

Energy Loss And Energy Loss Straggling In Stripper Foils

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February 1984

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U.S. Department of Energy

USDOE Office of Science (SC)

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ENERGY LOSS AND
ENERGY LOSS STRAGGLING
IN STRIPPER FOILS

Glenn Young

February 27, 1984

Brookhaven National Laboratory

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2/27/84

Energy loss and Energy loss straggling in Stripper Foils

In the following tables, values for the kinetic energy loss per a.m.u. are given for stripping at the tandem (or linac) exit and at the booster exit.

For the tandem energies, tables of Northcliffe and Schilling were used:

LC Northcliffe and RF Schilling, Nuclear Data Tables A7, 233-463 (1970)
A relevant subset, for ^{12}C , ^{32}S , ^{63}Cu , ^{127}I and ^{197}Au plus some explanatory material, is attached.

For the booster energies, tables of Ziegler were used:

JF Ziegler, "The Stopping Powers & Ranges of Ions in Matter" volume 5
library # Q C 794.6, 58

The Tandem Van de Graaff has a copy in the control room; the library does not have the relevant volume. Tables for all ions stopping in C, Cu and Ta foils are attached.

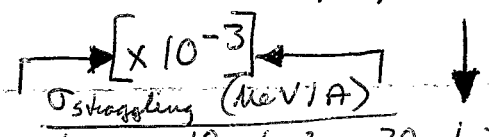
At the tandem exit, the effect of energy loss & energy loss straggling is very small for ^{12}C and ^{32}S . For heavier ions such as ^{127}I and ^{197}Au the straggling leads to an increase in σ_E/E to about 10^{-3} , which actually might help with RF capture at injection into the booster.

The rule of thumb I use is $\text{FWHM}_{\text{straggling}} = 25\% \Delta E_{\text{loss}}$
So the rms $\sigma = \frac{1}{2.35} \text{FWHM}$ becomes

$$\sigma_{\text{straggling}} = 0.106 * \Delta E_{\text{loss}}$$

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Energy loss, Tandem Exit, Carbon foils



Ion	E/A (MeV/A)	ΔE (MeV/A)			Stopping (MeV/A) $\times 10^{-3}$		
		5 $\mu\text{g}/\text{cm}^2$	10 $\mu\text{g}/\text{cm}^2$	20 $\mu\text{g}/\text{cm}^2$	5 $\mu\text{g}/\text{cm}^2$	10 $\mu\text{g}/\text{cm}^2$	20 $\mu\text{g}/\text{cm}^2$
^{12}C (Z=6)	6.5	.000863	.00173	.00345	.091	.183	.366
	7	.000812	.00162	.00325	.086	.172	.344
	7.5	.000771	.00154	.00308	.082	.163	.326
	8	.00073	.00146	.00292	.077	.155	.309
	8.5	.00070	.00139	.00279	.074	.147	.296
^{32}S (Z=16)	3.5	.00245	.00490	.00980	.260	.519	1.04
	4	.00226	.00452	.00904	.240	.479	.958
	4.5	.00214	.00428	.00856	.227	.454	.907
	5	.00202	.00404	.00807	.214	.434	.865
	5.5	.00192	.00384	.00769	.204	.407	.815
^{63}Cu	2	.00306	.00612	.0122	.324	.649	1.29
	2.5	.00292	.00584	.0117	.309	.619	1.24
	3	.00278	.00556	.0111	.295	.589	1.18
	3.5	.00266	.00533	.0107	.282	.565	1.13
	4	.00255	.00509	.0102	.270	.539	1.08
^{127}I	.5	.00243	.00487	.00974	.258	.516	1.03
	1	.00289	.00578	.0116	.306	.613	1.23
	1.5	.00290	.00579	.0116	.307	.614	1.23
	2	.00286	.00572	.0114	.303	.606	1.21
^{197}Au	.5	.00206	.00412	.00823	.218	.437	.872
	1	.00262	.00523	.0105	.278	.554	1.11
	1.5	.00275	.00549	.01099	.292	.582	1.16

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Energy Loss, Booster Exit, Copper foils

Ion	MeV/A	ΔE (MeV/A)				$\sigma_{straggle}$ (MeV/A)			
		10 mg/cm ²	40 mg/cm ²	70 mg/cm ²	100 mg/cm ²	10 $\frac{mg}{cm^2}$	40 $\frac{mg}{cm^2}$	70 $\frac{mg}{cm^2}$	100 $\frac{mg}{cm^2}$
³² S	300	.194	.775	1.356	1.938	.021	.082	.144	.205
	350	.178	.713	1.247	1.781	.019	.076	.132	.189
	400	.166	.663	1.159	1.656	.018	.070	.122	.176
	450	.159	.638	1.116	1.594	.017	.068	.118	.169
	500	.150	.600	1.050	1.500	.016	.064	.111	.159
⁶³ Cu	300	.325	1.302	2.218	3.254	.034	.138	.235	.345
	350	.286	1.143	2.000	2.857	.030	.121	.212	.303
	400	.275	1.098	1.922	2.746	.029	.116	.204	.291
	450	.259	1.035	1.811	2.587	.027	.110	.192	.274
	500	.248	.990	1.733	2.476	.026	.105	.184	.262
¹²⁷ I	300	.527	2.110	3.693	5.276	.052	.224	.391	.559
	350	.488	1.953	3.417	4.882	.052	.207	.362	.517
	400	.457	1.827	3.197	4.567	.048	.194	.339	.484
	450	.441	1.764	3.087	4.409	.047	.187	.327	.467
	500	.417	1.669	2.921	4.173	.044	.177	.310	.442
¹⁹⁷ Au	300	.761	3.046	5.330	7.614	.081	.323	.565	.807
	350	.701	2.802	4.904	7.005	.074	.297	.520	.742
	400	.660	2.639	4.619	6.599	.070	.280	.490	.699
	450	.635	2.538	4.442	6.345	.067	.269	.471	.673
	500	.609	2.437	4.264	6.091	.065	.258	.452	.646



The FWHM due to energy loss straggling is ~25% of the energy loss, conservatively.
 The rms is then $\sigma_{straggle} = \frac{1}{2.35} FWHM_{straggle} = 0.106 E_{loss}$.

Considering values for gold, at the tandem exit + carbon
Stripper foils of 20 mg/cm^2 can be used, while at the booster
exit copper foils of $\sim 60 \text{ mg/cm}^2$ must be used.

For the booster, values of $\sigma_{\text{straggling}}/E$ of $1-2 \times 10^{-3}$
result. Two comments apply.

1) If the bunches from the booster are manipulated to a total time
length of 14 nsec , then for (e.g.) $350 \text{ MeV } ^{197}\text{Au}^{36+}$
leaving the booster and hitting a stripper, a bucket area of
 0.2 eV/A/sec corresponds to $\sigma_E = 3.87 \text{ MeV/A}$. Adding
the straggling due to a 70 mg/cm^2 $\sigma_{\text{straggling}}^{\text{max}}$ copper foil, which is
 $\sigma_{\text{straggling}} = 0.520 \text{ MeV/A}$, in quadrature, gives

$$\sigma_E^{\text{total}} = \sqrt{\sigma_{E_{\text{max}}}^2 + \sigma_{\text{straggling}}^2} = 3.90 \text{ MeV/A}, \text{ or a } 1\% \text{ change in}$$

bucket area. If σ_E is less than σ_E^{max} ($\sim 1.1\%$ rms energy spread)
then there should be no problem matching AGS RF buckets

2) At the expense of a few percent in stripping efficiency, a
gold foil of about 30 mg/cm^2 can be substituted for the
 70 mg/cm^2 of copper. As the energy loss of gold in copper at
 350 MeV/A is $\sim 14 \text{ MeV/mg/cm}^2$ while for gold in gold it is
 $\sim 11 \text{ MeV/mg/cm}^2$, the straggling width is reduced by $\frac{30}{70} \frac{11}{14} = 0.34$.

Thus, straggling due to stripper foils does not appear to cause problems.

RANGE AND STOPPING - POWER TABLES FOR HEAVY IONS*

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The electronic stopping power and range (corrected for nuclear stopping) are tabulated for representative ions of all atomic numbers $1 \leq z \leq 103$ in 24 different material media at 38 energies distributed logarithmically throughout the region $0.0125 \leq E/m \leq 12$ MeV/amu. The media include twelve solid elements (Be, C, Al, Ti, Ni, Ge, Zr, Ag, Eu, Ta, Au, and U), nine gaseous elements (H, He, N, O, Ne, Ar, Kr, Xe, and Rn), and three compounds (polyethylene, Mylar, and water). The tables are based on an investigation of the systematic relationships between observed data, guided by simple theoretical expectations and extrapolated into regions where no measurements have been made.

*This work was supported by the U. S. Atomic Energy Commission

Similarly, most of the points plotted in Fig. 8 are taken from the smoothed curves of Fig. 6 at the six indicated energies. In addition, several values of the relative stopping power at 4.43 MeV²⁸ are shown to verify its Z-dependence. The smoothed, isoergic curves through the data provide an estimate of the relative stopping power of O, Ne, Xe, and Rn as well as of other gaseous media. The complete family of relative stopping-power curves for gases is shown in Fig. 10.

G. Stopping Power of Compounds

Although there is some evidence that the Bragg additivity rule relating the stopping power of a compound to that of its constituents does not strictly hold,³⁰ the deviations from the rule are not large and have been observed mainly in the stopping power of hydrocarbons for protons. These deviations are poorly understood and difficult to systematize, and they have little effect on the calculated range of a high-energy ion. For present purposes the additivity rule is assumed to hold well enough to use in the calculation of stopping powers of polyethylene, Mylar, and water.

According to this rule, the relative stopping power of a compound of molecular weight *M* containing *N_i* atoms of atomic weight *A_i*, etc., is given by the formula

$$\frac{(dE/dx)_{\text{compound}}}{(dE/dx)_{\text{Al}}} = \frac{1}{M} \sum_i \frac{N_i A_i (dE/dx)_i}{(dE/dx)_{\text{Al}}}$$

where $(dE/dx)_i$ is the stopping power of the pure element

labeled by subscript *i*. In the case of Mylar (C₁₀H₈O₄) for example we have

$$\frac{(dE/dx)_{\text{Mylar}}}{(dE/dx)_{\text{Al}}} = \frac{1}{192} \left[120 \frac{(dE/dx)_{\text{C}}}{(dE/dx)_{\text{Al}}} + 8 \frac{(dE/dx)_{\text{H}}}{(dE/dx)_{\text{Al}}} + 64 \frac{(dE/dx)_{\text{O}}}{(dE/dx)_{\text{Al}}} \right]$$

This formula for Mylar and the analogous formulas for polyethylene ([CH₂]_{*n*}) and water (H₂O) were used to calculate relative stopping powers for these compounds from the relative stopping-power curves for elements (Figs. 9 and 10).³¹

H. Calculation of Stopping-Power Tables

As described in Part D of this section, each stopping-power curve of Fig. 2 was fitted at nine points in two sections by a general second-order polynomial with five coefficients (yielding ten coefficients per curve). The nine points were approximately equispaced on the scale of log *E/m* in the region 0.0125 ≤ *E/m* ≤ 12 MeV/amu. By the interpolation method described in Part E of this section the stopping power for an intermediate ion was determined at the same nine *E/m* values, and these nine points were fitted by the two-section polynomial (with 2 × 5 = 10 coefficients) which was used to calculate the stopping power for that ion in aluminum at any desired energy.

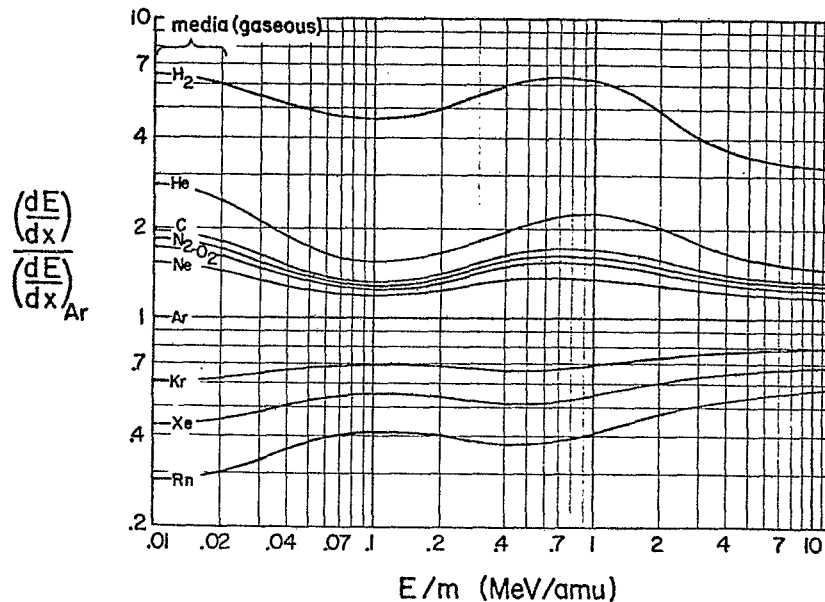


Fig. 10. Adopted curves for stopping power of various gases relative to Ar

RANGE AND STOPPING-POWER TABLES FOR HEAVY IONS

Table II. Unit conversion factors

To convert range or stopping power values of the main tabulation into units specified at the head of a column, multiply by the column entry for the desired material medium. The formula for the conversion factor is given at the foot of each column.

The 1959 international atomic weights W are for natural isotopic abundances on the chemical scale and are taken from the "CRC Handbook of Chemistry and Physics" (Chemical Rubber Publishing Co., Cleveland, 1966) 47th edition.

The densities ρ (in units of g/cm^3 at 20°C and 760 torr) are from the same source (gas densities have been converted to these standard conditions). The density of Mylar is that specified by the manufacturer (E. I. DuPont de Nemours and Co., Wilmington, Delaware). That of polyethylene is taken from the 39th edition of the CRC Handbook.

	W	ρ	Range	Stopping Power	
			for (mm) multiply by	for (MeV/mm) multiply by	for ($\text{eV cm}^2/\text{atom}$) $\times 10^{-15}$ multiply by
Be	9.013	1.848	.005411	184.8	14.96
C	12.011	2.25	.004444	225	19.94
Al	26.98	2.6989	.003705	269.9	44.80
Ti	47.90	4.54	.002203	454	79.53
Ni	58.71	8.902	.001123	890.2	97.48
Ge	72.60	5.323	.001879	532.3	120.54
Zr	91.22	6.53	.001531	653	151.45
Ag	107.873	10.50	.0009524	1050	179.1
Eu	152.0	5.259	.0019015	525.9	252.4
Ta	180.95	16.6	.0006024	1660	300.4
Au	197.0	19.32	.0005176	1932	327.1
U	238.07	18.95	.0005277	1895	395.3
H	1.008	.00008375	119.4	.008375	1.674
He	4.003	.0001663	60.13	.01663	6.646
N	14.008	.0011652	8.582	.11652	23.26
O	16	.0013315	7.510	.13315	26.57
Ne	20.183	.0008388	11.92	.08388	33.51
Ar	39.944	.0016619	6.017	.1662	66.32
Kr	83.80	.003481	2.873	.3481	139.1
Xe	131.30	.005485	1.823	.5485	218.0
Rn	222	.009066	1.103	.9066	368.6
Mylar		1.395	.007168	139.5	
(CH_2) _n		.92	.01087	92	
Water		1.0	.01	100	
Conversion factor formula			$0.01/\rho$	100ρ	$1.6603W$

JF Ziegler
(IBM)

The Stopping Powers and Ranges of Ions in Matter
vol 5 55 library call # QC 794.6.58

H(1)

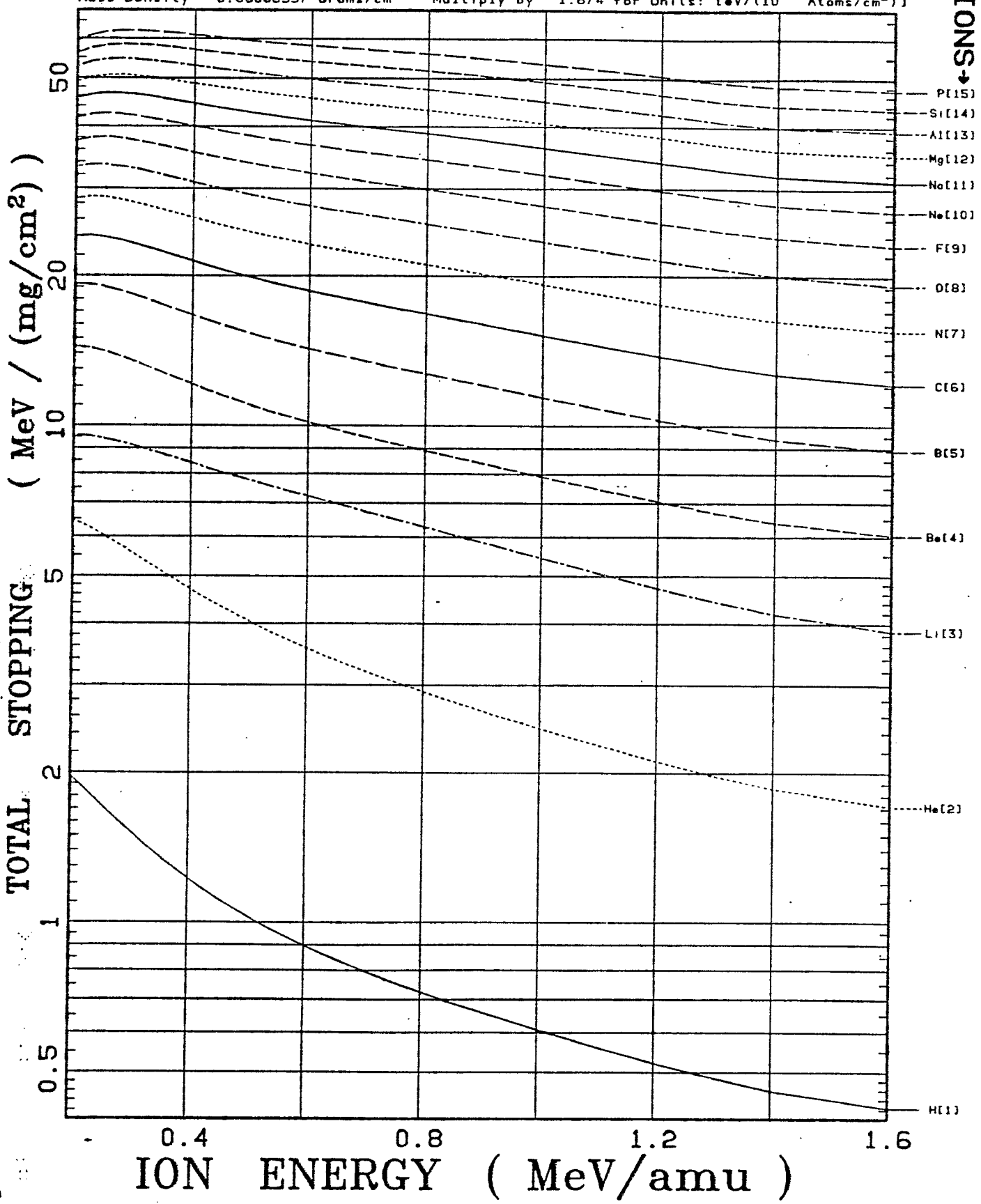
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H(1)

Tandem Van de
Graaff has a
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Atom Density = 5.376×10^{19} Atoms/cm³
Mass Density = 0.0008997 Grams/cm³

Multiply Total Stopping by 8.997 for Units: [keV/mm]
Multiply by 1.674 for Units: [eV/(10¹⁵ Atoms/cm²)]



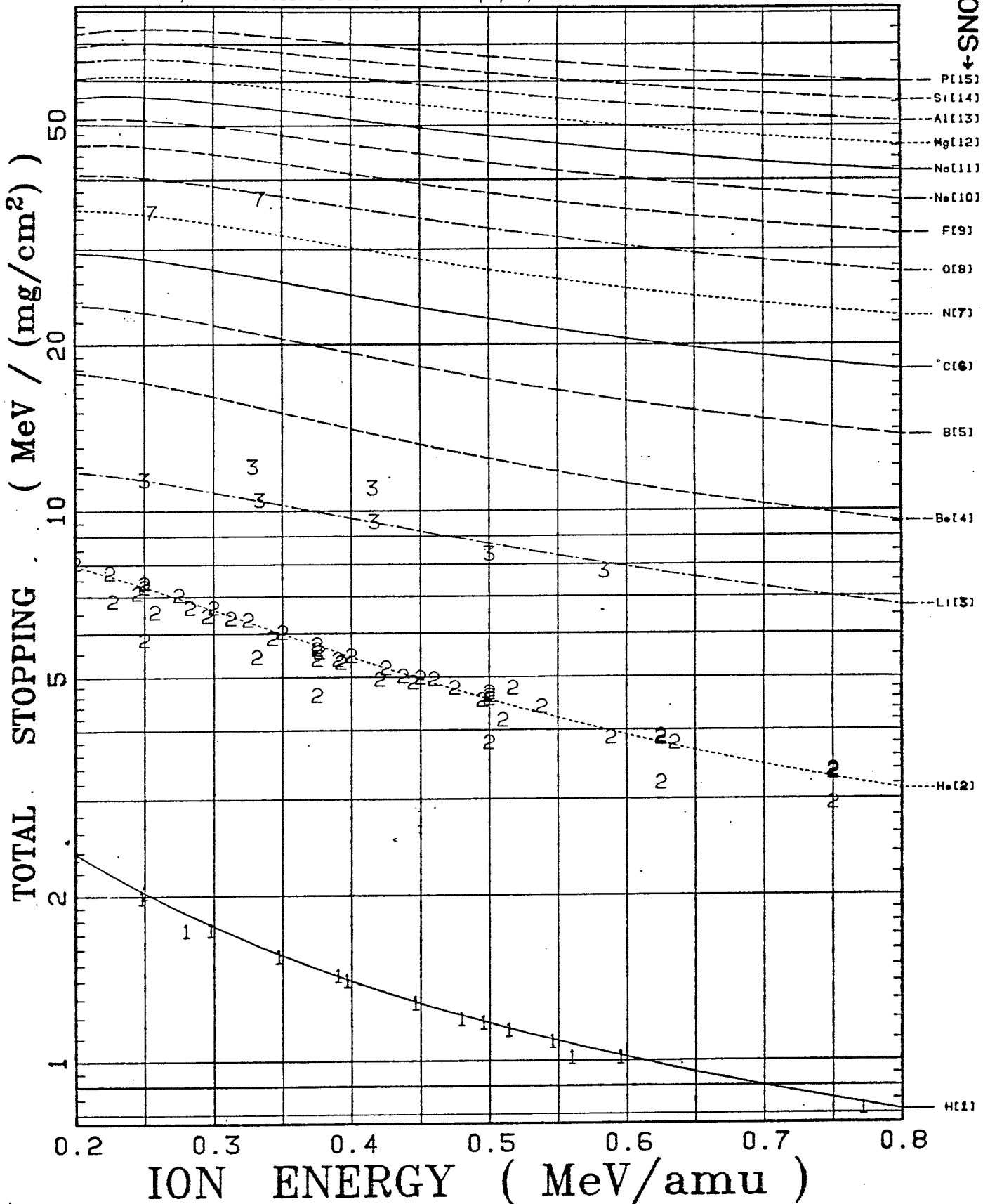
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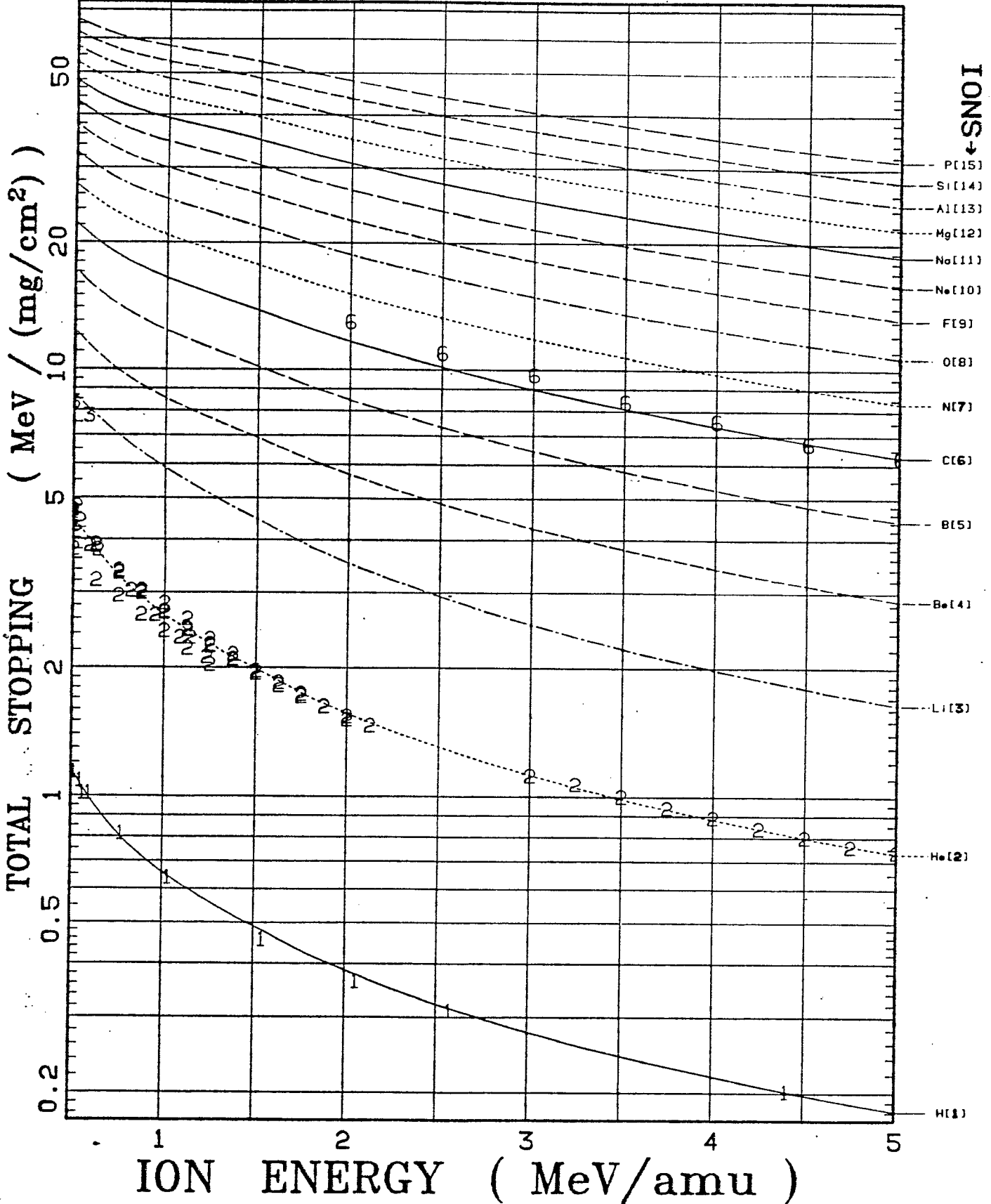
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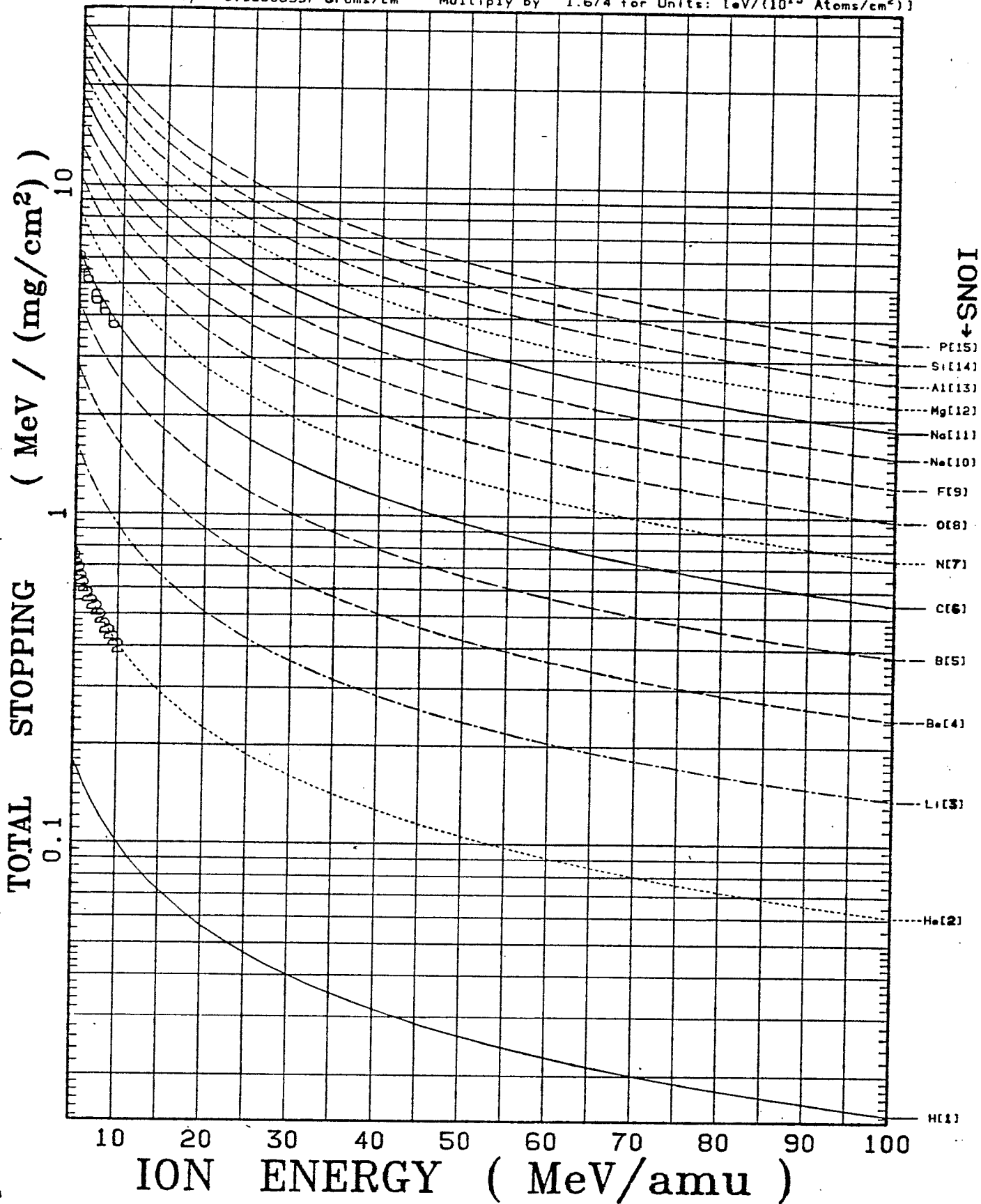
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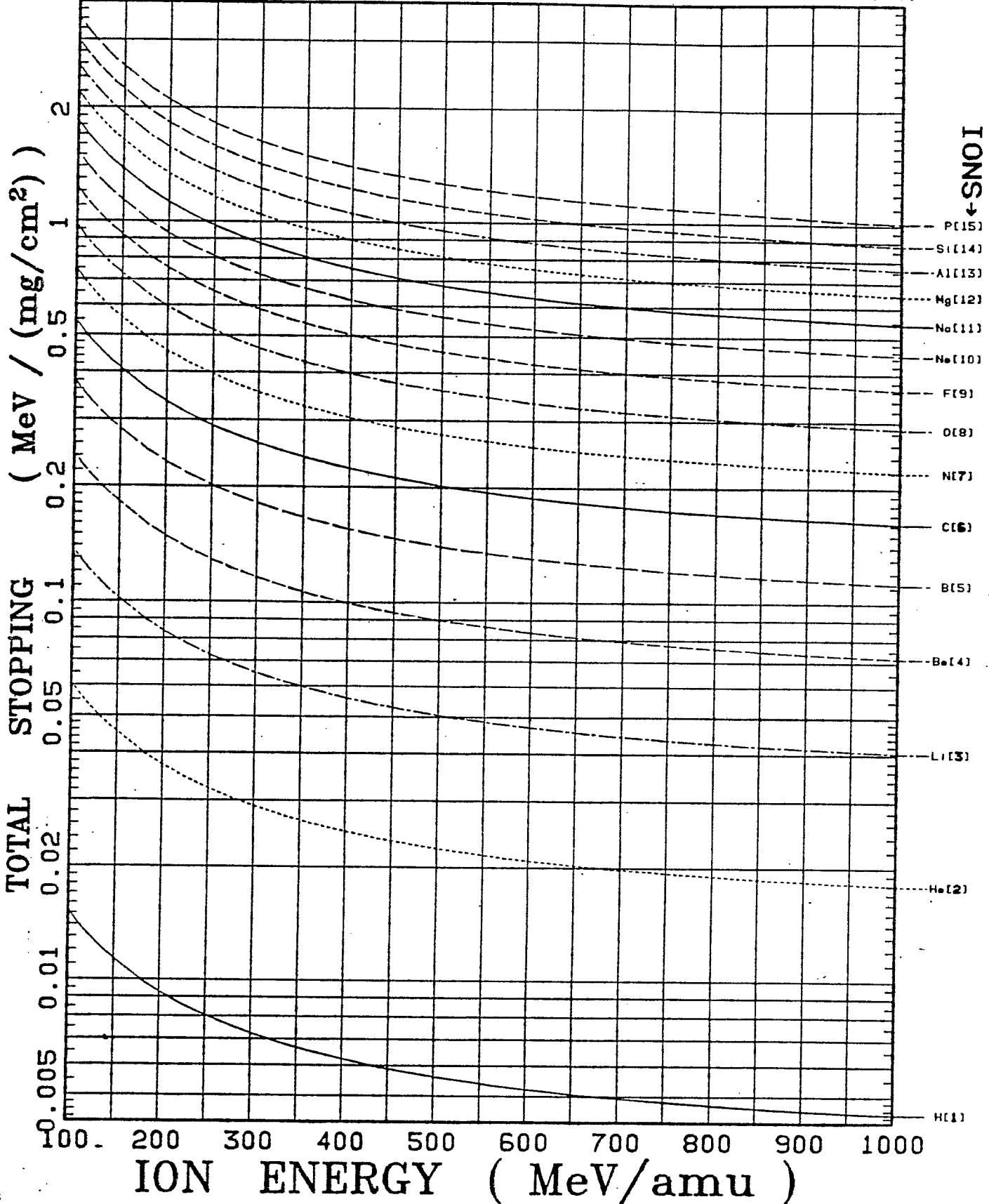
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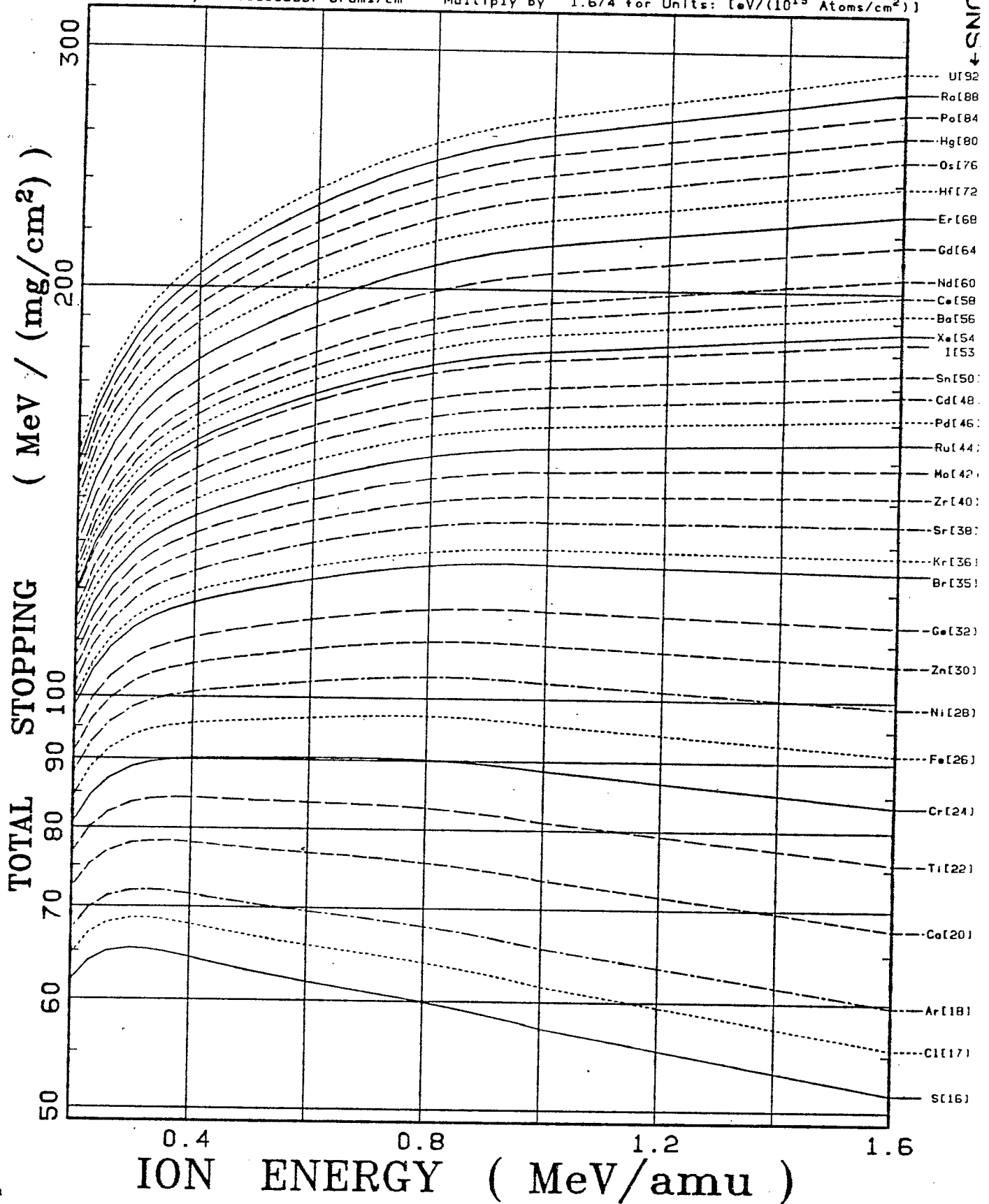
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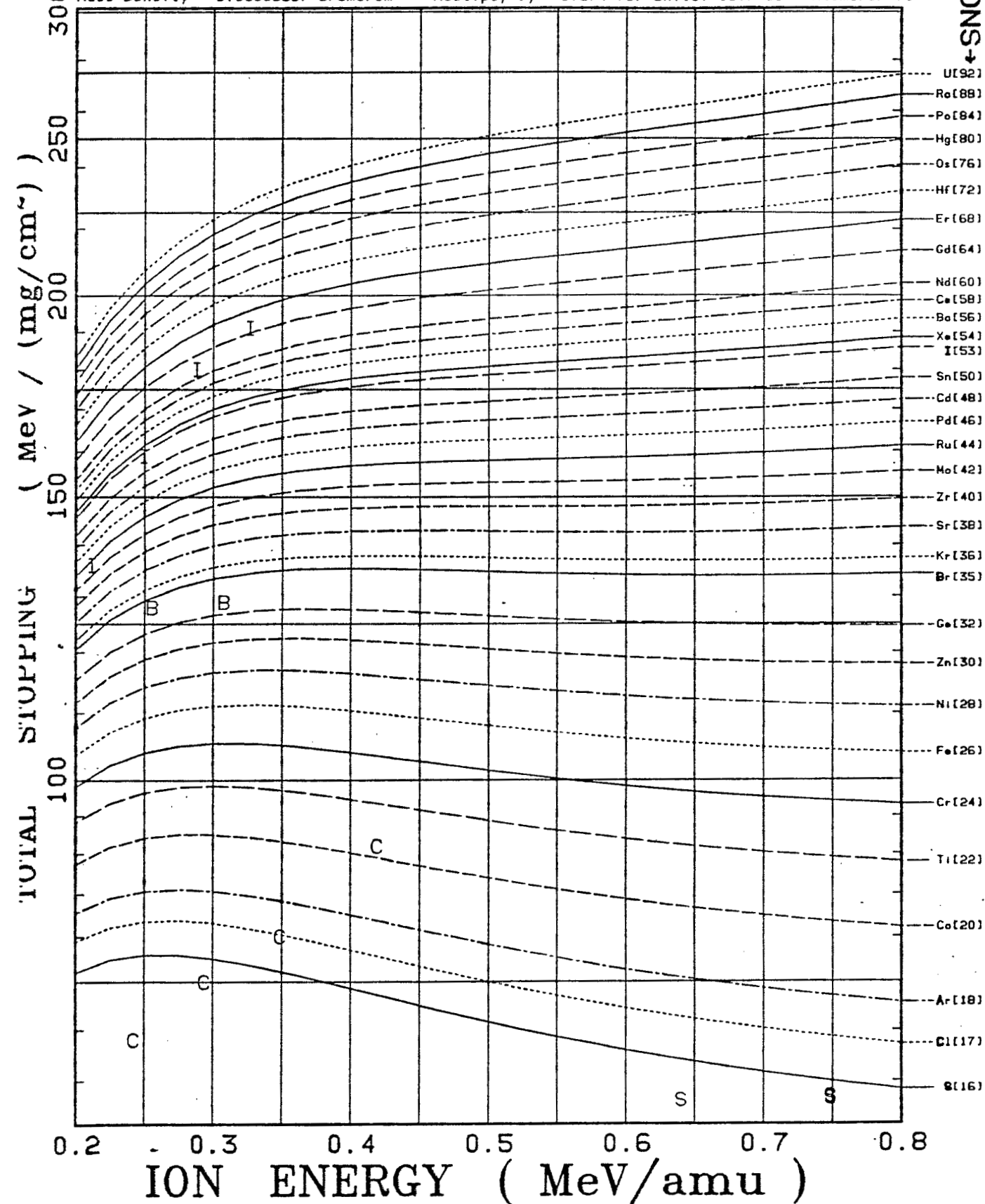
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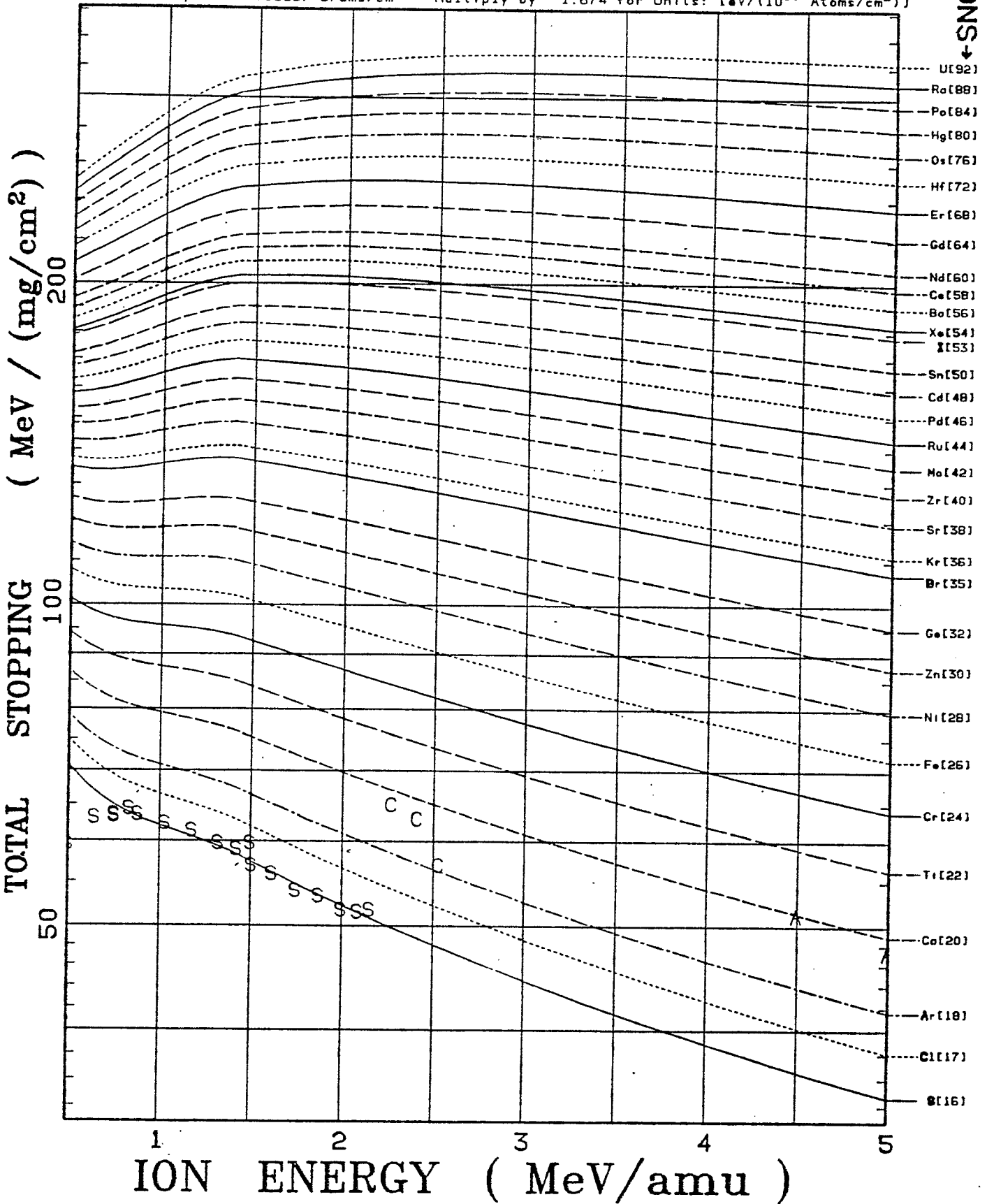
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IONS
← SNOI



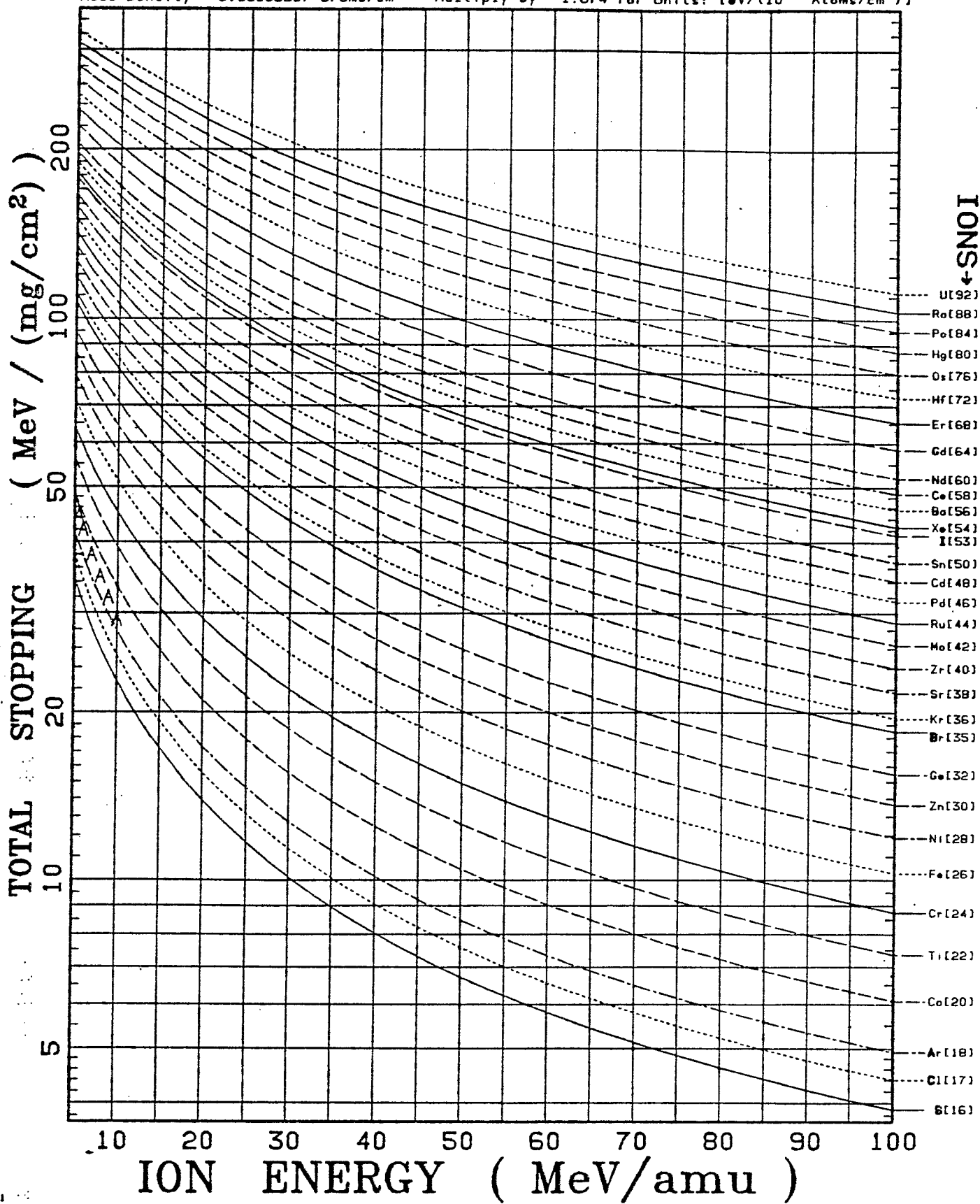
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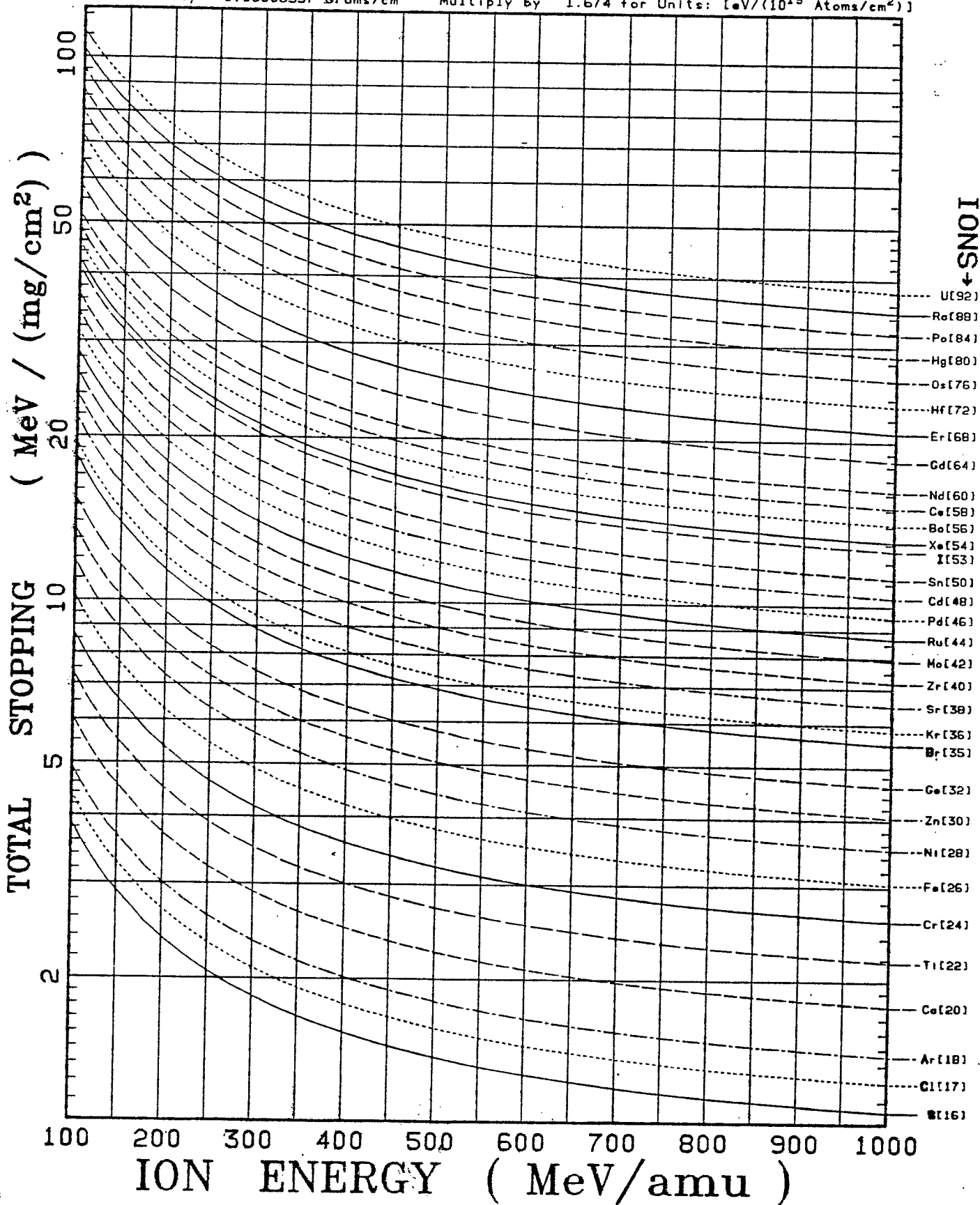
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C(6)

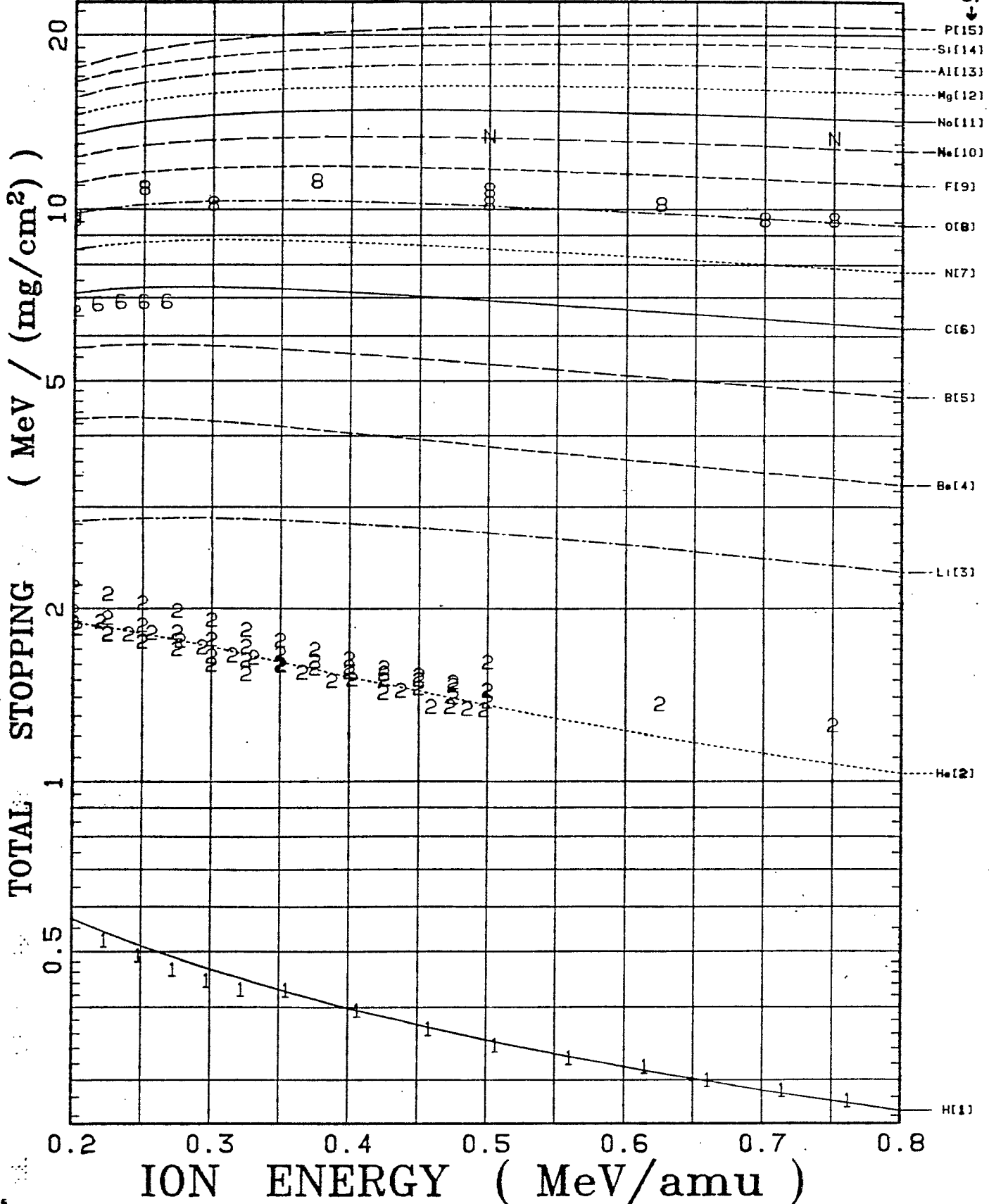
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C(6)

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Atom Density = 1.136×10^{23} Atoms/cm³
Mass Density = 2.266 Grams/cm³

Multiply Total Stopping by 226.6 for Units: [MeV/mm]
Multiply by 19.95 for Units: [eV/(10¹⁵ Atoms/cm²)]



C(6)

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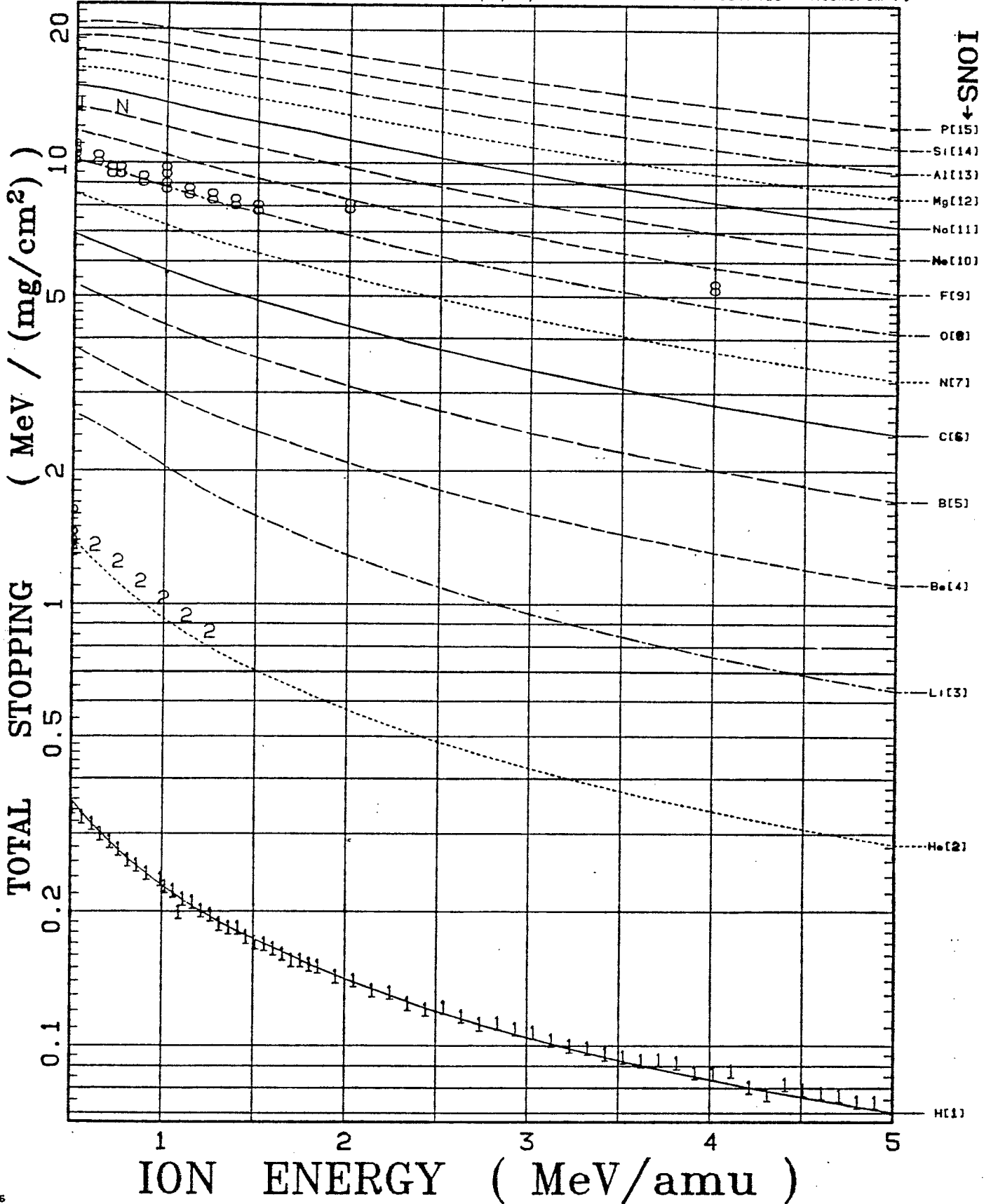
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Mass Density = 2.266 Grams/cm³

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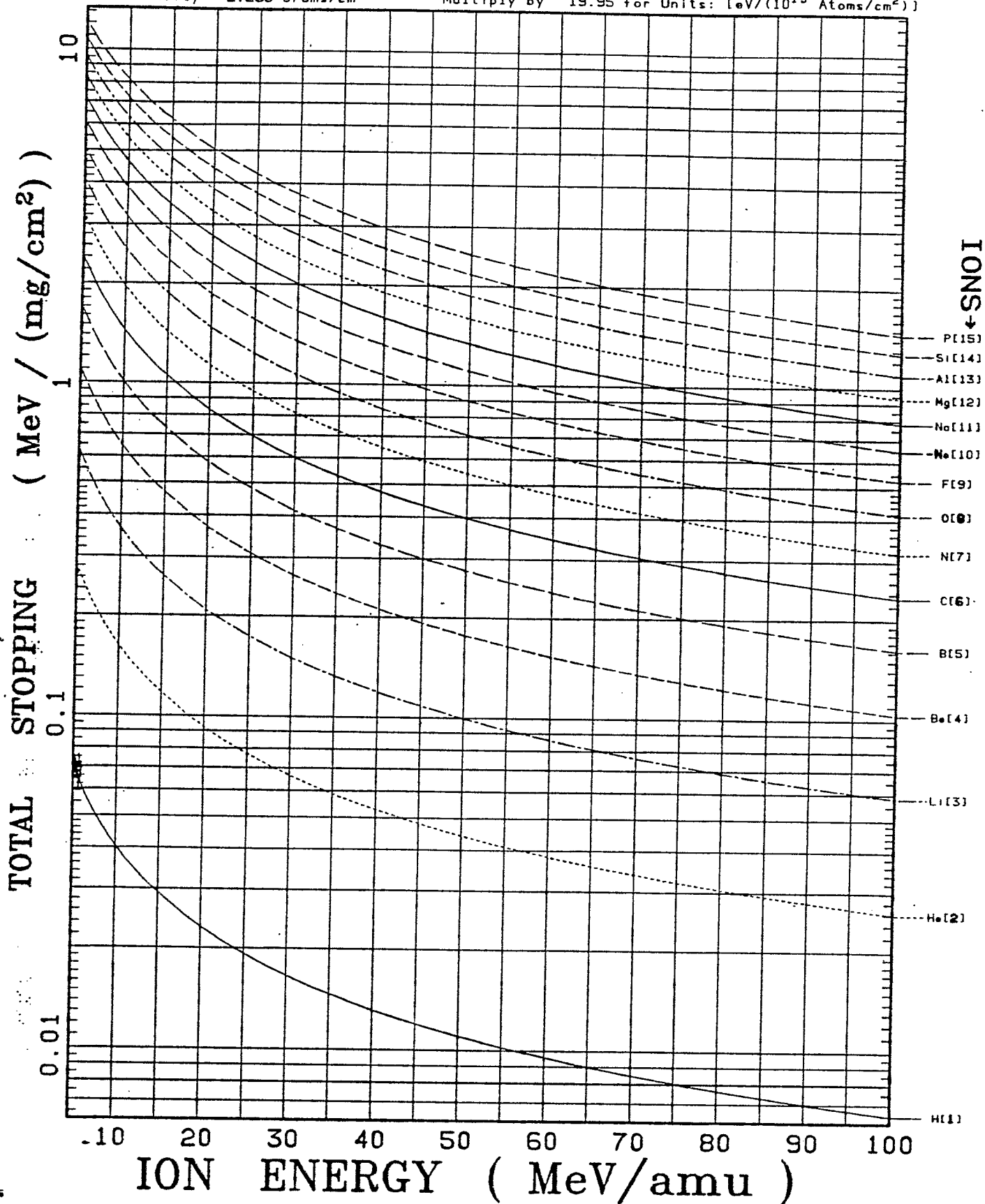
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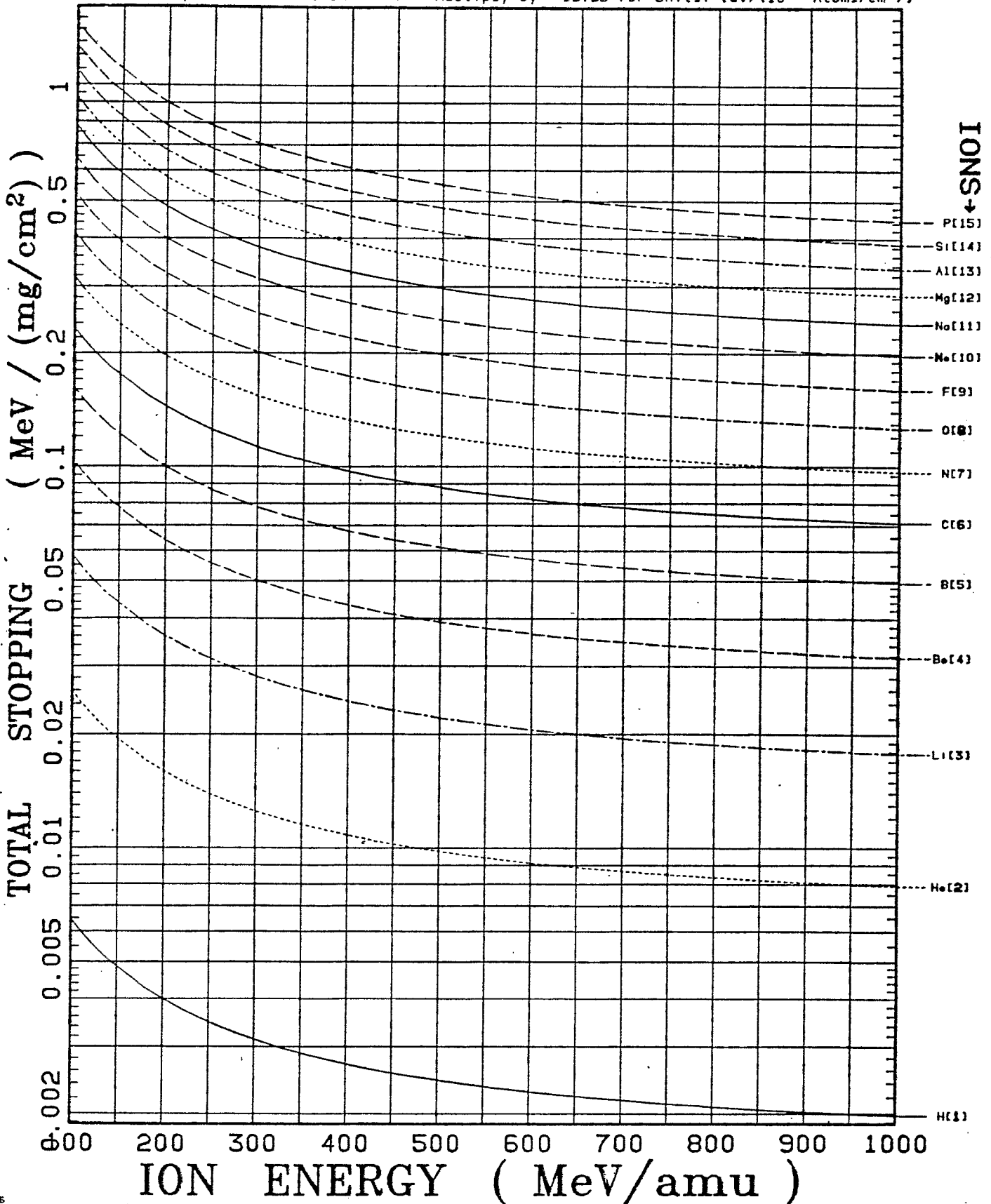
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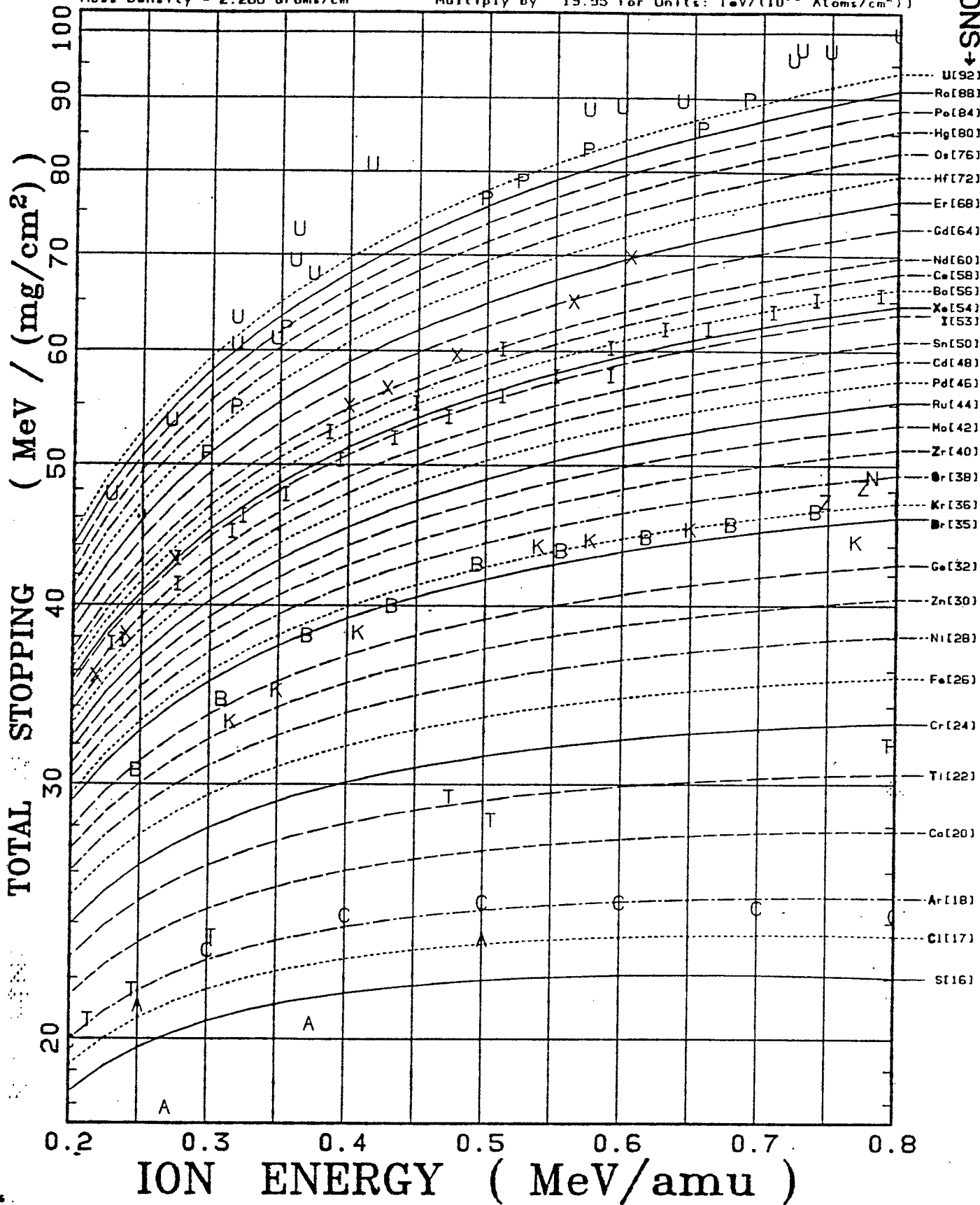
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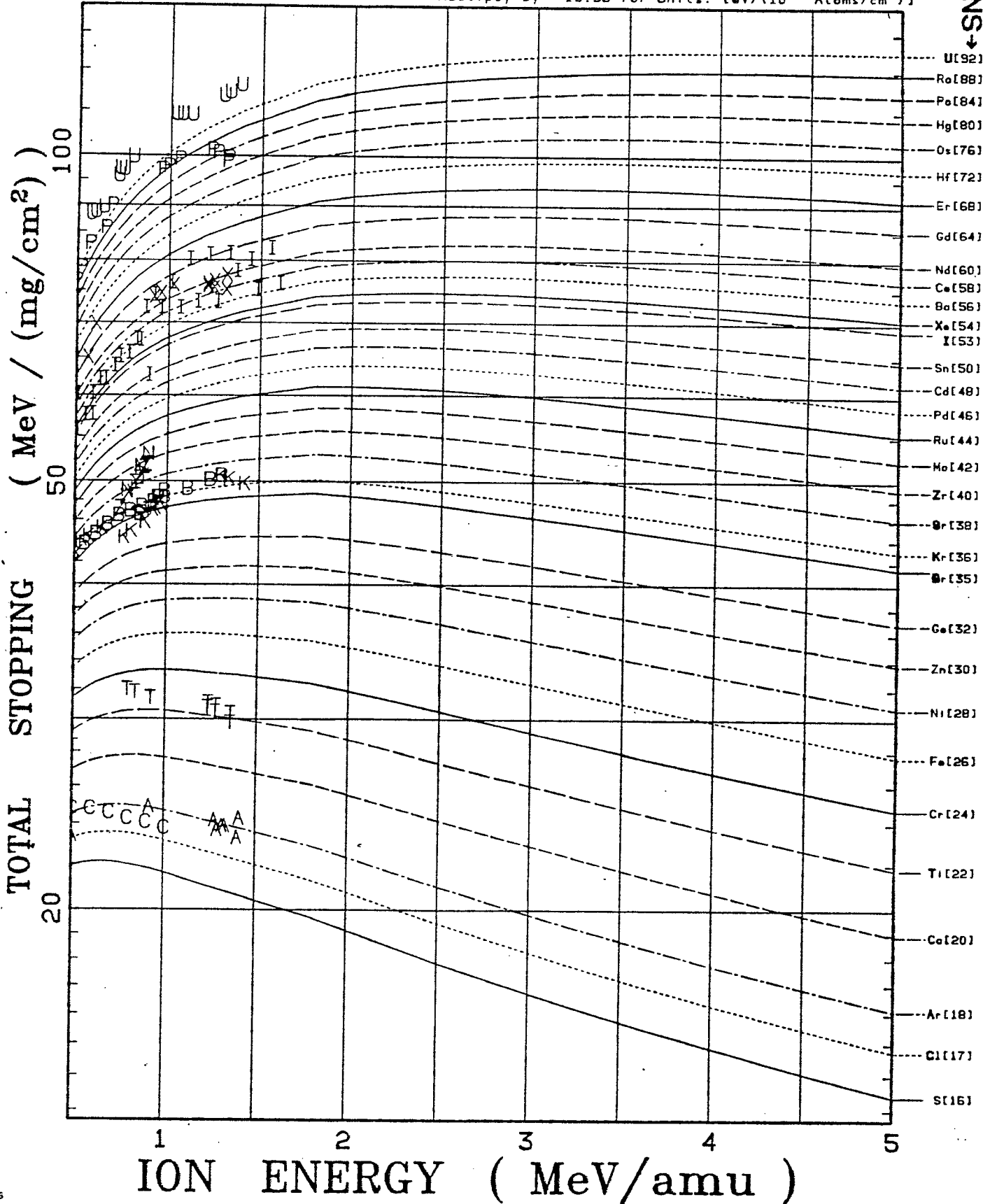
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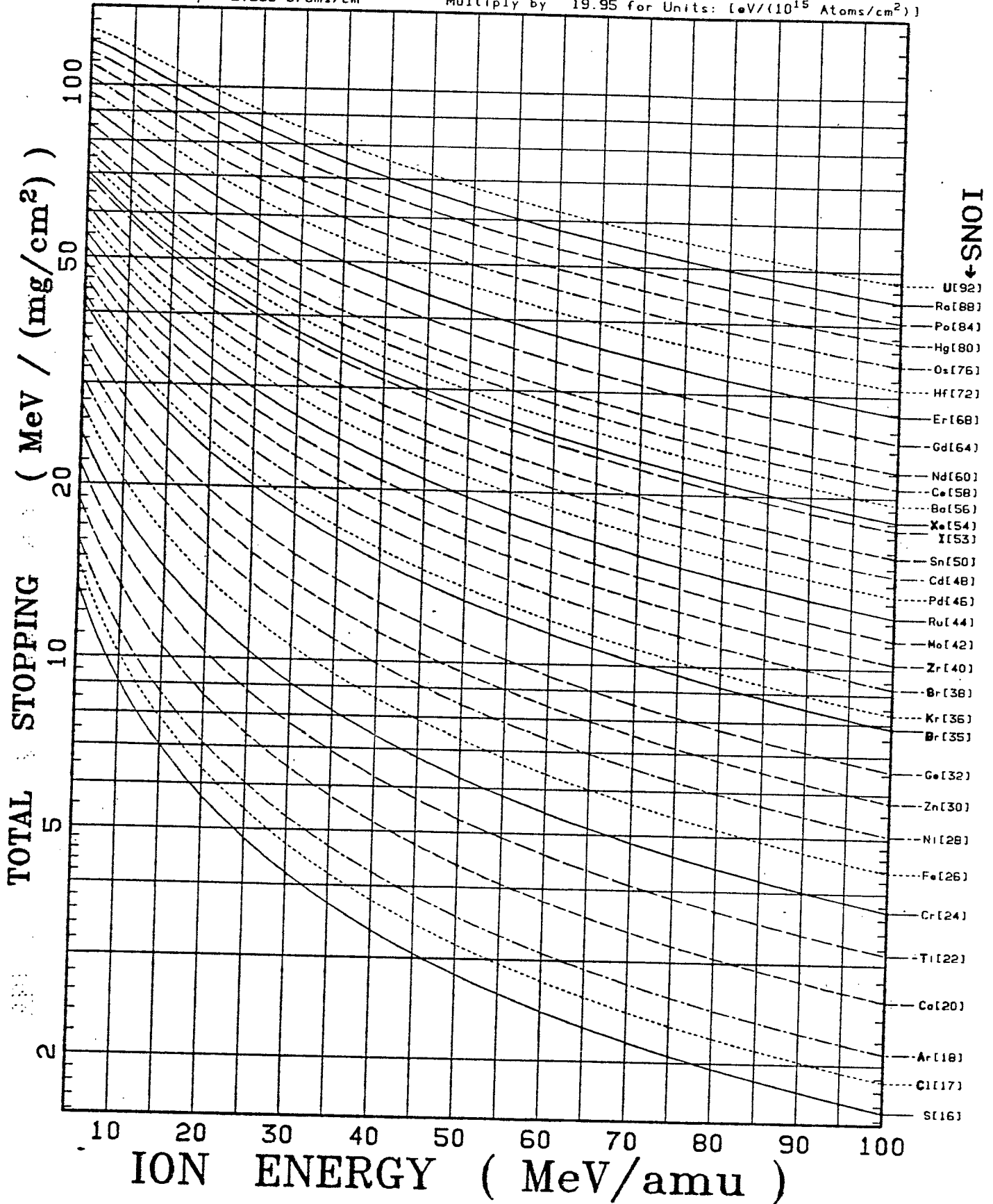
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 Mass Density = 2.266 Grams/cm³

Multiply Total Stopping by 226.6 for Units: [MeV/mm]
 Multiply by 19.95 for Units: [eV/(10¹⁵ Atoms/cm²)]



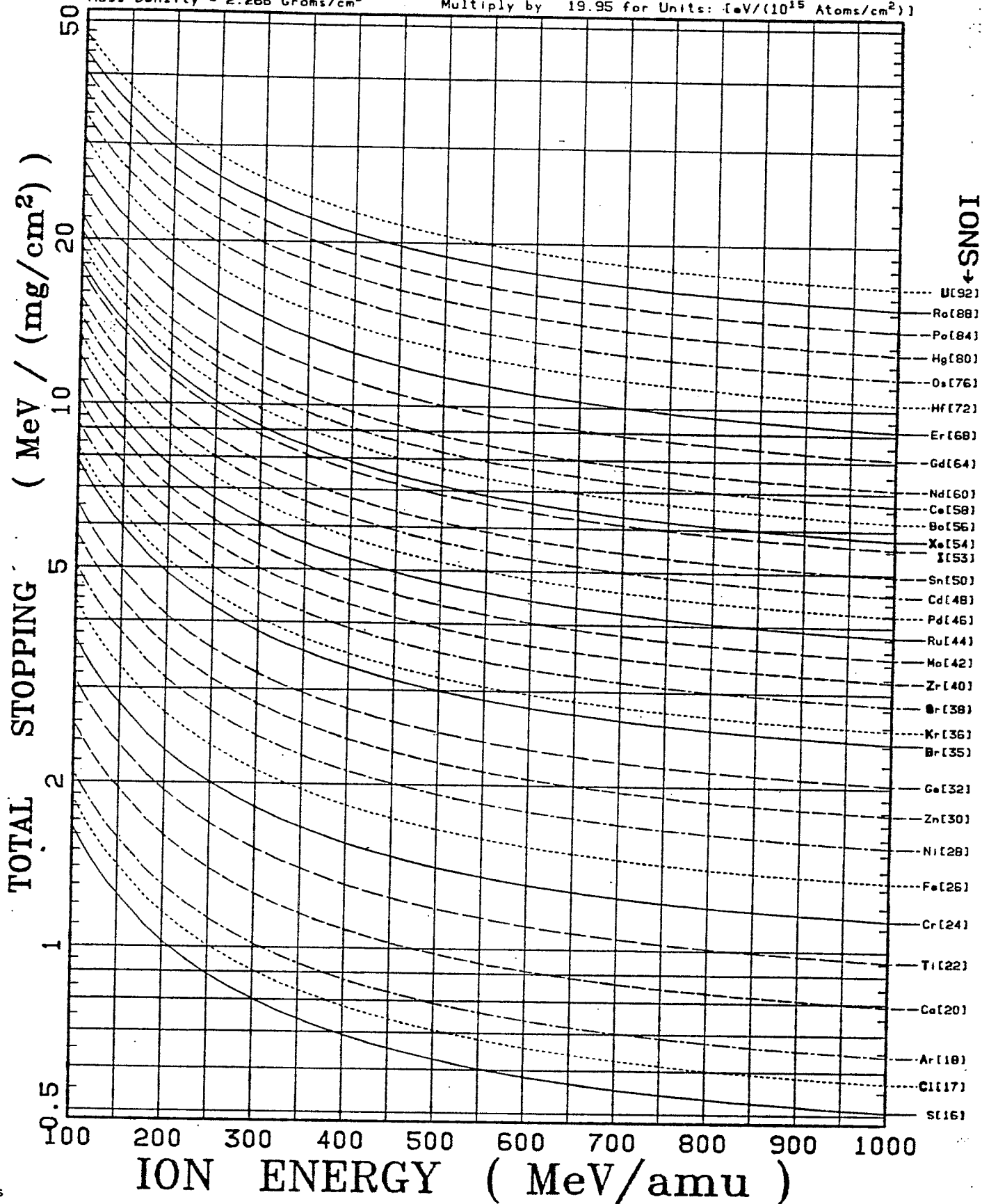
C(6)

←←← TARGET →→→

C(6)

Atom Density = 1.136×10^{23} Atoms/cm³
 Mass Density = 2.266 Grams/cm³

Multiply Total Stopping by 226.6 for Units: [MeV/mm]
 Multiply by 19.95 for Units: [eV/(10¹⁵ Atoms/cm²)]



Cu(29)

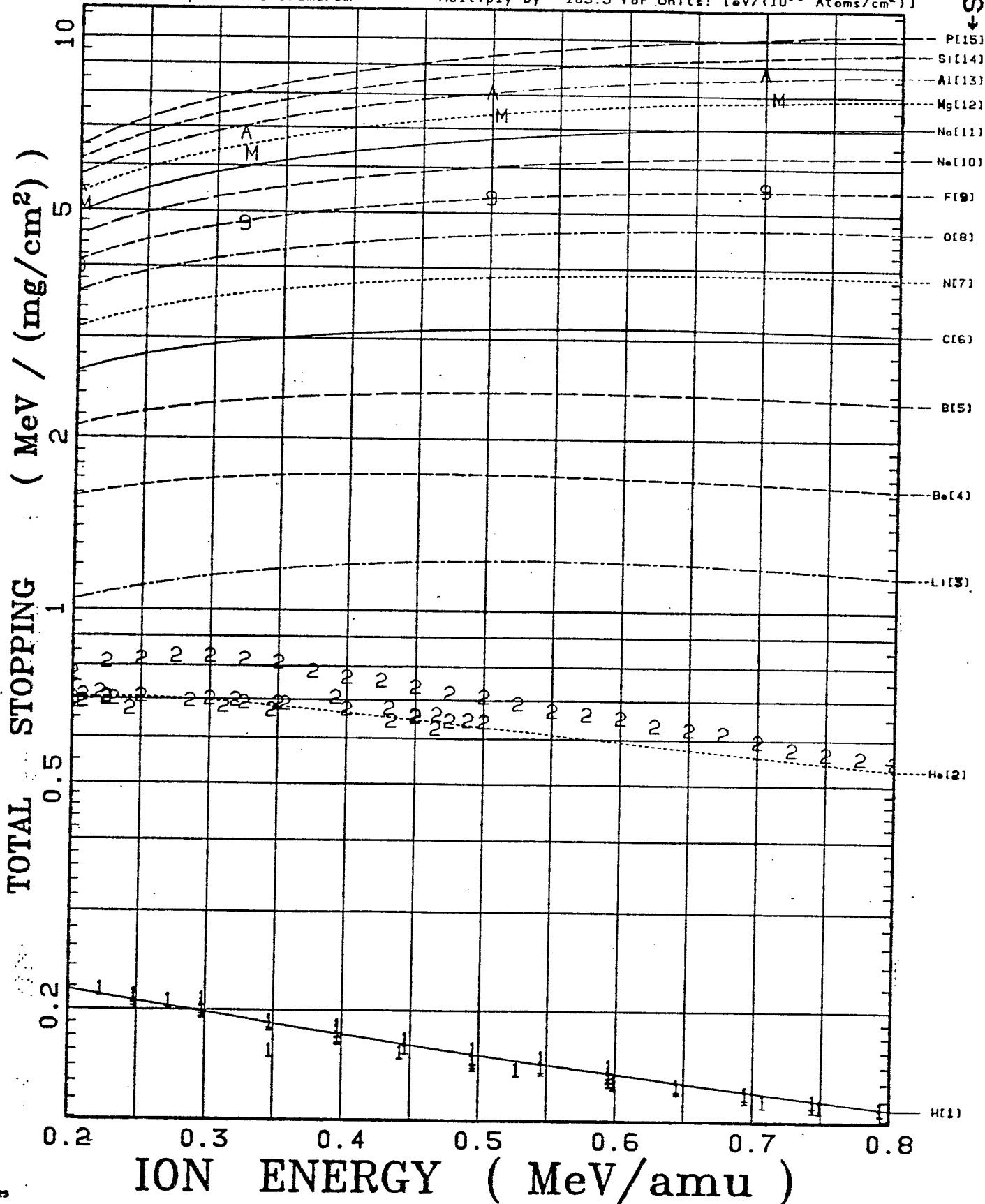
←←← TARGET →→→

Cu(29)

Atom Density = 8.483×10^{22} Atoms/cm³
 Mass Density = 8.949 Grams/cm³

Multiply Total Stopping by 894.9 for Units: [MeV/mm]
 Multiply by 105.5 for Units: [eV/(10¹⁵ Atoms/cm²)]

←SNOI



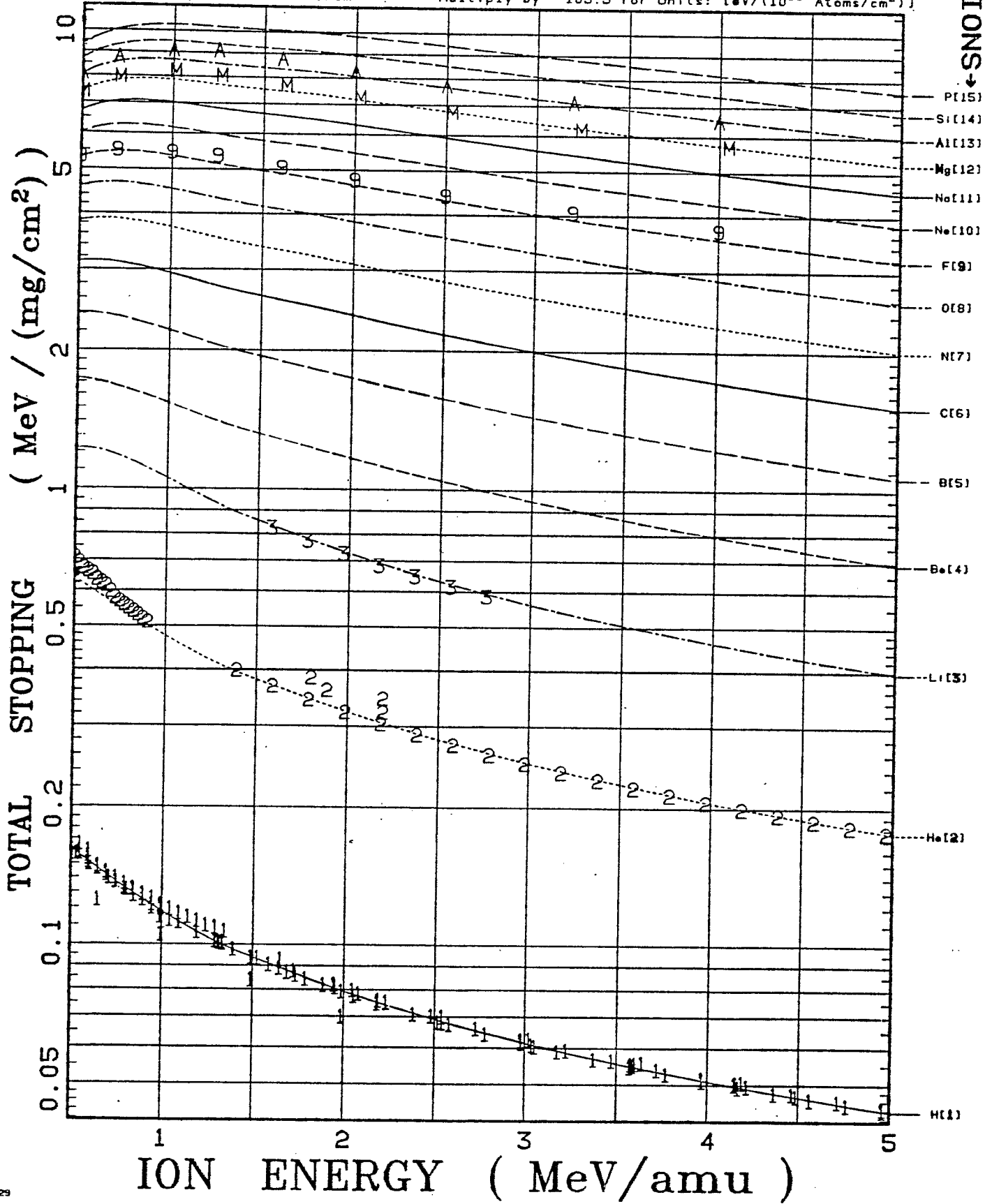
Cu(29)

←←← TARGET →→→

Cu(29)

Atom Density = 8.483×10^{22} Atoms/cm³
Mass Density = 8.949 Grams/cm³

Multiply Total Stopping by 894.9 for Units: (MeV/mm).
Multiply by 105.5 for Units: (eV/(10¹⁵ Atoms/cm²))



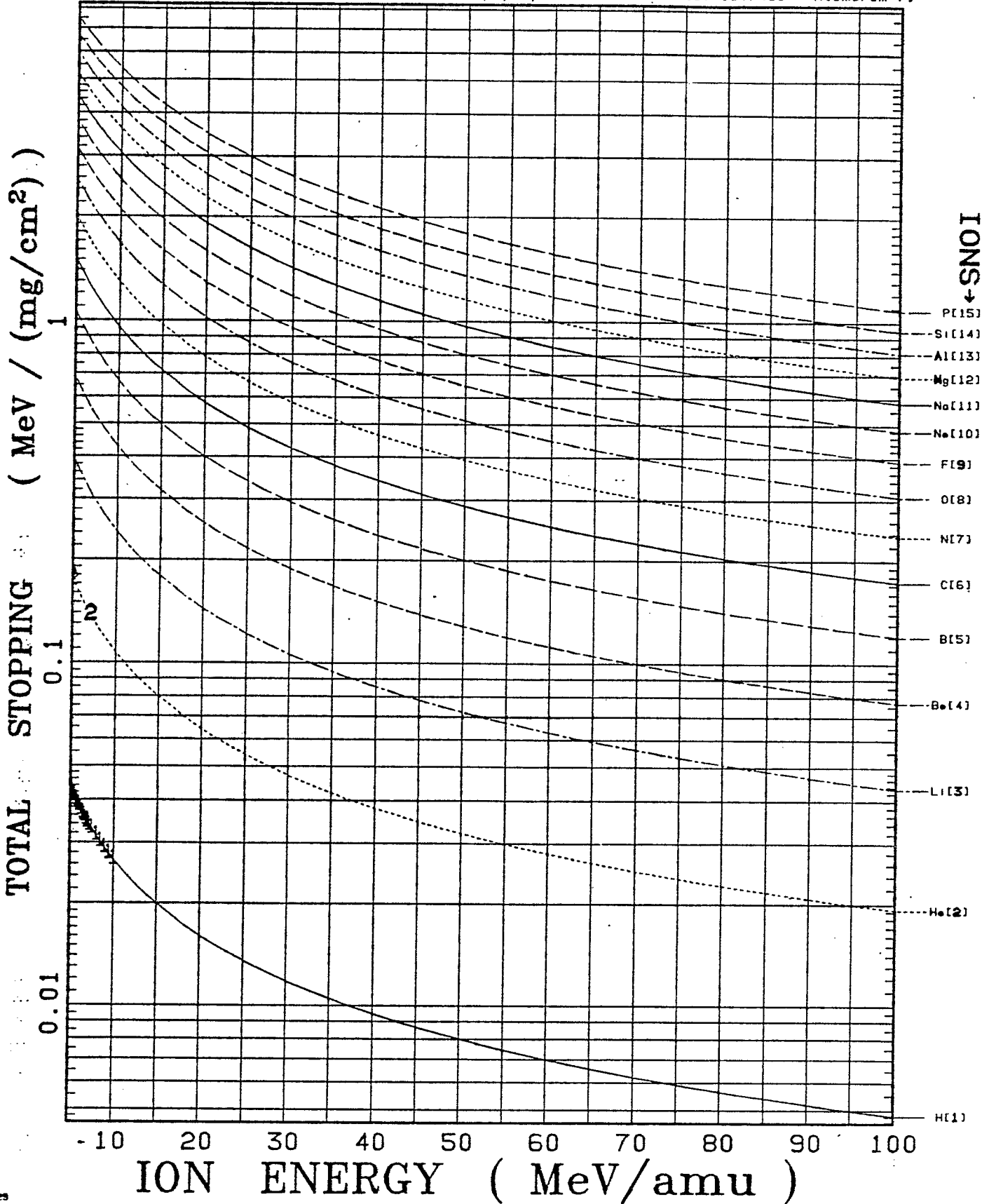
Cu(29)

←←← TARGET →→→

Cu(29)

Atom Density = 8.483×10^{22} Atoms/cm³
 Mass Density = 8.949 Grams/cm³

Multiply Total Stopping by 894.9 for Units: (MeV/mm)
 Multiply by 105.5 for Units: (eV/(10¹⁵ Atoms/cm²))



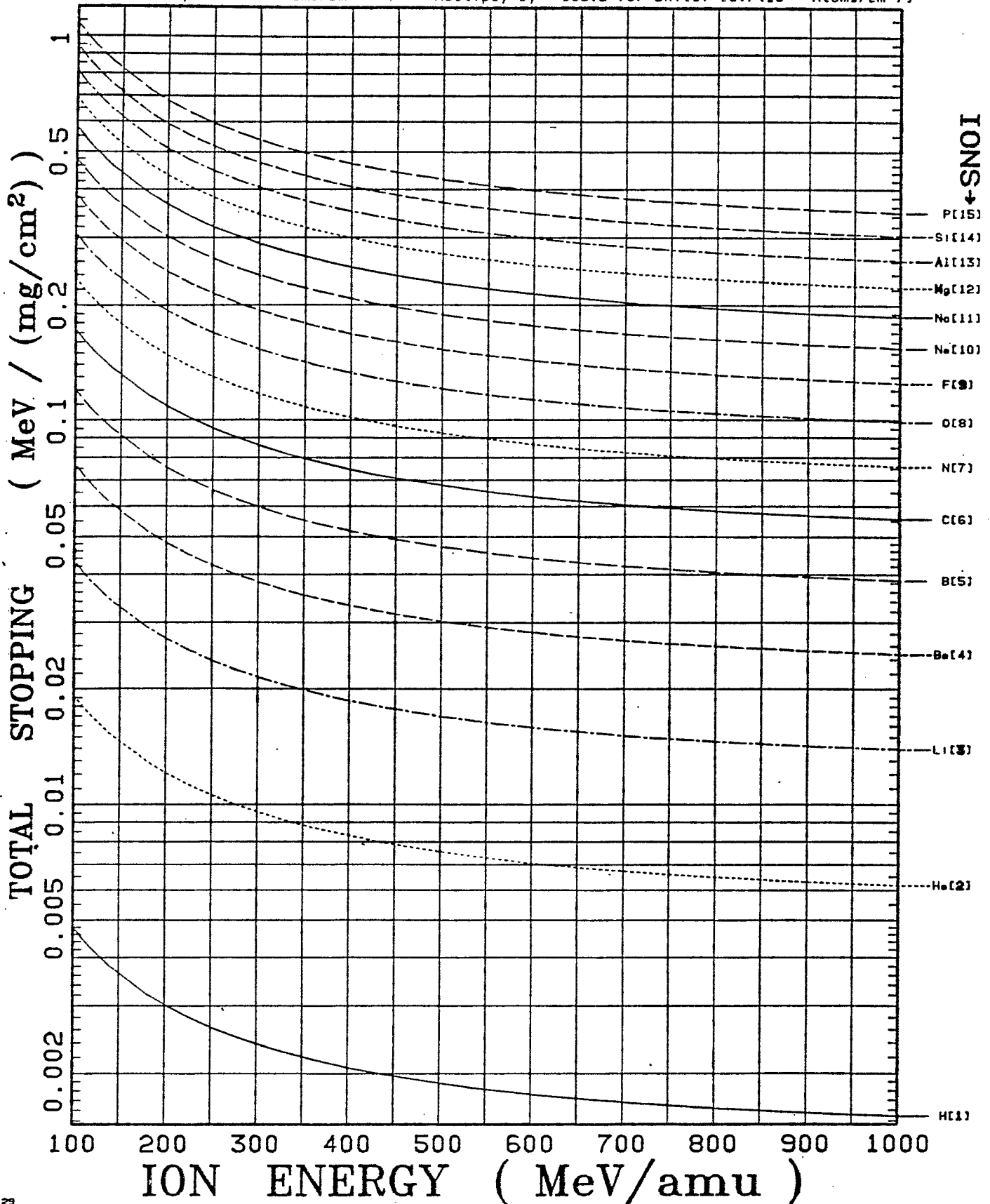
Cu(29)

←←← TARGET →→→

Cu(29)

Atom Density = 8.483×10^{22} Atoms/cm³
 Mass Density = 8.949 Grams/cm³

Multiply Total Stopping by 894.9 for Units: [MeV/mm]
 Multiply by 105.5 for Units: [eV/(10¹⁵ Atoms/cm²)]



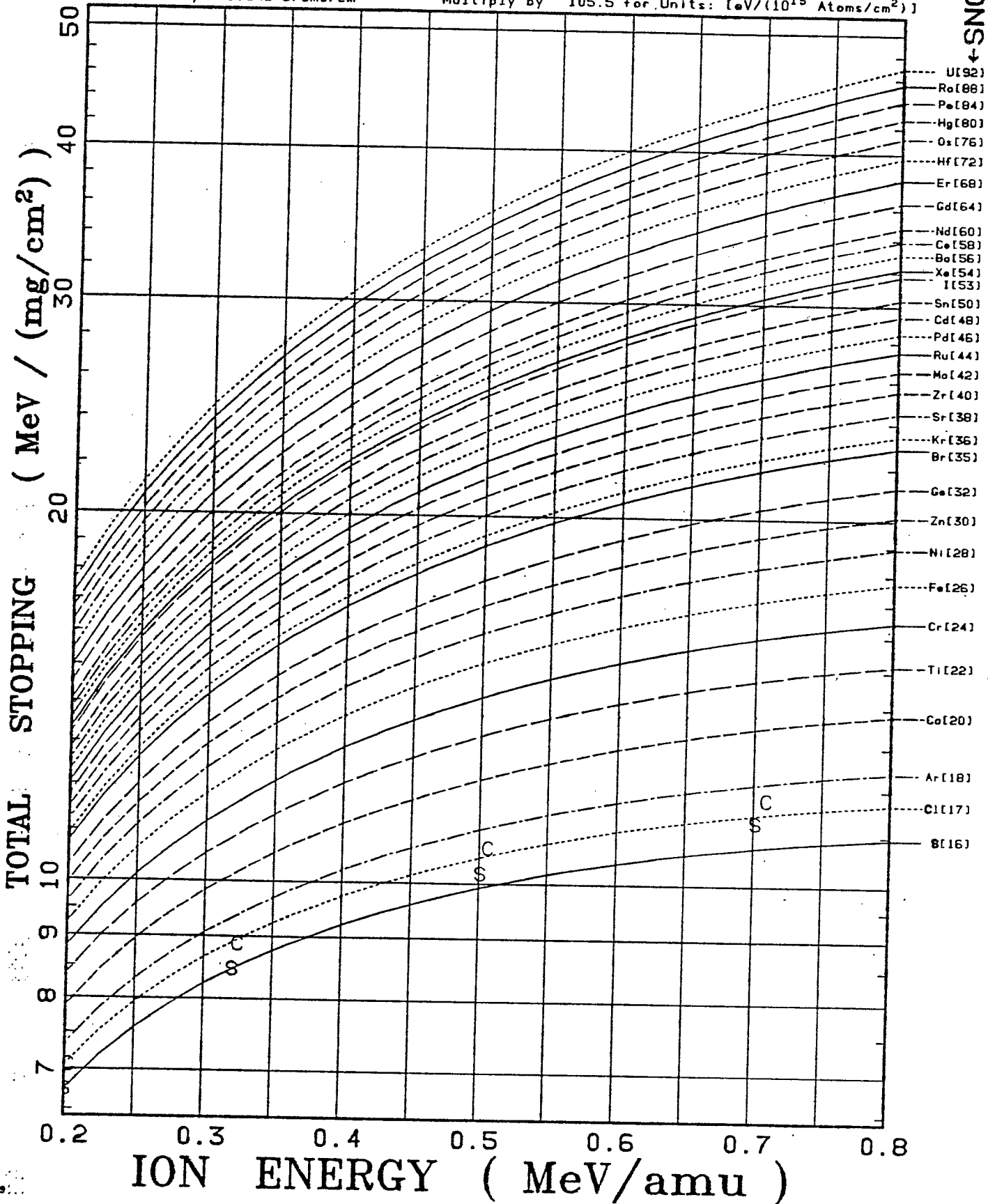
Cu(29)

←←← TARGET →→→

Cu(29)

Atom Density = 8.483×10^{22} Atoms/cm³
Mass Density = 8.949 Grams/cm³

Multiply Total Stopping by 894.9 for Units: [MeV/mm]
Multiply by 105.5 for Units: [eV/(10¹⁵ Atoms/cm²)]



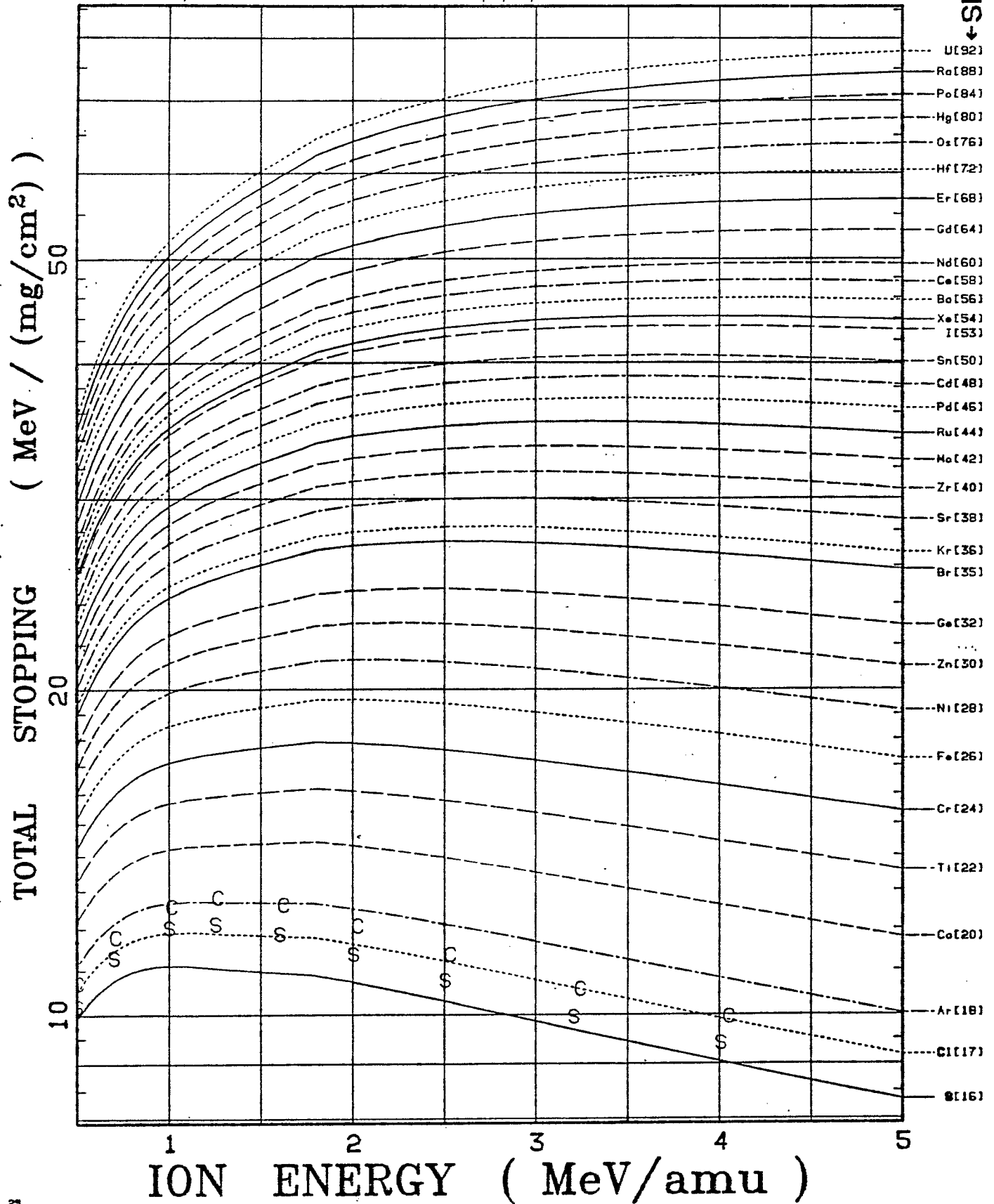
Cu(29)

←←← TARGET →→→

Cu(29)

Atom Density = 8.483×10^{22} Atoms/cm³
Mass Density = 8.949 Grams/cm³

Multiply Total Stopping by 894.9 for Units: [MeV/mm]
Multiply by 105.5 for Units: [eV/(10¹⁵ Atoms/cm²)]



← SNOI

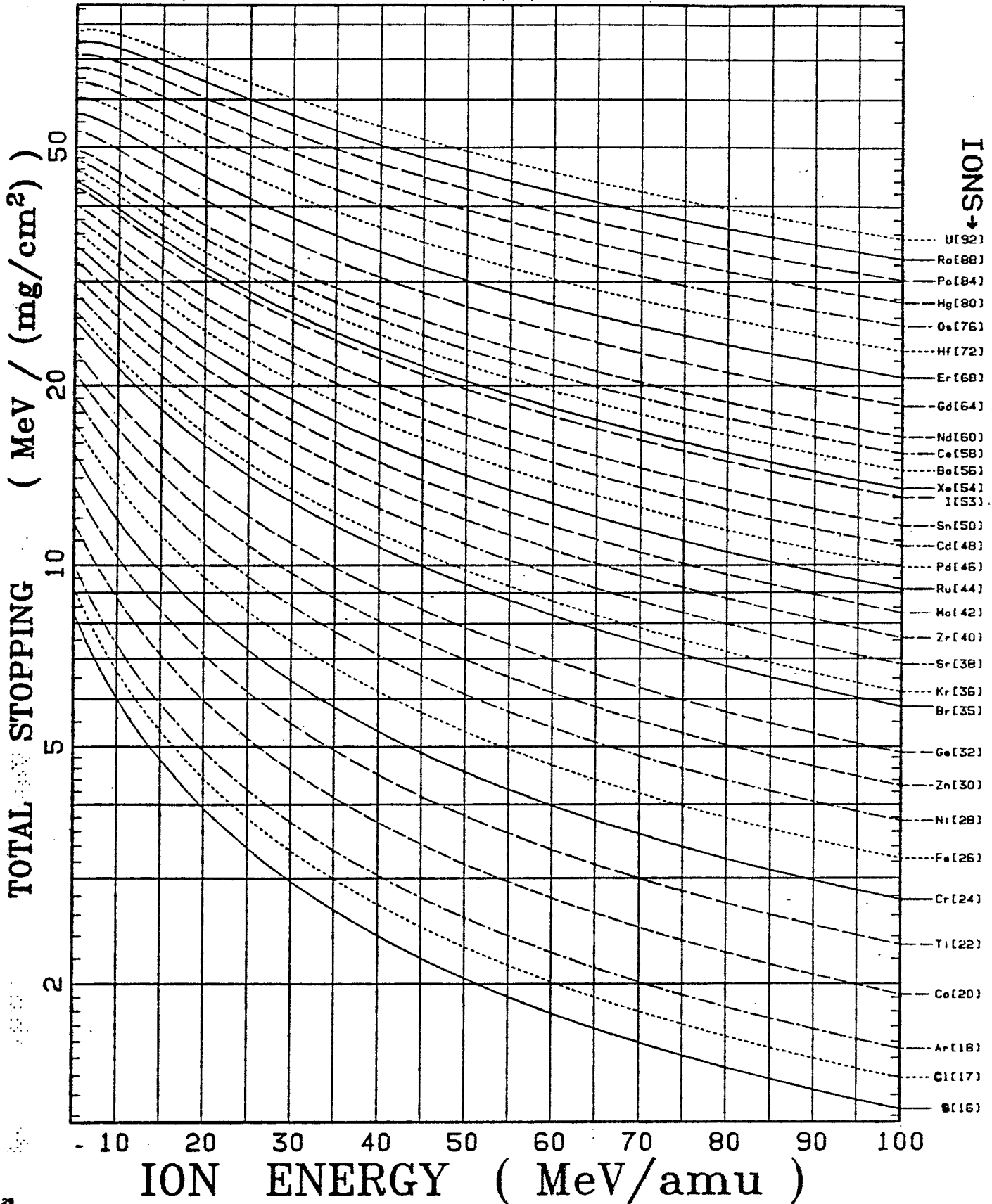
Cu(29)

←←← TARGET →→→

Cu(29)

Atom Density = 8.483×10^{22} Atoms/cm³
 Mass Density = 8.949 Grams/cm³

Multiply Total Stopping by 894.9 for Units: [MeV/mm]
 Multiply by 105.5 for Units: [eV/(10¹⁵ Atoms/cm²)]



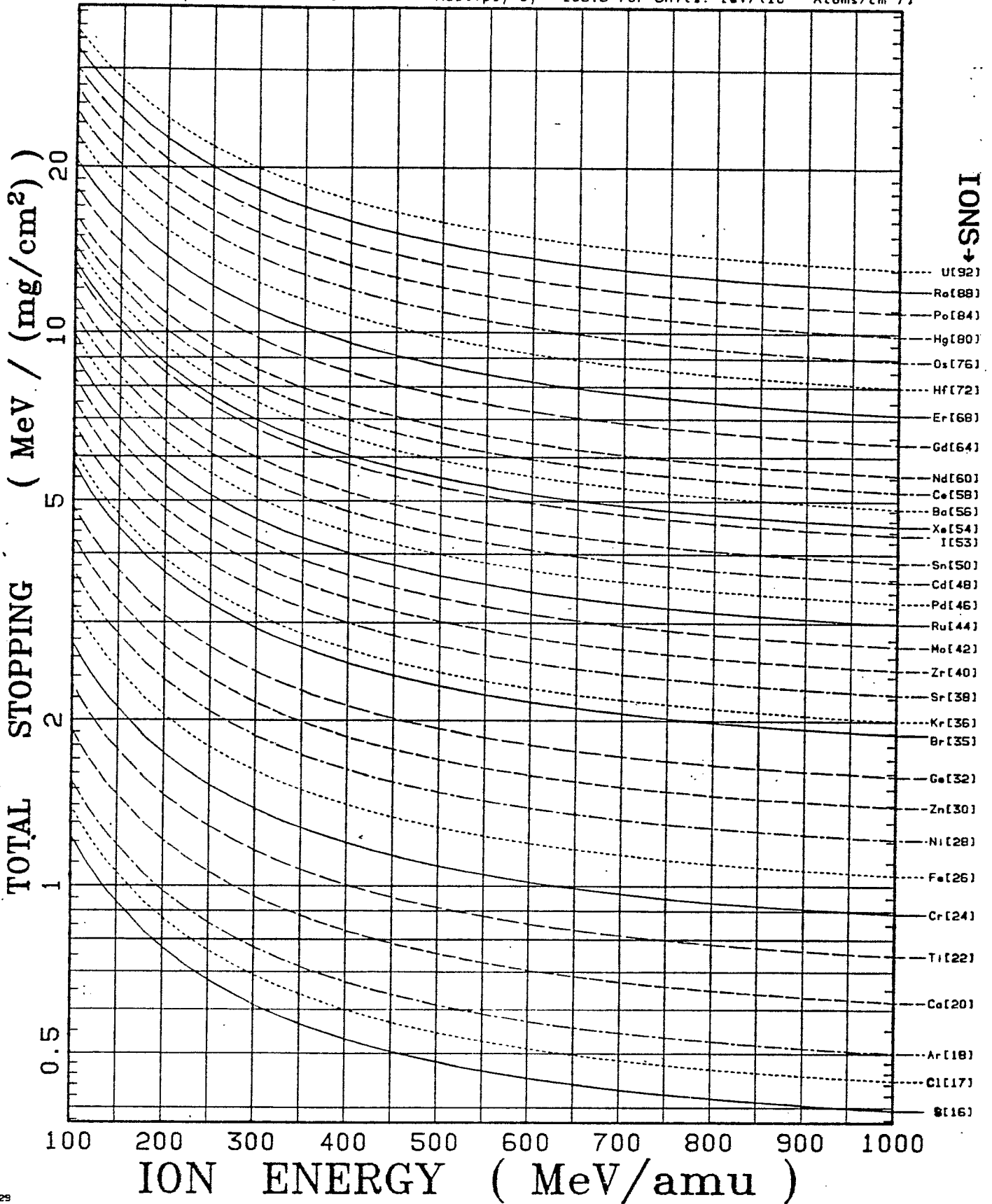
Cu(29)

←←← TARGET →→→

Cu(29)

Atom Density = 8.483×10^{22} Atoms/cm³
 Mass Density = 8.949 Grams/cm³

Multiply Total Stopping by 894.9 for Units: [MeV/mm]
 Multiply by 105.5 for Units: [eV/(10¹⁵ Atoms/cm²)]



Ta(73)

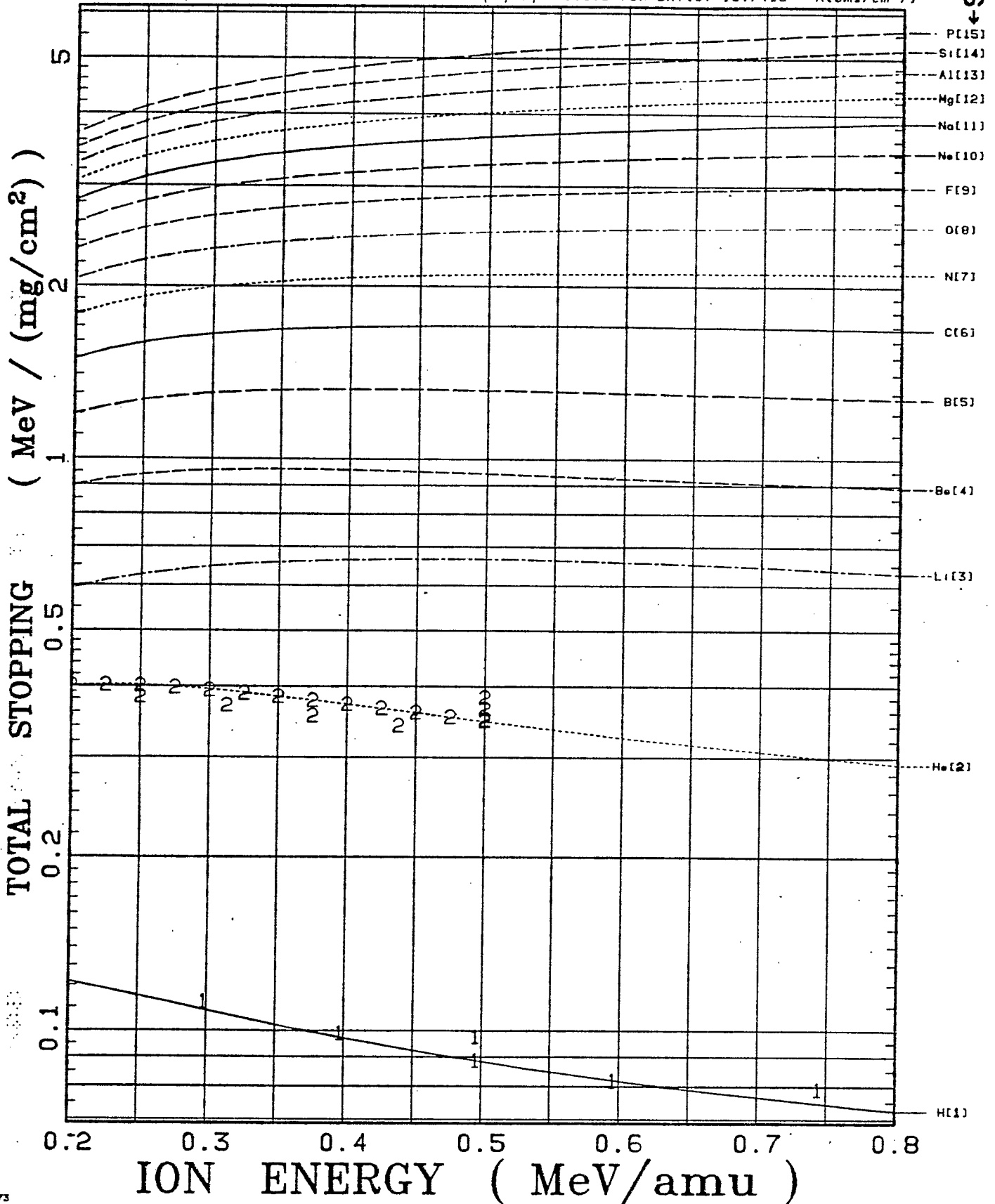
←←← TARGET →→→

Ta(73)

Atom Density = 5.526×10^{22} Atoms/cm³
 Mass Density = 16.6 Groms/cm³

Multiply Total Stopping by 1660 for Units: [MeV/mm]
 Multiply by 300.5 for Units: [eV/(10¹⁵ Atoms/cm²)]

IONS
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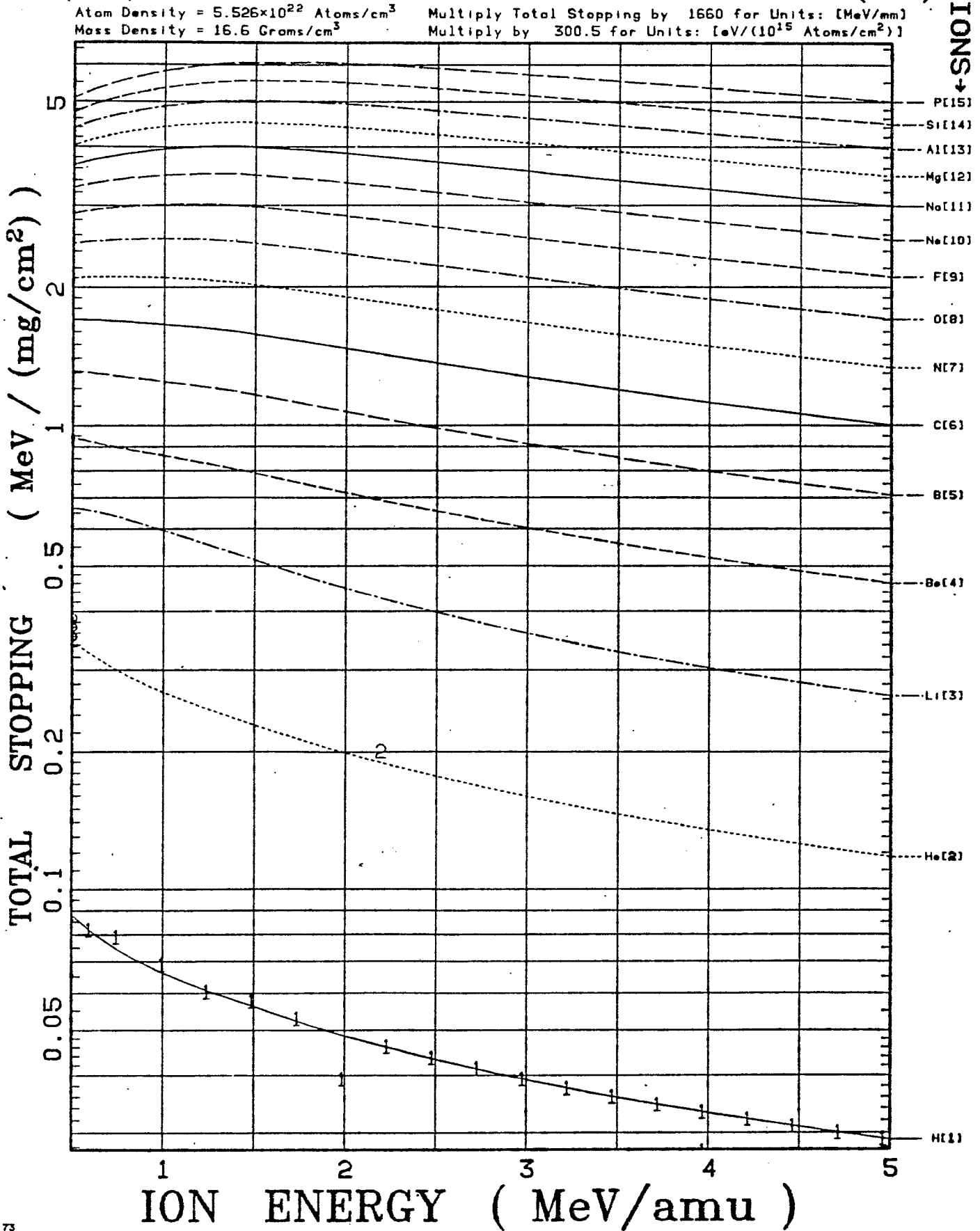
Ta(73)

←←← TARGET →→→

Ta(73)

Atom Density = 5.526×10^{22} Atoms/cm³
 Mass Density = 16.6 Grams/cm³

Multiply Total Stopping by 1660 for Units: [MeV/mm]
 Multiply by 300.5 for Units: [eV/(10¹⁵ Atoms/cm²)]



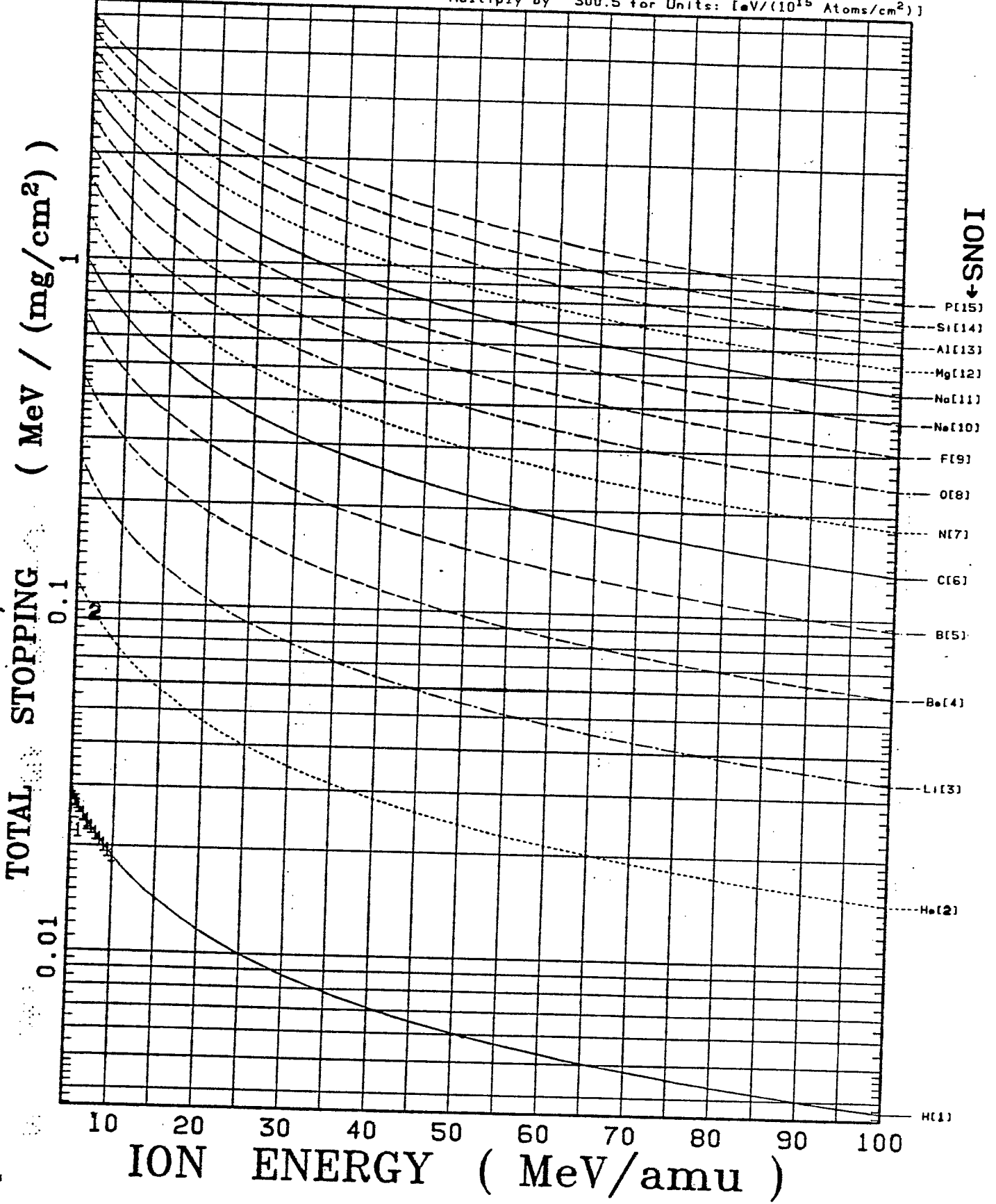
Ta(73)

←←← TARGET →→→

Ta(73)

Atom Density = 5.526×10^{22} Atoms/cm³
Mass Density = 16.6 Grams/cm³

Multiply Total Stopping by 1660 for Units: [MeV/mm]
Multiply by 300.5 for Units: [eV/(10¹⁵ Atoms/cm²)]



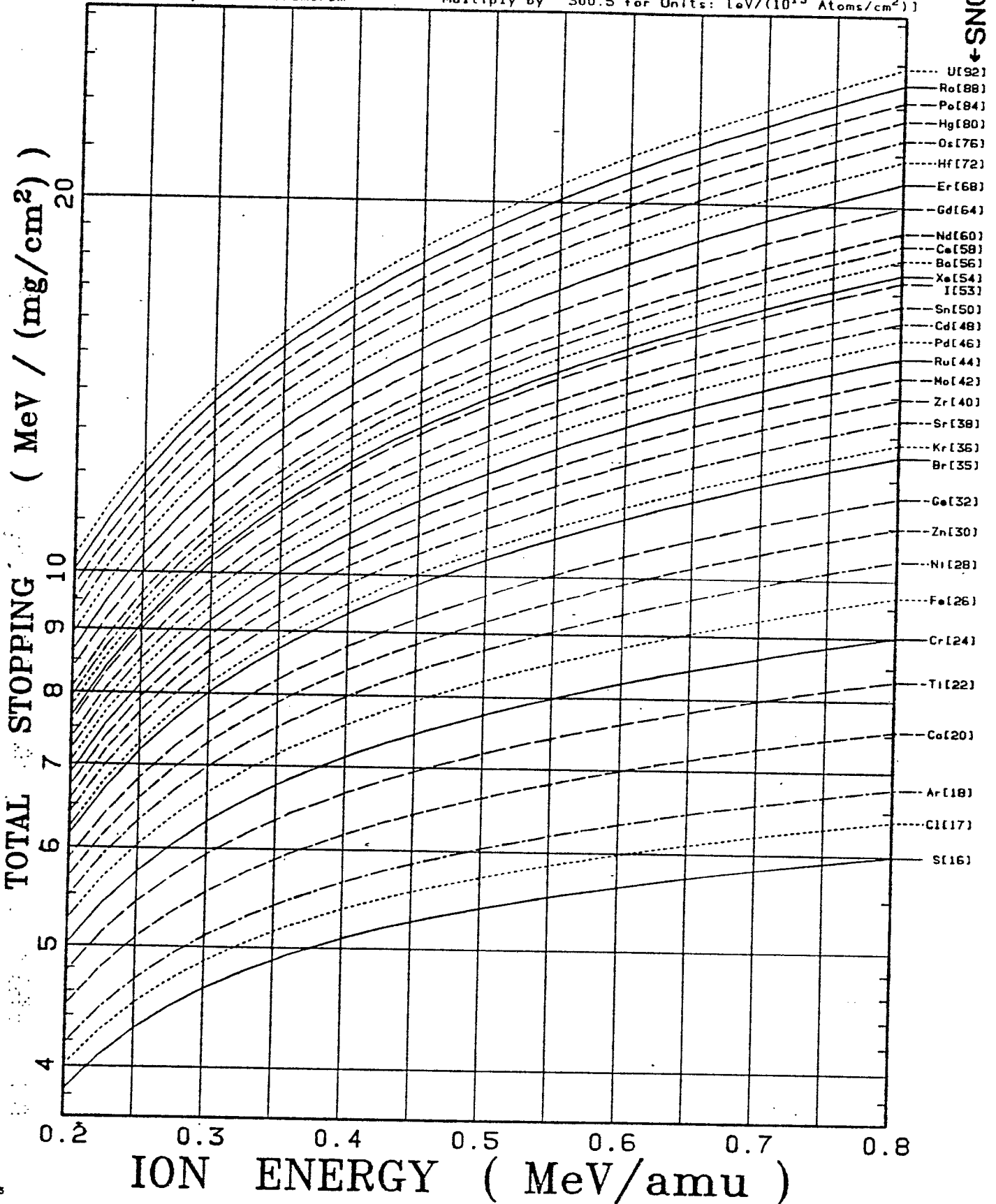
Ta(73)

←←← TARGET →→→

Ta(73)

Atom Density = 5.526×10^{22} Atoms/cm³
Mass Density = 16.6 Grams/cm³

Multiply Total Stopping by 1660 for Units: [MeV/mm]
Multiply by 300.5 for Units: [eV/(10¹⁵ Atoms/cm²)]



Ta(73)

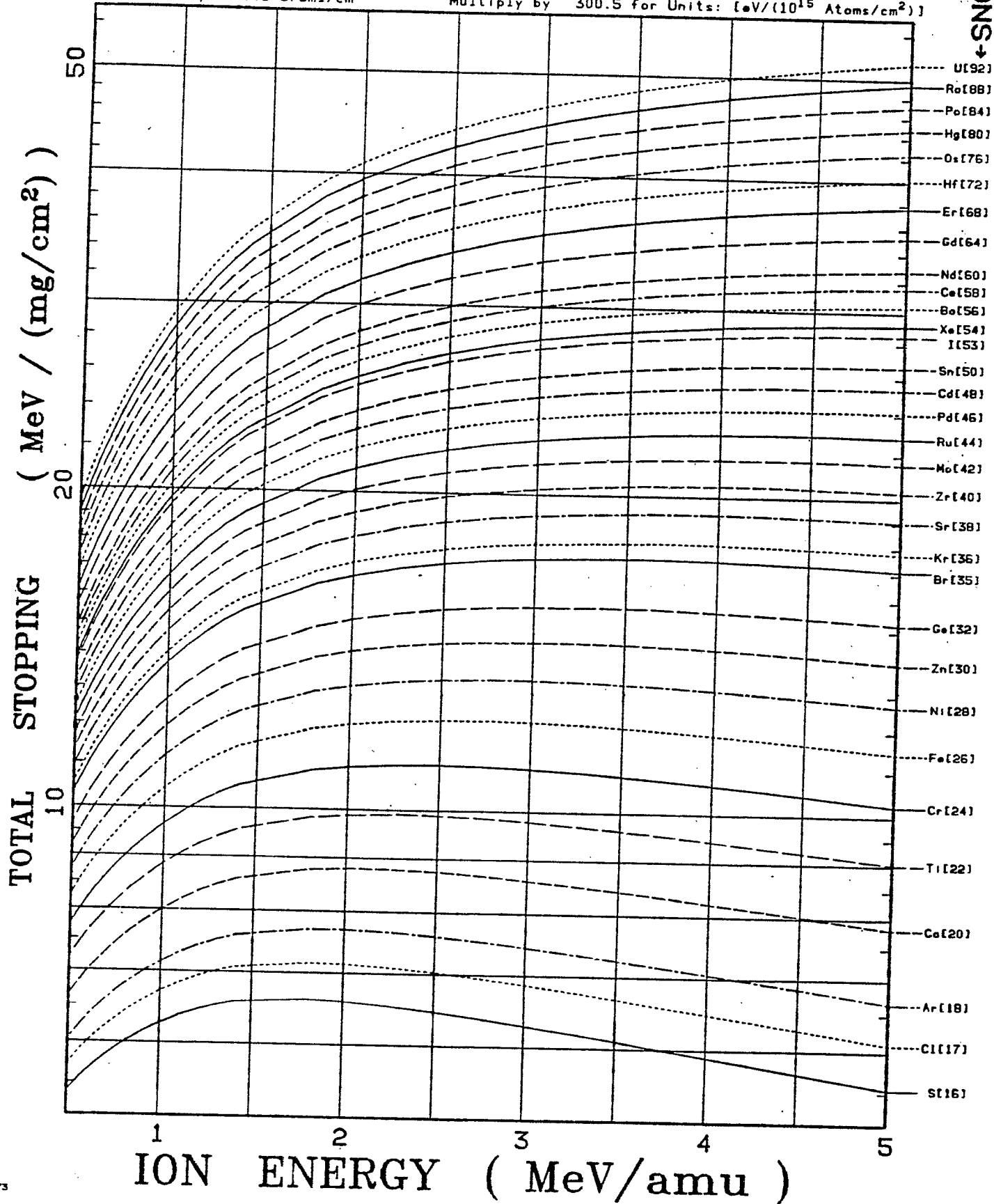
←←← TARGET →→→

Ta(73)

Atom Density = 5.526×10^{22} Atoms/cm³
Mass Density = 16.6 Grams/cm³

Multiply Total Stopping by 1660 for Units: [MeV/mm]
Multiply by 300.5 for Units: [eV/(10¹⁵ Atoms/cm²)]

← SNOI



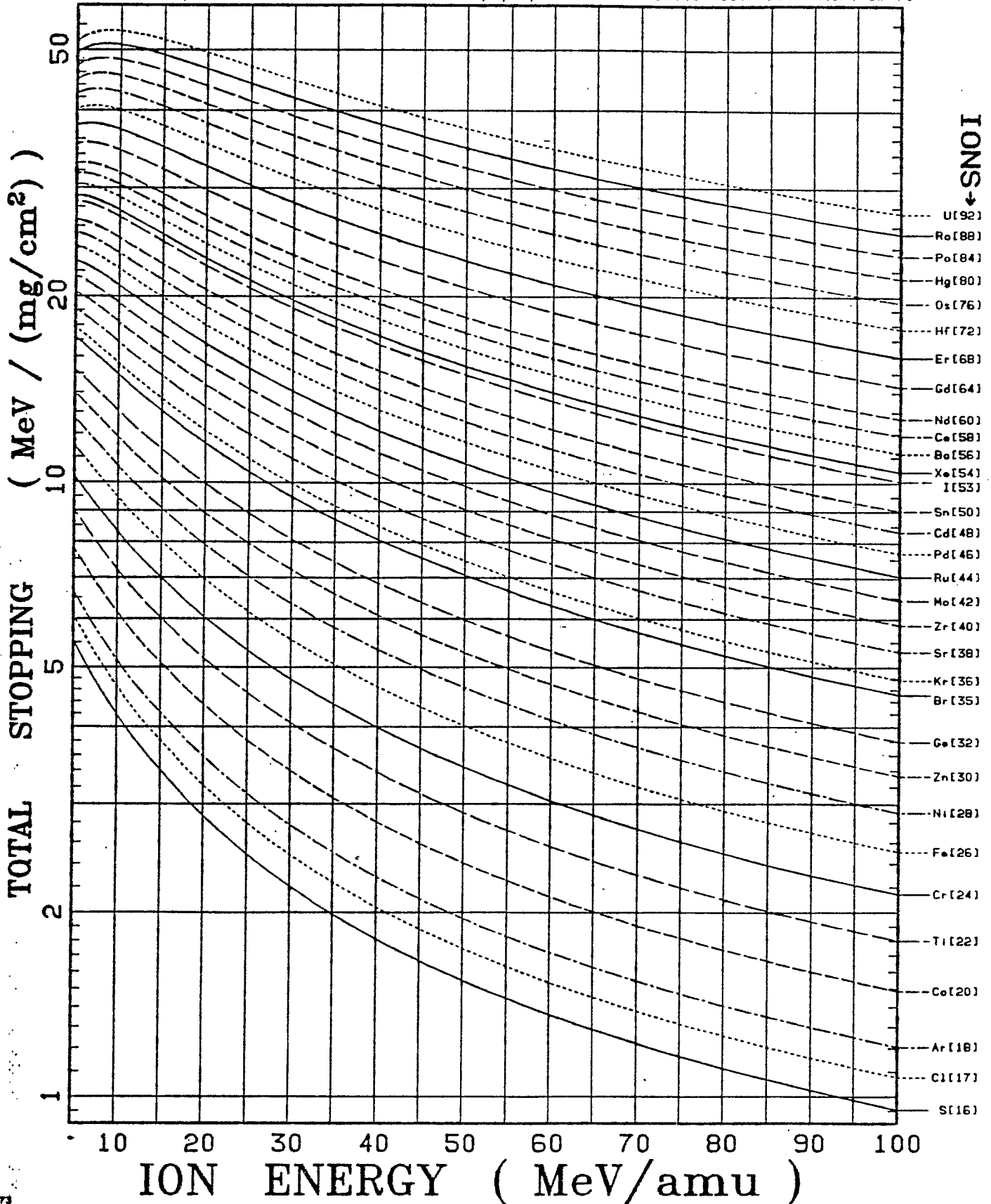
Ta(73)

←←← TARGET →→→

Ta(73)

Atom Density = 5.526×10^{22} Atoms/cm³
 Mass Density = 16.6 Grams/cm³

Multiply Total Stopping by 1660 for Units: [MeV/mm]
 Multiply by 300.5 for Units: [eV/(10¹⁵ Atoms/cm²)]



Ta(73)

←←← TARGET →→→

Ta(73)

Atom Density = 5.526×10^{22} Atoms/cm³
 Mass Density = 16.6 Grams/cm³

Multiply Total Stopping by 1660 for Units: [MeV/mm]
 Multiply by 300.5 for Units: [eV/(10¹⁵ Atoms/cm²)]

