Computer Program for Parameterization of Nucleus-Nucleus Electromagnetic Dissociation Cross Sections

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Symbols

\( A \) nucleon number
\( d \) overlap distance, fm
\( \text{EM} \) electromagnetic
\( E_{\text{photon max}} \) maximum photon energy, MeV
\( \text{GDR} \) giant dipole resonance
\( g_n \) neutron branching ratio
\( g_p \) proton branching ratio
\( N_{\text{pts}} \) number of integration intervals
\( R_{0.1} \) 10-percent-charge density radius, fm
\( T_{\text{th}} \) threshold energy, MeV
\( Z \) proton number
\( \Gamma \) GDR width, MeV
\( \sigma_{\text{EM}} \) electromagnetic dissociation cross section, mb
Introduction

As the United States space program heads toward the era of permanent occupation of the near-Earth environment via the habitation of a permanent Space Station, the problem of protection of astronauts from the harmful effects of cosmic radiation assumes greater and greater importance. Of special concern are the effects of galactic cosmic rays in the form of relativistic nuclei (ref. 1). When a relativistic nucleus impinges upon a spacecraft wall, it undergoes several reactions, an important one of which is fragmentation, whereby the nucleus breaks up into smaller pieces which subsequently decay. It is these secondary particles which contribute to the radiation environment inside a spacecraft. The problem of fragmentation of relativistic nuclei is the subject of a continuing research effort by the present authors and others (ref. 2). An alternative mechanism, which can produce the same sort of radiation environment as the fragmentation mechanism, is that of electromagnetic dissociation by which the electromagnetic field of one nucleus excites states in another nucleus which subsequently decay. Norbury and Townsend have led a study (ref. 3) of the significance of this mechanism to galactic heavy ion breakup and have concluded that it is of major importance (i.e., large cross section) for the removal of a few nucleons when a relativistic nucleus impinges upon a spacecraft wall. Consequently, the mechanism of the electromagnetic dissociation must be included when one is trying to predict the radiation environment in the interior of a spacecraft when the exterior environment is composed of galactic heavy ions.

In the present work, it is assumed that the photonuclear cross section is totally dominated by the giant dipole resonance (GDR) (refs. 4 through 9) and, furthermore, that the GDR decays only via single nucleon emission.

Parameterizations

The theoretical formulations of electromagnetic (EM) dissociation cross sections (ref. 3) are certainly adequate as they stand. However, because of the large number of parameters that need to be input "by hand" into the EM code (ref. 3) in an interactive session, one cannot use the EM code as an integral part of a heavy ion transport code. Thus, parameterizations are provided for the giant dipole resonance width \( \Gamma \), the 10-percent-charge density radius \( R_{0.1} \), the photoneutron and photoproton threshold energies \( T_{th} \) and branching ratios \( g_p \) and \( g_n \), the nucleus-nucleus overlap distance \( d \), and finally the number of integration intervals used in the numerical integration of the photon spectrum and photonuclear cross section.

An adequate parameterization of all of these quantities means that the only inputs required for the EM code are the projectile kinetic energy and the mass \( (A) \) and charge \( (Z) \) numbers of the projectile and target.

Giant Dipole Resonance Width

Inspection of table 1 of reference 3 indicates that light nuclei have large widths (of the order of 10 MeV) and heavy nuclei have relatively small widths (around 4-5 MeV). However, attempts to parameterize \( \Gamma \) have not been very successful (ref. 5) as it can be sensitive to nuclear structure effects. Fortunately, the EM cross sections are not very sensitive to \( \Gamma \) (ref. 3), and a very simple parameterization seems to be adequate. Thus, we take

\[
\begin{align*}
\Gamma &= 10 \text{ MeV} & (A \leq 50) \\
\Gamma &= 4.5 \text{ MeV} & (A \geq 50)
\end{align*}
\]

These values are listed for a representative sample of some nuclei in table 1, together with the values from reference 3.

Branching Ratios

Consistent with our assumption that the GDR decays only via single nucleon emission, the neutron branching ratio is

\[ g_n = 1 - g_p \]  

where it remains to parameterize \( g_p \), the proton branching ratio. We shall use the one provided by Westfall et al. (ref. 6) as

\[ g_p = \text{Min} \left[ \frac{Z}{A}, 1.95 \exp(-0.0075Z) \right] \]

which denotes the minimum value of the two quantities in brackets. Again these values are listed in table 1.

Photonuclear Reaction Thresholds

The cross section is not strongly dependent upon the particle reaction thresholds; therefore, we use 0.001 MeV to avoid obtaining an infinite value in the EM codes (note that a value of 0 MeV would cause numerical difficulty). However, the true value is on the order of 10 MeV (see table 2), and one would therefore think that this would be a poor approximation, especially as the dominant contribution to the virtual photon spectrum occurs at low energy. This effect is offset due to the giant dipole cross section becoming negligible near the threshold and therefore
contributing nothing to the total EM cross section. As a result of
\[ T_{th} = 0.001 \text{ MeV} \] (5)
(see table 2), the code now no longer requires nuclear mass excesses as input; this is a considerable improvement in simplicity.

**10-Percent-Charge Density Radius**

Nuclear radii are well parameterized by \( 1.18A^{1/3} \text{ fm} \). Motivated by this result, we investigated the possibility of adding a constant to this form in order to fit the 10-percent-charge density radii. (See table 3 of ref. 3.) The best fit was obtained with
\[ R_{0.1} = 1.18A^{1/3} + 0.75 \text{ fm} \] (6)
and the results are listed in table 3, together with the results of reference 3 where a variety of complicated models were used to calculate \( R_{0.1} \). As can be seen, equation (6) reproduces the 10-percent-charge radii very accurately.

**Overlap Distance**

The nucleus-nucleus overlap distance was chosen as
\[ d = 0 \text{ fm} \] (7)

**Integration Variables**

The simple trapezoidal rule was used in the numerical integration. A very reliable result can be obtained with the number of integration intervals being
\[ N_{pts} = 50 \] (8)
Furthermore, just as the lower limit in energy is taken as 0.001 MeV, inspection of figures 10 through 30 of reference 3 indicates that an upper energy limit
\[ E_{\text{photon max}} = 70 \text{ MeV} \] (9)
is sufficient to cover the entire GDR region. The reader is reminded that the relatively small value used in equation (9) results from the dynamics of the GDR and is not strongly dependent upon the incident kinetic energy of the projectile.

**Results**

Equations (1) through (9) summarize all the parameterizations of the nucleus-nucleus EM dissociation cross sections. The only required inputs to the new EM code (see listing in the appendix) are the projectile kinetic energy and the charge and mass numbers of the projectile and target.

The theoretical (ref. 3) and experimental GDR photonuclear reaction cross sections (refs. 5, 10, and 11), which appear in figures 1 through 13, are presented with these parameterizations. The comparison between the present work and that of reference 3 is quite good except for \(^{58}\text{Ni}\) and \(^{54}\text{Fe}\). The case of \(^{54}\text{Fe}\) is particularly bad because the present parameterization of \( g_p \) leads to poor results for nuclei far from stability. We shall return to this point later.

The total nucleus-nucleus EM dissociation cross sections are presented in tables 4 through 8. (Note that table 7 presents results for target fragmentation, whereas all the other results are for projectile fragmentation. To calculate target fragmentation with the code in the appendix, one should simply swap the projectile and target.) Also included in these tables are the calculations of reference 3. Experimental data (refs. 7, 8, and 9) are also included in tables 5, 6, and 7.

The agreement between the parameterization of \( \sigma_{EM} \) and the data is reasonably good. However, generally the parameterization gives a larger result than the projectile fragmentation data of tables 5 and 6 and a smaller result than the target fragmentation data of table 7. The reason for this is that the parameters were adjusted to give the best overall agreement with the data. Note however, that the errors associated with the data are very large. The errors in the data of Heckman and Lindstrom (ref. 7) in table 5 are typically 50 percent and those of Mercier et al. (ref. 9) in table 7 are around 25 percent. Thus, even though our parameterization agrees with the data usually within 20 percent, this very large uncertainty in the data means that the parameterizations are really as uncertain as the data. Therefore, there is a very urgent need for more accurate data.

The \(^{18}\text{O}\) (ref. 8) in table 6 has very small errors, and our parameterization typically overestimates the data. There are two reasons for this. First, the photonuclear cross section (figs. 10 and 11) displays features very different from the normal giant dipole resonance. Thus, any attempt to fit the standard GDR is bound to fail. Second, the parameterization of the branching ratio in equation (4) is most accurate for stable nuclei. For unstable nuclei like \(^{18}\text{O}\) and \(^{54}\text{Fe}\) (refer to earlier discussion), its accuracy is limited. Fortunately, however, the production cross section of these rare nuclei is reasonably small, and the corresponding inaccuracy will not manifest itself as a large inaccuracy in a transport code. Nevertheless, a good description of the electromagnetic cross sections for unstable nuclei would be valuable.
Finally, as seen from tables 4 through 8, agreement between our parameterizations and the results of reference 3 is excellent.

Concluding Remarks and Future Needs

The parameterizations presented herein are able to match the experimental data to within the uncertainty of the data. This work has demonstrated that the following points need to be further addressed (in order of importance):

1. Much more accurate data are needed
2. A more accurate theoretical model is needed to describe the photonuclear reaction cross sections; this would consequently improve the parameterizations
3. A better description of unstable nuclei (such as $^{16}$O and $^{54}$Fe) is needed, particularly
4. the branching ratios and photomuclear cross sections
5. Multiple nucleon emission should be included
6. Alternatives to the Weizsäcker-Williams method for obtaining the photon spectrum should be investigated
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8. A more accurate theoretical model is needed to describe the photonuclear reaction cross sections; this would consequently improve the parameterizations
9. A better description of unstable nuclei (such as $^{16}$O and $^{54}$Fe) is needed, particularly
10. Multiple nucleon emission should be included
11. Alternatives to the Weizsäcker-Williams method for obtaining the photon spectrum should be investigated

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Appendix

Computer Code

The computer program of reference 3 has been modified to include the parameterizations of the present work. The only required inputs are the projectile kinetic energy and the projectile and target mass and charge numbers. At the end of the program, a sample output is provided.

Program Listing

```
10 REM COULOMB PARAMETERIZATION
20 REM
30 REM
40 REM
50 REM
60 REM
70 REM
80 DIM Ephoton(900)
90 DIM Sigmanu(900)
100 DIM Ne(900)
110 REM
120 REM
130 REM Fsc = Fine Structure Constant
140 Fsc=1/137.03604
150 Hbarc=197.32858
160 Mncsq=938.95
170 Mneutron=939.5731
180 Mproton=938.2796
190 Amu=931.5016
200 Mstar=.7*Mncsq
210 J=36.8
220 Q=17
230 Epsilon=.0768
240 INPUT "ENTER Z OF TARGET",Zt
250 INPUT "ENTER A OF TARGET",At
260 Nt=At-Zt
270 INPUT "ENTER Z OF PROJECTILE",Zp
280 INPUT "ENTER A OF PROJECTILE",Ap
290 Np=Ap-Zp
300 IF Ap<50 THEN Width=10.0
310 IF Ap>=50 THEN Width=4.5
320 Frac1=1.95*EXP(-.075*Zp)
330 Frac2=Zp/Ap
340 IF Frac1=Frac2 THEN Fracproton=Frac1
350 IF Frac2>Frac1 THEN Fracproton=Frac2
360 R10t=1.18*At^(1/3)+.75
370 R10p=1.18*Ap^(1/3)+.75
380 Dee=0
390 Bmin=R10t+R10p-Dee
400 INPUT "WHAT IS KE IN OF PROJECTILE (MeV/H)?",T1ab
410 Gamma=1+T1ab/Mncsq
420 Vel=SOR(1-1/Gamma^2)
430 REM Gamma IS THE RELATIVISTIC GAMMA FACTOR OF PROJ
440 REM Vel IS VELOCITY OF PROJ IN UNITS OF C (RELATIVISTIC BETA FACTOR)
450 Sigman=120*Np*Zp/(PI*Ap*Width)
460 Ro=1.18*Ap^(1/3)
470 U=2*J*Ap^(-1/3)/Q
480 Egdr=SOR(8.0*J*Hbarc^2/(Mstar*Ro^2)*1/(1+U-(1+Epsilon+3*U)*Epsilon/(1+Epsilon+U))
490 REM
500 REM NUMERICAL INTEGRATION OR PLOT
510 REM
```
Ephoton(1) = .001
REM IF Ethreshgp>Ethreshgn THEN Ephoton(1)=Ethreshgp
Ephotonmax=70
Npts=50
REM
REM Eint is defined as the integration or plot interval
REM
Eint=(Ephotonmax-Ephoton(1))/(Npts-1)
Sum=0
Sump=0
Sumn=0
REM
FOR I=1 TO Npts
Ephoton=Ephoton(1)+(I-1)*Eint
Sigmanu=Sigmanu/(1+(Ephoton^2-Egdr^2)/2/(Ephoton^2*Width^2))
Sigmamub=Sigmanub/(1+(Ephoton^2-Egdr^2)/2/(Ephoton^2*Width^2))
Ecutoff=Hbarc*Gamma*Vel/Min
G=Ephoton/Ecutoff
CALL Bessel(K0,K1)
Ne=2*Zt^2*Fsc/(Ephoton*PI*Vel^2)+G*K0*K1-.5*Vel^2*G^2*(K1^2-K0^2)
Ne(I)=Ne
Function=Sigmanu*Ne
IF I=1 THEN Function=.5*Function
IF I=Npts THEN Function=.5*Function
Sum=Sum+Function
FOR I=1 TO Npts
Functionp=Fracproton*Function
Functionn=(1-Fracproton)*Function
IF Ephoton<Ethreshgp THEN Functionp=0
IF Ephoton<Ethreshgn THEN Functionn=0
Sump=Sump+Functionp
Sumn=Sumn+Functionn
NEXT I
REM
REM Integral p=Eint*Sump
Integral n=Eint*Sumn
Integral=Integral p+Integral n
REM
IF Ephotonmax-Egdr<48 THEN PRINT "WARNING: increase Ephotonmax"
PRINT "Width (MeV)> Width"
PRINT "Zt",Zt
PRINT "At",At
PRINT "Zp",Zp
PRINT "KE/N (MeV/N)> Tab"
PRINT "Lower limit of integration (MeV)> Ephoton(1)
PRINT "Upper limit of integration (MeV)> Ephotonmax
PRINT "Number of integration intervals is"> Npts
PRINT "Value of integration interval width (MeV)> Eint
PRINT "Ro (fm)> Ro"
PRINT "Sigmanu (mb)> Sigmanu
PRINT "Sigmam (mb)> Sigmam
PRINT "Ro (fm)> Ro"
1140 PRINT "U",U
1150 PRINT "GDR Energy (MeV)",Egdr
1160 PRINT
1170 PRINT
1180 PRINT
1190 PRINT "PROJ VELOCITY (=Beta factor)-units of c",Vel
1200 PRINT "RELATIVISTIC GAMMA FACTOR OF PROJ (MeV/N)",Gamma
1210 PRINT "Ecutoff (MeV)",Ecutoff
1220 PRINT "10 percent charge radius of target (fm) ",R10t
1230 PRINT "10 percent charge radius of projectile (fm)",R10p
1240 PRINT "Dee",Dee
1250 PRINT "Bmin (fm)",Bmin
1260 PRINT
1270 PRINT
1280 PRINT
1290 PRINT "COULOMB DISSOCIATION CROSS SECTION (Sigma(w)> (mb)",Integral
1300 PRINT
1310 PRINT "Sigma(gamma,p) (mb)",Integralp
1320 PRINT "Sigma(gamma,n) (mb)",Integraln
1330 STOP
1340 END
1350 SUB Bessel(G,K0,K1)
1360 A1=3.5156229
1370 A2=3.0899424
1380 A3=1.2067492
1390 A4=.2659732
1400 A5=.0360768
1410 A6=.0045813
1420 A7=.39894228
1430 A8=.01328592
1440 A9=.00225319
1450 A10=.00157565
1460 A11=.00916281
1470 A12=.02057706
1480 A13=.02635537
1490 A14=.01647633
1500 A15=.00392377
1510 A16=.8790594
1520 A17=.51498869
1530 A18=.15084934
1540 A19=.02658733
1550 A20=.00301532
1560 A21=.00032411
1570 A22=.39894228
1580 A23=.03988024
1590 A24=.0362018
1600 A25=.00163801
1610 A26=.01031555
1620 A27=.02262967
1630 A28=.02895312
1640 A29=.01787654
1650 A30=.00420059
1660 B1=.57721566
1670 B2=.42278420
1680 B3=.23069756
1690 B4=.00348859
1700 B5=.00262698
1710 B6=.001075
1720 B7=.0000074
1730 B8=1.25331414
1740 B9=.07832358
1750 B10=.02189568
1760  B11=.01062446
1770  B12=.00587872
1780  B13=.00251540
1790  B14=.00053208
1800  B15=.15443144
1810  B16=.67278579
1820  B17=.18156897
1830  B18=.01919402
1840  B19=.00118404
1850  B20=.0004686
1860  B21=1.25331414
1870  B22=.23498619
1880  B23=.03655620
1890  B24=.01580468
1900  B25=.00780353
1910  B26=.00325614
1920  B27=.00068245
1930  T=G/3.75
1940  IF G<=3.75 THEN I0=1+A1*T^2+A2*T^4+A3*T^6+A4*T^8+A5*T^10+A6*T^12
1950  IF G>3.75 THEN I0=1/SQR(G)*EXP(G)*(A7+A8/T+A9/T^2-A10/T^3+A11/T^4-A12/T^5+A13/T^6-A14/T^7+A15/T^8)
1970  IF G>3.75 THEN I1=1/SQR(G)*EXP(G)*(A22-A23/T-A24/T^2+A25/T^3-A26/T^4+A27/T^5-A28/T^6+A29/T^7-A30/T^8)
1980  S=G/2
1990  IF G<=2 THEN K0=-LOG(S)*I0+B1+B2*S^2+B3*S^4+B4*S^6+B5*S^8+B6*S^10+B7*S^12
2000  IF G>2 THEN K0=1/SQR(G)*EXP(-G)*(B8-B9/S+B10/S^2-B11/S^3+B12/S^4-B13/S^5+B14/S^6)
2010  IF G<=2 THEN K1=LOG(S)*I1+1/G*(1+B15*S^2-B16*S^4-B17*S^6-B18*S^8-B19*S^10-B20*S^12
2020  IF G>2 THEN K1=1/SQR(G)*EXP(-G)*(B21+B22/S-B23/S^2+B24/S^3-B25/S^4+B26/S^5-B27/S^6)
2030  SUBEND
Sample Output

| Width (MeV)  | 4.50 |
| Zt          | 82.00 |
| At          | 208.00 |
| Zp          | 26.00 |
| Ap          | 56.00 |
| KE/N (MeV/N)| 1880.00 |

| Lower limit of integration (MeV) | .00 |
| Upper limit of integration (MeV) | 70.00 |
| Number of integration intervals is | 50.00 |
| Value of integration interval width (MeV) | 1.43 |

| Sigma nu (mb)  | .56 |
| Sigma m (mb)   | 118.23 |
| Ro (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) | 3.00 |
Ecutoff (MeV) | 42.95 |
10 percent charge radius of target (fm) | 7.74 |
10 percent charge radius of projectile (fm) | 5.26 |
Dee | 0.00 |
Bmin (fm) | 13.01 |

COULOMB DISSOCIATION CROSS SECTION (Sigma nuw) (mb) | 1020.04 |

| Sigma(gamma,p) (mb) | 283.00 |
| Sigma(gamma,n) (mb) | 737.05 |
References


Table 1. Resonance Widths and Proton Branching Ratios

<table>
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<tr>
<th>Nucleus</th>
<th>$\Gamma$, MeV</th>
<th>$g_p$</th>
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<tbody>
<tr>
<td></td>
<td>Reference 3</td>
<td>Present work</td>
</tr>
<tr>
<td>$^7$Li</td>
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Table 2. Giant Dipole Resonance Particle Thresholds

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<th>Neutron threshold, MeV</th>
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<td>Reference 3</td>
<td>Present work</td>
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<td>$^{12}$C</td>
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<td>$^{197}$Au</td>
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Table 3. The 10-Percent-Charge Density Radii

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<th>Reference 3</th>
<th>Present work</th>
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<td>$^{64}\text{Cu}$</td>
<td>5.45</td>
<td>5.47</td>
</tr>
<tr>
<td>$^{90}\text{Zr}$</td>
<td>5.90</td>
<td>6.04</td>
</tr>
<tr>
<td>$^{108}\text{Ag}$ and $^{107}\text{Ag}$</td>
<td>6.32</td>
<td>6.37</td>
</tr>
<tr>
<td>$^{160}\text{Gd}$</td>
<td></td>
<td>7.16</td>
</tr>
<tr>
<td>$^{181}\text{Ta}$</td>
<td>7.79</td>
<td>7.42</td>
</tr>
<tr>
<td>$^{197}\text{Au}$</td>
<td>7.56</td>
<td>7.62</td>
</tr>
<tr>
<td>$^{208}\text{Pb}$</td>
<td>7.83</td>
<td>7.74</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>8.13</td>
<td>8.06</td>
</tr>
</tbody>
</table>
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>$\sigma_{EM}(W)$, mb ($a$)</th>
<th>$\sigma_{EM}$, mb, for $d = 0$ fm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{56}$Fe</td>
<td>1.88</td>
<td>$^{7}$Li</td>
<td>2</td>
<td>1.9, Present work</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{9}$Be</td>
<td>3</td>
<td>3.3, Present work</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{12}$C</td>
<td>7</td>
<td>7.3, Present work</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{32}$S</td>
<td>46</td>
<td>46, Present work</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{63}$Cu</td>
<td>130</td>
<td>140, Present work</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{107}$Ag</td>
<td>306</td>
<td>377, Present work</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{181}$Ta</td>
<td>629</td>
<td>717, Present work</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{208}$Pb</td>
<td>834</td>
<td>901, Present work</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{238}$U</td>
<td>1008</td>
<td>1105, Present work</td>
</tr>
</tbody>
</table>

\(a\)This column represents the isotope-averaged calculations of Westfall et al. (ref. 6).
Table 5. Calculated Total Electromagnetic Reaction Cross Sections for $^{12}\text{C}$ and $^{16}\text{O}$ Incident Upon Various Targets

<table>
<thead>
<tr>
<th>Projectile</th>
<th>Energy, GeV/N</th>
<th>Target</th>
<th>Final state</th>
<th>$\sigma_{EM}(HL)$, mb</th>
<th>$\sigma_{EM}$, mb, for $d = 0$ fm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}\text{C}$</td>
<td>2.1</td>
<td>$^{208}\text{Pb}$</td>
<td>$^{11}\text{C} + n$</td>
<td>50 ± 18</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{11}\text{B} + p$</td>
<td>50 ± 25</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>1.05</td>
<td></td>
<td>$^{11}\text{C} + n$</td>
<td>38 ± 24</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{11}\text{B} + p$</td>
<td>50 ± 26</td>
<td>36</td>
</tr>
<tr>
<td>$^{16}\text{O}$</td>
<td>2.1</td>
<td>$^{108}\text{Ag}$</td>
<td>$^{15}\text{O} + n$</td>
<td>50 ± 25</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{15}\text{N} + p$</td>
<td>97 ± 17</td>
<td>87</td>
</tr>
<tr>
<td>$^{12}\text{C}$</td>
<td>2.1</td>
<td>$^{64}\text{Cu}$</td>
<td>$^{11}\text{C} + n$</td>
<td>22 ± 12</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{11}\text{B} + p$</td>
<td>20 ± 12</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>1.05</td>
<td></td>
<td>$^{11}\text{C} + n$</td>
<td>22 ± 12</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{11}\text{B} + p$</td>
<td>25 ± 20</td>
<td>15</td>
</tr>
<tr>
<td>$^{16}\text{O}$</td>
<td>2.1</td>
<td>$^{108}\text{Ag}$</td>
<td>$^{15}\text{O} + n$</td>
<td>26 ± 13</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{15}\text{N} + p$</td>
<td>29 ± 18</td>
<td>33</td>
</tr>
<tr>
<td>$^{12}\text{C}$</td>
<td>2.1</td>
<td>$^{27}\text{Al}$</td>
<td>$^{11}\text{C} + n$</td>
<td>10 ± 6</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{11}\text{B} + p$</td>
<td>4 ± 8</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>1.05</td>
<td></td>
<td>$^{11}\text{C} + n$</td>
<td>10 ± 7</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{11}\text{B} + p$</td>
<td>5 ± 8</td>
<td>6.5</td>
</tr>
<tr>
<td>$^{16}\text{O}$</td>
<td>2.1</td>
<td>$^{12}\text{C}$</td>
<td>$^{15}\text{O} + n$</td>
<td>10 ± 7</td>
<td>12.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{15}\text{N} + p$</td>
<td>14 ± 9</td>
<td>14</td>
</tr>
<tr>
<td>$^{12}\text{C}$</td>
<td>2.1</td>
<td>$^{12}\text{C}$</td>
<td>$^{11}\text{C} + n$</td>
<td>0 ± 3</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{11}\text{B} + p$</td>
<td>0 ± 3</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>1.05</td>
<td></td>
<td>$^{11}\text{C} + n$</td>
<td>1 ± 3</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{11}\text{B} + p$</td>
<td>1 ± 3</td>
<td>1.6</td>
</tr>
<tr>
<td>$^{16}\text{O}$</td>
<td>2.1</td>
<td>$^{12}\text{C}$</td>
<td>$^{15}\text{O} + n$</td>
<td>0 ± 3</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{15}\text{N} + p$</td>
<td>0 ± 0</td>
<td>3.2</td>
</tr>
<tr>
<td>$^{12}\text{C}$</td>
<td>2.1</td>
<td>$^{12}\text{C}$</td>
<td>$^{11}\text{C} + n$</td>
<td>0 ± 1</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{11}\text{B} + p$</td>
<td>0 ± 3</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>1.05</td>
<td></td>
<td>$^{11}\text{C} + n$</td>
<td>0 ± 2</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{11}\text{B} + p$</td>
<td>0 ± 1</td>
<td>0.40</td>
</tr>
<tr>
<td>$^{16}\text{O}$</td>
<td>2.1</td>
<td>$^{12}\text{C}$</td>
<td>$^{15}\text{O} + n$</td>
<td>0 ± 2</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{15}\text{N} + p$</td>
<td>0 ± 3</td>
<td>0.76</td>
</tr>
</tbody>
</table>

aThis column represents the measurements (isotope averaged) of Heckman and Lindstrom (ref. 7).
Table 6. Calculated Total Electromagnetic Reaction Cross Sections for $^{18}\text{O}$ 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>$\sigma_{EM}(O)$, mb $(a)$</th>
<th>$\sigma_{EM}$, mb, for $d = 0$ fm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{18}\text{O}$</td>
<td>1.7</td>
<td>$^{48}\text{Ti}$</td>
<td>$^{17}\text{O} + n$</td>
<td>$8.7 \pm 2.7$</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{17}\text{N} + p$</td>
<td>$0.5 \pm 1.0$</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{17}\text{O} + n$</td>
<td>$136 \pm 2.9$</td>
<td>123</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{17}\text{N} + p$</td>
<td>$20.2 \pm 1.8$</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{17}\text{O} + n$</td>
<td>$140.8 \pm 4.1$</td>
<td>151</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{17}\text{N} + p$</td>
<td>$2.51 \pm 1.6$</td>
<td>30</td>
</tr>
</tbody>
</table>

(a) This column represents the measurements (isotope averaged) of Olson et al. (ref. 8).

Table 7. Target Fragmentation—Calculated Total Electromagnetic Reaction Cross Sections for Various Projectiles Incident Upon $^{197}\text{Au}$

<table>
<thead>
<tr>
<th>Projectile</th>
<th>Energy, GeV/N</th>
<th>Target</th>
<th>Final state</th>
<th>$\sigma_{EM}(M)$, mb $(a)$</th>
<th>$\sigma_{EM}$, mb, for $d = 0$ fm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}\text{C}$</td>
<td>2.1</td>
<td>$^{197}\text{Au}$</td>
<td>$^{196}\text{Au} + n$</td>
<td>$66 \pm 20$</td>
<td>37</td>
</tr>
<tr>
<td>$^{20}\text{Ne}$</td>
<td>2.1</td>
<td></td>
<td></td>
<td>$136 \pm 21$</td>
<td>97</td>
</tr>
<tr>
<td>$^{40}\text{Ar}$</td>
<td>1.8</td>
<td></td>
<td></td>
<td>$420 \pm 120$</td>
<td>278</td>
</tr>
<tr>
<td>$^{56}\text{Fe}$</td>
<td>1.7</td>
<td></td>
<td></td>
<td>$680 \pm 160$</td>
<td>546</td>
</tr>
</tbody>
</table>

(a) This column represents the data of Mercier et al. (ref. 9).
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>$\sigma_{EM}$, mb, for $d = 0$ fm</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, $^{11}$B + p</td>
<td>0.09, 0.11</td>
</tr>
<tr>
<td></td>
<td>350 MeV/N</td>
<td></td>
<td></td>
<td>$^{107}$Ag</td>
<td>$^{11}$C + n, $^{11}$B + p</td>
<td>6, 7</td>
</tr>
<tr>
<td></td>
<td>1.05 GeV/N</td>
<td></td>
<td></td>
<td>$^{197}$Au</td>
<td>$^{11}$C + n, $^{11}$B + p</td>
<td>31, 34</td>
</tr>
<tr>
<td></td>
<td>2.1 GeV/N</td>
<td></td>
<td></td>
<td>$^{197}$Au</td>
<td>$^{11}$C + n, $^{11}$B + p</td>
<td>53, 57</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, $^{15}$N + p</td>
<td>0.31, 0.34</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$^{12}$C</td>
<td>$^{15}$O + n, $^{15}$N + p</td>
<td>0.71, 0.76</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$^{208}$Pb</td>
<td>$^{15}$O + n, $^{15}$N + p</td>
<td>80, 87</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>$^{39}$Ar + n, $^{39}$Cl + p</td>
<td>1.2, 0.9</td>
</tr>
<tr>
<td>$^{56}$Fe</td>
<td>1.88 GeV/N</td>
<td>5.0</td>
<td>0.28</td>
<td>$^{12}$C</td>
<td>$^{55}$Fe + n, $^{55}$Mn + p</td>
<td>5.3, 2.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$^{108}$Ag</td>
<td>$^{55}$Fe + n, $^{55}$Mn + p</td>
<td>242, 97</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$^{208}$Pb</td>
<td>$^{55}$Fe + n, $^{55}$Mn + p</td>
<td>645, 258</td>
</tr>
<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, $^{237}$Pa + p</td>
<td>33, 0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$^{27}$Al</td>
<td>$^{237}$U + n, $^{237}$Pa + p</td>
<td>142, 0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$^{28}$Si</td>
<td>$^{237}$U + n, $^{237}$Pa + p</td>
<td>165, 0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$^{64}$Cu</td>
<td>$^{237}$U + n, $^{237}$Pa + p</td>
<td>628, 0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$^{181}$Ta</td>
<td>$^{237}$U + n, $^{237}$Pa + p</td>
<td>3208, 0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$^{208}$Pb</td>
<td>$^{237}$U + n, $^{237}$Pa + p</td>
<td>4034, 0</td>
</tr>
</tbody>
</table>
Theoretical, parameterized, and experimental photoneutron reaction cross sections for $^{12}\text{C}$. Theoretical $\Gamma = 8\ \text{MeV}$; Parameterized $\Gamma = 10\ \text{MeV}$; Theoretical $g_p = $ Parameterized $g_p = 0.5$; thus, photoneutron and photoproton cross sections are identical.

Figure 1.

Theoretical, parameterized, and experimental photoneutron reaction cross sections for $^{16}\text{O}$. $\Gamma = 10\ \text{MeV}$; Theoretical $g_p = $ Parameterized $g_p = 0.5$; thus, the photoneutron and photoproton cross sections are identical.

Figure 2.
Photonuclear reaction cross section, \( \text{mb} \)

Theoretical (ref. 3)  
Experimental (ref. 5)  
Parameterized

Figure 3. Theoretical, parameterized, and experimental photoneutron reaction cross sections for \(^{28}\text{Si}\). Theoretical  \( \Gamma = 10 \text{ MeV} \); Theoretical  \( g_p = 0.5 \); thus, the photoneutron and photoproton cross sections are identical.

Photonuclear reaction cross section, \( \text{mb} \)

Theoretical (ref. 3)  
Experimental (ref. 5)  
Parameterized photoneutron  
Parameterized photoproton

Figure 4. Theoretical, parameterized, and experimental photoneutron reaction cross sections for \(^{58}\text{Ni}\). Theoretical  \( \Gamma = 10 \text{ MeV} \); Parameterized  \( \Gamma = 4.5 \text{ MeV} \); Theoretical  \( g_p = 0.5 \); thus, the theoretical photoneutron and photoproton cross sections are identical; Parameterized  \( g_p = 0.24 \). Resultant parameterized photoproton cross section is also displayed.
Figure 5. Theoretical, parameterized, and experimental photoneutron reaction cross sections for $^{90}\text{Zr}$. Theoretical $\Gamma = 4$ MeV; Parameterized $\Gamma = 4.5$ MeV; Theoretical $g_p = 0.05$; Parameterized $g_p = 0.1$.

Figure 6. Theoretical, parameterized, and experimental photoneutron reaction cross sections for $^{160}\text{Gd}$. Theoretical $\Gamma = 4$ MeV; Parameterized $\Gamma = 4.5$ MeV; Theoretical $g_p = 0$; Parameterized $g_p = 0.02$. 
Figure 7. Theoretical, parameterized, and experimental photoneutron reaction cross sections for $^{197}$Au. Theoretical $\Gamma = 3.5$ MeV; Parameterized $\Gamma = 4.5$ MeV; Theoretical $g_p = 0$; Parameterized $g_p = 0.01$.

Figure 8. Theoretical, parameterized, and experimental photoneutron reaction cross sections for $^{208}$Pb. Theoretical $\Gamma = 3.9$ MeV; Parameterized $\Gamma = 4.5$ MeV; Theoretical $g_p = 0$; Parameterized $g_p = 0$. 

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Figure 9. Theoretical, parameterized, and experimental photoneutron reaction cross sections for $^{238}\text{U}$. Theoretical $\Gamma = 5$ MeV; Parameterized $\Gamma = 4.5$ MeV; Theoretical $g_p = $ Parameterized $g_p = 0$.

Figure 10. Theoretical, parameterized, and experimental photoproton reaction cross sections for $^{18}\text{O}$. Theoretical $\Gamma = 12$ MeV; Parameterized $\Gamma = 10$ MeV; Theoretical $g_p = 0.40$; Parameterized $g_p = 0.44$. 
Photonuclear reaction cross section, mb

Virtual photon energy, MeV

Figure 11. Theoretical, parameterized, and experimental photoneutron reaction cross sections for $^{18}$O. Theoretical $\Gamma = 12$ MeV; Parameterized $\Gamma = 10$ MeV; Theoretical $g_n = 0.60$; Parameterized $g_n = 0.56$.

Photonuclear reaction cross section, mb

Virtual photon energy, MeV

Figure 12. Theoretical, parameterized, and experimental photoproton reaction cross sections for $^{54}$Fe. Theoretical $\Gamma = 3$ MeV; Parameterized $\Gamma = 4.5$ MeV; Theoretical $g_p = 0.70$; Parameterized $g_p = 0.28$. 
Figure 13. Theoretical, parameterized, and experimental photoneutron reaction cross sections for $^{54}$Fe. Theoretical $\Gamma = 3$ MeV; Parameterized $\Gamma = 4.5$ MeV; Theoretical $g_n = 0.30$; Parameterized $g_n = 0.72$. 
# Computer Program for Parameterization of Nucleus-Nucleus Electromagnetic Dissociation Cross Sections

## Abstract

A computer subroutine parameterization of electromagnetic dissociation cross sections for nucleus-nucleus collisions is presented that is suitable for implementation in a heavy ion transport code. The only inputs required are the projectile kinetic energy and the projectile and target charge and mass numbers.

## Key Words

- Parameterization
- Nucleus-nucleus
- Electromagnetic dissociation
- Cross sections

## Distribution Statement

Unclassified—Unlimited

## Subject Category

73

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Washington, DC 20546-0001

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**Supplementary Notes:**

John W. Norbury: University of Idaho, Moscow, Idaho.
Lawrence W. Townsend: Langley Research Center, Hampton, Virginia.

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