
<td>11.62</td>
<td>15.67</td>
</tr>
<tr>
<td>$^{18}$O</td>
<td>23.5</td>
<td>15.44</td>
<td>8.05</td>
</tr>
<tr>
<td>$^{40}$Ar</td>
<td>19.8</td>
<td>12.02</td>
<td>9.87</td>
</tr>
<tr>
<td>$^{56}$Fe</td>
<td>18.4</td>
<td>9.67</td>
<td>11.20</td>
</tr>
<tr>
<td>$^{197}$Au</td>
<td>13.7</td>
<td>5.27</td>
<td>8.07</td>
</tr>
</tbody>
</table>
### TABLE 3. - THE 10-PERCENT-CHARGE DENSITY RADII

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>10-percent radius, fm</th>
<th>Model (a)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$^7$Li</td>
<td>3.04</td>
<td>HO</td>
<td></td>
</tr>
<tr>
<td>$^9$Be</td>
<td>3.32</td>
<td>HO</td>
<td></td>
</tr>
<tr>
<td>$^{12}$C</td>
<td>3.33</td>
<td>HO</td>
<td></td>
</tr>
<tr>
<td>$^{16}$O</td>
<td>3.77</td>
<td>HO</td>
<td></td>
</tr>
<tr>
<td>$^{18}$O</td>
<td>3.88</td>
<td>HO</td>
<td></td>
</tr>
<tr>
<td>$^{20}$Ne</td>
<td>4.06</td>
<td>2pF</td>
<td></td>
</tr>
<tr>
<td>$^{27}$Al</td>
<td>4.21</td>
<td>2pF</td>
<td></td>
</tr>
<tr>
<td>$^{28}$Si</td>
<td>4.18</td>
<td>2pF</td>
<td></td>
</tr>
<tr>
<td>$^{32}$S</td>
<td>4.53</td>
<td>3pF</td>
<td></td>
</tr>
<tr>
<td>$^{40}$Ar</td>
<td>4.73</td>
<td>2pF</td>
<td>3pF</td>
</tr>
<tr>
<td>$^{40}$Ca</td>
<td>4.80</td>
<td>2pF</td>
<td>3pF</td>
</tr>
<tr>
<td>$^{48}$Ti</td>
<td>5.00</td>
<td>2pF</td>
<td></td>
</tr>
<tr>
<td>$^{54}$Fe</td>
<td>5.19</td>
<td>2pF</td>
<td></td>
</tr>
<tr>
<td>$^{56}$Fe</td>
<td>5.28</td>
<td>2pF</td>
<td></td>
</tr>
<tr>
<td>$^{58}$Ni</td>
<td>5.37</td>
<td>2pF</td>
<td></td>
</tr>
<tr>
<td>$^{64}$Cu</td>
<td>5.45</td>
<td>2pF</td>
<td></td>
</tr>
<tr>
<td>$^{90}$Zr</td>
<td>5.90</td>
<td>3pG</td>
<td></td>
</tr>
<tr>
<td>$^{108}$Ag</td>
<td>6.32</td>
<td>2pF</td>
<td></td>
</tr>
<tr>
<td>$^{107}$Ag</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{160}$Cd</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{181}$Ta</td>
<td>7.79</td>
<td>2pF</td>
<td></td>
</tr>
<tr>
<td>$^{197}$Au</td>
<td>7.56</td>
<td>2pF</td>
<td></td>
</tr>
<tr>
<td>$^{208}$Pb</td>
<td>7.83</td>
<td>2pF</td>
<td>3pG</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>8.13</td>
<td>2pF</td>
<td></td>
</tr>
</tbody>
</table>

*The models are defined in appendix B and are as follows: HO, harmonic-oscillator; 2pF, 2-parameter Fermi; 3pF, 3-parameter Fermi; and 3pG, 3-parameter Gaussian.*
### TABLE 4.- CALCULATED TOTAL ELECTROMAGNETIC ABSORPTION CROSS SECTION FOR 1.88 GeV/N $^{56}$Fe INCIDENT UPON VARIOUS TARGETS

<table>
<thead>
<tr>
<th>Projectile</th>
<th>Energy, GeV/N</th>
<th>Target</th>
<th>$\sigma_{\text{EM}}$ (W), mb</th>
<th>$\sigma_{\text{EM'}}$ mb, for -</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{56}$Fe</td>
<td>1.88</td>
<td></td>
<td>(a)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^7$Li</td>
<td>2</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^9$Be</td>
<td>3</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{12}$C</td>
<td>7</td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{16}$O</td>
<td>46</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{19}$F</td>
<td>130</td>
<td>122</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{30}$Ne</td>
<td>306</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{39}$K</td>
<td>629</td>
<td>630</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{82}$Pb</td>
<td>834</td>
<td>793</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{92}$U</td>
<td>1008</td>
<td>973</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{63}$Cu</td>
<td>40</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{47}$Ag</td>
<td>122</td>
<td>140</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{73}$Ta</td>
<td>306</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{82}$Pb</td>
<td>717</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{92}$U</td>
<td>901</td>
<td></td>
</tr>
</tbody>
</table>

\(\text{aThis column represents the isotope-averaged calculations of Westfall et al. (ref. 27).}\)
<table>
<thead>
<tr>
<th>Projectile</th>
<th>Energy, GeV/N</th>
<th>Target</th>
<th>Final state</th>
<th>$\sigma_{EM}(HL)$, mb (a)</th>
<th>$\sigma_{EM}$, mb, for -</th>
<th>d = -1.5 fm</th>
<th>d = 0 fm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}C$</td>
<td>2.1</td>
<td>$^{208}Pb$</td>
<td>$^{11}C + n$</td>
<td>50 ± 18</td>
<td>46</td>
<td>54</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{11}B + p$</td>
<td>50 ± 25</td>
<td>51</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.05</td>
<td></td>
<td>$^{11}C + n$</td>
<td>38 ± 24</td>
<td>25</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{11}B + p$</td>
<td>50 ± 26</td>
<td>28</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>$^{16}O$</td>
<td>2.1</td>
<td>$^{108}Ag$</td>
<td>$^{15}O + n$</td>
<td>50 ± 25</td>
<td>67</td>
<td>78</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{15}N + p$</td>
<td>97 ± 17</td>
<td>75</td>
<td>87</td>
<td></td>
</tr>
<tr>
<td>$^{12}C$</td>
<td>2.1</td>
<td>$^{64}Cu$</td>
<td>$^{11}C + n$</td>
<td>22 ± 12</td>
<td>18</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{11}B + p$</td>
<td>20 ± 12</td>
<td>18</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.05</td>
<td></td>
<td>$^{11}C + n$</td>
<td>22 ± 12</td>
<td>10.4</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{11}B + p$</td>
<td>25 ± 20</td>
<td>11.7</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>$^{16}O$</td>
<td>2.1</td>
<td>$^{27}Al$</td>
<td>$^{15}O + n$</td>
<td>26 ± 13</td>
<td>26</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{15}N + p$</td>
<td>29 ± 18</td>
<td>29</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>$^{12}C$</td>
<td>2.1</td>
<td>$^{12}C$</td>
<td>$^{11}C + n$</td>
<td>10 ± 6</td>
<td>7.5</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{11}B + p$</td>
<td>4 ± 8</td>
<td>8.2</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.05</td>
<td></td>
<td>$^{11}C + n$</td>
<td>10 ± 7</td>
<td>4.5</td>
<td>5.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{11}B + p$</td>
<td>5 ± 8</td>
<td>5.1</td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td>$^{16}O$</td>
<td>2.1</td>
<td></td>
<td>$^{15}O + n$</td>
<td>10 ± 7</td>
<td>11</td>
<td>12.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{15}N + p$</td>
<td>14 ± 9</td>
<td>12</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>$^{12}C$</td>
<td>2.1</td>
<td></td>
<td>$^{11}C + n$</td>
<td>0 ± 3</td>
<td>1.7</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{11}B + p$</td>
<td>0 ± 3</td>
<td>1.9</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.05</td>
<td></td>
<td>$^{11}C + n$</td>
<td>1 ± 3</td>
<td>1.1</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{11}B + p$</td>
<td>1 ± 3</td>
<td>1.3</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>$^{16}O$</td>
<td>2.1</td>
<td></td>
<td>$^{15}O + n$</td>
<td>0 ± 3</td>
<td>2.5</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{15}N + p$</td>
<td>0 ± 0</td>
<td>2.7</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>$^{12}C$</td>
<td>2.1</td>
<td>$^{12}C$</td>
<td>$^{11}C + n$</td>
<td>0 ± 1</td>
<td>0.4</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{11}B + p$</td>
<td>0 ± 3</td>
<td>0.5</td>
<td>0.54</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.05</td>
<td></td>
<td>$^{11}C + n$</td>
<td>0 ± 2</td>
<td>0.3</td>
<td>0.36</td>
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<td></td>
<td></td>
<td></td>
<td>$^{11}B + p$</td>
<td>0 ± 1</td>
<td>0.3</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>$^{16}O$</td>
<td>2.1</td>
<td></td>
<td>$^{15}O + n$</td>
<td>0 ± 2</td>
<td>0.58</td>
<td>0.70</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{15}N + p$</td>
<td>0 ± 3</td>
<td>0.64</td>
<td>0.76</td>
<td></td>
</tr>
</tbody>
</table>

(a) This column represents the measurements (isotope averaged) of Heckman and Lindstrom (ref. 26).
### TABLE 6. - CALCULATED TOTAL ELECTROMAGNETIC REACTION CROSS SECTIONS FOR $^{18}_0$ AT 1.7 GeV/N INCIDENT UPON VARIOUS TARGETS

<table>
<thead>
<tr>
<th>Projectile</th>
<th>Energy, GeV/N</th>
<th>Target</th>
<th>Final state</th>
<th>$\sigma_{EM}(0)$, mb</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{18}_0$</td>
<td>1.7</td>
<td>$^{48}$Ti</td>
<td>$^{17}_0 + n$</td>
<td>8.7 ± 2.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{17}_N + p$</td>
<td>-0.5 ± 1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{208}$Pb</td>
<td>$^{17}_0 + n$</td>
<td>136 ± 2.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{17}_N + p$</td>
<td>20.2 ± 1.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{238}$U</td>
<td>$^{17}_0 + n$</td>
<td>140.8 ± 4.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{17}_N + p$</td>
<td>25.1 ± 1.6</td>
</tr>
</tbody>
</table>

*This column represents the measurements (isotope averaged) of Olson et al. (ref. 28).*

### TABLE 7. - TARGET FRAGMENTATION - CALCULATED TOTAL ELECTROMAGNETIC REACTION CROSS SECTIONS FOR VARIOUS PROJECTILES INCIDENT UPON $^{197}$Au

<table>
<thead>
<tr>
<th>Projectile</th>
<th>Energy, GeV/N</th>
<th>Target</th>
<th>Final state</th>
<th>$\sigma_{EM}(M)$, mb</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}$C</td>
<td>2.1</td>
<td>$^{197}$Au</td>
<td>$^{196}$Au + n</td>
<td>66 ± 20</td>
</tr>
<tr>
<td>$^{20}$Ne</td>
<td>2.1</td>
<td></td>
<td></td>
<td>136 ± 21</td>
</tr>
<tr>
<td>$^{40}$Ar</td>
<td>1.8</td>
<td></td>
<td></td>
<td>420 ± 120</td>
</tr>
<tr>
<td>$^{56}$Fe</td>
<td>1.7</td>
<td></td>
<td></td>
<td>680 ± 160</td>
</tr>
</tbody>
</table>

*This column represents the data of Mercier et al. (ref. 29).*
### TABLE 8.- ELECTROMAGNETIC DISSOCIATION CROSS SECTIONS FOR A VARIETY OF REACTIONS WITH $d = 0$ fm

<table>
<thead>
<tr>
<th>Projectile</th>
<th>Energy</th>
<th>$\Gamma$, MeV</th>
<th>$q_p$</th>
<th>Target</th>
<th>Final state</th>
<th>$d_{EM'}$ mb</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}$C</td>
<td>86 MeV/N</td>
<td>8.0</td>
<td>0.5</td>
<td>$^{12}$C</td>
<td>$^{11}$C + n</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>350 MeV/N</td>
<td></td>
<td></td>
<td></td>
<td>$^{11}$B + p</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>1.05 GeV/N</td>
<td></td>
<td></td>
<td>$^{107}$Ag</td>
<td>$^{11}$C + n</td>
<td>6</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$^{11}$B + p</td>
<td>7</td>
</tr>
<tr>
<td>$^{197}$Au</td>
<td>2.1 GeV/N</td>
<td></td>
<td></td>
<td>$^{197}$Au</td>
<td>$^{11}$C + n</td>
<td>31</td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td>$^{11}$B + p</td>
<td>34</td>
</tr>
<tr>
<td>$^{16}$O</td>
<td>2.1 GeV/N</td>
<td>10.0</td>
<td>0.5</td>
<td>$^9$Be</td>
<td>$^{15}$O + n</td>
<td>0.31</td>
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<tr>
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<td></td>
<td>$^{15}$N + p</td>
<td>0.34</td>
</tr>
<tr>
<td>$^{12}$C</td>
<td>1.05 GeV/N</td>
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<td></td>
<td></td>
<td>$^{15}$O + n</td>
<td>0.71</td>
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<td>$^{15}$N + p</td>
<td>0.76</td>
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<tr>
<td>$^{208}$Pb</td>
<td>2.1 GeV/N</td>
<td>10.0</td>
<td>0.45</td>
<td>$^{12}$C</td>
<td>$^{39}$Ar + n</td>
<td>1.2</td>
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<tr>
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<td></td>
<td></td>
<td></td>
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<td>$^{39}$Cl + p</td>
<td>0.9</td>
</tr>
<tr>
<td>$^{40}$Ar</td>
<td>213 MeV/N</td>
<td>10.0</td>
<td>0.45</td>
<td>$^{12}$C</td>
<td>$^{55}$Fe + n</td>
<td>5.3</td>
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<td>$^{55}$Mn + p</td>
<td>2.1</td>
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<tr>
<td>$^{56}$Fe</td>
<td>1.88 GeV/N</td>
<td>5.0</td>
<td>0.28</td>
<td>$^{108}$Ag</td>
<td>$^{55}$Fe + n</td>
<td>242</td>
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<td></td>
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<td>$^{55}$Mn + p</td>
<td>97</td>
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<td></td>
<td>$^{208}$Pb</td>
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<td></td>
<td>$^{55}$Fe + n</td>
<td>645</td>
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<td></td>
<td></td>
<td>$^{55}$Mn + p</td>
<td>258</td>
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<tr>
<td>$^{238}$U</td>
<td>900 MeV/N</td>
<td>5.0</td>
<td>0</td>
<td>$^{12}$C</td>
<td>$^{237}$U + n</td>
<td>33</td>
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<td></td>
<td></td>
<td>$^{237}$Pa + p</td>
<td>0</td>
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<tr>
<td>$^{27}$Al</td>
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<td>$^{237}$U + n</td>
<td>142</td>
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<tr>
<td>$^{28}$Si</td>
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<td>$^{237}$U + n</td>
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<td></td>
<td>$^{237}$Pa + p</td>
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<tr>
<td>$^{64}$Cu</td>
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<td>$^{237}$U + n</td>
<td>628</td>
<td></td>
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<td>$^{237}$Pa + p</td>
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<tr>
<td>$^{181}$Ta</td>
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<td>$^{237}$U + n</td>
<td>3208</td>
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<td></td>
<td>$^{237}$Pa + p</td>
<td>0</td>
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<tr>
<td>$^{208}$Pb</td>
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<td></td>
<td></td>
<td>$^{237}$U + n</td>
<td>4034</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>$^{237}$Pa + p</td>
<td>0</td>
</tr>
</tbody>
</table>
Figure 1.- Schematic diagram of peripheral fragmentation (involving one-nucleon removal) of $^{56}_{\text{Fe}}$ nucleus by $^{208}_{\text{Pb}}$ target.

Figure 2.- Schematic diagram of electromagnetic dissociation (involving one-nucleon removal) of $^{56}_{\text{Fe}}$ nucleus by $^{208}_{\text{Pb}}$ target.
Figure 3.- Reaction diagram of projectile fragmentation induced by nuclear interaction. (Final state interactions are ignored.)

Figure 4.- Reaction diagram of peripheral fragmentation involving one-nucleon removal.
Figure 5.- Reaction diagram of projectile fragmentation induced by electromagnetic interaction.

Figure 6.- Reaction diagram of electromagnetic dissociation leading to one-nucleon removal.
Figure 7. - Reaction diagram of electromagnetic dissociation induced by virtual photon field of an electron such as will be studied at CEBAF.

Figure 8. - Frequency spectrum of virtual quanta corresponding to figure 15.8 of Jackson (ref. 35) for the reaction $^{180}$O onto $^{238}$U at 1.7 GeV/N with the overlap distance $d = -1.5$ fm. The nuclear radii were taken from Olson et al. (ref. 28) and not table 3; thus, $R_{0.1}(^{238}U) = 7.92$ fm, $R_{0.1}(^{18}O) = 3.84$ fm, $b_{\text{min}} = 10.2$ fm.
Figure 9.- Number spectrum of virtual quanta as in figure 8.

Figure 10.- Theoretical and experimental photoneutron reaction cross section for $^{12}$C. Width, $\Gamma = 8$ MeV, has been adjusted to fit data. Proton branching ratio, $g_n = 0.5$, is $1 - Z_p/A_p$; thus, theoretical photoneutron and photoproton cross sections are identical.
Figure 11.- Theoretical and experimental photoneutron reaction cross section for 
$^{16}O$. Width, $\Gamma = 10$ MeV, has been adjusted to fit data. Neutron branching ratio, $g_n = 0.5$, is $1 - Z_p/A_p$; thus, theoretical photoneutron and photoproton cross sections are identical.

Figure 12.- Theoretical and experimental photoneutron reaction cross section for 
$^{28}Si$. Width, $\Gamma = 10$, has been fitted to data. Neutron branching ratio, 
$g_n = 0.5$, is $1 - Z_p/A_p$; thus, theoretical photoneutron and photoproton cross sections are identical.
Figure 13.- Theoretical and experimental photoneutron reaction cross section for $^{58}\text{Ni}$. Width, $\Gamma = 10$ MeV, has been fitted to data. Neutron branching ratio, $q_n = 0.5$, is $1 - Z_p/A_p$; thus, theoretical photoneutron and photoproton cross sections are identical.

Figure 14.- Theoretical and experimental photoneutron reaction cross section for $^{90}\text{Zr}$. Width, $\Gamma = 4$ MeV, has been obtained from figure 46 of reference 39. Neutron branching ratio, $q_n = 0.95$, is obtained from proton branching ratio, $q_p = 0.05$, given in reference 44.
Figure 15.- Theoretical and experimental photoneutron reaction cross section for $^{160}$Gd. Width, $\Gamma = 4$ MeV, has been obtained from figure 46 of reference 39. Neutron branching ratio, $q_n = 1$, is obtained from proton branching ratio, $q_p = 0$, given in reference 44.

Figure 16.- Theoretical and experimental photoneutron reaction cross section for $^{197}$Au. Width, $\Gamma = 3.5$, has been obtained by fitting and from figure 46 of reference 39. Neutron branching ratio is $q_n = 1$ (ref. 44); thus, photoproton cross section is negligible.
Figure 17.- Theoretical and experimental photoneutron reaction cross section for $^{208}\text{Pb}$. Width, $\Gamma = 3.9$, has been obtained from figure 46 of reference 39. Neutron branching ratio is $g_n = 1$ (ref. 44); thus, photoproton cross section is negligible.

Figure 18.- Theoretical and experimental photoneutron reaction cross section for $^{238}\text{U}$. Width, $\Gamma = 5$, has been fitted to data. Neutron branching ratio is $g_n = 1$ (ref. 44); thus, photoproton cross section is negligible.
Figure 19. - Theoretical and experimental photoproton reaction cross section for $^{180}$O. Width, $\Gamma = 12$ MeV, and proton branching ratio, $g_p = 0.4$, have both been adjusted to fit data.

Figure 20. - Theoretical and experimental photoneutron reaction cross section for $^{180}$O. Width, $\Gamma = 12$ MeV, and neutron branching ratio, $g_n = 0.6$, have both been adjusted to fit data.
Figure 21.- Theoretical and experimental photoproton reaction cross section for $^{54}$Fe. Width, $\Gamma = 3$ MeV, and proton branching ratio, $q_p = 0.7$, have both been adjusted to fit data.

Figure 22.- Theoretical and experimental photoneutron reaction cross section for $^{54}$Fe. Width, $\Gamma = 3$ MeV, and neutron branching ratio, $q_n = 0.3$, have both been adjusted to fit data.
Figure 23.— Theoretical photoneutron and photoproton reaction cross sections for $^{20}\text{Ne}$ for various widths. The branching ratios, $g_p = g_n = 0.5$ (table 1), indicate that photoproton and photoneutron cross sections are identical.

Figure 24.— Theoretical photoneutron and photoproton reaction cross sections for $^{40}\text{Ar}$. Widths and branching ratios are as in table 1.
Figure 25.- Theoretical photoneutron and photoproton reaction cross sections for $^{40}\text{Ca}$. The branching ratios, $q_p = q_n = 0.5$ (table 1), indicate that photoproton and photoneutron cross sections are identical.

Figure 26.- Theoretical photoneutron and photoproton reaction cross sections for $^{56}\text{Fe}$. Width, $\Gamma = 5$ MeV, is taken from Westfall et al. (ref. 27) and branching ratios are as in table 1.
Figure 27.- Theoretical photoneutron and photoproton reaction cross sections for $^{64}\text{Cu}$ for various widths. Branching ratios are as in table I.

Figure 28.- Theoretical photoneutron reaction cross section for $^{108}\text{Ag}$. Photoproton cross section is negligible; i.e., $g_p = 0$ (ref. 44).
Methods for calculating cross sections for the breakup of galactic heavy ions by the Coulomb fields of the interacting nuclei are presented. By using the Weizsäcker-Williams method of virtual quanta, estimates of electromagnetic dissociation cross sections for a variety of reactions applicable to galactic cosmic ray shielding studies are presented and compared with other predictions and with available experimental data.