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National Aeronautics
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Scientific and Technica
Information Branch

Introduction

In the approaching era of career astronauts and space workers, knowledge of galactic cosmic ray interaction and transport in bulk matter is required to accurately analyze requirements for shielding from space radiation. Although particles lighter than lithium comprise over 98 percent of the particle abundance of cosmic radiation (ref. 1, p. 47), the high-energy heavy-ion (HZE) component of galactic cosmic radiation (GCR) is expected to become of major radiobiological significance in future manned space flights. For the first time in the history of the space program, exposure to low-intensity HZE particles will accumulate to biologically significant levels. Of particular concern at present is the formation of unique biological events, called microlesions, when these HZE particles interact with tissue. Reference 2 is an excellent overview of the known biological effects of these microlesions. It is also known that high-LET (linear energy transfer) particles, which compose GCR, 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 16), a comprehensive nuclear interaction theory capable of describing incident particle absorption, total, and fragmentation cross sections has been developed for use as input to a radiation transport theory under concurrent development (refs. 17 to 20). The latter is needed for reliable analyses of self-shielding factors, as well as for determinations of personal and bulk shielding requirements. In the present report, the nuclear interaction theory is used to generate tables of nucleon, deuteron, and heavy-ion absorption cross sections for incident energies of interest in cosmic ray shielding studies. These tables represent the culmination of the development of the absorption cross section formalism and supersede the preliminary compilations published previously (refs. 7, 13, and 14). Extensive experimental data for nucleon-nucleus, deuteron-nucleus, and nucleus-nucleus collisions are compared with the tubular cross sections.

Symbols

A	nuclear mass number
a	parameter in harmonic well function, fm
$B(e)$	average slope parameter of nucleon-nucleon scattering amplitude, fm^2 or $(\text{GeV } c^{-1})^{-2}$, $[1 \text{ fm}^2 = 0.0389 (\text{GeV } c^{-1})^{-2}]$
$\mathbf{b}$	projectile impact parameter vector, fm
$\tilde{C}$	average correlation function
c	speed of light, m/sec
E_{lab}	laboratory energy of projectile per unit mass, GeV/nucleon
e	two-nucleon kinetic energy in their center-of-mass frame, GeV
$\text{Im}\ \chi(\mathbf{b})$	imaginary part of eikonal phase shift function
$\mathbf{k}$	projectile momentum vector relative to target, fm^{-1}
k_F	Fermi momentum wave number, fm^{-1}
m	nucleon mass, kg
R	radius at half-density, fm
$\mathbf{r}$	position vector, fm
r_p	proton root-mean-square charge radius, fm
s	defined in equation (12)
s_o	parameter in equation (17)
s'	square of total energy in center-of-mass reference frame, GeV^2
t	skin thickness, fm
$\tilde{t}$	average two-nucleon transition amplitude, MeV
$U(\mathbf{x})$	reduced potential, MeV^2
$W(\mathbf{x})$	optical potential (defined in eq. (4)), MeV
$\mathbf{x}$	relative position vector of projectile $(\mathbf{x} = \mathbf{b} + \mathbf{z})$, fm
$\mathbf{y}$	two-nucleon relative position vector, fm
$\mathbf{z}$	position vector of projectile in beam direction, fm
$\alpha(e)$	average ratio of real part to imaginary part of nucleon-nucleon scattering amplitude
β	defined in equation (16)
γ	harmonic well distribution parameter (see eq. (10))
ξ_T	collection of constituent relative coordinates for target, fm
$\delta(\mathbf{r})$	Dirac delta function
ρ	nuclear density, fm^{-3}

ρ_o	normalization constant in equations (10) and (13), fm^{-3}
$\sigma(e)$	average nucleon-nucleon total cross section, mb
σ_{abs}	heavy-ion absorption cross section, mb
$\chi(\mathbf{b})$	eikonal phase shift function

Subscripts:

A	matter
c	charge
n	neutron
P	projectile
p	proton
T	target

Abbreviations:

HW	harmonic well
WS	Woods-Saxon

Theoretical Development

From eikonal scattering theory, the collision absorption cross sections are given by

$$\sigma_{\text{abs}} = 2\pi \int_0^\infty \{1 - \exp[-2\,\text{Im}\,\chi(\mathbf{b})]\}\, b\, db \tag{1}$$

where the complex phase function, in terms of the reduced potential U, is

$$\chi(\mathbf{b}) = -\frac{1}{2k}\int_{-\infty}^{\infty} U(\mathbf{b}, z)\, dz \tag{2}$$

For composite particle scattering, the reduced potential is written as

$$U(\mathbf{x}) = 2mA_P A_T (A_P + A_T)^{-1} W(\mathbf{x}) \tag{3}$$

where m is the nucleon mass, A_P is the nuclear mass number of the projectile, and A_T is the nuclear mass number of the target. From references 11 and 12, the nucleus-nucleus potential including Pauli correlation effects is

$$W(\mathbf{x}) = A_P A_T \int d^3\xi_T\, \rho_T(\xi_T) \int d^3\mathbf{y}\, \rho_P(\mathbf{x} + \mathbf{y} + \xi_T) \times \tilde{t}(e, \mathbf{y})[1 - \tilde{C}(\mathbf{y})] \tag{4}$$

This potential was derived from an optical model potential approximation to the exact composite-particle multiple-scattering series and does not inherently depend on the eikonal approximation, although we are using it in that context.

In equation (4), $\tilde{t}$ is the constituent-averaged energy-dependent two-body transition amplitude

$$\tilde{t}(e, \mathbf{y}) = \left(\frac{e}{m}\right)^{1/2} \sigma(e)[\alpha(e) + i][2\pi B(e)]^{-3/2} \exp\left[\frac{-y^2}{2B(e)}\right] \tag{5}$$

and the correlation function is taken to be

$$\tilde{C}(\mathbf{y}) = 0.25 \exp\left(\frac{-k_F^2 y^2}{10}\right) \tag{6}$$

For the analyses of this work, the Fermi momentum is assumed to be that of infinite matter, $k_F = 1.36\ \text{fm}^{-1}$.

Nuclear Density Distributions

The correct nuclear density distributions $\rho_j\,(j = P, T)$ to use in equation (4) are the nuclear ground state, single-particle number densities for the collision pair. Since these are not experimentally known, the number densities are obtained from their experimental charge density distributions by assuming that

$$\rho_c(\mathbf{r}) = \int \rho_p(\mathbf{r}')\rho_A(\mathbf{r} + \mathbf{r}')\, d^3\mathbf{r}' \tag{7}$$

where ρ_c is the nuclear charge distribution, ρ_p is the proton charge distribution, and ρ_A is the desired nuclear single-particle density. All density distributions in equation (7) are normalized to unity. The proton charge distribution is taken to be the usual Gaussian form

$$\rho_p(\mathbf{r}) = \left(\frac{3}{2\pi r_p^2}\right)^{3/2} \exp\left(\frac{-3r^2}{2r_p^2}\right) \tag{8}$$

where $r_p = 0.87$ fm (ref. 21) is the proton root-mean-square charge radius.

When the projectile is a nucleon, equation (7) yields a delta function for ρ_A:

$$\rho_A(\mathbf{r} + \mathbf{r}') = \delta(\mathbf{r} + \mathbf{r}') \tag{9}$$

since ρ_c and ρ_p are identical.

For nuclei-lighter than neon ($A < 20$), the nuclear charge distribution is the harmonic well (HW) form given by reference 22 as

$$\rho_c(\mathbf{r}) = \rho_o\left[1 + \gamma\left(\frac{r}{2}\right)^2\right] \exp\left(\frac{-r^2}{a^2}\right) \tag{10}$$

where ρ_o is the normalization constant, r is the radial coordinate, and a and γ are charge parameters. Values for a and γ used herein are listed in table 1.

Substituting equations (8) and (10) into equation (7) yields (ref. 11)

$$\rho_A(\mathrm{r}) = \frac{\rho_o a^3}{8s^3}\left(1 + \frac{3\gamma}{2} - \frac{3\gamma a^2}{8s^2} + \frac{\gamma a^2 r^2}{16s^4}\right)\exp\left(\frac{-r^2}{4s^2}\right) \tag{11}$$

where

$$s^2 = \frac{a^2}{4} - \frac{r_p^2}{6} \tag{12}$$

For neon and heavier nuclei ($A > 20$), the nuclear charge distribution is taken to be the Woods-Saxon (WS) form given by reference 11:

$$\rho_c(\mathrm{r}) = \frac{\rho_o}{1 + \exp[(r - R)/c]} \tag{13}$$

where R is the radius at half-density, and the surface diffuseness c is related to the nuclear skin thickness t through

$$c = \frac{t}{4.4} \tag{14}$$

Values for R and t used herein are listed in table 1. Most values in table 1 are taken from reference 22. Inserting equations (8) and (13) into equation (7) yields, after some simplification (ref. 8), a number density ρ_A that is of the WS form (see eq. (13)) with the same R, but different overall normalization factor ρ_o and surface thickness. The latter is given by

$$t_A = \frac{8.8r_p}{3^{1/2}}\left[\ln\left(\frac{3\beta - 1}{3 - \beta}\right)\right]^{-1} \tag{15}$$

where

$$\beta = \exp\left(\frac{4.4r_p}{t_c 3^{1/2}}\right) \tag{16}$$

with t_c denoting the charge skin thickness obtained by using equation (14) and the charge distribution surface diffuseness values listed in reference 22.

Nucleon-Nucleon Scattering Parameters

The nucleon-nucleon cross sections, $\sigma(e)$, used in the energy-dependent two-body transition amplitude (eq. (5)) are obtained by performing a spline interpolation of values taken from various compilations (refs. 23 to 26). The results are displayed in figures 1 and 2 as a function of incident energy. No curve for neutron-neutron cross sections is displayed since only limited quantities of experimental data exist for these collisions. For computation purposes, we assumed that the proton-proton values for each energy listed adequately represent the neutron-neutron cross sections. Details of the constituent averaging for $\sigma(e)$ are given in reference 7.

Since scattering at these energies is mainly diffractive, the nucleon-nucleon slope parameters $B(e)$ are those appropriate to purely diffractive scattering. From reference 27 these are given by

$$B(e) = 10 + 0.5\ln\left(\frac{s'}{s_o}\right) \tag{17}$$

where s' is the square of the nucleon-nucleon center-of-mass energy and $s_o = 1(\mathrm{GeV}\ c^{-1})^{-2}$. Typical values from equation (17), displayed in figure 3, differ markedly from the nondiffractive compilation values of $B \approx 5(\mathrm{GeV}\,c^{-1})^{-2}$ used previously (refs. 13 and 14). The improved agreement between theory and experiment obtained with equation (17) is clearly demonstrated in reference 28. Values of the parameter $\alpha(e)$ are not required for these analyses, since only the imaginary part of equation (5) is utilized in equations (1) and (2).

Results

Using the formalism described in the previous sections, absorption cross sections for nucleons, deuterons, and selected heavy ions colliding with various target nuclei have been calculated. The results are given in tables 2 to 14. The projectile and target nuclei were selected for their applicability to cosmic ray shielding studies. No significant errors are expected for values obtained by interpolating between energies or target mass numbers of nuclei displayed in the tables.

Nucleon-Nucleus Cross Sections

Theoretical predictions for nucleon-nucleus scattering, from table 2, and representative experimental results (refs. 29 to 31) are compared in figures 4 to 9. Also displayed are the predictions using the empirical parameterization of reference 32. The agreement between theory, empirical predictions, and experimental data is excellent.

Deuteron-Nucleus Cross Sections

Figures 10 and 11 compare the theoretical predictions, from table 3, for deuteron-helium and deuteron-carbon scattering with experimental results from reference 33. For the helium target, theory and experiment agree to within 1 percent. For the carbon target, the disagreement between theory and experiment is less than 3 percent.

Nucleus-Nucleus Cross Section

Heavy-ion absorption cross sections, taken from tables 4 to 14, are compared with experimental data (refs. 33 to 44) in figures 12 to 21. The agreement between theory and experiment is excellent, even for energies lower than 100 MeV/nucleon where the validity of the eikonal formalism is questionable (ref. 45).

For example, at 83 MeV/nucleon (fig. 14), the discrepancy between theory and experiment (ref. 39) is less than 3 percent for all data points except the aluminum ($A = 27$) target where it is approximately 6 percent. At 30 MeV/nucleon (fig. 19), the theory and experiment (ref. 39) agree to within 10 percent. At energies greater than 100 MeV/nucleon, theory and experiment again agree to within 3 percent, and are usually within the quoted experimental uncertainties. For all these calculations, there are no arbitrarily adjusted parameters to improve the agreement between theory and experiment. These tabulated cross sections are suitably accurate for use in radiation transport and shielding analyses.

Concluding Remarks

Extensive tables of nucleon, deuteron, and heavy-ion absorption cross sections for use in cosmic ray shielding studies have been generated over a broad range of energies. Extensive comparisons of the calculated values with available experimental data show substantial agreement (within 3 percent) for energies higher than 80 MeV/nucleon. For low energies (approximately 30 MeV/nucleon), where the validity of the eikonal approximation is questionable, the disagreement between theory and experiment is only approximately 10 percent. Clearly, the tabulated cross sections are suitable for use in radiation shielding analyses, although additional experimental data are needed at all displayed energies.

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TABLE I. NUCLEAR CHARGE DISTRIBUTION PARAMETERS FROM ELECTRON SCATTERING DATA

Nucleus	Distribution*	γ (HW) or t, fm (WS)	a, fm (HW) or R, fm (WS)
^{2}H	HW	0	1.71
^{4}He	HW	0	1.33
^{7}Li	HW	.327	1.77
^{9}Be	HW	.611	1.791
^{11}B	HW	.811	1.69
^{12}C	HW	1.247	1.649
^{14}N	HW	1.291	1.729
^{16}O	HW	1.544	1.833
^{20}Ne	WS	2.517	2.74
^{27}Al	WS	2.504	3.05
^{40}Ar	WS	2.693	3.47
^{56}Fe	WS	2.611	3.971
^{64}Cu	WS	2.504	4.20
^{80}Br	WS	2.306	4.604
^{108}Ag	WS	2.354	5.139
^{138}Ba	WS	2.621	5.618
^{208}Pb	WS	2.416	6.624

*The harmonic well (HW) distribution (eq. (10)) is used for $A < 20$ and the Woods-Saxon (WS) distribution (eq. (13)) for $A \geq 20$.

TABLE 2. NUCLEON-NUCLEUS ABSORPTION CROSS SECTIONS

Energy, MeV/nucleon	Absorption cross section, millibarns, for target nucleus -										
	He	C	O	Al	Ar	Fe	Cu	Br	Ag	Ba	Pb
25	212	451	568	714	931	1078	1120	1082	1423	1763	2168
50	151	336	426	560	738	879	930	956	1236	1521	1923
75	134	303	384	515	682	821	874	913	1177	1446	1846
100	114	261	333	458	614	748	803	857	1103	1356	1750
125	103	238	305	427	575	707	762	822	1059	1302	1693
150	98	228	291	411	555	685	740	804	1035	1273	1662
175	93	218	278	396	536	665	719	785	1012	1245	1633
200	89	209	268	383	521	648	702	770	993	1222	1608
225	86	203	260	374	508	635	689	758	977	1203	1587
250	84	198	254	366	499	624	678	748	965	1188	1571
275	83	195	250	361	492	617	671	741	957	1178	1560
300	82	193	248	359	489	614	667	738	952	1172	1554
350	82	193	248	359	488	613	666	737	951	1170	1553
400	83	196	252	363	493	618	671	741	956	1176	1560
500	90	212	272	386	520	649	702	768	990	1213	1605
600	97	226	290	406	544	676	728	791	1018	1246	1643
700	101	234	299	417	557	690	743	803	1034	1264	1663
800	103	240	306	425	566	700	752	812	1044	1276	1677
900	105	243	310	430	572	707	759	817	1052	1285	1686
1000	106	246	313	433	576	711	764	821	1057	1291	1693
1250	107	248	316	436	580	715	768	825	1062	1297	1699
1500	107	248	316	436	581	716	769	826	1063	1299	1700
1750	107	248	316	436	581	716	769	826	1063	1299	1700
2000	107	247	316	436	581	716	769	826	1063	1299	1700
2500	107	246	314	435	579	714	767	825	1061	1297	1698
3000	106	244	311	432	576	710	763	822	1058	1293	1693
3500	105	243	310	430	573	708	761	820	1055	1290	1690
4000	105	242	308	429	572	706	759	819	1053	1288	1687
5000	105	241	307	427	570	704	758	818	1051	1285	1685
6000	104	240	306	426	568	703	756	816	1050	1283	1683
7000	104	239	305	424	567	701	754	815	1047	1281	1680
8000	103	238	304	423	565	699	752	814	1046	1279	1678
9000	103	237	303	422	564	698	751	813	1045	1278	1677
10000	103	237	302	422	563	697	751	812	1044	1277	1676
12500	103	236	301	421	562	696	749	811	1042	1274	1673
15000	102	235	300	419	560	693	747	809	1040	1271	1670
17500	102	234	298	417	557	691	744	807	1037	1268	1667
20000	101	233	297	416	556	689	742	806	1035	1265	1664
22500	101	233	297	415	555	688	742	805	1034	1264	1663

TABLE 3. DEUTERON-NUCLEUS ABSORPTION CROSS SECTIONS

Energy, MeV/nucleon	Absorption cross section, millibarns, for target nucleus -										
	He	C	O	Al	Ar	Fe	Cu	Br	Ag	Ba	Pb
25	449	783	929	1132	1390	1586	1649	1680	2049	2414	2928
50	301	578	698	882	1102	1286	1353	1416	1736	2053	2547
75	262	522	634	814	1023	1204	1271	1341	1648	1953	2440
100	216	454	556	729	926	1102	1169	1247	1538	1827	2304
125	194	417	514	684	874	1046	1114	1195	1478	1758	2230
150	183	400	494	662	848	1019	1086	1170	1448	1724	2193
175	173	384	475	641	824	994	1061	1146	1420	1692	2158
200	165	370	460	623	804	972	1039	1125	1396	1665	2129
225	159	360	447	610	788	955	1022	1109	1377	1643	2105
250	155	352	438	599	776	943	1009	1097	1363	1627	2088
275	152	347	432	593	769	934	1001	1089	1354	1617	2076
300	151	344	429	589	765	930	997	1085	1349	1612	2071
350	151	344	429	589	765	930	997	1085	1349	1612	2071
400	153	349	435	595	772	938	1004	1092	1358	1621	2081
500	168	375	465	629	811	980	1047	1132	1404	1674	2139
600	182	398	492	659	845	1016	1083	1167	1445	1720	2189
700	189	410	506	675	864	1036	1103	1185	1466	1744	2215
800	195	419	516	686	876	1049	1116	1198	1481	1761	2233
900	198	425	523	693	885	1058	1126	1207	1491	1772	2246
1000	201	429	527	698	890	1064	1131	1212	1497	1780	2254
1250	202	432	531	702	895	1069	1136	1216	1502	1786	2260
1500	203	432	531	702	895	1069	1136	1217	1503	1786	2260
1750	202	432	531	702	895	1069	1136	1217	1503	1786	2260
2000	202	431	530	702	894	1068	1136	1216	1502	1785	2260
2500	201	429	528	699	891	1065	1132	1213	1498	1781	2255
3000	199	426	524	695	887	1060	1128	1209	1493	1775	2249
3500	197	424	521	692	883	1057	1124	1206	1489	1771	2244
4000	196	422	520	690	881	1054	1122	1203	1487	1768	2241
5000	196	421	518	688	879	1052	1120	1202	1485	1765	2239
6000	195	419	516	686	877	1050	1117	1200	1482	1762	2235
7000	193	417	514	684	874	1047	1114	1197	1479	1759	2231
8000	192	416	512	682	871	1044	1112	1195	1476	1756	2228
9000	192	415	511	681	870	1043	1111	1193	1475	1754	2226
10000	192	414	510	680	869	1042	1110	1193	1474	1753	2225
12500	191	413	509	679	868	1040	1108	1191	1472	1751	2223
15000	190	411	507	676	865	1037	1105	1189	1469	1747	2219
17500	188	409	504	674	862	1034	1102	1186	1466	1743	2215
20000	187	407	502	671	859	1032	1099	1183	1463	1740	2212
22500	187	406	501	670	858	1031	1098	1182	1462	1739	2210

TABLE 4. HELIUM-NUCLEUS ABSORPTION CROSS SECTIONS

Energy, MeV/nucleon	Absorption cross section, millibarns, for target nucleus - He	C	O	Al	Ar	Fe	Cu	Br	Ag	Ba	Pb
25	440	776	934	1129	1405	1585	1630	1595	1993	2390	2867
50	334	620	752	928	1162	1337	1391	1404	1750	2095	2566
75	305	578	702	873	1098	1271	1326	1350	1683	2014	2482
100	270	525	641	807	1019	1189	1246	1282	1599	1914	2378
125	251	496	607	771	975	1145	1203	1245	1554	1860	2322
150	242	482	591	753	956	1123	1182	1227	1531	1834	2294
175	234	469	576	737	936	1103	1162	1210	1510	1809	2267
200	227	458	563	723	920	1086	1145	1195	1493	1788	2246
225	221	450	553	712	907	1073	1132	1184	1479	1772	2228
250	217	443	546	704	898	1063	1122	1175	1468	1759	2215
275	214	439	541	699	892	1056	1116	1169	1461	1751	2206
300	213	437	539	696	889	1053	1113	1167	1458	1747	2202
350	213	437	539	697	889	1053	1113	1167	1458	1748	2202
400	215	441	543	701	894	1059	1118	1172	1464	1755	2210
500	229	462	568	728	926	1092	1151	1201	1499	1796	2253
600	241	481	590	752	954	1121	1180	1225	1529	1831	2291
700	248	491	601	764	968	1137	1195	1239	1546	1851	2311
800	252	498	609	773	979	1147	1205	1248	1557	1864	2325
900	255	503	615	779	986	1154	1213	1254	1564	1873	2335
1000	257	506	618	783	990	1159	1217	1258	1569	1878	2341
1250	259	508	621	786	994	1163	1221	1261	1573	1883	2346
1500	259	508	621	786	994	1163	1222	1262	1574	1884	2346
1750	259	508	621	786	994	1163	1222	1262	1574	1884	2346
2000	259	508	621	786	994	1163	1221	1262	1573	1883	2346
2500	258	507	619	784	991	1161	1219	1260	1571	1880	2343
3000	257	504	617	781	988	1157	1216	1257	1567	1876	2339
3500	256	503	615	779	985	1154	1213	1255	1565	1873	2335
4000	255	501	613	777	984	1153	1211	1253	1563	1871	2333
5000	254	501	612	776	982	1151	1210	1253	1562	1869	2332
6000	254	500	611	775	981	1150	1208	1251	1560	1867	2330
7000	253	498	609	773	978	1147	1206	1250	1558	1864	2327
8000	252	497	608	772	977	1146	1205	1248	1556	1862	2325
9000	252	496	607	771	976	1145	1204	1248	1555	1861	2324
10000	251	496	607	771	975	1144	1203	1248	1555	1861	2323
12500	251	495	606	770	974	1143	1202	1247	1554	1859	2322
15000	250	494	604	768	972	1141	1200	1245	1552	1857	2319
17500	249	493	603	766	970	1139	1198	1244	1550	1854	2317
20000	248	491	601	765	968	1137	1196	1242	1548	1852	2314
22500	248	491	601	764	968	1136	1196	1242	1547	1851	2313

TABLE 5. LITHIUM-NUCLEUS ABSORPTION CROSS SECTIONS

Energy, MeV/nucleon	Absorption cross section, millibarns, for target nucleus –										
	He	C	O	Al	Ar	Fe	Cu	Br	Ag	Ba	Pb
25	697	1111	1294	1529	1841	2056	2116	2114	2547	2975	3526
50	532	895	1052	1268	1540	1748	1815	1852	2236	2614	3153
75	487	836	986	1198	1459	1665	1733	1780	2151	2516	3051
100	432	763	905	1111	1360	1562	1632	1688	2044	2394	2922
125	402	724	861	1064	1307	1507	1577	1639	1986	2328	2852
150	388	705	840	1042	1281	1480	1551	1615	1959	2296	2819
175	375	688	820	1020	1257	1455	1526	1592	1932	2267	2787
200	364	673	803	1003	1237	1434	1505	1573	1910	2242	2760
225	355	661	790	989	1221	1418	1489	1558	1893	2222	2739
250	348	652	780	978	1209	1405	1476	1547	1880	2207	2723
275	344	647	774	972	1202	1398	1468	1540	1871	2197	2713
300	342	644	771	968	1198	1394	1465	1536	1867	2193	2708
350	342	644	771	968	1198	1394	1465	1536	1868	2193	2708
400	346	649	777	974	1205	1401	1472	1543	1875	2202	2718
500	367	678	809	1009	1245	1443	1514	1581	1920	2253	2772
600	387	704	838	1040	1280	1479	1550	1615	1958	2297	2818
700	397	717	853	1056	1299	1498	1569	1632	1979	2321	2843
800	404	726	863	1067	1312	1512	1582	1644	1993	2337	2860
900	409	733	871	1075	1321	1521	1591	1653	2003	2348	2872
1000	412	737	875	1080	1326	1527	1597	1658	2009	2355	2879
1250	414	740	879	1084	1331	1531	1602	1662	2014	2360	2885
1500	415	741	879	1084	1331	1532	1602	1663	2014	2361	2885
1750	414	741	879	1084	1331	1532	1602	1663	2014	2360	2885
2000	414	740	879	1084	1330	1531	1602	1662	2014	2360	2885
2500	413	738	876	1081	1327	1528	1598	1659	2010	2356	2881
3000	410	735	873	1077	1323	1523	1594	1655	2006	2351	2875
3500	408	732	870	1074	1319	1520	1590	1652	2002	2346	2871
4000	407	731	868	1072	1317	1518	1588	1650	2000	2344	2868
5000	406	730	867	1071	1316	1516	1587	1649	1998	2342	2866
6000	405	728	865	1069	1313	1514	1585	1647	1996	2339	2863
7000	403	726	862	1067	1311	1511	1582	1645	1993	2336	2860
8000	402	724	861	1065	1308	1509	1579	1643	1991	2333	2857
9000	401	723	860	1064	1307	1507	1578	1642	1989	2332	2855
10000	401	723	859	1063	1307	1507	1578	1641	1989	2331	2855
12500	400	722	858	1062	1305	1505	1576	1640	1987	2329	2853
15000	399	720	856	1060	1303	1503	1574	1638	1985	2326	2850
17500	397	718	853	1057	1300	1500	1571	1636	1982	2323	2846
20000	396	716	851	1055	1297	1497	1569	1634	1979	2320	2843
22500	395	715	851	1054	1296	1496	1568	1633	1978	2319	2842

TABLE 6. BERYLLIUM-NUCLEUS ABSORPTION CROSS SECTIONS

Energy, MeV/nucleon	Absorption cross section, millibarns, for target nucleus -										
	He	C	O	Al	Ar	Fe	Cu	Br	Ag	Ba	Pb
25	772	1207	1399	1644	1970	2191	2251	2242	2692	3136	3698
50	600	985	1151	1377	1662	1877	1944	1978	2377	2770	3322
75	553	924	1083	1304	1579	1792	1861	1904	2291	2671	3218
100	495	849	999	1215	1477	1687	1758	1812	2183	2547	3089
125	464	809	954	1167	1423	1630	1702	1761	2124	2481	3019
150	449	789	933	1144	1397	1603	1675	1737	2096	2449	2985
175	434	771	912	1122	1372	1578	1650	1714	2069	2418	2953
200	423	755	895	1104	1352	1556	1629	1695	2047	2393	2926
225	413	743	881	1090	1335	1539	1612	1680	2029	2373	2904
250	406	734	871	1079	1323	1527	1599	1668	2016	2358	2888
275	402	728	865	1072	1315	1519	1591	1661	2008	2348	2878
300	399	725	861	1069	1312	1515	1587	1657	2004	2344	2873
350	399	725	861	1069	1312	1515	1588	1658	2004	2344	2873
400	404	731	867	1075	1319	1522	1595	1664	2012	2353	2883
500	427	761	901	1111	1360	1565	1637	1703	2056	2404	2937
600	447	787	930	1142	1396	1602	1674	1737	2095	2449	2984
700	458	801	946	1159	1415	1621	1694	1754	2116	2473	3009
800	465	811	957	1170	1428	1635	1707	1767	2130	2489	3025
900	471	818	964	1178	1437	1644	1716	1775	2140	2500	3037
1000	474	822	969	1184	1443	1650	1722	1780	2146	2507	3045
1250	477	825	973	1188	1447	1655	1727	1785	2151	2512	3051
1500	477	826	973	1188	1447	1655	1727	1785	2152	2513	3051
1750	477	826	973	1188	1447	1655	1727	1785	2152	2513	3051
2000	477	825	973	1187	1447	1655	1727	1785	2151	2512	3051
2500	475	823	970	1185	1444	1652	1723	1782	2148	2508	3047
3000	472	820	966	1181	1439	1647	1719	1778	2143	2503	3041
3500	470	817	964	1178	1436	1643	1715	1775	2140	2499	3037
4000	469	816	962	1176	1434	1641	1713	1773	2137	2496	3034
5000	468	814	960	1174	1432	1640	1712	1772	2136	2494	3032
6000	467	813	959	1172	1430	1637	1709	1770	2134	2492	3029
7000	465	811	956	1170	1427	1634	1707	1767	2131	2488	3026
8000	464	809	954	1168	1425	1632	1704	1766	2128	2485	3023
9000	463	808	953	1167	1423	1631	1703	1765	2127	2484	3022
10000	463	808	953	1166	1423	1630	1703	1764	2127	2483	3021
12500	462	806	951	1165	1421	1629	1701	1763	2125	2482	3019
15000	460	804	949	1163	1419	1626	1699	1761	2123	2479	3016
17500	458	802	947	1160	1416	1623	1696	1758	2120	2475	3013
20000	457	801	945	1158	1413	1621	1693	1756	2117	2472	3010
22500	456	800	944	1157	1412	1620	1692	1756	2116	2471	3008

TABLE 7. BORON-NUCLEUS ABSORPTION CROSS SECTIONS

Energy, MeV/nucleon	Absorption cross section, millibarns, for target nucleus - He	C	O	Al	Ar	Fe	Cu	Br	Ag	Ba	Pb
25	770	1207	1402	1647	1980	2196	2251	2224	2682	3137	3689
50	610	997	1167	1391	1682	1893	1957	1975	2383	2785	3329
75	567	940	1102	1322	1602	1812	1877	1906	2301	2690	3231
100	513	869	1023	1237	1504	1711	1779	1820	2199	2572	3108
125	484	831	980	1191	1452	1658	1726	1773	2144	2508	3041
150	469	813	960	1169	1427	1632	1701	1750	2117	2478	3009
175	456	795	940	1149	1404	1607	1676	1729	2092	2449	2979
200	445	781	924	1131	1384	1587	1656	1711	2071	2425	2954
225	436	769	911	1118	1368	1571	1640	1697	2054	2406	2933
250	430	761	901	1108	1357	1559	1629	1686	2041	2391	2918
275	426	755	895	1101	1349	1551	1621	1679	2033	2382	2909
300	424	752	892	1098	1346	1547	1617	1676	2030	2378	2904
350	424	753	892	1098	1346	1547	1617	1676	2030	2378	2904
400	427	757	898	1104	1353	1554	1624	1682	2037	2387	2913
500	449	786	930	1138	1392	1595	1664	1718	2079	2435	2964
600	468	811	957	1168	1425	1630	1699	1750	2116	2477	3008
700	478	824	972	1184	1444	1649	1718	1766	2136	2500	3032
800	485	833	983	1195	1457	1662	1730	1778	2149	2515	3048
900	490	840	990	1202	1465	1671	1739	1786	2158	2526	3059
1000	493	844	994	1207	1471	1676	1745	1791	2164	2533	3066
1250	496	847	998	1211	1475	1681	1750	1795	2169	2538	3072
1500	496	847	998	1211	1476	1681	1750	1795	2169	2538	3072
1750	496	847	998	1211	1476	1681	1750	1795	2169	2538	3072
2000	496	847	998	1211	1475	1681	1750	1795	2169	2538	3072
2500	494	845	995	1208	1472	1678	1747	1793	2166	2534	3068
3000	492	842	992	1205	1468	1674	1742	1789	2162	2529	3063
3500	490	839	989	1202	1465	1670	1739	1786	2158	2525	3059
4000	489	838	988	1200	1463	1668	1737	1784	2156	2523	3056
5000	488	837	986	1199	1461	1667	1736	1783	2155	2521	3055
6000	487	835	985	1197	1459	1665	1734	1782	2153	2519	3052
7000	485	833	982	1195	1456	1662	1731	1779	2150	2515	3049
8000	484	832	981	1193	1454	1660	1729	1778	2148	2513	3046
9000	483	831	980	1192	1453	1659	1728	1777	2147	2512	3045
10000	483	831	979	1191	1453	1658	1727	1776	2146	2511	3044
12500	482	830	978	1190	1451	1657	1726	1776	2145	2509	3043
15000	481	828	976	1188	1449	1654	1724	1774	2143	2507	3040
17500	480	826	974	1186	1446	1651	1721	1771	2140	2504	3037
20000	478	824	972	1184	1444	1649	1719	1770	2138	2501	3034
22500	478	824	971	1183	1443	1648	1718	1769	2137	2500	3033

TABLE 8. CARBON-NUCLEUS ABSORPTION CROSS SECTIONS

Energy, MeV/nucleon	Absorption cross section, millibarns, for target nucleus - He	C	O	Al	Ar	Fe	Cu	Br	Ag	Ba	Pb
25	776	1215	1412	1659	1996	2211	2263	2227	2691	3153	3701
50	620	1010	1181	1406	1701	1911	1974	1986	2398	2806	3348
75	577	953	1118	1338	1622	1831	1895	1919	2318	2712	3251
100	524	884	1040	1254	1526	1732	1799	1835	2218	2596	3131
125	496	847	998	1210	1474	1679	1747	1789	2164	2534	3066
150	482	828	977	1188	1449	1653	1721	1767	2138	2503	3034
175	469	811	958	1167	1426	1629	1698	1746	2113	2475	3004
200	458	797	942	1150	1406	1609	1678	1728	2092	2451	2979
225	450	786	930	1137	1391	1593	1662	1714	2076	2432	2959
250	443	777	920	1127	1379	1581	1650	1704	2063	2418	2944
275	439	772	914	1120	1372	1574	1643	1697	2056	2409	2935
300	437	769	911	1117	1368	1570	1639	1694	2052	2404	2930
350	437	769	911	1117	1368	1570	1639	1694	2052	2404	2930
400	441	774	916	1123	1375	1577	1646	1700	2059	2413	2939
500	462	802	948	1157	1413	1616	1685	1735	2100	2460	2988
600	481	827	975	1186	1447	1651	1719	1765	2135	2501	3031
700	491	840	990	1202	1465	1669	1737	1781	2154	2523	3054
800	498	849	1000	1212	1477	1682	1750	1792	2167	2538	3070
900	502	855	1007	1220	1486	1691	1759	1800	2176	2548	3081
1000	506	859	1012	1225	1491	1697	1764	1805	2182	2555	3088
1250	508	862	1015	1228	1496	1701	1769	1809	2187	2560	3094
1500	508	863	1015	1229	1496	1702	1769	1809	2188	2561	3094
1750	508	863	1015	1229	1496	1702	1769	1809	2188	2561	3094
2000	508	862	1015	1228	1496	1701	1769	1809	2187	2560	3094
2500	506	860	1013	1226	1493	1698	1766	1807	2185	2557	3090
3000	504	857	1009	1222	1488	1694	1762	1803	2180	2552	3085
3500	502	855	1007	1220	1485	1691	1759	1801	2177	2548	3081
4000	501	853	1005	1218	1483	1689	1757	1799	2175	2546	3079
5000	500	852	1004	1217	1482	1687	1755	1798	2174	2544	3077
6000	499	851	1002	1215	1480	1685	1753	1797	2172	2542	3075
7000	498	849	1000	1213	1477	1683	1751	1794	2169	2539	3072
8000	497	848	999	1211	1475	1681	1749	1793	2167	2536	3069
9000	496	847	998	1210	1474	1679	1748	1792	2166	2535	3068
10000	496	846	997	1210	1473	1679	1747	1792	2166	2534	3068
12500	495	845	996	1208	1472	1678	1746	1791	2164	2533	3066
15000	494	844	994	1206	1470	1675	1744	1789	2162	2530	3063
17500	492	842	992	1204	1467	1672	1741	1787	2160	2527	3060
20000	491	840	990	1202	1465	1670	1739	1785	2157	2525	3058
22500	491	840	989	1202	1464	1669	1738	1784	2157	2524	3057

TABLE 9. NITROGEN-NUCLEUS ABSORPTION CROSS SECTIONS

Energy, MeV/nucleon	He	C	O	Al	Ar	Fe	Cu	Br	Ag	Ba	Pb
	Absorption cross section, millibarns, for target nucleus -										
25	844	1302	1506	1761	2108	2329	2384	2350	2825	3296	3857
50	676	1086	1264	1498	1802	2019	2084	2098	2521	2939	3493
75	633	1027	1198	1427	1721	1936	2003	2027	2437	2842	3393
100	577	954	1117	1340	1621	1834	1902	1940	2334	2722	3270
125	546	915	1073	1293	1568	1779	1849	1892	2278	2658	3203
150	532	896	1052	1271	1542	1752	1823	1869	2251	2627	3170
175	518	878	1032	1250	1517	1727	1798	1847	2225	2597	3139
200	506	863	1015	1232	1497	1707	1778	1829	2204	2573	3114
225	497	851	1002	1218	1481	1690	1761	1815	2187	2553	3093
250	490	843	992	1207	1469	1678	1749	1804	2174	2539	3078
275	486	837	986	1201	1462	1670	1741	1797	2166	2529	3068
300	484	834	982	1197	1458	1666	1737	1793	2162	2525	3063
350	484	834	983	1197	1458	1666	1738	1794	2162	2525	3063
400	488	839	988	1203	1465	1673	1745	1800	2170	2533	3072
500	510	869	1021	1238	1504	1714	1785	1836	2212	2582	3123
600	530	894	1050	1269	1539	1750	1820	1867	2248	2624	3167
700	541	908	1065	1285	1558	1769	1839	1884	2268	2646	3191
800	548	917	1075	1296	1571	1782	1852	1896	2282	2662	3207
900	553	924	1083	1304	1579	1791	1861	1904	2291	2673	3218
1000	557	928	1087	1309	1585	1797	1867	1909	2297	2679	3225
1250	559	932	1091	1313	1590	1802	1871	1913	2302	2685	3231
1500	559	932	1091	1313	1590	1802	1872	1914	2302	2686	3232
1750	559	932	1091	1313	1590	1802	1872	1914	2303	2686	3232
2000	559	932	1091	1313	1590	1802	1871	1913	2302	2685	3231
2500	557	929	1089	1310	1587	1799	1869	1911	2299	2682	3228
3000	555	926	1085	1307	1582	1795	1864	1907	2295	2677	3223
3500	553	924	1082	1304	1579	1791	1861	1905	2291	2673	3219
4000	552	922	1081	1302	1577	1789	1859	1903	2289	2670	3216
5000	551	921	1079	1301	1576	1788	1857	1902	2288	2669	3214
6000	550	920	1078	1299	1573	1785	1855	1900	2286	2666	3212
7000	548	918	1075	1296	1571	1783	1853	1898	2283	2663	3209
8000	547	916	1074	1295	1569	1781	1851	1896	2281	2660	3206
9000	547	915	1073	1294	1567	1779	1850	1895	2280	2659	3205
10000	546	915	1072	1293	1567	1779	1849	1895	2280	2659	3204
12500	545	914	1071	1292	1565	1777	1848	1894	2278	2657	3203
15000	544	912	1069	1290	1563	1775	1845	1892	2276	2654	3200
17500	542	910	1067	1288	1560	1772	1843	1890	2273	2651	3197
20000	541	909	1065	1286	1558	1770	1841	1888	2271	2648	3194
22500	541	908	1064	1285	1557	1769	1840	1887	2270	2647	3193

TABLE 10. OXYGEN-NUCLEUS ABSORPTION CROSS SECTIONS

Energy, MeV/nucleon	Absorption cross section, millibarns, for target nucleus -										
	He	C	O	Al	Ar	Fe	Cu	Br	Ag	Ba	Pb
25	929	1408	1619	1884	2241	2471	2529	2501	2986	3467	4046
50	750	1178	1363	1608	1922	2148	2215	2234	2668	3096	3668
75	700	1116	1293	1533	1837	2061	2130	2160	2581	2995	3564
100	639	1038	1207	1441	1732	1953	2025	2067	2472	2871	3434
125	606	996	1161	1392	1676	1896	1969	2017	2414	2804	3365
150	590	976	1138	1368	1649	1868	1942	1993	2385	2771	3331
175	575	957	1117	1346	1624	1842	1916	1970	2358	2740	3299
200	562	941	1099	1327	1603	1820	1894	1950	2336	2715	3272
225	552	928	1086	1312	1586	1803	1877	1935	2318	2695	3251
250	545	919	1075	1301	1573	1790	1865	1924	2305	2680	3235
275	540	913	1068	1294	1565	1782	1856	1916	2296	2670	3225
300	538	910	1065	1290	1561	1778	1852	1913	2292	2665	3219
350	538	910	1065	1290	1561	1778	1852	1913	2292	2665	3220
400	542	915	1071	1297	1569	1785	1860	1919	2300	2674	3229
500	567	946	1106	1334	1610	1828	1902	1957	2344	2724	3282
600	589	974	1136	1366	1647	1866	1939	1991	2383	2768	3328
700	600	988	1152	1383	1666	1886	1959	2008	2403	2792	3352
800	608	998	1163	1395	1680	1899	1972	2020	2417	2808	3369
900	614	1005	1171	1403	1689	1909	1982	2029	2427	2819	3381
1000	617	1010	1176	1408	1695	1915	1988	2034	2434	2826	3388
1250	620	1014	1180	1412	1700	1920	1993	2039	2439	2832	3394
1500	620	1014	1180	1413	1700	1920	1993	2039	2439	2832	3395
1750	620	1014	1180	1413	1700	1921	1993	2039	2439	2832	3395
2000	620	1014	1180	1412	1700	1920	1993	2039	2439	2832	3395
2500	618	1011	1177	1410	1696	1917	1990	2037	2436	2828	3391
3000	615	1008	1174	1406	1692	1912	1985	2033	2431	2823	3385
3500	613	1005	1171	1403	1688	1909	1982	2030	2428	2819	3381
4000	612	1004	1169	1401	1686	1906	1979	2028	2426	2816	3378
5000	611	1002	1168	1399	1685	1905	1978	2027	2424	2815	3377
6000	610	1001	1166	1397	1682	1903	1976	2025	2422	2812	3374
7000	608	999	1163	1395	1679	1900	1973	2023	2419	2809	3371
8000	607	997	1161	1393	1677	1898	1971	2021	2417	2806	3368
9000	606	996	1160	1392	1676	1896	1970	2020	2416	2805	3367
10000	606	996	1160	1391	1675	1896	1969	2019	2415	2804	3366
12500	605	994	1159	1390	1674	1894	1968	2018	2414	2802	3364
15000	603	993	1157	1388	1671	1892	1965	2016	2411	2799	3361
17500	602	990	1154	1385	1668	1889	1962	2014	2408	2796	3358
20000	600	989	1152	1383	1666	1886	1960	2012	2406	2793	3355
22500	600	988	1151	1383	1665	1885	1959	2011	2405	2792	3354

TABLE 11. NEON-NUCLEUS ABSORPTION CROSS SECTIONS

Energy, MeV/nucleon	Absorption cross section, millibarns, for target nucleus -										
	He	C	O	Al	Ar	Fe	Cu	Br	Ag	Ba	Pb
25	996	1492	1710	1985	2354	2588	2647	2616	3113	3606	4195
50	810	1256	1449	1701	2027	2257	2325	2340	2786	3227	3808
75	760	1192	1378	1625	1940	2168	2238	2264	2697	3124	3702
100	697	1113	1290	1531	1834	2060	2132	2169	2587	2998	3571
125	664	1071	1243	1481	1777	2001	2074	2119	2528	2930	3501
150	647	1050	1220	1457	1749	1973	2047	2094	2499	2897	3466
175	632	1031	1199	1434	1723	1947	2021	2070	2472	2866	3434
200	619	1015	1181	1415	1702	1925	1999	2051	2449	2841	3407
225	609	1002	1167	1400	1685	1907	1982	2036	2432	2820	3386
250	601	992	1156	1389	1672	1894	1969	2024	2418	2805	3370
275	596	986	1149	1382	1664	1886	1961	2017	2410	2795	3360
300	594	983	1146	1378	1660	1882	1956	2013	2405	2790	3355
350	594	983	1146	1378	1660	1882	1957	2013	2405	2791	3355
400	598	989	1152	1385	1668	1889	1964	2020	2413	2799	3364
500	624	1020	1187	1422	1710	1932	2007	2058	2458	2850	3417
600	646	1048	1218	1455	1747	1970	2044	2092	2497	2894	3463
700	658	1063	1234	1472	1766	1991	2064	2110	2518	2918	3488
800	666	1073	1246	1484	1780	2005	2078	2122	2532	2934	3505
900	671	1080	1253	1492	1789	2014	2087	2131	2542	2946	3517
1000	675	1085	1258	1498	1795	2021	2094	2136	2548	2953	3525
1250	678	1089	1263	1502	1800	2026	2099	2141	2553	2959	3531
1500	678	1089	1263	1502	1801	2026	2099	2141	2554	2959	3531
1750	678	1089	1263	1503	1801	2026	2099	2141	2554	2960	3531
2000	678	1089	1263	1502	1800	2026	2099	2141	2554	2959	3531
2500	676	1086	1260	1499	1797	2023	2096	2138	2550	2955	3527
3000	673	1083	1256	1495	1793	2018	2091	2134	2546	2950	3522
3500	671	1080	1253	1492	1789	2014	2087	2131	2542	2946	3517
4000	670	1079	1251	1490	1787	2012	2085	2129	2540	2943	3515
5000	669	1077	1250	1489	1785	2010	2084	2128	2539	2941	3513
6000	667	1076	1248	1487	1783	2008	2082	2127	2536	2939	3510
7000	666	1074	1246	1485	1780	2005	2079	2124	2533	2935	3507
8000	664	1072	1244	1483	1778	2003	2077	2122	2531	2933	3504
9000	664	1071	1243	1482	1777	2002	2075	2121	2530	2932	3503
10000	663	1071	1242	1481	1775	2001	2075	2121	2530	2931	3502
12500	662	1069	1241	1480	1774	2000	2073	2120	2528	2929	3501
15000	661	1068	1239	1477	1772	1997	2071	2118	2526	2926	3498
17500	659	1065	1237	1475	1769	1994	2068	2116	2523	2923	3494
20000	658	1064	1235	1473	1767	1992	2066	2114	2521	2920	3492
22500	657	1063	1234	1472	1766	1991	2065	2113	2520	2919	3490

TABLE 12. ALUMINUM-NUCLEUS ABSORPTION CROSS SECTIONS

Energy, MeV/nucleon	Absorption cross section, millibarns, for target nucleus - He	C	O	Al	Ar	Fe	Cu	Br	Ag	Ba	Pb
25	1115	1640	1870	2157	2545	2787	2845	2805	3324	3838	4442
50	921	1396	1600	1865	2208	2447	2515	2523	2991	3451	4048
75	868	1329	1527	1786	2119	2356	2426	2446	2900	3346	3941
100	802	1247	1436	1690	2009	2244	2317	2350	2788	3218	3808
125	767	1203	1387	1638	1950	2184	2258	2298	2728	3149	3737
150	750	1182	1364	1613	1922	2155	2230	2273	2698	3115	3702
175	734	1162	1341	1589	1895	2128	2203	2249	2671	3084	3669
200	720	1145	1323	1570	1873	2105	2181	2229	2648	3058	3642
225	709	1132	1308	1554	1856	2087	2164	2214	2630	3037	3621
250	701	1122	1297	1543	1843	2074	2150	2202	2616	3022	3605
275	696	1116	1290	1535	1835	2065	2142	2194	2607	3012	3594
300	694	1112	1287	1532	1830	2061	2138	2191	2603	3007	3589
350	694	1112	1287	1532	1831	2061	2138	2191	2603	3007	3589
400	698	1118	1293	1539	1838	2069	2146	2198	2611	3016	3599
500	725	1151	1330	1577	1882	2114	2189	2237	2657	3068	3653
600	748	1180	1361	1611	1920	2153	2228	2271	2696	3113	3700
700	761	1196	1379	1629	1940	2174	2248	2290	2718	3138	3725
800	769	1206	1390	1641	1954	2188	2263	2302	2732	3154	3742
900	775	1213	1398	1650	1964	2198	2272	2311	2742	3166	3754
1000	779	1218	1403	1655	1970	2204	2279	2317	2749	3173	3762
1250	782	1222	1408	1660	1975	2210	2284	2321	2754	3179	3768
1500	782	1222	1408	1660	1976	2210	2284	2322	2755	3180	3769
1750	782	1222	1408	1660	1976	2210	2284	2322	2755	3180	3769
2000	782	1222	1408	1660	1975	2210	2284	2321	2754	3179	3768
2500	780	1220	1405	1657	1972	2206	2281	2319	2751	3176	3765
3000	777	1216	1401	1653	1967	2202	2276	2315	2747	3170	3759
3500	775	1213	1398	1650	1964	2198	2272	2312	2743	3166	3755
4000	774	1212	1396	1648	1961	2195	2270	2310	2741	3163	3752
5000	773	1210	1395	1646	1960	2194	2269	2309	2739	3161	3750
6000	771	1209	1393	1644	1957	2192	2266	2307	2737	3159	3748
7000	770	1207	1390	1642	1954	2189	2264	2305	2734	3155	3744
8000	768	1205	1389	1640	1952	2186	2261	2303	2732	3153	3742
9000	767	1204	1388	1639	1951	2185	2260	2302	2731	3152	3740
10000	767	1204	1387	1638	1950	2185	2260	2301	2730	3151	3740
12500	766	1202	1386	1637	1949	2183	2258	2300	2729	3149	3738
15000	765	1200	1384	1635	1946	2180	2256	2298	2726	3146	3735
17500	763	1198	1381	1632	1943	2177	2253	2296	2724	3143	3732
20000	761	1196	1379	1630	1941	2175	2250	2294	2721	3140	3729
22500	761	1196	1378	1629	1940	2174	2250	2293	2720	3139	3728

TABLE 13. ARGON-NUCLEUS ABSORPTION CROSS SECTIONS

Energy, MeV/nucleon	Absorption cross section, millibarns, for target nucleus -										
	He	C	O	Al	Ar	Fe	Cu	Br	Ag	Ba	Pb
25	1378	1958	2208	2523	2939	3202	3267	3238	3786	4328	4976
50	1149	1680	1904	2196	2568	2828	2903	2919	3417	3905	4545
75	1087	1605	1822	2108	2469	2727	2805	2832	3317	3792	4428
100	1010	1512	1720	2000	2348	2604	2684	2724	3193	3651	4283
125	969	1462	1665	1943	2284	2538	2619	2666	3126	3576	4205
150	949	1438	1639	1915	2253	2506	2588	2638	3094	3540	4168
175	930	1415	1614	1889	2223	2477	2559	2611	3064	3506	4132
200	914	1396	1593	1867	2199	2452	2534	2589	3039	3477	4103
225	902	1381	1577	1850	2180	2432	2515	2571	3019	3455	4079
250	892	1369	1565	1837	2166	2417	2500	2558	3004	3438	4062
275	886	1362	1557	1829	2156	2408	2491	2550	2994	3428	4051
300	883	1359	1553	1824	2152	2403	2487	2546	2990	3422	4045
350	883	1359	1553	1825	2152	2404	2487	2546	2990	3423	4045
400	889	1365	1560	1832	2161	2412	2495	2554	2999	3433	4056
500	920	1402	1601	1875	2209	2461	2544	2598	3049	3490	4115
600	947	1435	1636	1913	2251	2504	2586	2637	3094	3540	4166
700	962	1453	1656	1933	2274	2528	2609	2658	3117	3566	4194
800	971	1465	1669	1947	2289	2543	2625	2672	3133	3584	4213
900	978	1473	1678	1956	2300	2554	2636	2681	3144	3597	4226
1000	983	1478	1684	1962	2307	2561	2642	2688	3152	3605	4234
1250	986	1483	1688	1967	2312	2567	2648	2693	3157	3611	4241
1500	987	1483	1689	1968	2313	2567	2648	2693	3158	3612	4241
1750	987	1483	1689	1968	2313	2567	2648	2693	3158	3612	4241
2000	986	1483	1688	1967	2312	2567	2648	2693	3157	3611	4241
2500	984	1480	1685	1964	2308	2563	2644	2690	3154	3607	4237
3000	981	1476	1681	1960	2303	2558	2639	2685	3148	3601	4230
3500	978	1473	1677	1956	2299	2554	2635	2682	3144	3596	4225
4000	976	1471	1675	1954	2297	2551	2633	2680	3142	3593	4223
5000	975	1469	1674	1952	2295	2550	2631	2678	3140	3591	4221
6000	974	1468	1671	1950	2292	2547	2629	2676	3138	3589	4218
7000	972	1465	1669	1947	2289	2544	2625	2673	3134	3585	4214
8000	970	1463	1667	1945	2286	2541	2623	2671	3132	3582	4211
9000	969	1462	1665	1944	2285	2540	2621	2670	3131	3580	4210
10000	969	1462	1665	1943	2284	2539	2621	2670	3130	3580	4209
12500	967	1460	1663	1941	2283	2537	2619	2669	3129	3578	4207
15000	966	1458	1661	1939	2280	2534	2616	2666	3126	3575	4204
17500	963	1455	1658	1936	2276	2531	2613	2663	3123	3571	4200
20000	962	1453	1656	1934	2274	2528	2611	2661	3120	3568	4197
22500	961	1452	1655	1933	2273	2527	2610	2660	3119	3567	4196

TABLE 14. IRON-NUCLEUS ABSORPTION CROSS SECTIONS

Energy, MeV/nucleon	Absorption cross section, millibarns, for target nucleus - He	C	O	Al	Ar	Fe	Cu	Br	Ag	Ba	Pb
25	1562	2179	2446	2777	3219	3491	3555	3510	4089	4660	5325
50	1326	1894	2134	2442	2838	3107	3183	3188	3715	4231	4889
75	1262	1817	2049	2352	2736	3005	3083	3100	3614	4115	4771
100	1182	1720	1944	2241	2612	2878	2959	2991	3488	3972	4625
125	1138	1669	1888	2181	2545	2811	2893	2932	3420	3896	4547
150	1117	1644	1861	2152	2513	2778	2861	2904	3388	3859	4509
175	1097	1620	1835	2125	2483	2747	2831	2877	3357	3825	4473
200	1081	1600	1813	2103	2458	2722	2806	2855	3332	3796	4443
225	1068	1585	1796	2085	2438	2702	2786	2837	3311	3773	4420
250	1058	1573	1784	2072	2423	2687	2772	2824	3296	3756	4402
275	1051	1565	1775	2063	2414	2677	2762	2815	3286	3745	4391
300	1048	1562	1771	2059	2409	2672	2758	2811	3282	3740	4385
350	1048	1562	1771	2059	2409	2673	2758	2811	3282	3740	4385
400	1054	1569	1779	2067	2418	2681	2766	2819	3291	3750	4396
500	1087	1607	1821	2111	2468	2732	2816	2864	3342	3808	4455
600	1115	1641	1858	2150	2511	2776	2859	2903	3387	3858	4507
700	1131	1659	1878	2171	2534	2800	2883	2924	3410	3885	4535
800	1141	1672	1891	2185	2550	2816	2898	2938	3427	3904	4554
900	1148	1681	1901	2195	2561	2827	2910	2948	3438	3917	4567
1000	1153	1686	1907	2201	2569	2834	2917	2954	3445	3925	4575
1250	1157	1691	1912	2207	2574	2840	2922	2959	3451	3931	4582
1500	1157	1691	1912	2207	2575	2841	2923	2960	3452	3932	4583
1750	1157	1691	1912	2207	2575	2841	2923	2960	3452	3932	4583
2000	1157	1691	1912	2207	2574	2840	2922	2960	3451	3931	4582
2500	1154	1688	1909	2203	2570	2836	2919	2957	3448	3927	4578
3000	1151	1684	1904	2199	2565	2831	2914	2952	3442	3921	4572
3500	1148	1680	1900	2195	2561	2827	2909	2948	3438	3916	4567
4000	1146	1678	1898	2193	2558	2824	2907	2946	3436	3913	4564
5000	1145	1677	1897	2191	2556	2822	2905	2945	3434	3911	4562
6000	1144	1675	1895	2189	2554	2820	2903	2943	3432	3909	4560
7000	1141	1673	1892	2186	2550	2816	2900	2940	3429	3905	4556
8000	1140	1671	1890	2184	2548	2814	2897	2938	3426	3902	4553
9000	1139	1670	1888	2182	2547	2813	2896	2937	3425	3900	4551
10000	1138	1669	1888	2182	2546	2812	2895	2937	3424	3900	4551
12500	1137	1668	1886	2180	2544	2810	2894	2936	3423	3898	4549
15000	1135	1665	1884	2178	2541	2807	2891	2933	3420	3895	4546
17500	1133	1663	1881	2175	2538	2804	2888	2931	3417	3891	4542
20000	1131	1661	1879	2172	2535	2801	2885	2928	3414	3888	4539
22500	1131	1660	1878	2171	2534	2800	2884	2928	3413	3887	4538

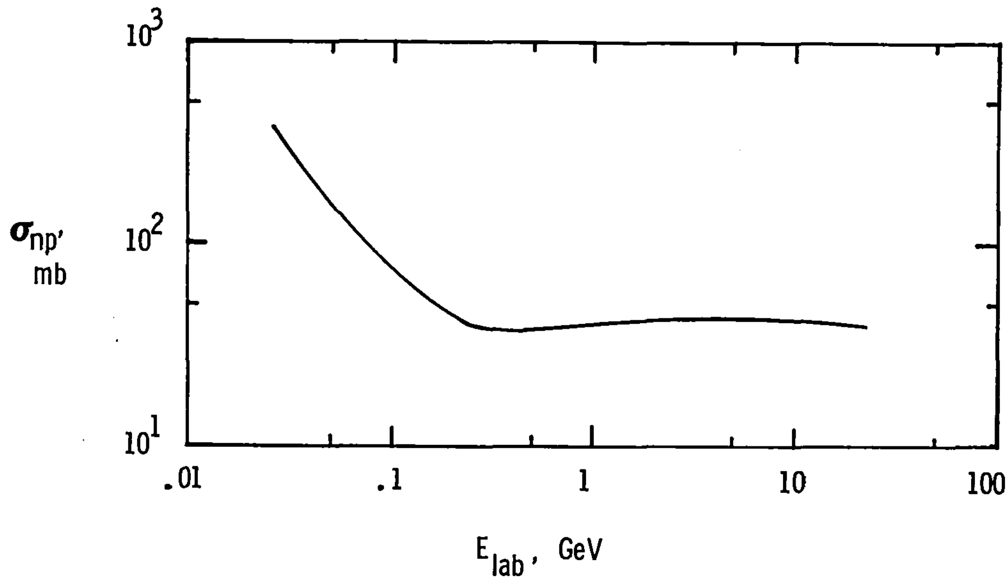

Figure 1. Neutron-proton total cross section as a function of incident kinetic energy.

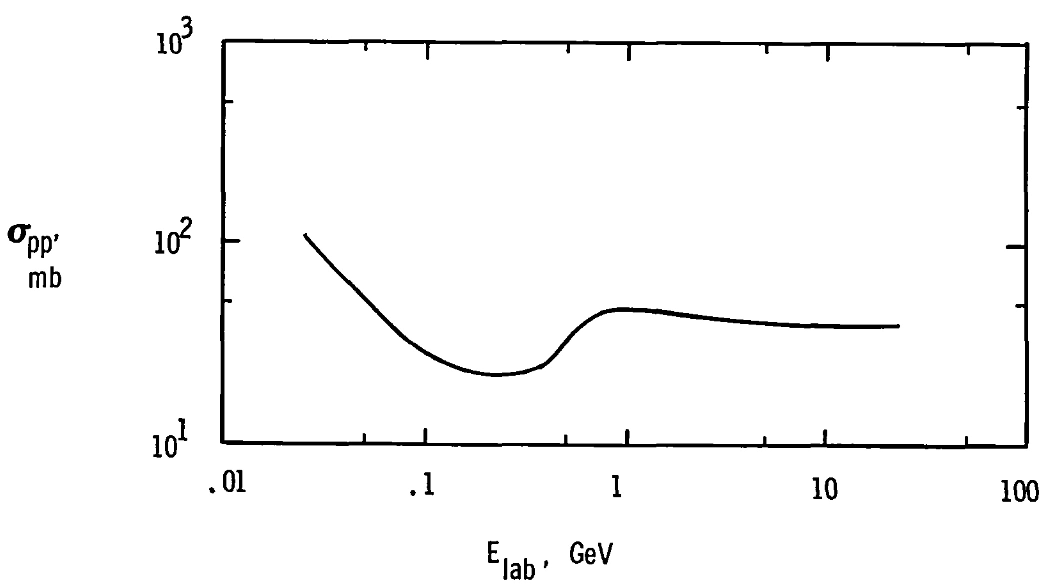

Figure 2. Proton-proton total cross section as a function of incident kinetic energy.

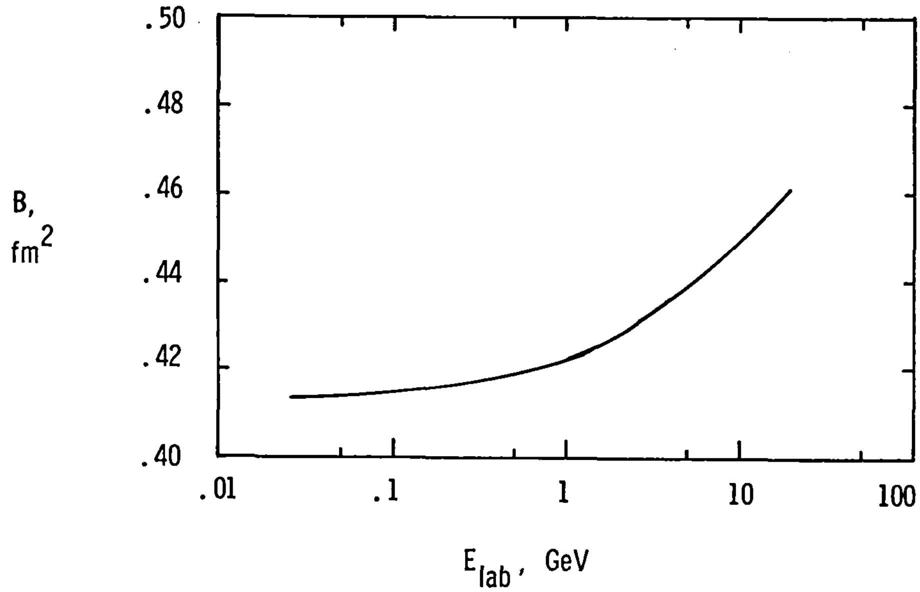

Figure 3. Nucleon-nucleon scattering slope parameter as a function of incident kinetic energy.

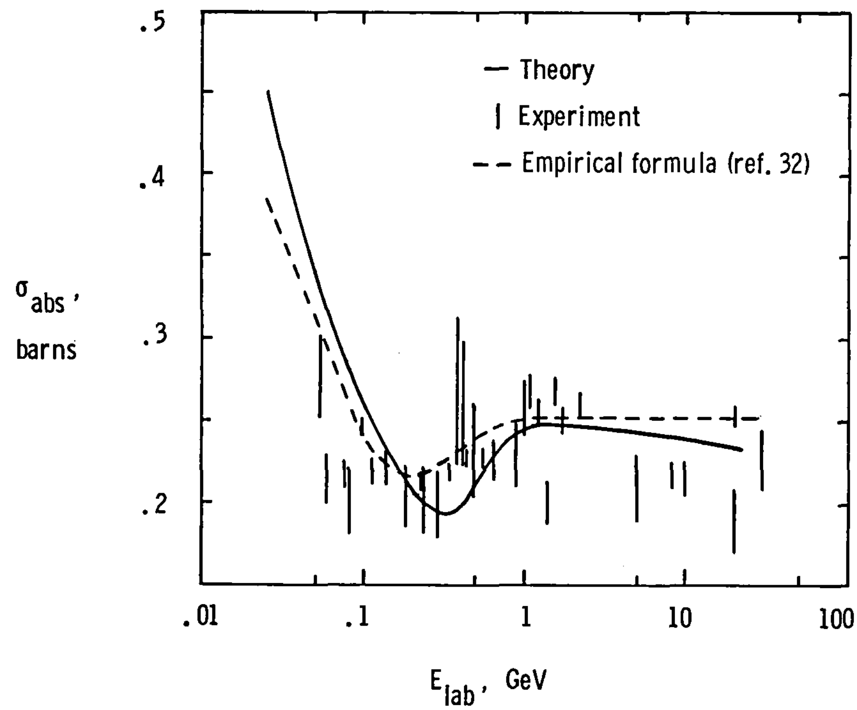

Figure 4. Nucleon-carbon absorption cross sections as a function of incident nucleon kinetic energy.

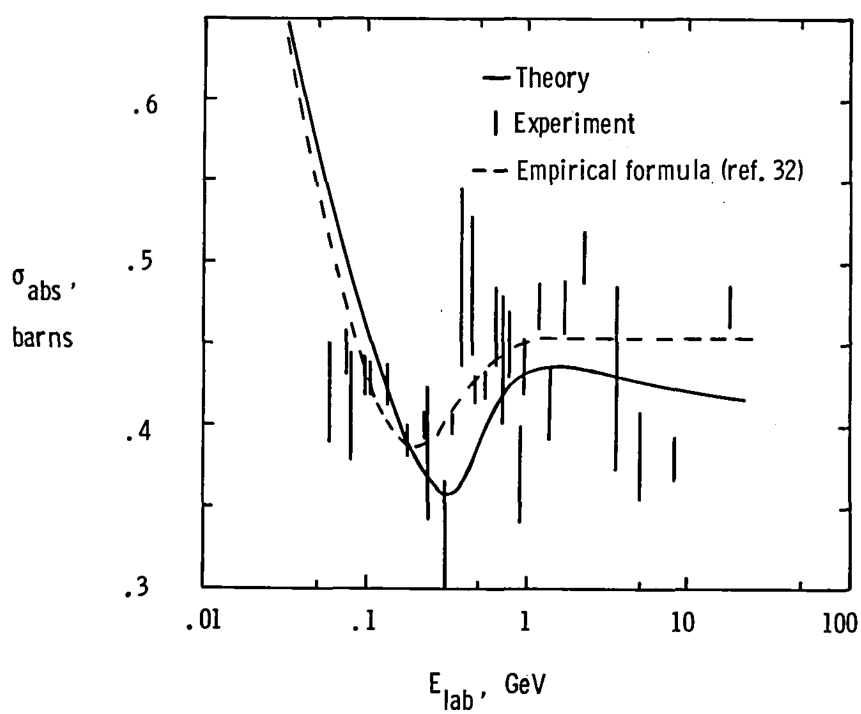

Figure 5. Nucleon-aluminum absorption cross sections as a function of incident nucleon kinetic energy.

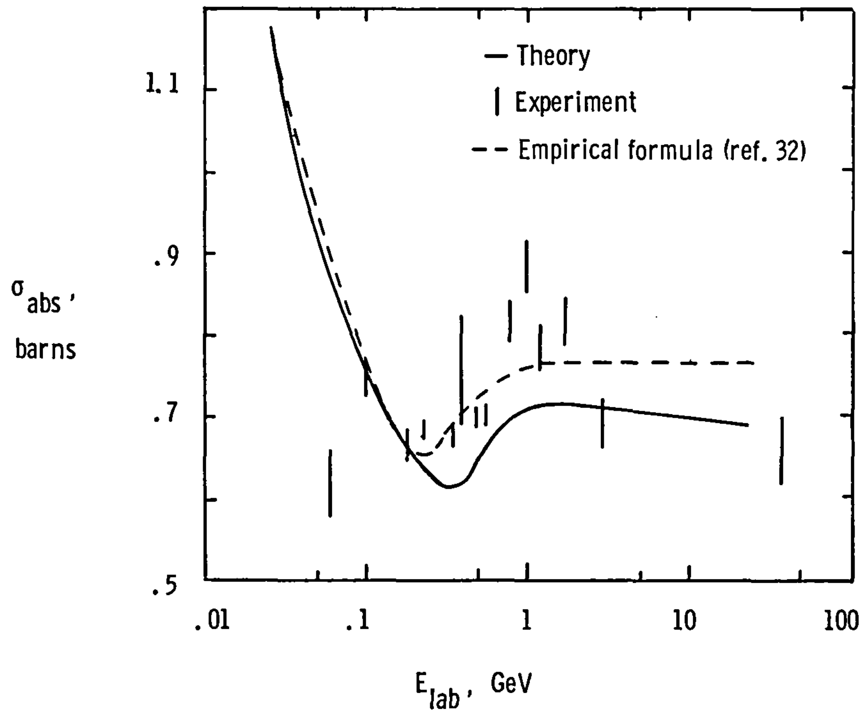

Figure 6. Nucleon-iron absorption cross sections as a function of incident nucleon kinetic energy.

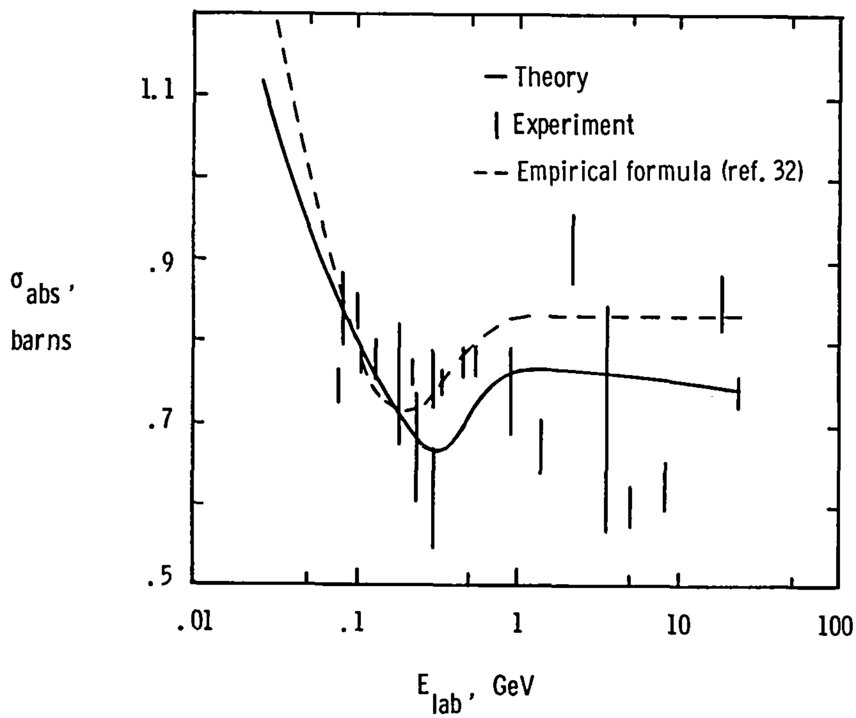

Figure 7. Nucleon-copper absorption cross sections as a function of incident nucleon kinetic energy.

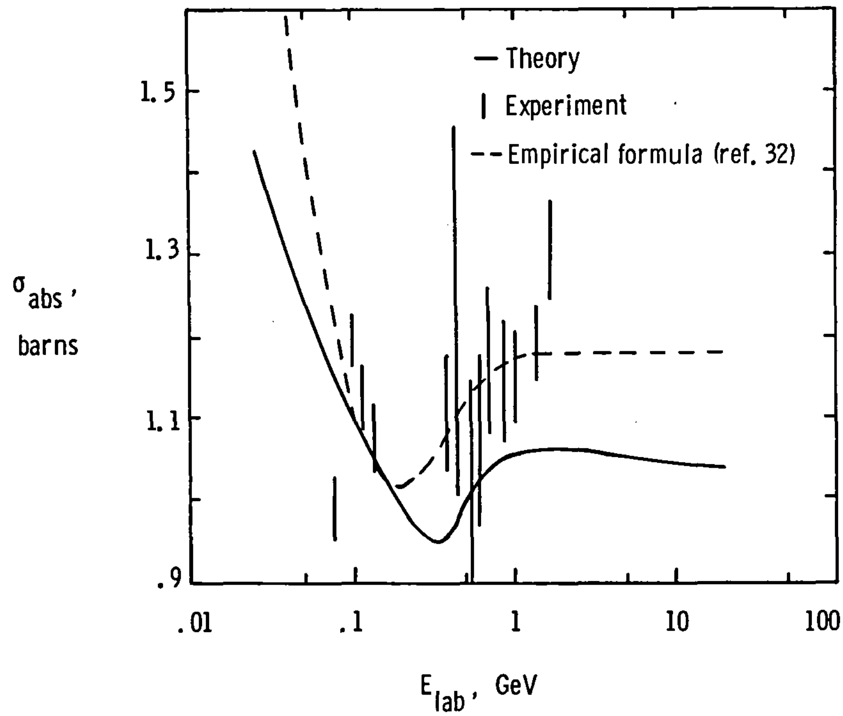

Figure 8. Nucleon-silver absorption cross sections as a function of incident nucleon kinetic energy.

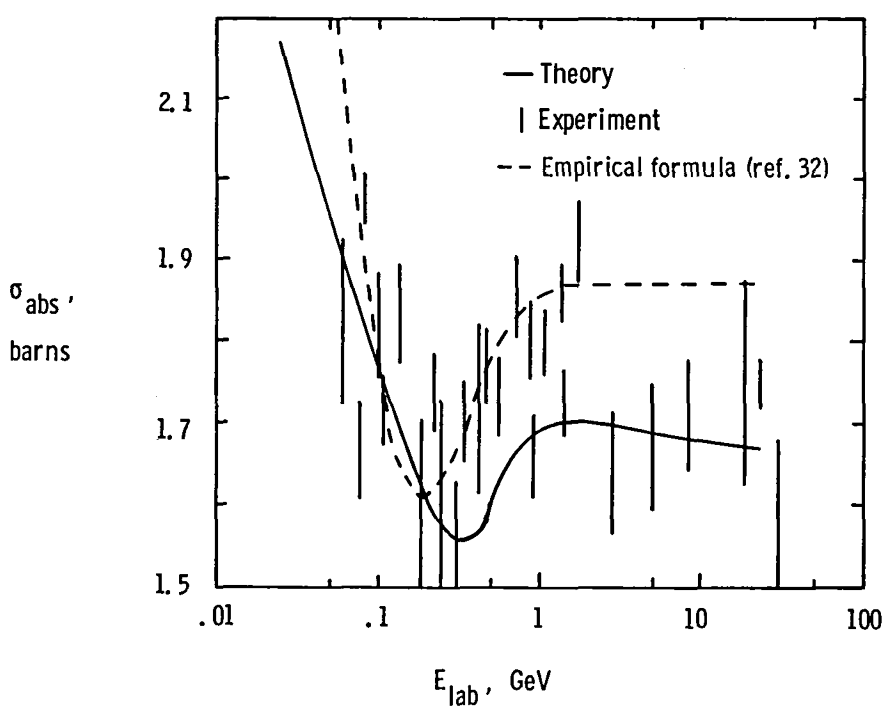

Figure 9. Nucleon-lead absorption cross sections as a function of incident nucleon kinetic energy.

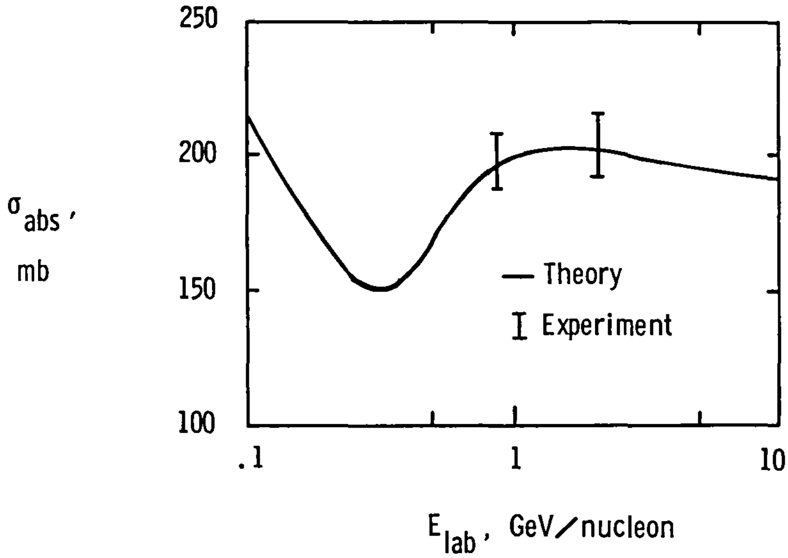

Figure 10. Absorption cross sections for deuteron-helium scattering as a function of incident kinetic energy.

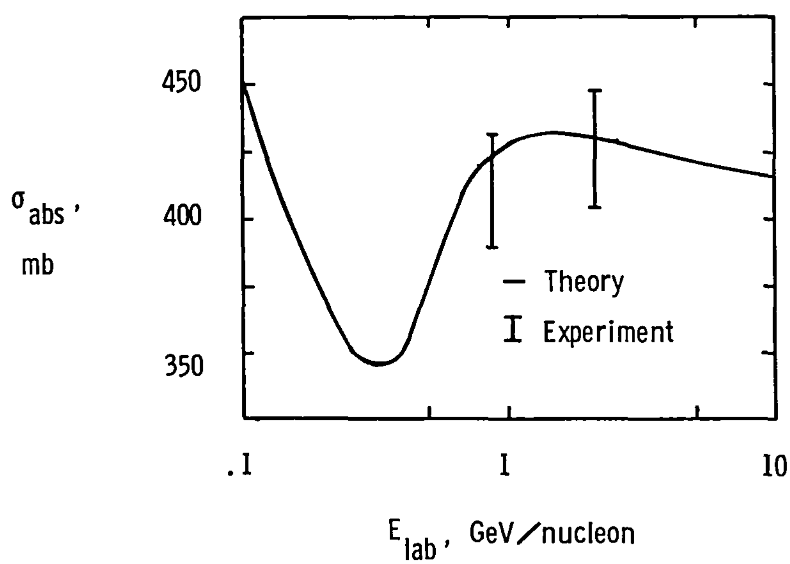

Figure 11. Absorption cross sections for deuteron-carbon scattering as a function of incident kinetic energy.

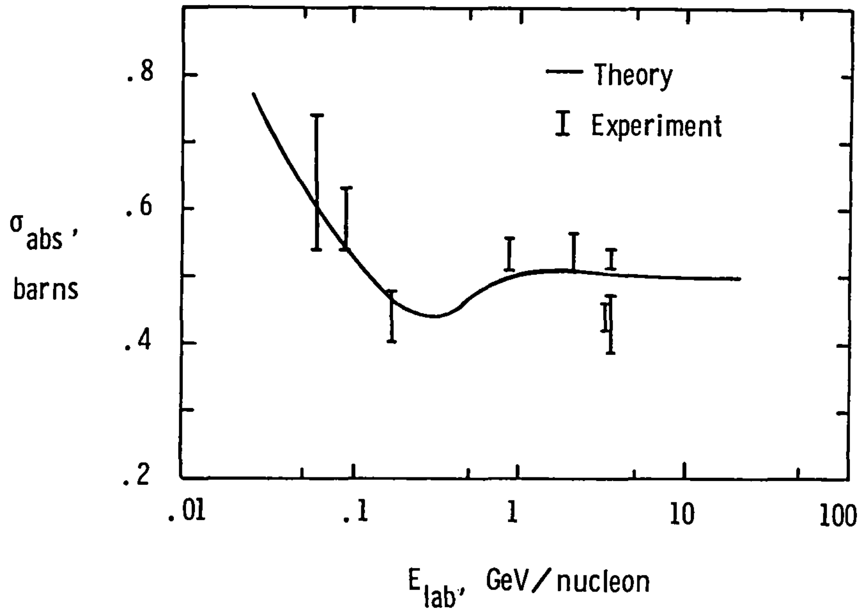

Figure 12. Absorption cross sections for helium-carbon scattering as a function of incident kinetic energy.

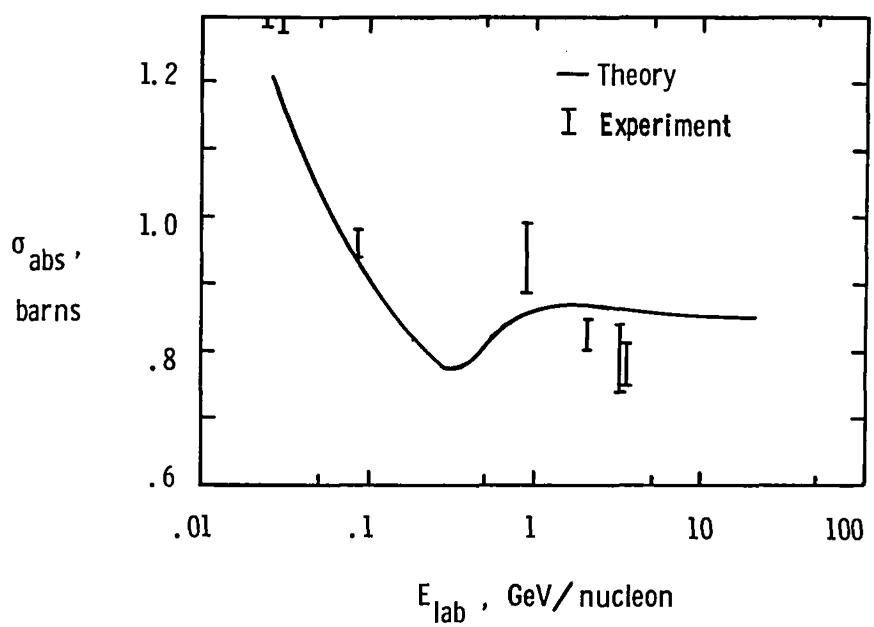

Figure 13. Absorption cross sections for carbon-carbon scattering as a function of incident kinetic energy.

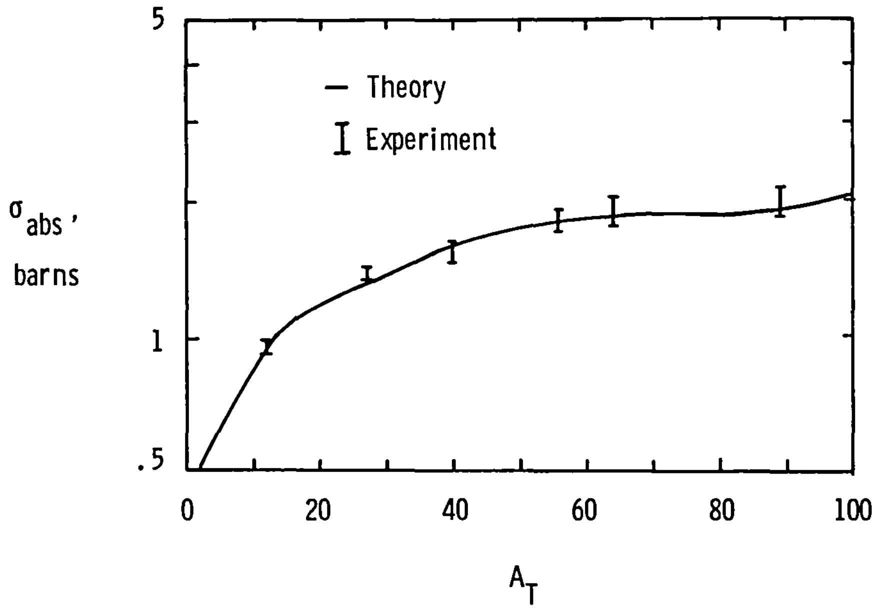

Figure 14. Absorption cross sections, as a function of target mass number, for carbon projectiles at 83 MeV/nucleon.

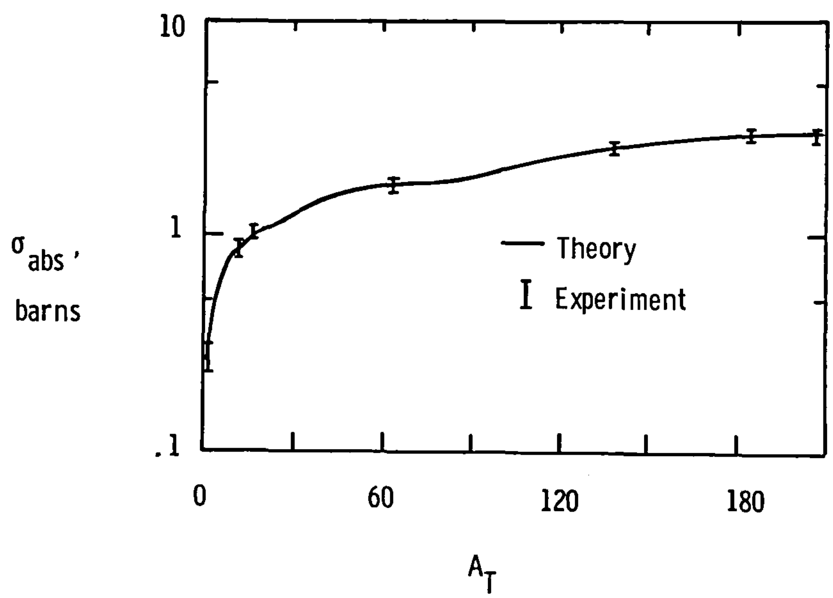

Figure 15. Absorption cross sections, as a function of target mass number, for carbon projectiles at 2.1 GeV/nucleon.

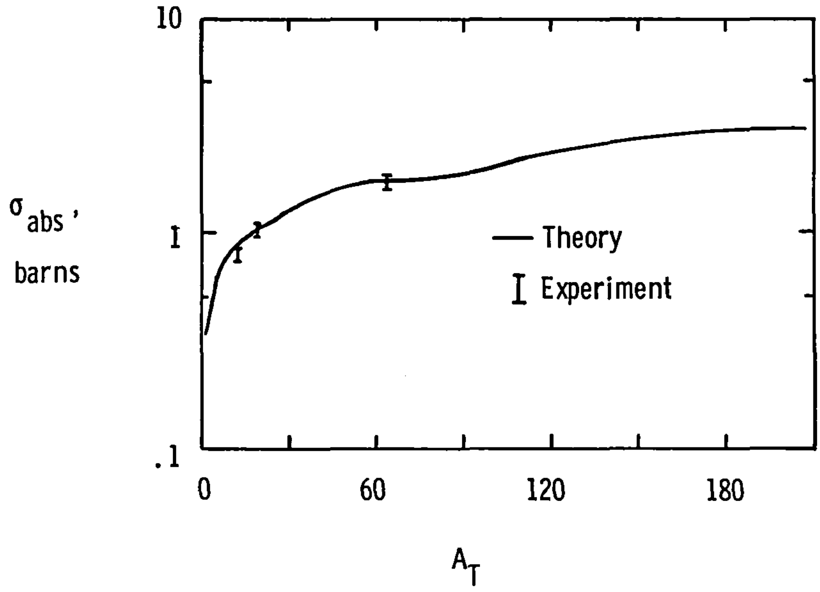

Figure 16. Absorption cross sections, as a function of target mass number, for carbon projectiles at 3.6 GeV/nucleon.

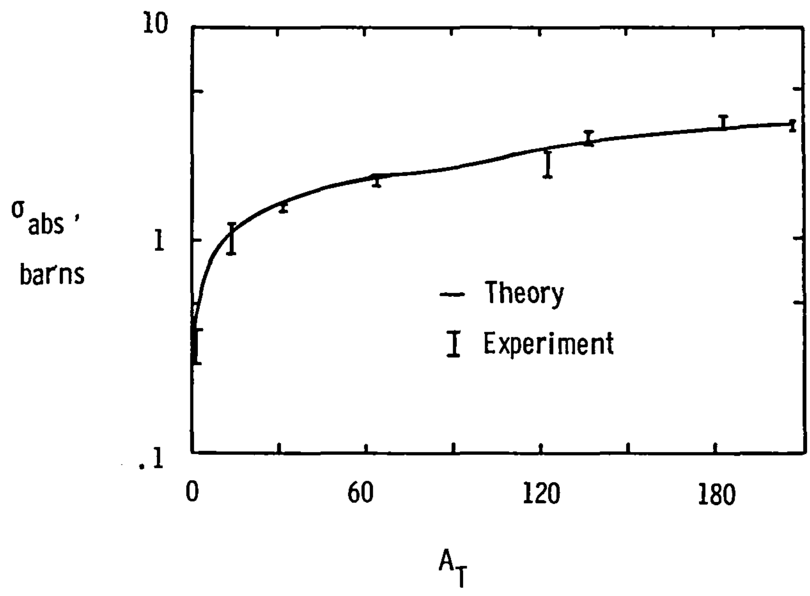

Figure 17. Absorption cross sections, as a function of target mass number, for oxygen projectiles at 2.1 GeV/nucleon.

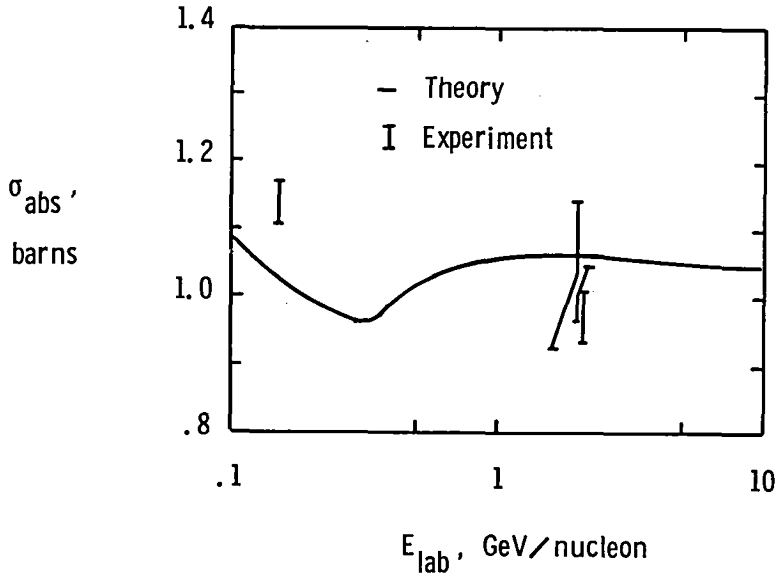

Figure 18. Absorption cross sections for oxygen-emulsion scattering as a function of energy.

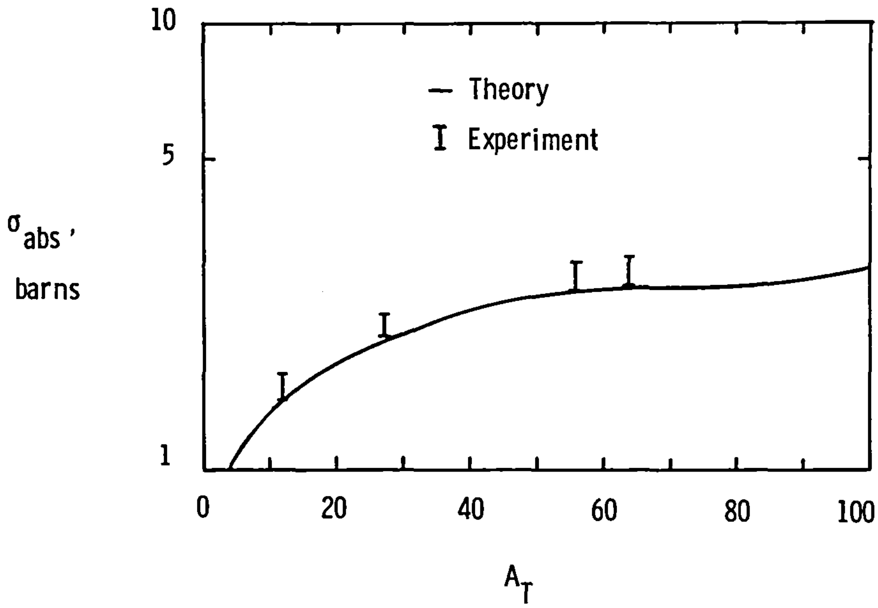

Figure 19. Absorption cross sections, as a function of target mass number, for neon projectiles at 30 MeV/nucleon.

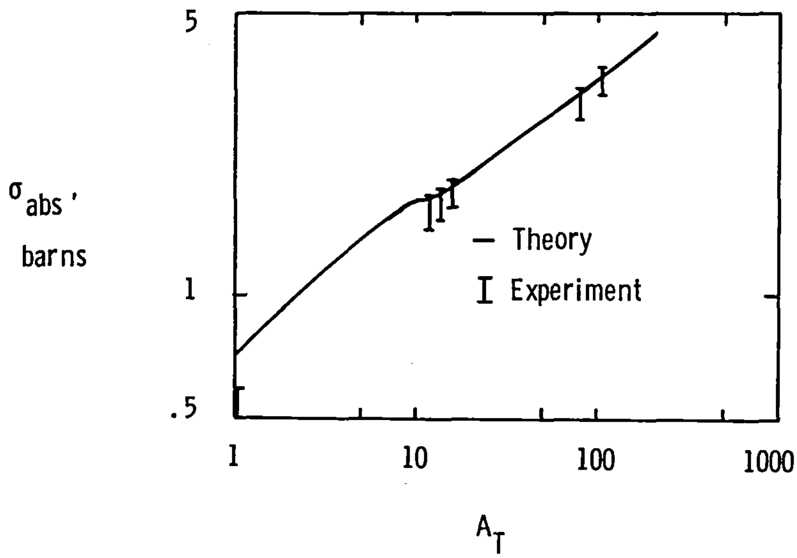

Figure 20. Absorption cross sections, as a function of target mass number, for iron projectiles at 1.88 GeV/nucleon. The experimental data were obtained with an emulsion target.

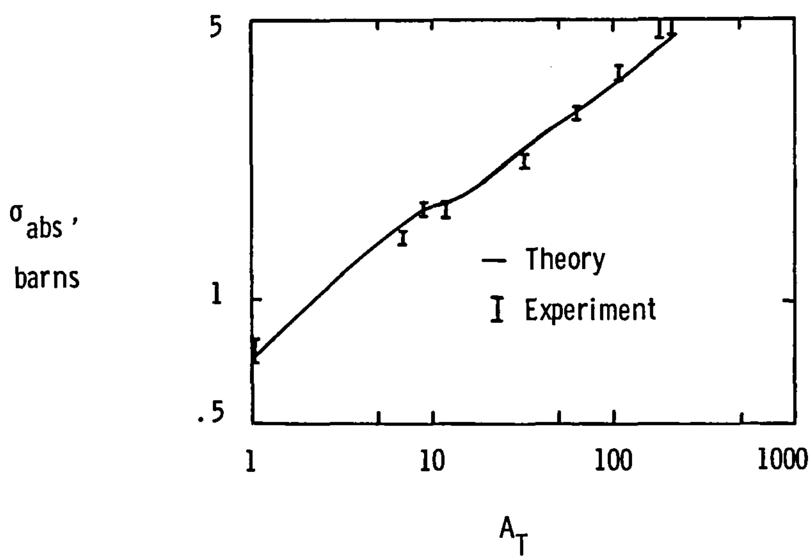

Figure 21. Absorption cross sections, as a function of target mass number, for iron projectiles at 1.88 GeV/nucleon. The experimental data are total cross sections for the removal of one or more nucleons.

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16. Abstract
A simple but comprehensive theory of nuclear reactions is presented. Extensive tables of nucleon, deuteron, and heavy-ion absorption cross sections over a broad range of energies are generated for use in cosmic ray shielding studies. Numerous comparisons of the calculated values with available experimental data show agreement to within 3 percent for energies above 80 MeV/nucleon and within approximately 10 percent for energies as low as 30 MeV/nucleon. These tables represent the culmination of the development of the absorption cross section formalism and supersede the preliminary absorption cross sections published previously in NASA TN D-8107, NASA TP-2138, and NASA TM-84636.

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