NBS TECHNICAL NOTE 901

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Comparison of Theoretical and Experimental Photoeffect Data 0.1 keV to 1.5 MeV

NATIONAL BUREAU OF STANDARDS

The National Bureau of Standards[1] was established by an act of Congress March 3, 1901. The Bureau's overall goal is to strengthen and advance the Nation's science and technology and facilitate their effective application for public benefit. To this end, the Bureau conducts research and provides: (1) a basis for the Nation's physical measurement system, (2) scientific and technological services for industry and government, (3) a technical basis for equity in trade, and (4) technical services to promote public safety. The Bureau consists of the Institute for Basic Standards, the Institute for Materials Research, the Institute for Applied Technology, the Institute for Computer Sciences and Technology, and the Office for Information Programs.

THE INSTITUTE FOR BASIC STANDARDS provides the central basis within the United States of a complete and consistent system of physical measurement; coordinates that system with measurement systems of other nations; and furnishes essential services leading to accurate and uniform physical measurements throughout the Nation's scientific community, industry, and commerce. The Institute consists of the Office of Measurement Services, the Office of Radiation Measurement and the following Center and divisions:

Applied Mathematics — Electricity — Mechanics — Heat — Optical Physics — Center for Radiation Research: Nuclear Sciences; Applied Radiation — Laboratory Astrophysics[2] — Cryogenics[2] — Electromagnetics[2] — Time and Frequency[2].

THE INSTITUTE FOR MATERIALS RESEARCH conducts materials research leading to improved methods of measurement, standards, and data on the properties of well-characterized materials needed by industry, commerce, educational institutions, and Government; provides advisory and research services to other Government agencies; and develops, produces, and distributes standard reference materials. The Institute consists of the Office of Standard Reference Materials, the Office of Air and Water Measurement, and the following divisions:

Analytical Chemistry — Polymers — Metallurgy — Inorganic Materials — Reactor Radiation — Physical Chemistry.

THE INSTITUTE FOR APPLIED TECHNOLOGY provides technical services to promote the use of available technology and to facilitate technological innovation in industry and Government; cooperates with public and private organizations leading to the development of technological standards (including mandatory safety standards), codes and methods of test; and provides technical advice and services to Government agencies upon request. The Institute consists of the following divisions and Centers:

Standards Application and Analysis — Electronic Technology — Center for Consumer Product Technology: Product Systems Analysis; Product Engineering — Center for Building Technology: Structures, Materials, and Life Safety; Building Environment; Technical Evaluation and Application — Center for Fire Research: Fire Science; Fire Safety Engineering.

THE INSTITUTE FOR COMPUTER SCIENCES AND TECHNOLOGY conducts research and provides technical services designed to aid Government agencies in improving cost effectiveness in the conduct of their programs through the selection, acquisition, and effective utilization of automatic data processing equipment; and serves as the principal focus within the executive branch for the development of Federal standards for automatic data processing equipment, techniques, and computer languages. The Institute consists of the following divisions:

Computer Services — Systems and Software — Computer Systems Engineering — Information Technology.

THE OFFICE FOR INFORMATION PROGRAMS promotes optimum dissemination and accessibility of scientific information generated within NBS and other agencies of the Federal Government; promotes the development of the National Standard Reference Data System and a system of information analysis centers dealing with the broader aspects of the National Measurement System; provides appropriate services to ensure that the NBS staff has optimum accessibility to the scientific information of the world. The Office consists of the following organizational units:

Office of Standard Reference Data — Office of Information Activities — Office of Technical Publications — Library — Office of International Relations — Office of International Standards.

---

[1] Headquarters and Laboratories at Gaithersburg, Maryland, unless otherwise noted; mailing address Washington, D.C. 20234.

[2] Located at Boulder, Colorado 80302.

Comparison of Theoretical and Experimental Photoeffect Data 0.1 keV to 1.5 MeV

J. H. Hubbell

Institute for Basic Standards
National Bureau of Standards
Washington, D.C. 20234

and

Wm. J. Veigele

Resource Science, Inc.
Colorado Springs, Colorado 80903

This work was supported by the

NBS Office of Standard Reference Data
Washington, D.C. 20234

and

The Defense Nuclear Agency
Washington, D.C. 20305

U.S. DEPARTMENT OF COMMERCE, Elliot L. Richardson, *Secretary*

James A. Baker, III, *Under Secretary*

Dr. Betsy Ancker-Johnson, *Assistant Secretary for Science and Technology*

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Acting Director*

Issued April 1976

National Bureau of Standards Technical Note 901

Nat. Bur. Stand. (U.S.), Tech. Note 901, 43 pages (Apr. 1976)

CODEN: NBTNAE

Comparison of Theoretical and Experimental Photoeffect Data 0.1 keV to 1.5 MeV

J. H. Hubbell*
National Bureau of Standards
Washington, D. C. 20234

Wm. J. Veigele+ #
Resource Science, Inc.
Colorado Springs, Colorado 80903

Graphs of calculated and experimental atomic photoeffect cross sections as a function of photon energy 0.1 keV to 1.5 MeV are presented for all elements Z = 1 to 94. The calculated results presented are (a) the non-relativistic Hartree-Fock self-consistent-field (SCF) results of Veigele, Henry, et al., over the range 0.1 keV to between 1.0 and 8.0 keV for all elements Z = 1 to 94 and (b) the relativistic Hartree-Slater SCF results of Scofield over the range 1.0 keV to 1.5 MeV for all elements Z = 1 to 101. The "experimental" data-points are derived by subtracting theoretical scattering cross sections from total attenuation coefficient measurements in the literature. Differences between theoretical and experimental photoeffect data are typically a factor of two from 0.1 to 1.0 keV, 5-10% from 1.0 to 5.0 keV and 1-5% from 5.0 keV up to energies, ranging from 20 keV for carbon up to 500 keV for lead, above which the photoeffect cross section becomes fractionally too small to be accurately determined from the total attenuation coefficient.

Key words: Attenuation coefficients, cross sections, gamma rays, photoelectric effect, photons, x-rays.

1. Introduction

The atomic photoeffect, in which an atom absorbs a photon and ejects an electron, is the predominate process by which photon radiation is attenuated by matter in the vacuum ultraviolet (VUV) (10 eV to 100 eV) and soft x-ray (100 eV to 10 keV) portions of the electromagnetic spectrum. At higher energies the attenuation is dominated by two other processes, first incoherent scattering commencing in importance at around 10 keV for the lowest-Z elements and at a few hundred keV for the highest-Z elements,

---

*Work supported by the NBS Office of Standard Reference Data. Some support was also received from the Defense Nuclear Agency.

+Work done at Kaman Sciences Corp., Colorado Springs, Colorado 80907.

#Work supported by the Defense Nuclear Agency.

then pair production which proceeds from a threshold of 1.022 MeV ($2\ m_e c^2$) to dominate over all other processes in the high energy limit.

As an example, figure 1 shows the total measured attenuation cross section (small circles) for photons from 10 eV to 100 GeV in copper, decomposed into the theoretical contributions from the above three processes: photoeffect (τ), incoherent (bound-electron Compton) scattering (σ_{INCOH}) and pair production (κ), indicating the region where each predominates. For lower-Z elements the incoherent scattering cross section dominates over a broader range (for hydrogen, incoherent scattering dominates the total cross section from a few keV to 100 MeV) and for higher-Z elements the range of σ_{INCOH} dominance narrows to the point where for plutonium (Z = 94) its contribution to the total reaches a maximum of 70% at 1.5 - 2.0 MeV and its relative importance rapidly decreases toward lower and higher energies. Also shown in figure 1 are two additional processes: coherent scattering (σ_{COH}) and the photonuclear giant resonance ($\sigma_{PH,N}$) of some significance but which contribute less than 10% to the total cross section at any given energy.

Pratt, Ron and Tseng [1][1] have recently extensively reviewed the existing calculations and measurements of the atomic photoeffect over the range 10 keV to 100 MeV (including material extending down to 1 keV), complementing an earlier review by Fano and Cooper [2] of theoretical and measured photoeffect data over the range 10 eV to 10 keV.

In the latter (soft x-ray) region, where the atomic photoeffect can be taken directly from measured total attenuation coefficients with only small or negligible corrections for the scattering contribution, additional recent reviews and surveys of experimental photoeffect cross section data include those by Henke and Tester [3], Hudson and Kieffer [4], [5] and Zimkina and Fomichev [6]. Higher-energy photoeffect measurements, both by direct methods (e.g., photoelectron and fluorescence x-ray coincidences) and by indirect methods (subtraction of scattering and pair-production contributions from total attenuation measurements) have also been recently reviewed by Parthasaradhi [7].

In the above and other recent photoeffect reviews, the graphical and/or numerical comparisons of theoretical and photoeffect data have in each case been for a limited number of specific elements of interest, over limited ranges of photon energy. Thus we consider it a useful adjunct to the above reviews, for an over-all perspective, to systematically compare available experimental total and photoeffect cross sections in the extensive data-collections of Veigele [8] and Hubbell [9] with present state-of-the-art theoretical photoeffect cross sections for all elements Z = 1 to 94 over the photon energy range 0.1 keV to 1.5 MeV.

For this purpose we have selected the low-energy photoeffect calculations by Veigele, Henry and Bates [8], [10] for Z = 1 to 94 and photon energies 0.1 keV to from 1.0 to 8.0 keV, and the higher-energy calculations

---

[1]Figures in brackets indicate the literature references at the end of this paper.

by Scofield [11] for Z = 1 to 101, 1.0 keV to 1.5 MeV. These and some additional photoeffect calculations are listed and described in the following section.

2. Photoeffect Calculations

Prior to 1960, as discussed in more detail in the review article by Pratt et al. [1], theoretical numerical tabulations of the atomic photoeffect cross section, including those in the attenuation coefficient tables of Davisson and Evans [12] and of Grodstein [13], were based primarily on work (reviewed by Hall [14]) dating from the period 1930 to 1935:

(1) The Stobbe [15] exact nonrelativistic K- and L-shell results in the point-Coulomb potential,

(2) The Sauter [16], [17] relativistic K-shell Born result in the point-Coulomb potential,

(3) The Hall [18] and Hall and Rarita [19] high-energy limit results for the K- and L-shells in the point-Coulomb potential,

(4) Exact relativistic point-Coulomb K-shell numerical results for six cases (Z = 26, 50 and 84 at 0.35 and 1.13 MeV) by Hulme, McDougall, Buckingham and Fowler [20], and

(5) A semi-empirical prescription by Slater [21] to take into account inner-electron screening effects.

Renewed interest in theoretical understanding of the photoeffect process began in the late 1950's and continues to the present, resulting from (a) increasingly exacting photon-interaction needs by the medical, scientific and engineering communities, (b) availability of high-speed computers and (c) new higher-accuracy photoeffect and total attenuation coefficient measurements. New analytical work in this period includes corrections by Erber [22], Pratt [23,24] and by Gorshkov and Mikhailov [25] to the theoretical high-energy limit, extension of the relativistic Born approximation by Gavrila [26,27] and Nagel [28], dipole-approximation calculations in the ultra-soft x-ray region by Cooper [29], estimates of the quadrupole contribution by Guttmann and Wagenfeld [30], and additional work more exhaustively reviewed by Pratt et al. [1] and Fano and Cooper [2].

Based on the above work and further refinements, recent pilot and systematic numerical calculations of the photoeffect cross section include the following, listed approximately in chronological order:

(1) Hultberg et al. [31], [32]: relativistic, point-Coulomb, K shell, 21 elements Z = 1 to 100, 1 keV to 10 MeV,

(2) Pratt et al. [33]: relativistic, point-Coulomb, K shell, 6 elements Z = 13 to 92, 200 keV to 2 MeV,

(3) Alling and Johnson [34]: relativistic, point-Coulomb, K-L-shells, Pb and U, 81 keV to 1.33 MeV,

(4) Matese and Johnson [35]: relativistic, exponential screening, K-, L-shells, Ag, Hg, Pb and U, 81 keV to 1.33 MeV,

(5) Hall and Sullivan [36]: relativistic, Thomas-Fermi screening, K-shell, Fe, Sn, Po and U, 300 keV to 1.23 MeV,

(6) Rakavy and Ron [37], [38]: relativistic, Fermi-Amaldi screening for Al, Fe, Sn and W, Thomas-Fermi screening for U, 1 keV to 2 MeV,

(7) Schmickley and Pratt [39]: relativistic, Hartree-Fock-Slater screening, 14 elements Z = 13 to 92, 10 keV to 5 MeV,

(8) Bell and Kingston [40], [41]: non-relativistic, dipole-length and -velocity formulations, Hartree-Fock screening, He, 25 to 310 keV,

(9) Combet-Farnoux and Héno [42], [43]: non-relativistic, Hartree-Fock-Slater screening, Ta, Pt, Au and Bi, 50 to 500 eV,

(10) Manson and Cooper [44]: non-relativistic, Hartree-Fock-Slater screening, 9 elements Z = 18 to 100, 10 eV to 2 keV,

(11) Brysk and Zerby [45]: relativistic, Dirac-Slater screening, Al and U, 1 to 150 keV,

(12) McGuire [46]: non-relativistic, dipole-length formulation, Hartree-Fock-Slater screening, Z = 2 to 54, 6 eV to 62 keV,

(13) Amusia et al. [47], [48]: non-relativistic, Hartree-Fock screening, Ar, Kr and Xe, 15 eV to 1 keV,

(14) Storm and Israel [49]: Brysk-Zerby program [45], Z = 1 to 100, 1 to 200 keV; extended table to 100 MeV by interpolation and extrapolation of Schmickley and Pratt [39] and Rakavy and Ron [38] theoretical results, above,

(15) Cromer and Liberman [50]: relativistic, Dirac-Slater, Kohn-Sham screening, Z = 3 to 98, 5.4 to 22.2 keV,

(16) Veigele et al. [8], [10]: non-relativistic, Hartree-Fock-Slater screening, Z = 1 to 94, 100 eV to 8 keV,

(17) Kennedy and Manson [51]: non-relativistic, Hartree-Fock and Hartree-Slater, dipole-length and -velocity formulations, Ne, Ar, Kr and Xe, 10 eV to 1.5 keV,

(18) Scofield [11]: relativistic, Hartree-Slater screening, Z = 1 to 101, 1 keV to 1.5 MeV, and

(19) Hildebrandt et al. [52], [53]: non-relativistic, revised Slater screening constants, dipole and quadrupole components given, Z = 6 to 54, 5 to 25 keV.

In the most recent NBS x-ray cross section tabulation (NSRDS-NBS 29, covering the energy range 10 keV to 100 GeV) [54], photoeffect cross sections in the range 10 to 100 keV were obtained from total attenuation coefficient measurements [9] by subtracting theoretical scattering contributions [49] except for uranium which was taken directly from the above Rakavy-Ron [37], [38] theoretical results. Above 100 keV, for all 23 elements in the NSRDS-NBS 29 tabulation [54], the Rakavy-Ron results were combined with the high-energy numerical calculations and analytical formulas of Gavrila [26], Pratt et al. [23], [33] and Hultberg [32] to extend the tabulations up to 100 MeV.

In the McMaster et al. [55], [56] LLL (Lawrence Livermore Lab.) - NBS x-ray cross section tabulation, source of the 1 keV-1 MeV photoeffect values in the present ENDF (Evaluated Nuclear Data File, ERDA) tape library [57], the theoretical values of Schmickley and Pratt [39] were weighted into the iterative cubic log-log least-squares fit of photoeffect cross sections which were otherwise obtained by subtraction of theoretical scattering contributions from total attenuation coefficient measurements.

3. Explicit Photoeffect Measurements

In the photon energy range $\sim$ 100 keV to 2.6 MeV, where the above "subtraction method" (total attenuation coefficient measurement minus theoretical scattering contribution) ceases to be useful, there exist a few explicit measurements of total and subshell photoeffect cross sections, as summarized by Pratt et al. [1] and by Parthasaradhi [7], with uncertainties of the order of 4% to 15% or greater. Additional new measurements beyond those listed in these summaries include:

(1) Sahota [58]: L-shell, fluorescence x-ray detection, U, 145, 192, 662 and 1250 keV,

(2) Allawadhi and Sood [59], [60]: K-shell, fluorescence x-ray detection, 15 elements Z = 33 to 74, 37 and 74 keV,

(3) Gowda and Sanjeevaiah [61] - [65]: total and K-shell, photoelectron detection, 8 elements Z = Al to Pb, 145, 279, 412 and 662 keV, and

(4) Goswami and Chaudhuri [66]: total photoeffect, cylindrical-shell adaptation of the spherical-shell transmission method of Ghose [67], Pb, 662 and 1250 keV.

Because of the substantial inherent difficulties and uncertainties in the above and earlier explicit measurements, this source of photoeffect data has as yet been given little weight, as compared with theory, in constructing photon cross section tabulations, and is not included in the graphical comparisons in figures 2 to 95.

4. Graphical Comparison of Experimental Points with Veigele et al. and Scofield Theoretical Results

As can be seen in figure 1, the photoeffect cross section, τ, decreases approximately as E^{-3} from the K absorption edge up to 1 MeV, with a similar $\sim E^{-3}$ dependence at lower energies in the segments between absorption edges

down to 1 keV. Above 1 MeV the photoeffect behavior is seen changing to the high-energy-limit E^{-1} dependence [17], [22], [23]. Below 1 keV the slope of the cross section again decreases, and the cross section, particularly for medium- and high-Z elements, becomes characterized by outer-subshell maxima and minima with little interpolable regularity as a function of E and Z.

In the region 1 keV to 1 MeV where τ decreases rapidly as a function of E, relative differences between photoeffect data are difficult to see on an ordinary log-log plot of τ vs. E as in figure 1. Thus, in figures 2 to 95 we have plotted $\tau \cdot E^2$, instead of τ, which reduces the number of logarithmic cycles required to display the data and has the effect of magnifying the relative differences. The quantity $\tau \cdot E^3$ is less suitable for graphing purposes because of the absorption edges which, for all but the lightest elements, superimpose an effective positive power of E on the energy-range 1 keV to 1 MeV as a whole for a net over-all dependence $\tau \propto \sim E^{-2}$ including absorption edges.

In figures 35-95 ($Z \geq 34$) the number of logarithmic cycles used was determined for each figure by the $\tau \cdot E^2$ maximum and minimum values from the Scofield data in the range 1.0 keV to 1.5 MeV. As a result, some experimental points and portions of the Veigele et al. calculated results near 0.1 keV are off-scale and not shown in these figures.

For elements H(Z = 1) to K(Z = 19), in figures 2 to 20, the Veigele et al. calculated results extend only over the range 0.1 to 1.0 keV and hence have only the 1.0-keV point in common with the 1.0 keV to 1.5 MeV range of the Scofield results. For the remaining elements Ca(Z = 20) to Pu(Z = 94) the Veigele et al results overlap the Scofield results by amounts ranging from 1.0 - 1.6 keV for Kr(Z = 36), Rb(Z = 37) and Sr(Z = 38) up to 1.0 - 8.0 keV for Pu (Z = 94).

Since the Veigele et al. and Scofield values in this overlap region are not identifiable as to which is which, numerical values in kilobarns/atom (without the factor $[E(keV)^2]$) at 1.0 and 2.0 keV are listed in table I. Also in table I are percent differences obtained at 100% x (V-S)/S, where V and S are the Veigele et al. and Scofield values, respectively, for a given element and energy.

Comparing the Veigele et al. results with those of Scofield at 1 keV, the agreement is seen to be better than 10% for all elements except for -16% for Cs(Z = 55) and +31% for Nd(Z = 60), the latter two differences attributable to displacements in absorption-edge energies. For elements Z = 1 to 59 (excluding Z = 55) at 1 keV, where the photoeffect cross section is primarily due to the K-, L- and M-shell atomic electrons, the results of Veigele et al. are systematically lower than those of Scofield by an average of 2%. For the higher-Z elements Z = 61 to 94, where the photoeffect cross section in the overlap region is primarily due to N-shell electrons, the trend reverses, with the Veigele et al. results systematically higher than Scofield by an average of 6% at 1 keV for Z = 61 to 89, and higher by an average of 9% at 2 keV for Z = 90 to 94.

The experimental points (x's) in figures 2 to 95 are taken from the automated 8000-data-point file of Veigele et al. obtained from 153 sources for the period 1920 - 1970 cited and cross-referenced as to element in reference [8], updated to Jan. 1974. Excluded from this file are data deduced for elements from measurements made on compounds, and a number of discrepant data-points. An additional relevant measurement-set reported by Del Grande and Oliver [68] for uranium at 1 to 10 keV is shown as the circles in figure 93.

A characteristic feature of figures 2 to 95 is the diverging scatter of experimental points toward higher energies. This divergence, commencing at a few hundred keV for the heaviest elements, occurs when the photoeffect, obtained by subtracting theoretical scattering cross sections from total attenuation coefficients, becomes small and similar in magnitude to the uncertainties in the latter two quantities. Thus figures 2 to 95 indicate, as a function of Z, approximate upper energy limits for obtaining meaningful values of the photoeffect cross section from total attenuation coefficient measurements.

5. Conclusions

In the graphs in figures 2 to 95, the theoretical results of Veigele et al. in the region 0.1 to 1.0 keV are seen to represent the experimental data to within typically 10% to a factor of two, the best agreement being found for elements available as gases. Differences of this order are attributable at least in part to chemical binding effects on the outer shell electrons which determine the photoionization cross section in this energy region.

In the region 1.0 to 5.0 keV the Veigele et al. and Scofield values represent the experimental data to within typically 5% to 10%. For the high-Z elements where the theoretical sets systematically differ from each other by 5% to 10% in this energy region, the available measurements for Au, Pb, Bi and U suggest that the theoretical sets would be best joined by taking the Veigele et al. set below and the Scofield set above the M_5 absorption edge.

Above 5 keV, up to energies ranging from 20 keV for carbon up to 500 keV for lead, the Scofield data, with a few exceptions, can be seen to represent the available experimental data to within the 1% to 5% "envelope of uncertainty" obtainable from measurements of the total attenuation coefficient. Among the exceptions is tellurium (figure 53) for which the Scofield values are systematically 10% to 30% lower than the extensive measurements of Biermann (1936) [69], Schulz (1936) [70] and Wrede (1939) [71] over the range 1.3 to 97 keV, but for which the Scofield values agree within 1% with the L-edge cross section measurements by Nordfors and Noreland (1961) [72] in the region 4.3 to 5.0 keV.

The above (Te) and other examples in figures 2 to 95 point out elements and energy-regions where further attenuation coefficient measurements, taken with modern detectors and sample-purities, would afford a more critical test of present theory and would reduce the uncertainties in present photon cross section tabulations.

The authors thank Dean Kaul for his encouragement of this work, Martin Berger for suggesting this presentation, Edith Briggs for data preparation and Larry Bates for programming and computing assistance.

6. References

[1] Pratt, R.H., Ron, A., and Tseng, H. K., Atomic Photoelectric Effect above 10 keV, Rev. Mod. Phys. 45, 273-325 (1973); 45, 663-664 (1973).

[2] Fano, U. and Cooper, J. W., Spectral Distribution of Atomic Oscillator Strengths, Rev. Mod. Phys. 40, 441-507 (1968).

[3] Henke, B. L., and Tester, M. A., Techniques of Low Energy X-Ray Spectroscopy, Adv. X-Ray Anal. 18 (1975) (in press).

[4] Hudson, R. D., and Kieffer, L. J., Bibliography of Photoabsorption Cross Section Data, J. Inst. Lab. Astrophys. Rep. No. 11 (1970), 45 p.

[5] Hudson, R. D., and Kieffer, L. J., Compilation of Atomic Ultraviolet Photoabsorption Cross Sections for Wavelengths between 300 and 10 Å, At. Data 2, 205-262 (1971).

[6] Zimkina, T. M., and Fomichev, V. A., Ultrasoft X-Ray Spectroscopy (Leningrad Univ., 1971), 132 p.

[7] Parthasaradhi, K., Experimental Total Photoelectric Cross Sections, J. Sci. Ind. Res. 31, 470-476 (1972).

[8] Veigele, Wm. J., Photon Cross Sections from 0.1 keV to 1 MeV for Elements Z = 1 to Z = 94, At. Data 5, 51-111 (1973).

[9] Hubbell, J. H., Survey of Photon Attenuation Coefficient Measurements 10 eV to 100 GeV, At. Data 3, 241-297 (1971).

[10] Henry, E. M., Bates, L. C., and Veigele, Wm. J., Low-Energy Photoionization, Phys. Rev. A 6. 2131-2138 (1972).

[11] Scofield, J. H., Theoretical Photoionization Cross Sections from 1 to 1500 keV, UCRL-51326 (1973), 375 p.

[12] Davisson, C. M., and Evans, R. D., Gamma-Ray Absorption Coefficients, Rev. Mod. Phys. 24, 79-107 (1952).

[13] Grodstein, G. W., X-Ray Attenuation Coefficients from 10 keV to 100 MeV, Nat. Bur. Stand. (U.S.) Circ. 583 (1957), 54 p.

[14] Hall, H., The Theory of Photoelectric Absorption for X-Rays and γ-Rays, Rev. Mod. Phys. 8, 358-397 (1936).

[15] Stobbe, M., On the Quantum Mechanics of Photoelectric Processes, Ann. Phys. (Leipzig) 7, 661-715 (1930).

[16] Sauter, F., On the Atomic Photoeffect in the Case of Extremely Hard Incident Radiation, Ann. Phys. (Leipzig) 9, 217-248 (1931).

[17] Sauter, F., On the Atomic Photoeffect in the K-Shell According to the Relativistic Wave Mechanics of Dirac, Ann. Phys. (Leipzig) 11, 454-488 (1931).

[18] Hall, H., The Photoelectric Effect for High Energy Quanta, Phys. Rev. 45, 620-627 (1934).

[19] Hall, H., and Rarita, W., On the Photoelectric Effect for the L-Shell, Phys. Rev. 46, 143 (1934).

[20] Hulme, H. R., McDougall, J., Buckingham, R. A., and Fowler, R. H., The Photoelectric Absorption of γ-Rays in Heavy Elements, Proc. Roy. Soc. London, Ser. A, 149, 131-151 (1935).

[21] Slater, J. C., Atomic Shielding Constants, Phys Rev. 36, 57-64 (1930).

[22] Erber, T., The Photoelectric Effect at High Energies, Ann. Phys. (N.Y.) 8, 435-472 (1959).

[23] Pratt, R. H., Atomic Photoeffect at High Energies, Phys. Rev. 117, 1017-1028 (1960).

[24] Pratt, R. H., Photoeffect from the L Shell, Phys. Rev. 119, 1619-1626 (1960).

[25] Gorshkov, V. G., and Mikhailov, A. I., Atomic Photoeffect at High Energies, Zh. Eksp. Teor. Fiz. 44, 2142-2149 (1963); Sov. Phys. JETP 17, 1439-1443 (1963).

[26] Gavrila, M., Relativistic K-Shell Photoeffect, Phys. Rev. 113, 514-526 (1959).

[27] Gavrila, M., Relativistic L-Shell Photoeffect, Phys. Rev. 124, 1132-1141 (1961).

[28] Nagel, B., On the Relativistic Photoeffect in the K-Shell, Ark. Fys. 18, 1-28 (1960).

[29] Cooper, J. W., Photoionization from the Outer Atomic Subshells. A Model Study, Phys. Rev. 128, 681-693 (1962).

[30] Guttmann, A. J., and Wagenfeld, H., A Theoretical Calculation of X-Ray Absorption Cross Sections, Acta Crystallogr. 22, 334-337 (1967).

[31] Hultberg, S., Nagel, B., and Olsson, P., Relativistic Differential and Total K-Shell Photoelectric Cross-Sections and Photoelectron Polarizations, Ark. Fys. 20, 555-557 (1961).

[32] Hultberg, S., Nagel, B., and Olsson, P., Numerical Calculation of K-Shell Photoeffect, Ark. Fys. 38, 1-96 (1968).

[33] Pratt, R. H., Levee, R. D., Pexton, R. L., and Aron, W., K-Shell Photoelectric Cross Section from 200 keV to 2 MeV, Phys. Rev. 134, A898-A915 (1964).

[34] Alling, W. R., and Johnson, W. R., Exact Calculation of K-Shell and L-Shell Photoeffect, Phys. Rev. 139, A1050-A1062 (1965).

[35] Matese, J. J., and Johnson, W. R., Influence of Screening on the Atomic Photoeffect, Phys. Rev. 140, A1-A7 (1965).

[36] Hall, H., and Sullivan E. C., K-Shell Photoelectric Cross Sections for the Fermi-Thomas Potential from 300 keV to 1.3 MeV, Phys. Rev. 152, 4-9 (1966).

[37] Rakavy, G., and Ron, A., Total Cross Sections of the Photoelectric Effect for Uranium, Phys. Lett. 19, 207-208 (1965).

[38] Rakavy, G., and Ron, A., Atomic Photoeffect in the Range $E\gamma$ = 1-2000 keV, Phys. Rev. 159, 50-56 (1967).

[39] Schmickley, R. D., and Pratt, R. H., K-, L-, and M-Shell Atomic Photoeffect for Screened-Potential Models, Phys. Rev. 164, 104-116 (1967).

[40] Bell, K. L., and Kingston, A. E., Photoionization of the Helium Atom, Proc. Phys. Soc., London, 90, 31-37 (1967).

[41] Bell, K. L., Kingston, A. E., and Taylor, I. R., Photoionization of the 1^1S State of Helium, J. Phys. B 6, 1228-1236 (1973).

[42] Combet-Farnoux, F., and Héno, Y., Calculation of Photoionization Cross Sections of Gold and Bismuth Atoms in the Ultrasoft X-Ray Region, C. R. Acad. Sci., Ser. B, 264, 138-141 (1967).

[43] Combet-Farnoux, F., Photoionization of Heavy Atoms: Theoretical Study with a Non-Relativistic Central Potential Model, J. Phys. (Paris) 30, 521-530 (1969).

[44] Manson, S. T., and Cooper, J. W., Photo-Ionization in the Soft X-Ray Range: Z Dependence in a Central Potential Model, Phys. Rev. 165, 126-138 (1968).

[45] Brysk, H., and Zerby, C. D., Photoelectric Cross Sections in the keV Range, Phys. Rev. 171, 292-298 (1968).

[46] McGuire, E. J., Photo-Ionization Cross Sections of the Elements Helium to Xenon, Phys. Rev. 175, 20-30 (1968).

[47] Amusia, M. Ya., Cherepkov, N. A., Chernysheva, L. V., and Sheftel, S. I., Calculation of the Photo-Ionization Cross Section for Argon in the Hartree-Fock Approximation, Zh. Eksp. Teor. Fiz. 56, 1897-1903 (1969); Sov. Phys. JETP 29, 1018-1021 (1969).

[48] Amusia, M. Ya., Cherepkov, N. A., and Chernysheva, L. V., Cross Section for the Photoionization of Noble-Gas Atoms with Allowance for Multi-electron Correlations, Zh. Eksp. Teor. Fiz. 60, 160-174 (1971); Sov. Phys. JETP 33, 90-96 (1971).

[49] Storm, E., and Israel, H. I., Photon Cross Sections from 1 keV to 100 MeV for Elements Z = 1 to Z = 100, Nucl. Data Tables A 7, 565-681 (1970).

[50] Cromer, D. T., and Liberman, D., Relativistic Calculation of Anomalous Scattering Factors for X-Rays, J. Chem. Phys. 53, 1891-1898 (1970).

[51] Kennedy, D. J., and Manson, S. T., Photoionization of the Noble Gases: Cross Sections and Angular Distributions, Phys. Rev. A 5, 227-247 (1972).

[52] Hildebrandt, G., Stephenson, J. D., and Wagenfeld, H., Photoelectric Atomic Absorption Cross Sections for Elements Z = 6 to 54 in the Medium Energy X-Ray Range (5 to 25 keV). Part I., Z. Naturforsch., Teil A, 30, 697-707 (1975).

[53] Wagenfeld, H., Normal and Anomalous Photoelectric Absorption of X-Rays in Crystals, Phys. Rev. 144, 216-224 (1966).

[54] Hubbell, J. H., Photon Cross Sections, Attenuation Coefficients, and Energy Absorption Coefficients from 10 keV to 100 GeV, Nat. Stand. Ref. Data Ser., Nat. Bur. Stand. 29 (1969), 80 p.

[55] McMaster, W. H., Del Grande, N. K., Mallett, J. H., and Hubbell, J. H., Compilation of X-Ray Cross Sections, UCRL-50174, Sec. 1 (1970), 18 p., Sec. 2, Rev. 1 (1969), 353 p., Sec. 3 (1969), 194 p., Sec. 4 (1969) 40 p.

[56] Hubbell, J. H., McMaster, W. H., Del Grande, N. K., and Mallett, J. H., Sec. 2.1 of Ibers, J. A., and Hamilton, W. C., eds., International Tables for X-Ray Crystallography, Vol. IV (Kynoch Press, Birmingham, 1974) p. 47-70.

[57] Dudziak, D. J., ENDF Formats and Procedures for Photon Production and Interaction Data, ENDF-102, Rev. Vol. 2, LA-4549 (1971).

[58] Sahota, H. S., Measurement of K-Shell Photoelectric Cross Sections in Uranium, Phys. Lett. A 33, 430-431 (1970).

[59] Allawadhi, K. L., and Sood, B. S., K-Shell Photoelectric Cross-Section Measurements at 36.818 keV in Elements $33 \leq Z \leq 53$, Curr. Sci. 42, 852 (1973).

[60] Allawadhi, K. L., and Sood, B. S., K-Shell Photoelectric Cross Sections for Intermediate Z Elements at 37 and 74 keV, Phys. Rev. A 11, 1928-1932 (1975).

[61] Gowda, R., and Sanjeevaiah, B., Photoelectric Cross Sections of Al, Cu, Zr, Ag, Sn, Ta and Pb for 145 keV γ Rays, J. Phys. A 6, 1041-1045 (1973).

[62] Gowda, R., and Sanjeevaiah, B., K-Shell Photoelectric Cross Sections for 145-keV Gamma Rays, Phys. Rev. A 8. 2425-2428 (1973).

[63] Gowda, R., and Sanjeevaiah, B., K-Shell Photoelectric Cross Sections of Cu, Zr, Ag, Sn, Ta, Au, and Pb for 279.1- and 411.8-keV γ Rays, Phys. Rev. A 10, 1188-1191 (1974).

[64] Gowda, R., and Sanjeevaiah, B., Photoelectric Cross Sections for 279.1 keV and 411.8 keV γ Rays, J. Phys. B 7, 1772-1775 (1974).

[65] Gowda, R., and Sanjeevaiah, B., The Total and K Shell Photoelectric Cross Sections for 661.6 keV Gamma Rays, Can. J. Phys. 53, 846-849 (1975).

[66] Goswami, B., and Chaudhuri, N., Photoelectric Cross-Sections of Gamma-Rays for Low-, Medium-, and High-Z Atoms in the Energy Range 88 keV to 1.33 MeV, Nuovo Cimento A 24, 49-60 (1974).

[67] Ghose, A. M., Photoelectric Cross Sections of Gamma Rays for Heavy Elements, Nucl. Phys. 75, 539-548 (1966).

[68] Del Grande, N. K., and Oliver, A. J., Soft X-Ray Cross Section Measurements for Uranium, Bull. Am. Phys. Soc. (Ser. 2) 18, 635 (1973).

[69] Biermann, H.-H., The Mass Attenuation Coefficients for Monochromatic X-Rays in Cellophane, Al, Se, Ag, Cd, Sn, Sb, and Te to 10 Å, Ann. Phys. (Leipzig) 26, 740-760 (1936).

[70] Shulz, K., The Mass Attenuation Coefficients of Monochromatic X-Rays for Se, Ag, Cd, Te, Au, Pb, and Bi to about 2 Å, Ann. Phys. (Leipzig) 27, 1-14 (1936).

[71] Wrede, W., The Mass Attenuation Coefficients for Monochromatic X-Rays in 24 Elements between C (6) and Ce (58) for Wavelengths from 0.1279 to 1.433 Å, Ann. Phys. (Leipzig) 36, 681-695 (1939).

[72] Nordfors, B., and Noreland, E., The X-Ray L-Absorption Spectra of 48 Cd - 52 Te, Ark. Fys. 20, 1-23 (1961).

[73] Wyckoff, J. M., Ziegler, B., Koch, H. W. and Uhlig, R., Total Photonuclear Cross Sections for Low Atomic Number Elements, Phys. Rev. 137, B576-B594 (1965).

Table I. Comparison of [1] Veigele et al. [8], [10] and Scofield [11] theoretical photoeffect cross section values (in kilobarns/atom) at 1.0 and 2.0 keV. The Veigele et al. values in parenthesis for 2 keV photons in Z = 70, 71 and 72 are interpolated from adjacent energies.

	1.0 keV			2.0 keV		
Z	Veigele et al. τ (kb)	Scofield τ (kb)	% diff.	Veigele et al. τ (kb)	Scofield τ (kb)	% diff.
1	0.0109	0.011414	-4.5%	(Veigele et al. max. energy 1.0 keV)		
2	.404	.40177	+ .8	"		
3	2.63	2.6909	-2.3	"		
4	8.86	9.0314	-1.9	"		
5	21.4	22.046	-2.9	"		
6	42.9	44.073	-2.7	"		
7	76.0	76.990	-1.3	"		
8	119.	121.92	-2.4	"		
9	177.	178.17	- .7	"		
10	257.	248.20	+3.5	"		
11	24.5	24.900	-1.6	"		
12	36.5	37.146	-1.7	"		
13	51.7	52.999	-2.5	"		
14	71.0	73.101	-2.9	"		
15	96.5	98.248	-1.8	"		
16	127.	129.19	-1.7	"		
17	163.	166.55	-2.1	"		
18	210.	211.01	- .5	"		
19	259.	263.22	-1.6	"		
20	315.	323.67	-2.7	52.1	53.034	-1.8%
21	382.	390.72	-2.2	63.8	64.767	-1.5
22	452.	466.34	-3.1	76.7	78.151	-1.9
23	530.	549.09	-3.5	91.3	93.275	-2.1
24	629.	638.99	-1.6	108.	109.77	-1.6
25	715.	737.89	-3.1	126.	129.30	-2.6
26	821.	842.08	-2.5	147.	150.45	-2.3
27	931.	958.20	-2.8	170.	173.71	-2.1
28	924.	959.94	-3.7	195.	199.25	-2.1
29	1110.	1114.8	- .4	226.	226.79	- .4
30	166.	168.07	-1.2	256.	257.33	- .5
31	190.	195.91	-3.0	289.	290.62	- .6
32	222.	227.55	-2.4	325.	326.35	- .4
33	258.	263.23	-2.0	365.	364.8	+ .3
34	299.	303.12	-1.4	409.	405.59	+ .8
35	342.	347.37	-1.6	455.	451.41	+ .8
36	398.	396.30	+ .4	(Veigele et al. max. energy 1.6 keV)		
37	444.	449.60	-1.3	"		
38	499.	507.44	-1.7	"		
39	562.	569.52	-1.3	107.	108.75	-1.6
40	627.	636.72	-1.5	120.	122.06	-1.7

Z	1.0 keV Veigele et al. τ (kb)	1.0 keV Scofield τ (kb)	% diff.	2.0 keV Veigele et al. τ (kb)	2.0 keV Scofield τ (kb)	% diff.
41	707.	708.56	- .2%	135.	136.28	- .9%
42	778.	786.27	-1.1	150.	151.86	-1.2
43	847.	869.65	-2.6	165.	168.71	-2.2
44	948.	958.39	-1.1	185.	186.81	-1.0
45	1040.	1052.9	-1.2	205.	206.31	- .6
46	1160.	115.4	+ .5	227.	227.10	0
47	1250.	1259.4	- .8	249.	249.61	- .2
48	1370.	1370.6	0	273.	273.72	- .3
49	1480.	1487.4	- .5	299.	299.50	- .2
50	1600.	1606.4	- .4	326.	326.83	- .3
51	1720.	1733.5	- .8	355.	355.83	- .2
52	1740.	1861.6	-6.5	387.	386.71	0
53	1880.	1915.0	-1.8	420.	419.20	+ .2
54	2040.	2050.4	- .5	459.	453.49	+1.2
55	1740.	2065.0	-15.7	496.	489.50	+1.3
56	1860.	1946.1	-4.4	533.	527.02	+1.1
57	1960.	2094.1	-6.4	567.	566.65	0
58	2200.	2257.3	-2.5	620.	604.84	+2.5
59	2370.	2474.0	-4.2	663.	645.73	+2.7
60	2080.	1585.1	+31.2	704.	687.44	+2.4
61	501.	492.46	+1.7	750.	731.37	+2.6
62	537.	523.56	+2.6	801.	776.95	+3.1
63	570.	556.64	+2.4	850.	825.04	+3.0
64	600.	595.74	+ .7	892.	875.04	+1.9
65	655.	629.70	+4.0	963.	923.16	+4.3
66	702.	670.17	+4.8	952.	932.95	+2.0
67	750.	713.61	+5.1	1010.	980.77	+3.0
68	808.	760.23	+6.3	1070.	1037.0	+3.2
69	871.	810.25	+7.5	1130.	1031.3	+9.6
70	931.	863.88	+7.7	(932.)	1088.1	-14.4
71	977.	922.72	+5.9	(978.)	999.98	-2.2
72	1050.	985.30	+6.6	(1040.)	1063.4	-2.2
73	1120.	1051.3	+6.5	(Veigele et al. max. energy 1.7 keV)		
74	1190.	1120.9	+6.2	"		
75	1260.	1193.6	+5.6	"		
76	1330.	1269.6	+4.8	(Veigele et al. max. energy 1.9 keV)		
77	1430.	1350.5	+5.9	"		
78	1530.	1432.3	+6.8	"		
79	1630.	1517.6	+7.4	390.	368.12	+5.9
80	1750.	1604.9	+9.0	415.	390.53	+6.3

Z	1.0 keV Veigele et al. τ (kb)	1.0 keV Scofield τ (kb)	1.0 keV % diff.	2.0 keV Veigele et al. τ (kb)	2.0 keV Scofield τ (kb)	2.0 keV % diff.
81	1820.	1695.5	+7.3%	439.	413.96	+6.0%
82	1920.	1788.4	+7.4	466.	438.35	+6.3
83	2010.	1883.7	+6.7	492.	463.61	+6.1
84	2120.	1981.9	+7.0	524.	489.76	+7.0
85	2130.	2041.9	+4.3	555.	516.93	+7.4
86	2250.	2143.0	+5.0	588.	545.01	+7.9
87	2360.	2248.1	+5.0	621.	573.97	+8.2
88	2470.	2322.7	+6.3	654.	603.79	+8.3
89	2520.	2433.8	+3.5	681.	634.72	+7.3
90	2300.	2543.5	-9.6	717.	666.43	+7.6
91	2440.	2660.6	-8.3	761.	698.71	+8.9
92	2530.	2613.8	-3.2	798.	732.29	+9.0
93	2650.	2730.7	-3.0	839.	767.22	+9.4
94	2830.	2850.5	- .7	889.	803.28	+10.7

Figure Captions

Figure 1.

Total measured cross sections (σ_{TOT}, circles), and theoretical photoeffect (τ), coherent scattering (σ_{COH}), incoherent scattering (σ_{INCOH}), and pair production (κ) cross sections for copper for photon energies 10 eV to 100 GeV. The total photonuclear cross section ($\sigma_{PH.N.}$) measured by Wyckoff et al. [73] is also shown.

Figures 2 - 95.

Comparisons of theoretical photoeffect data (curves) of Veigele et al., [8], [10] extending below 1 keV and Scofield [11] 1 keV to 1.5 MeV with experimental data (points) for elements H (Z = 1) to Pu (Z = 94). The data$_2$(in units of barns/atom) in each case have been multiplied by $[E(keV)]^2$. The number of vertical-scale graph cycles was in each case determined by the Scofield data. For elements $Z \geq 34$ this results in an apparent low-energy cut-off in the Veigele et al. data which in reference [8] and [19] extends down to 0.1 keV for all elements Z=1 to 94.

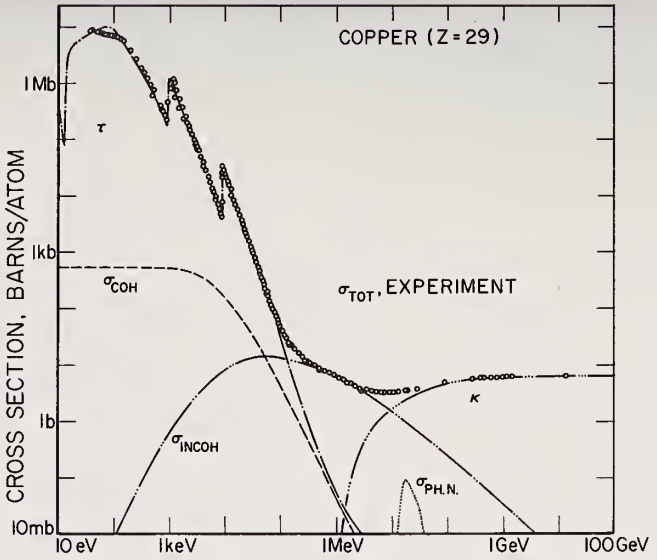


Figure 1

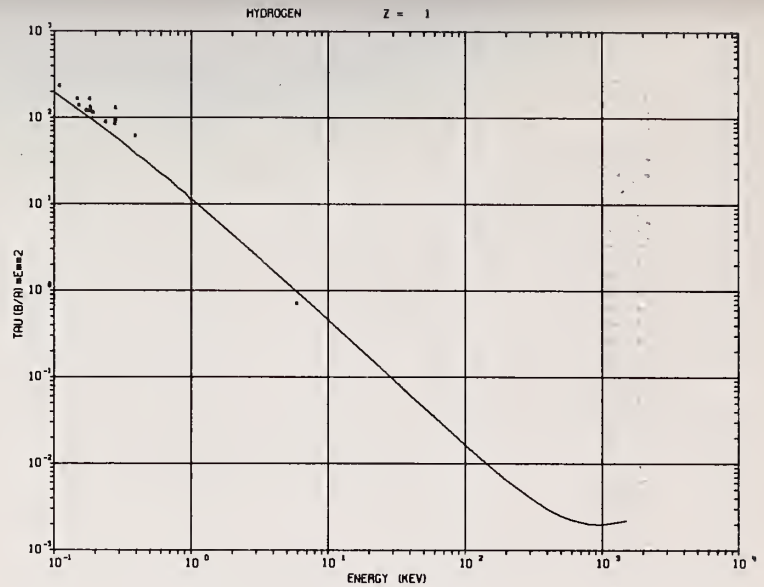


Figure 2

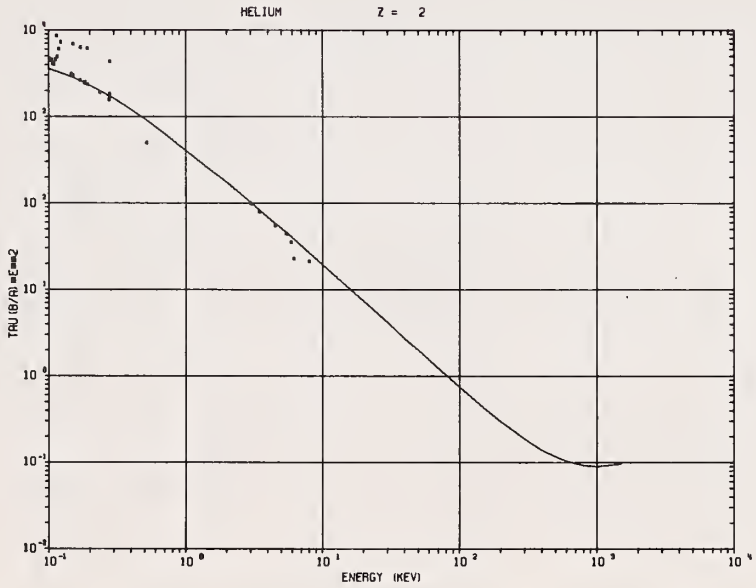


Figure 3

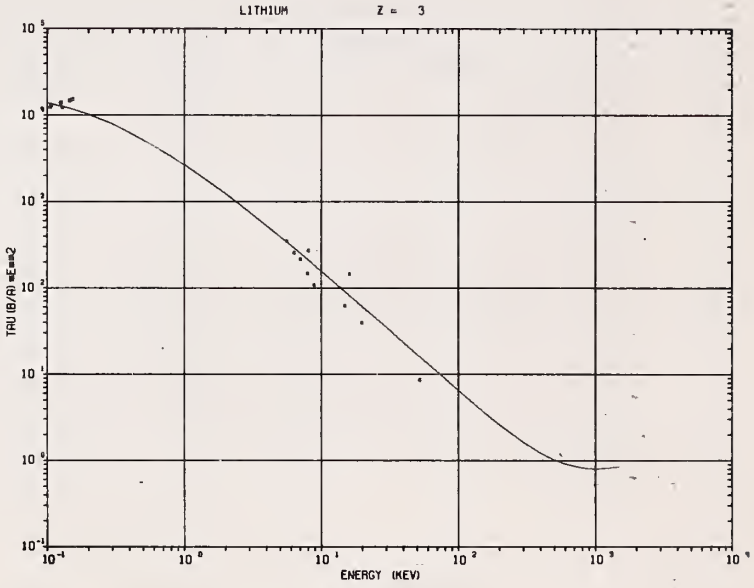


Figure 4

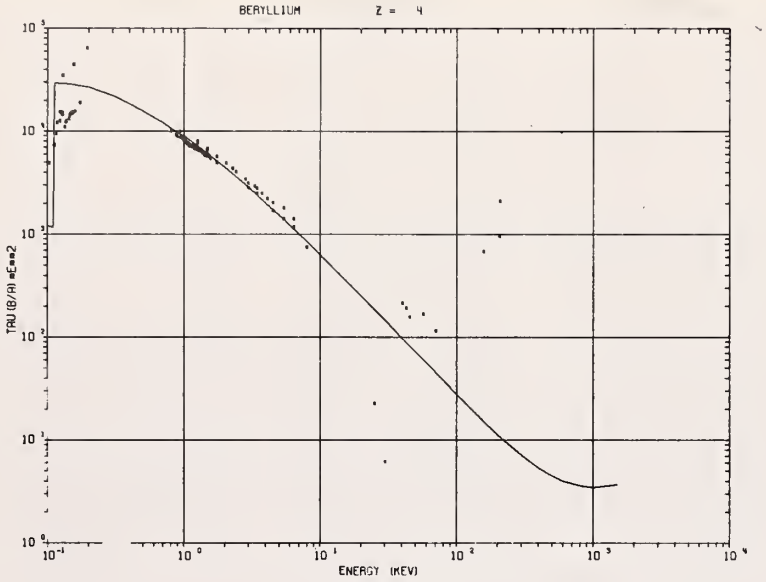


Figure 5

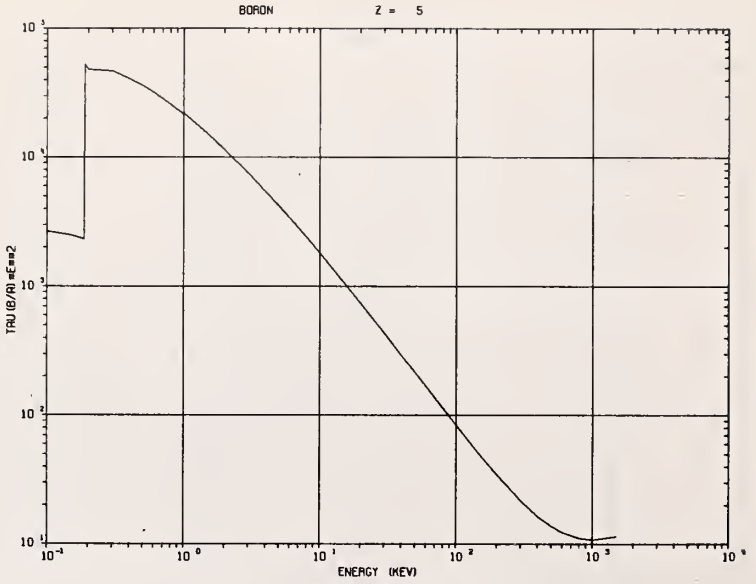


Figure 6

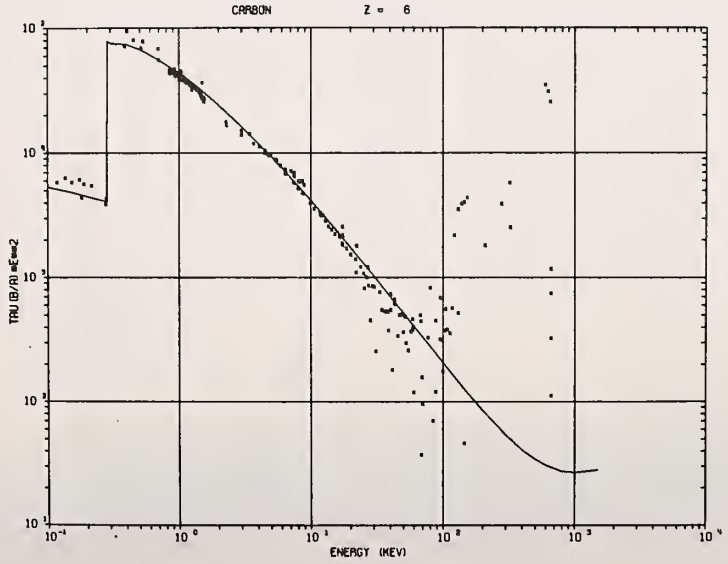


Figure 7

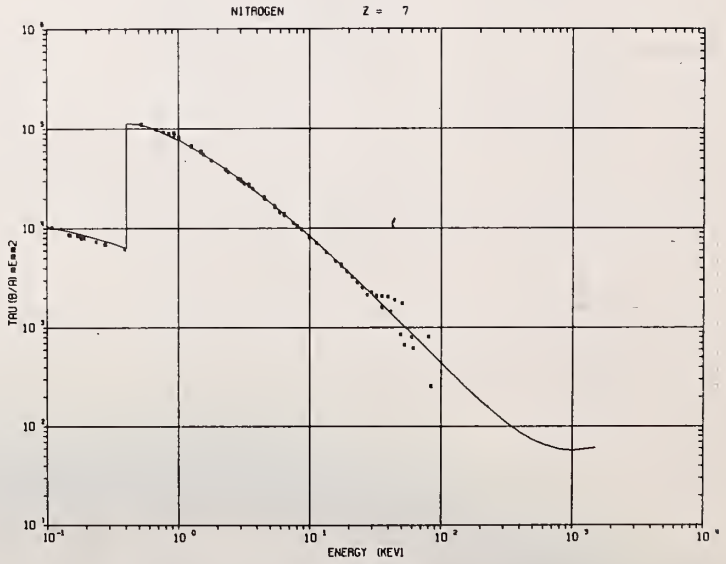


Figure 8

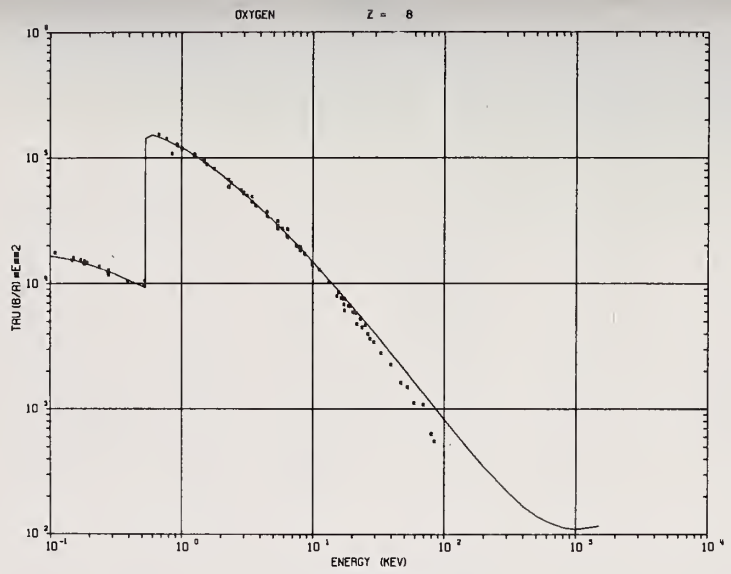


Figure 9

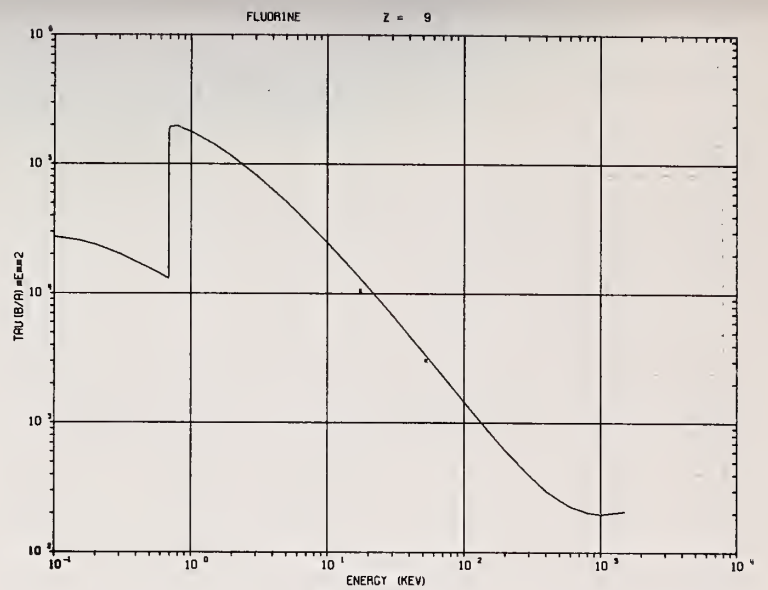


Figure 10

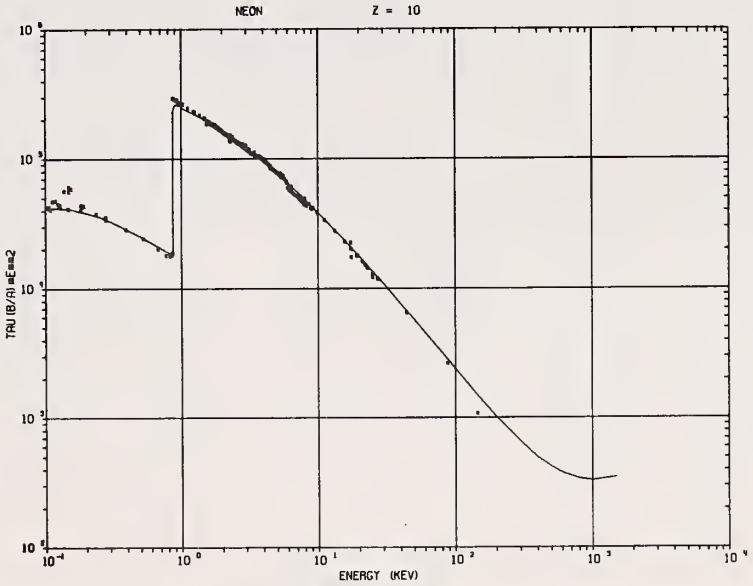


Figure 11

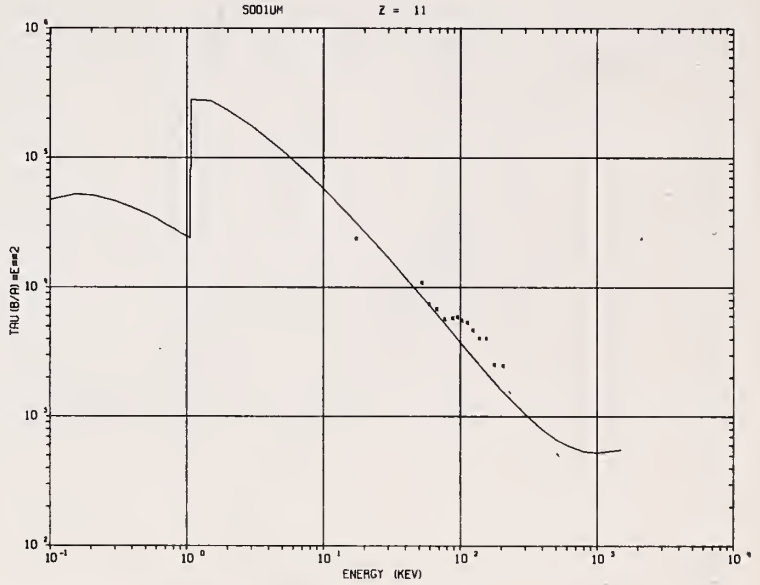


Figure 12

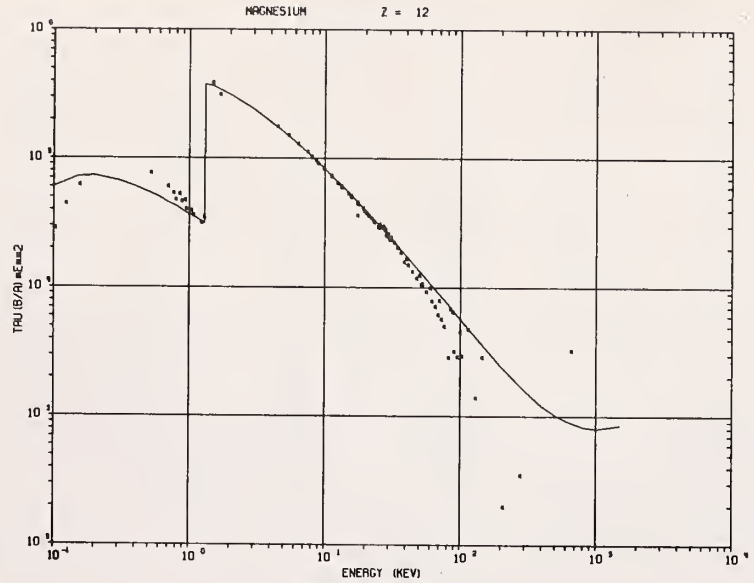


Figure 13

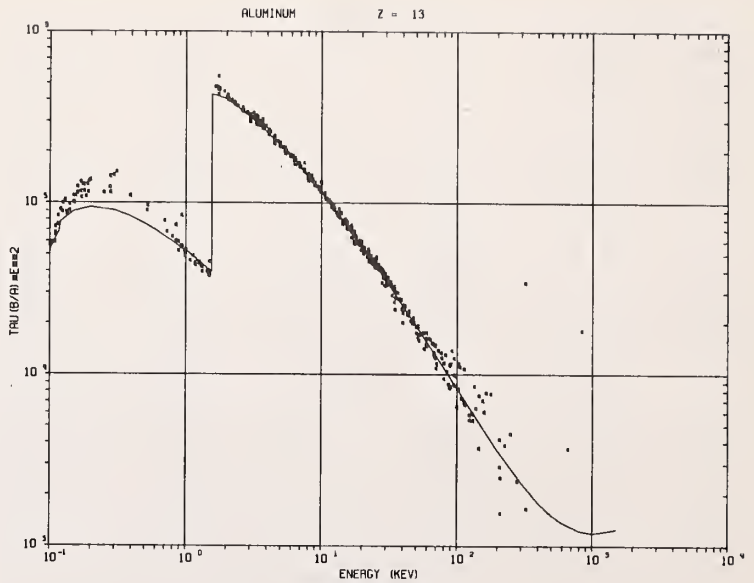


Figure 14

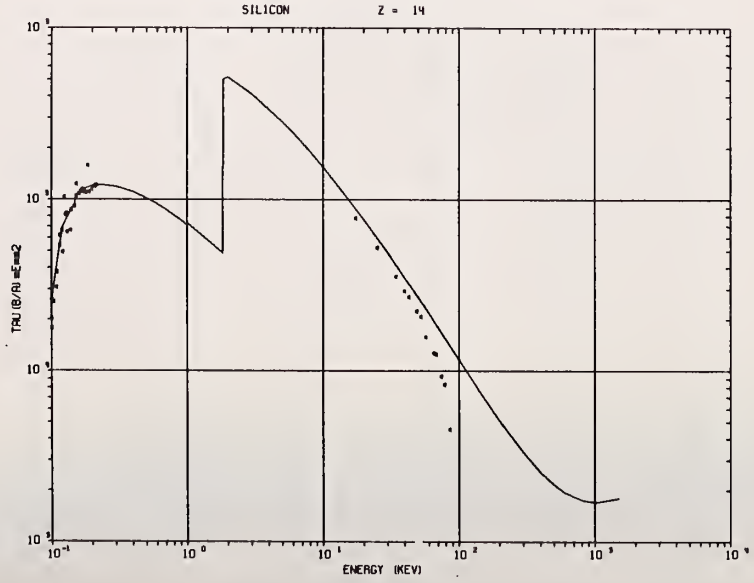


Figure 15

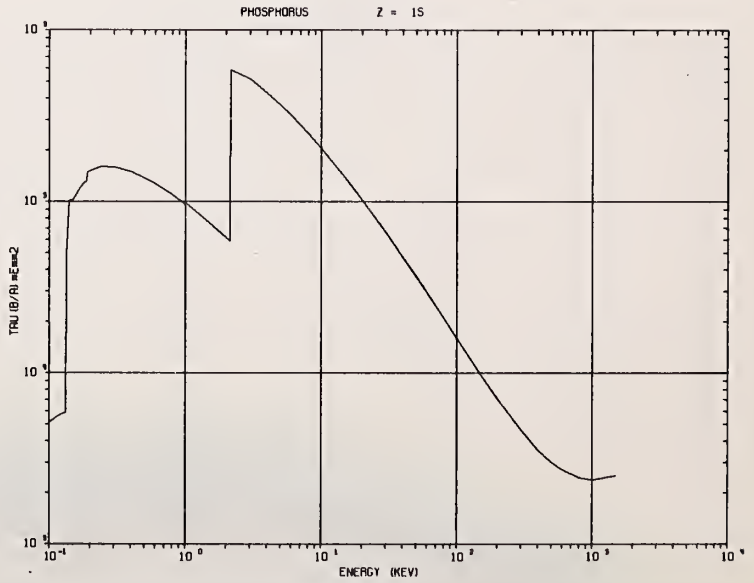


Figure 16

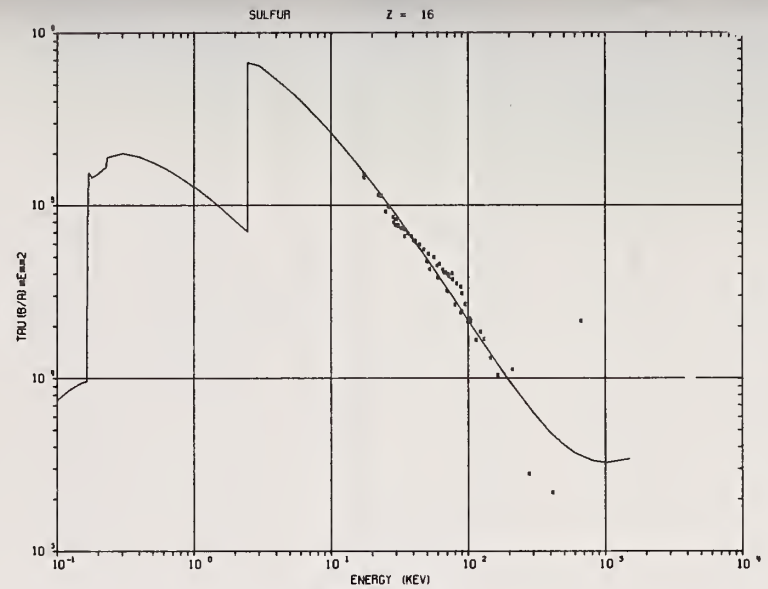


Figure 17

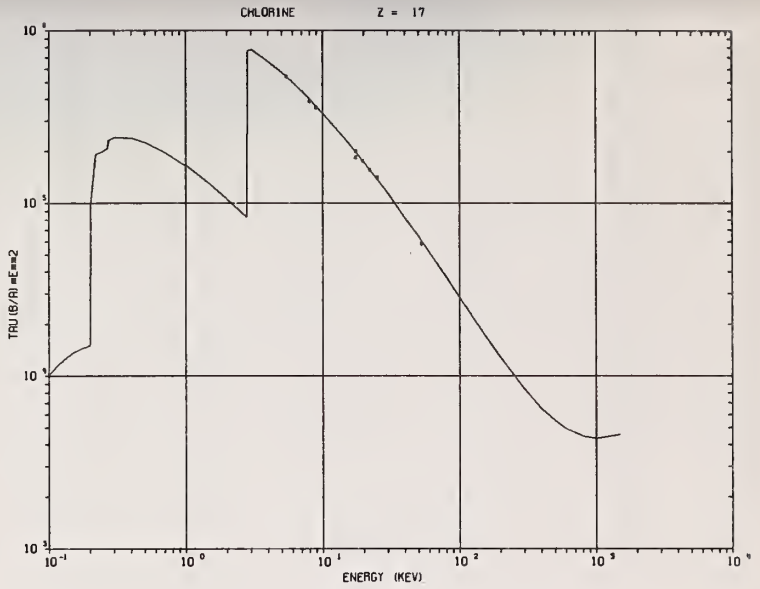


Figure 18

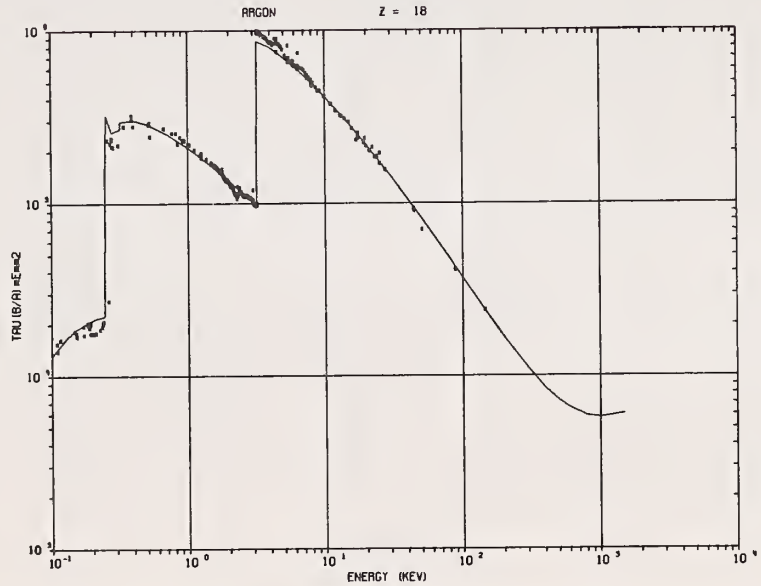


Figure 19

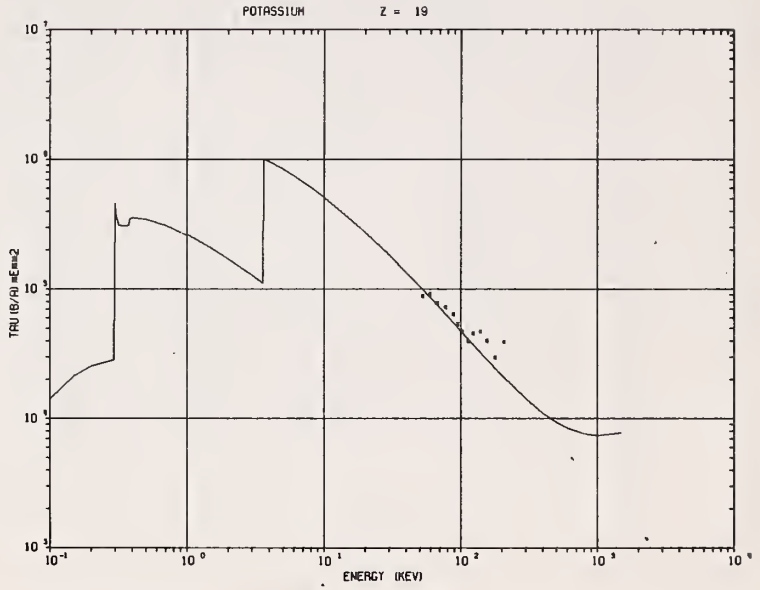


Figure 20

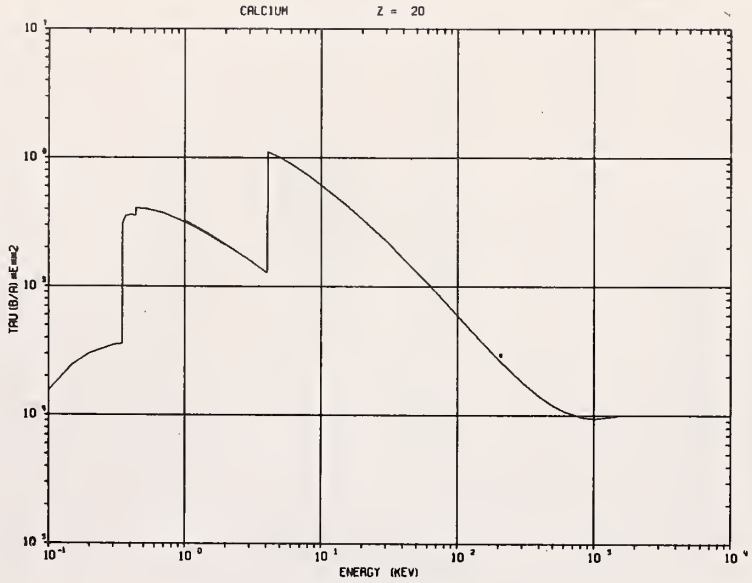


Figure 21

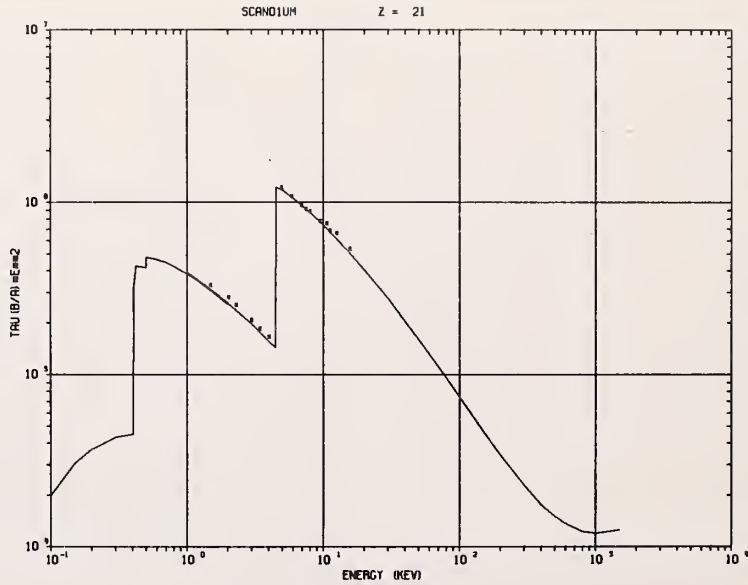


Figure 22

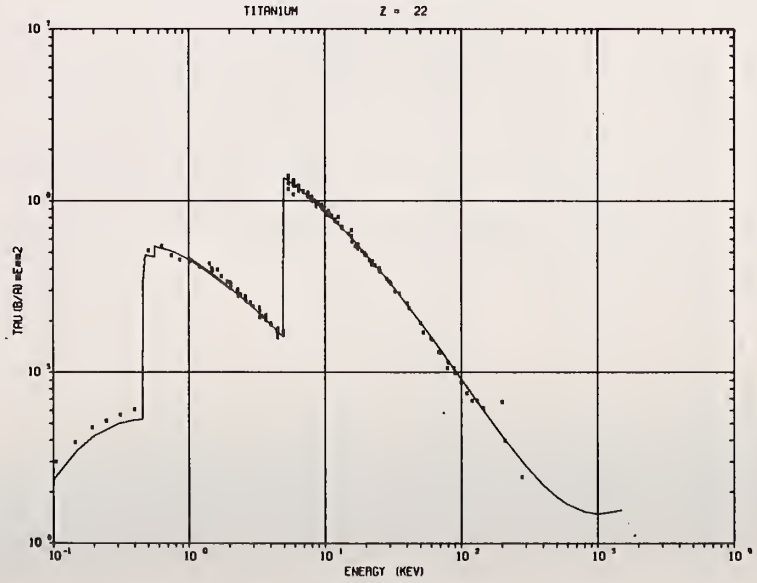


Figure 23

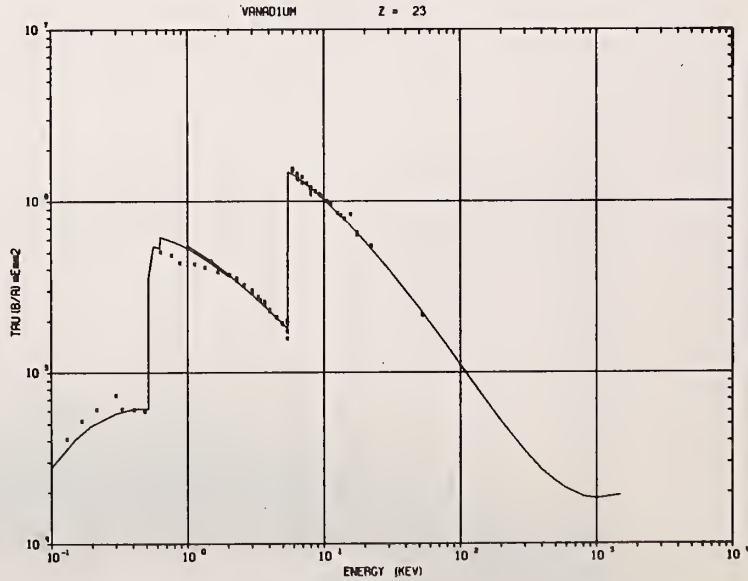


Figure 24

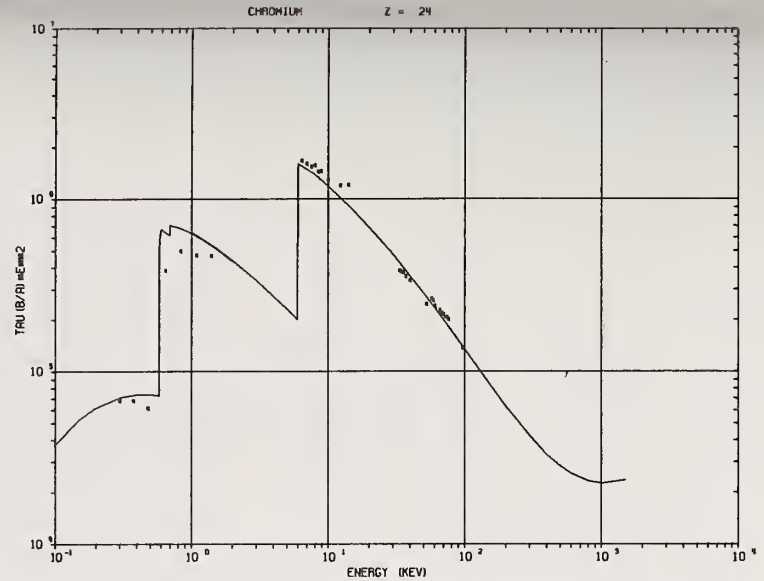


Figure 25

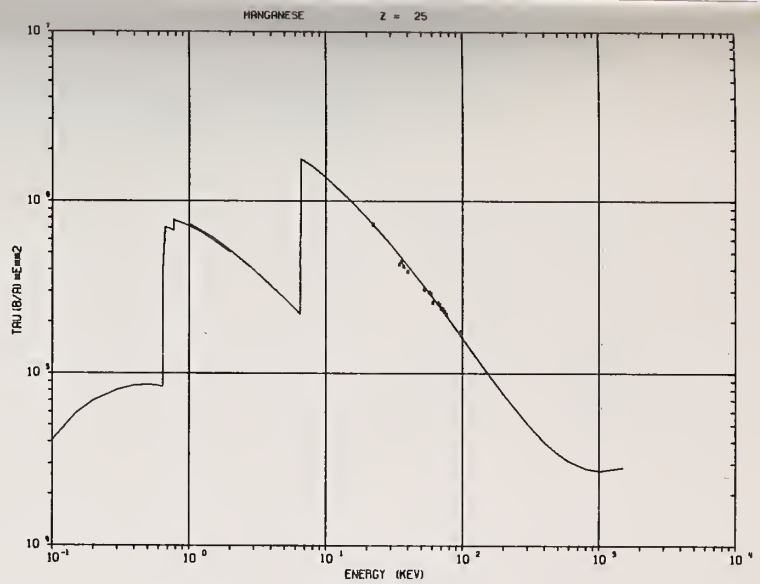


Figure 26

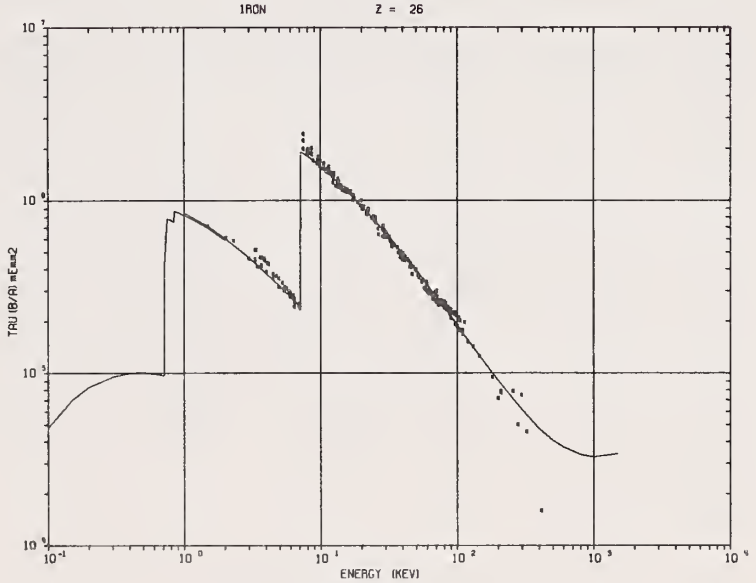


Figure 27

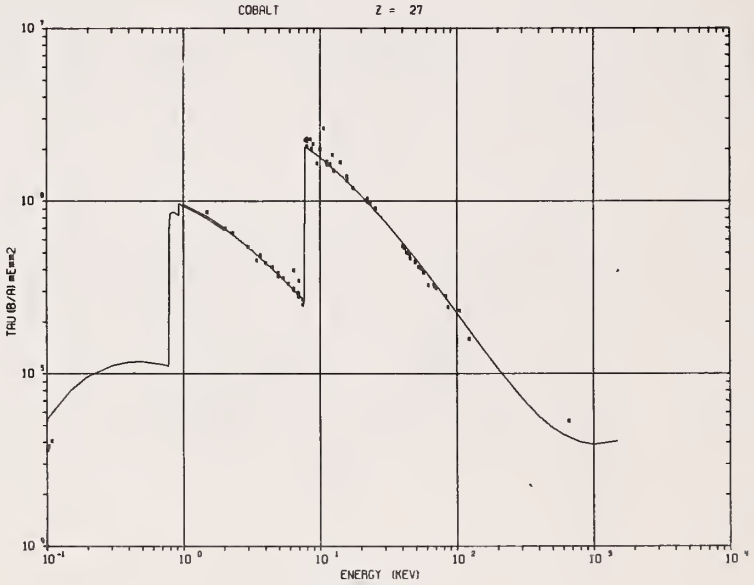


Figure 28

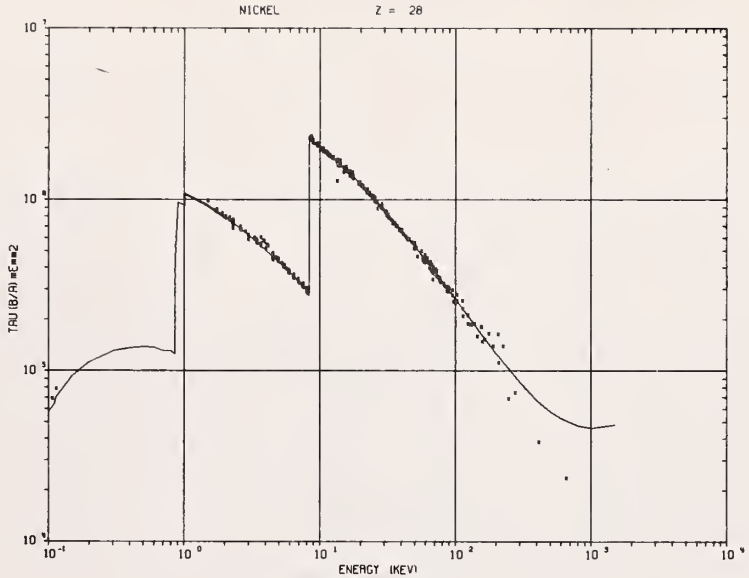


Figure 29

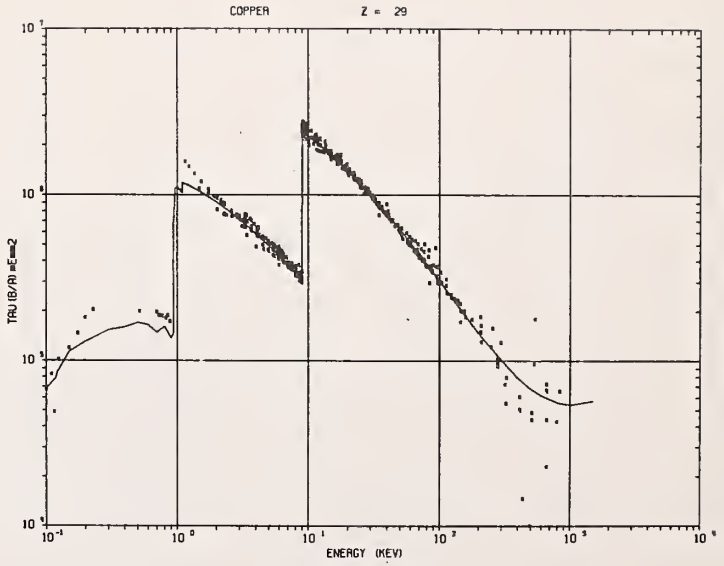


Figure 30

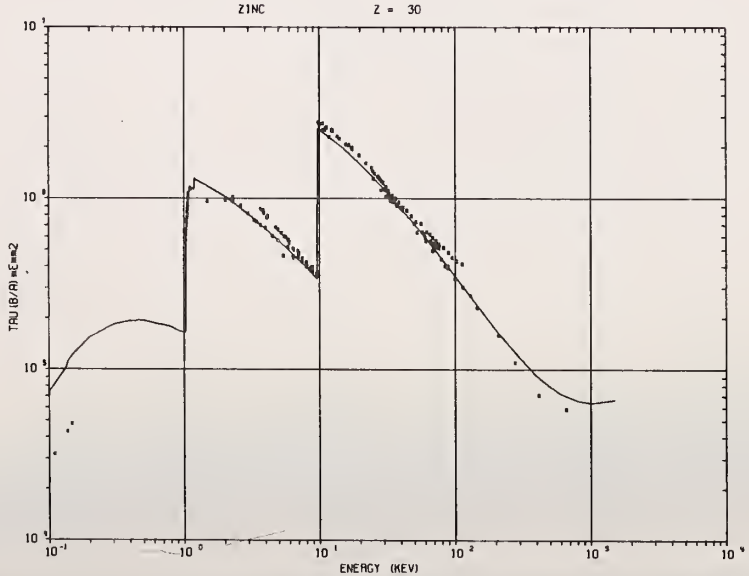


Figure 31

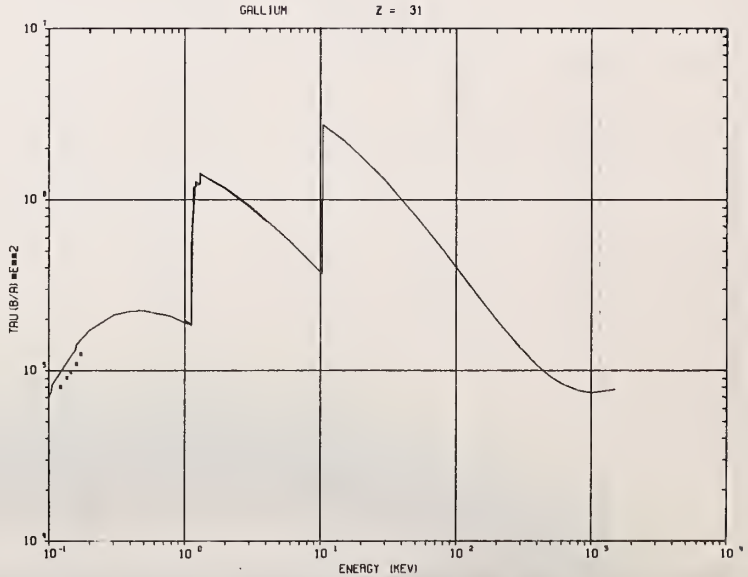


Figure 32

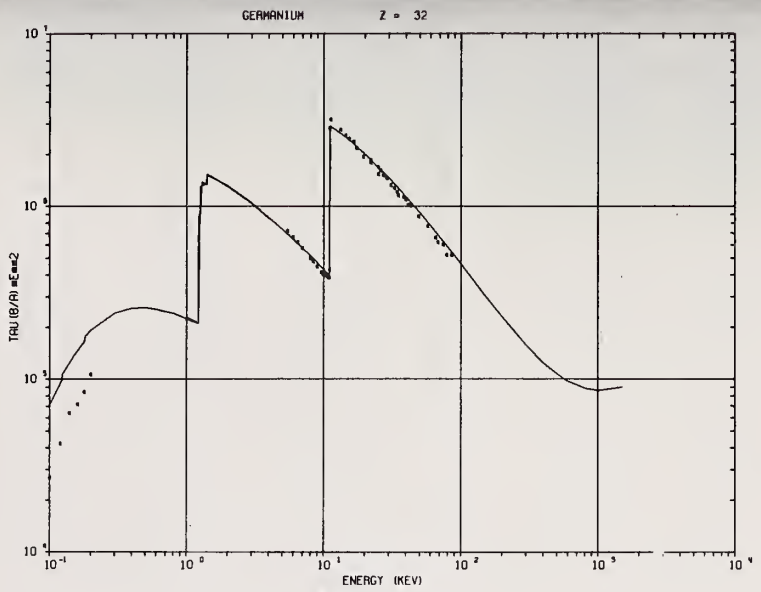


Figure 33

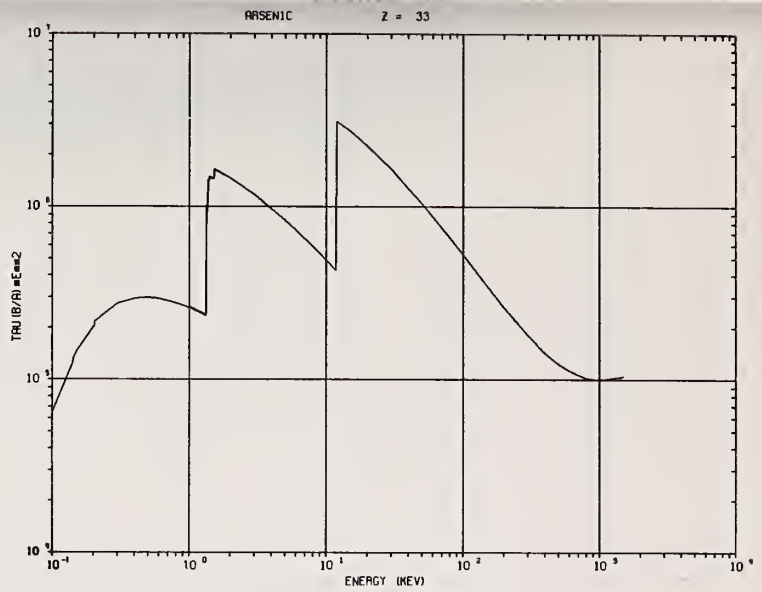


Figure 34

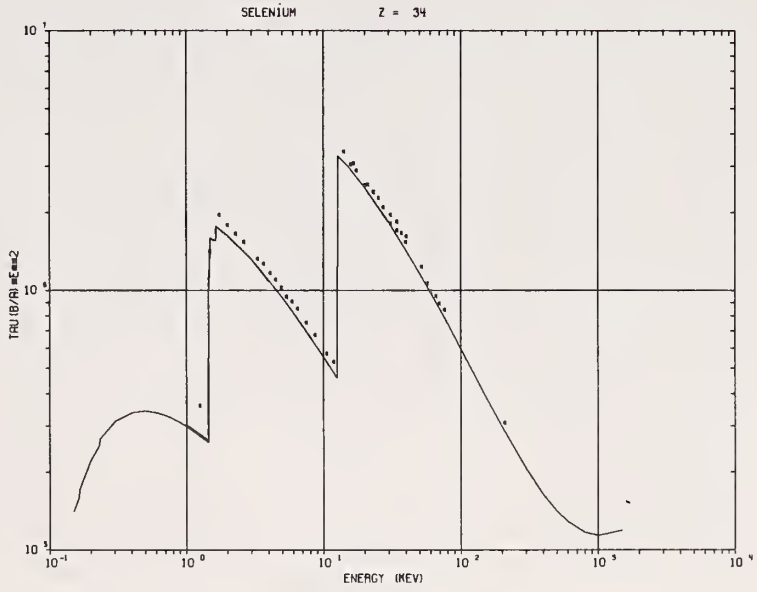


Figure 35

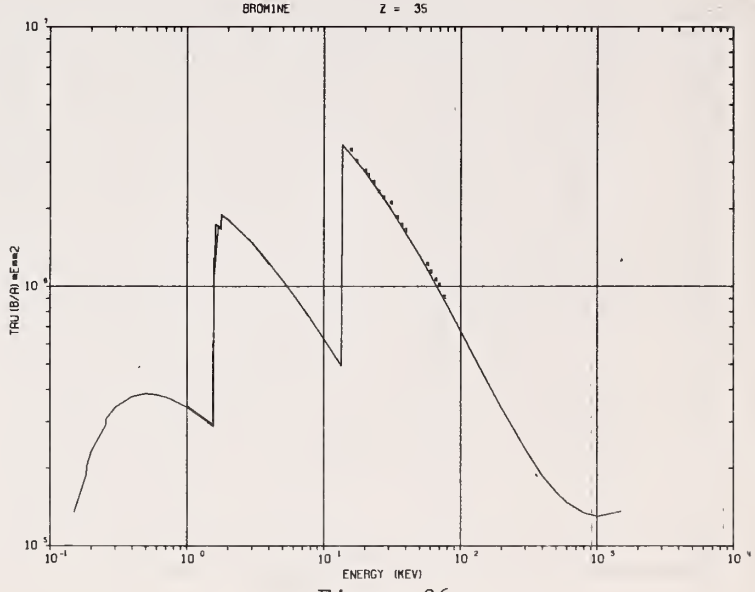


Figure 36

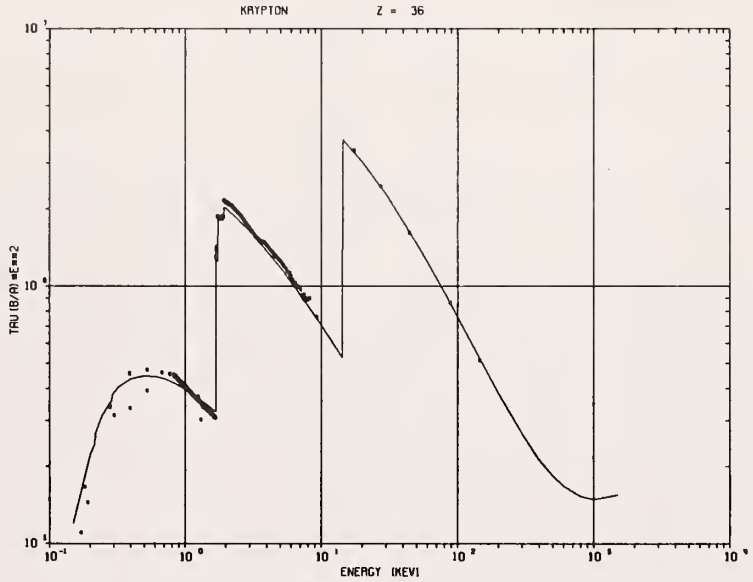


Figure 37

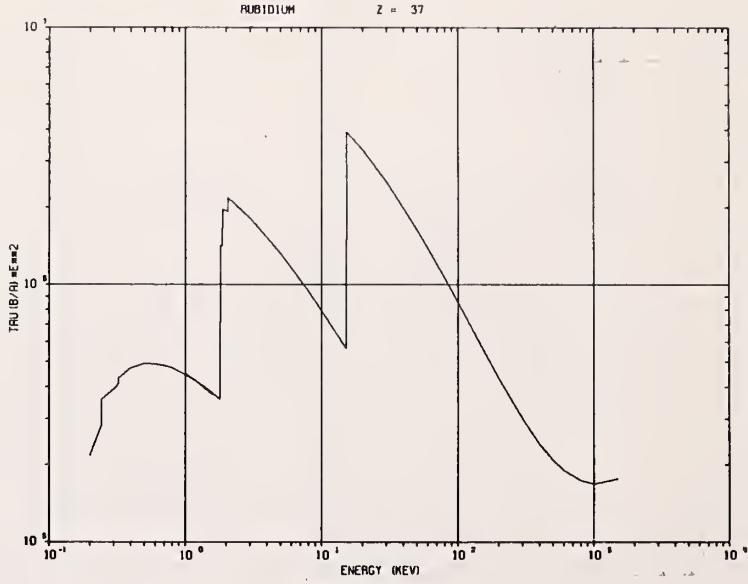


Figure 38

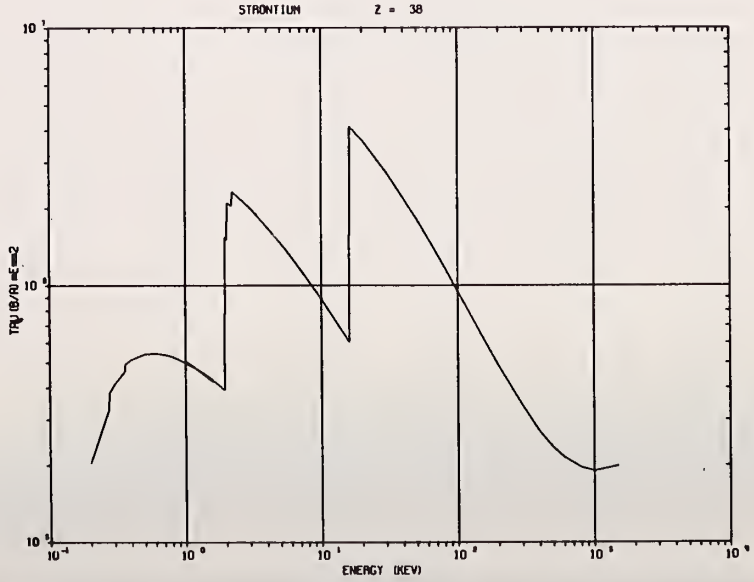


Figure 39

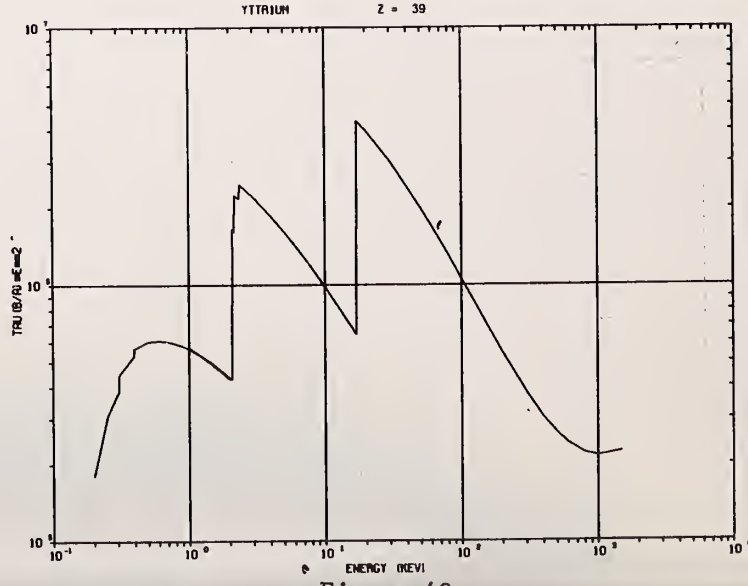


Figure 40

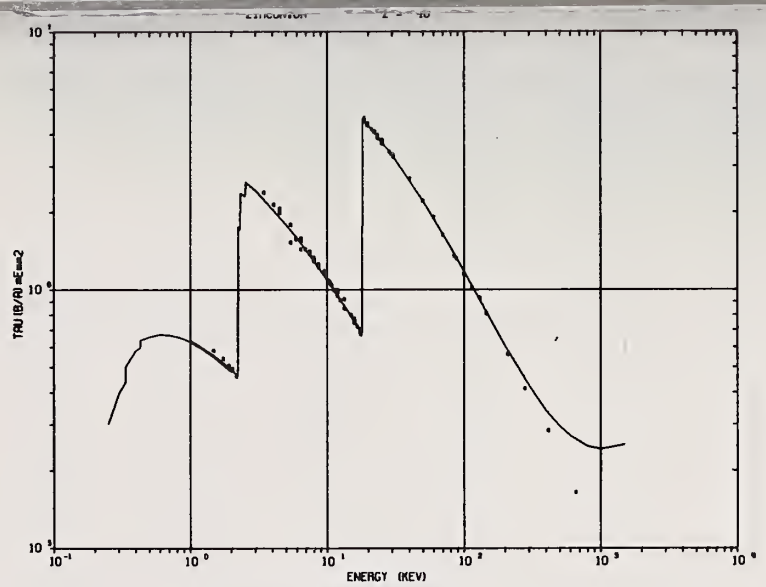


Figure 41

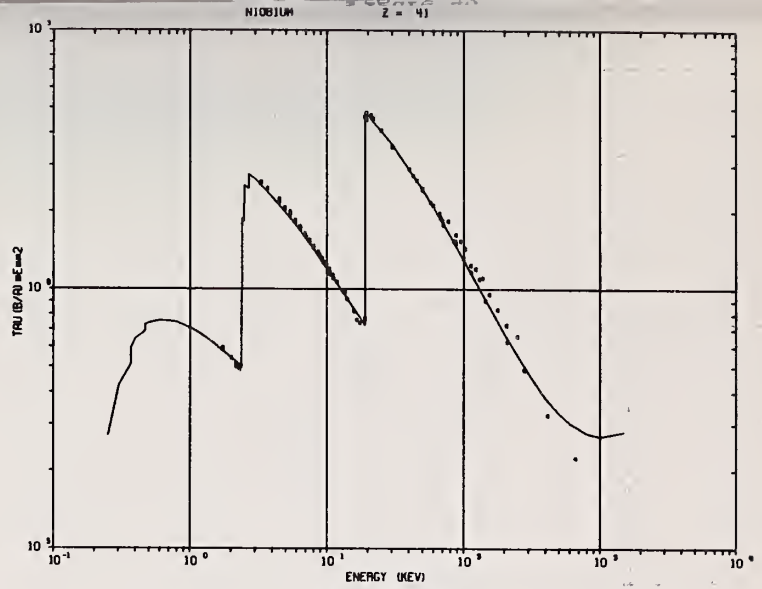


Figure 42

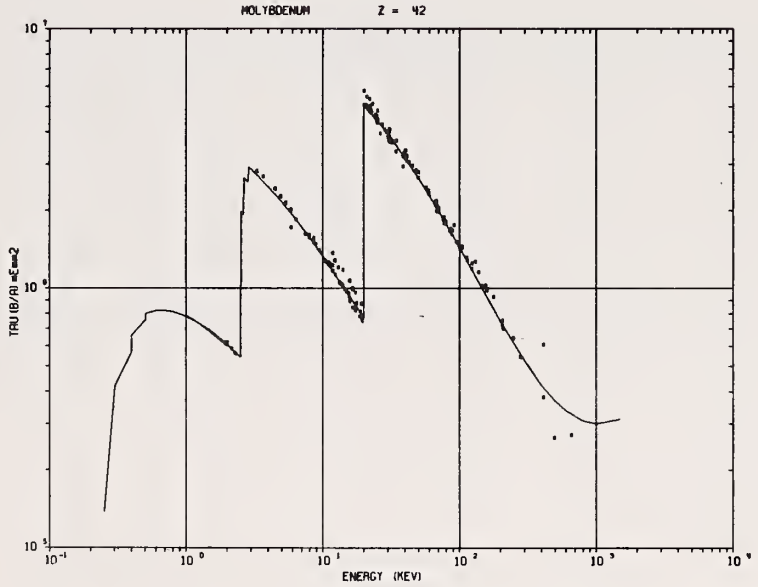


Figure 43

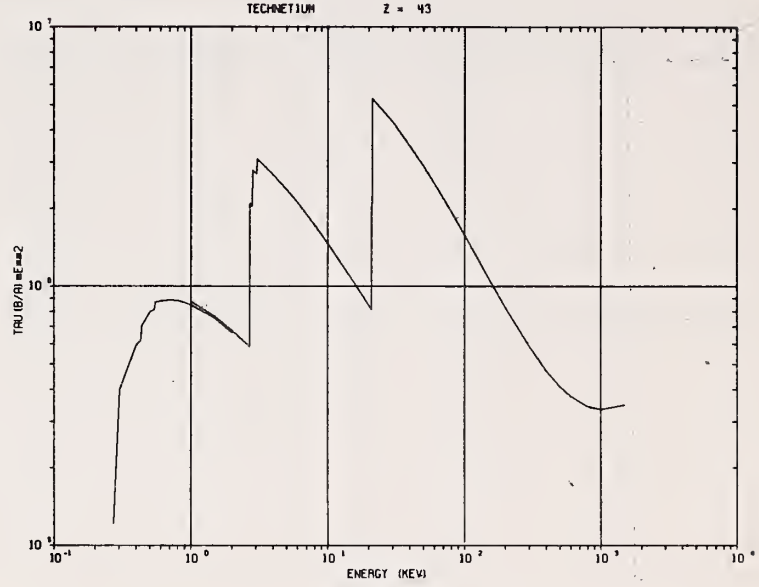


Figure 44

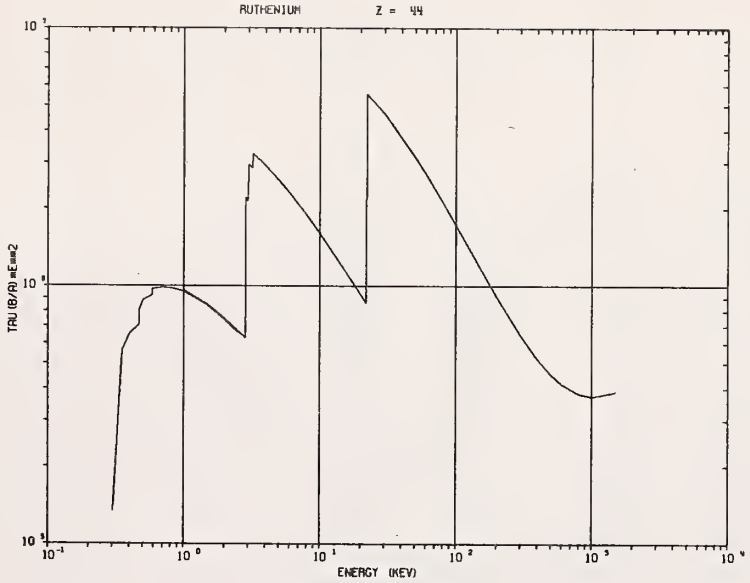


Figure 45

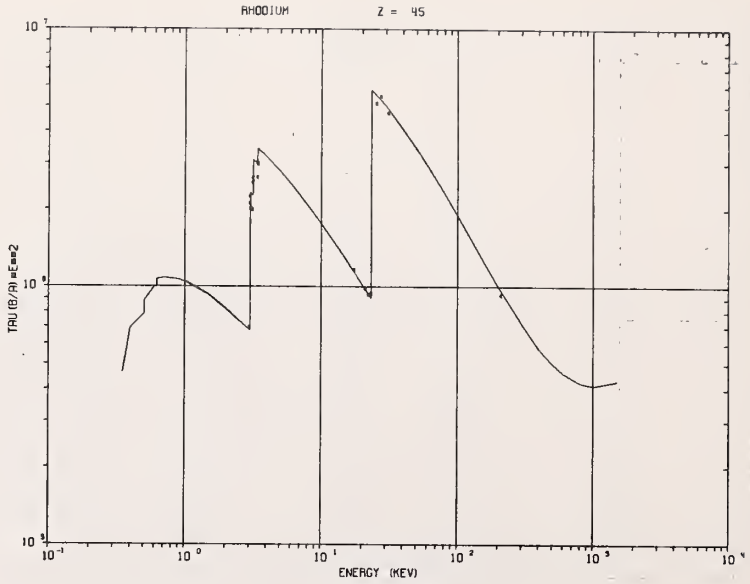


Figure 46

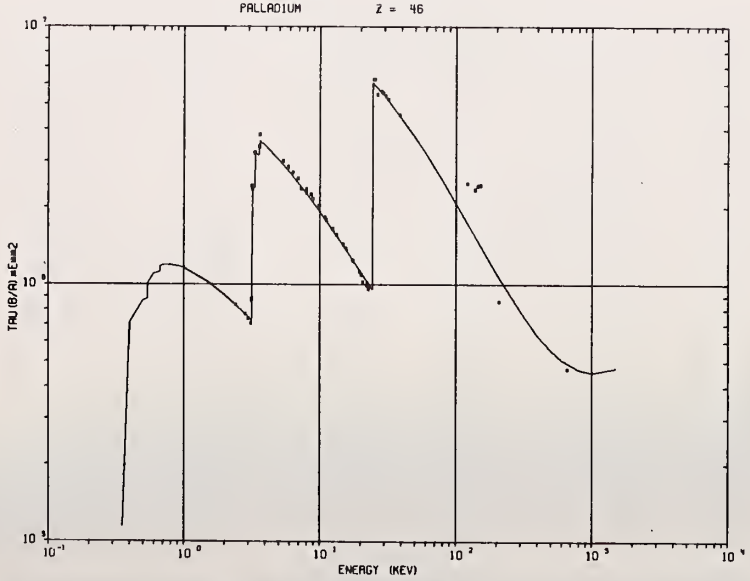


Figure 47

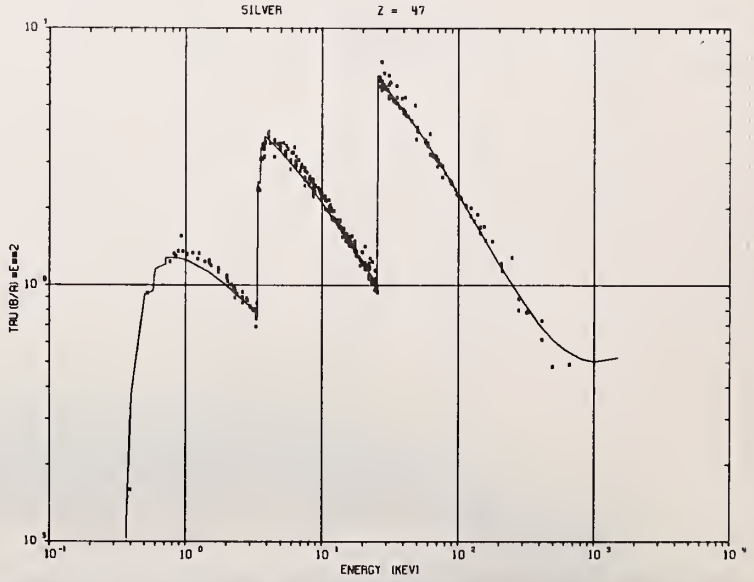


Figure 48

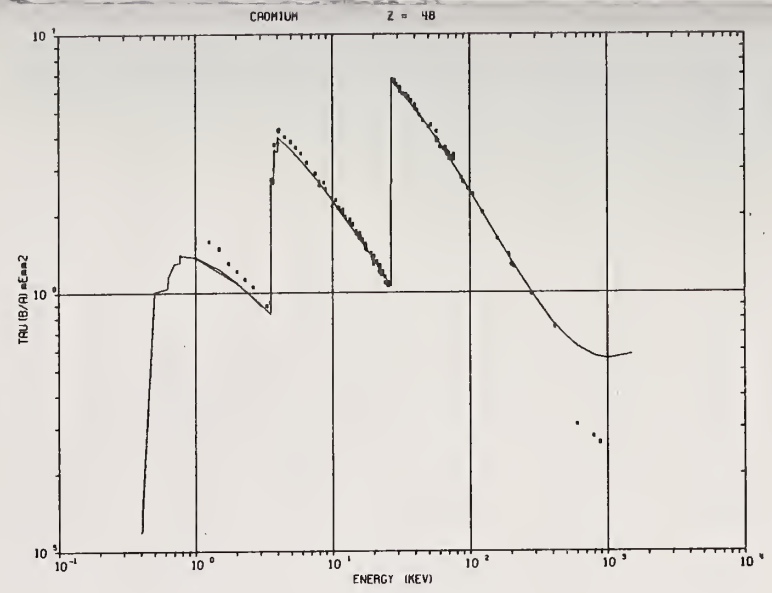


Figure 49

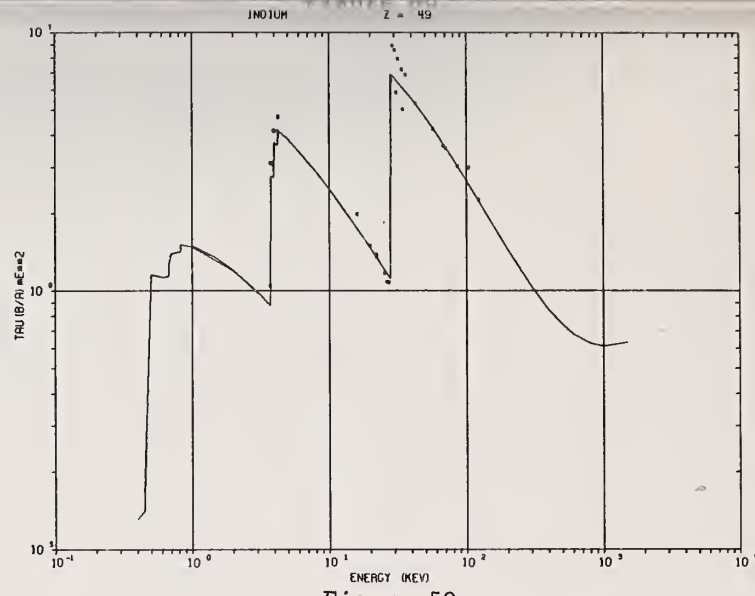


Figure 50

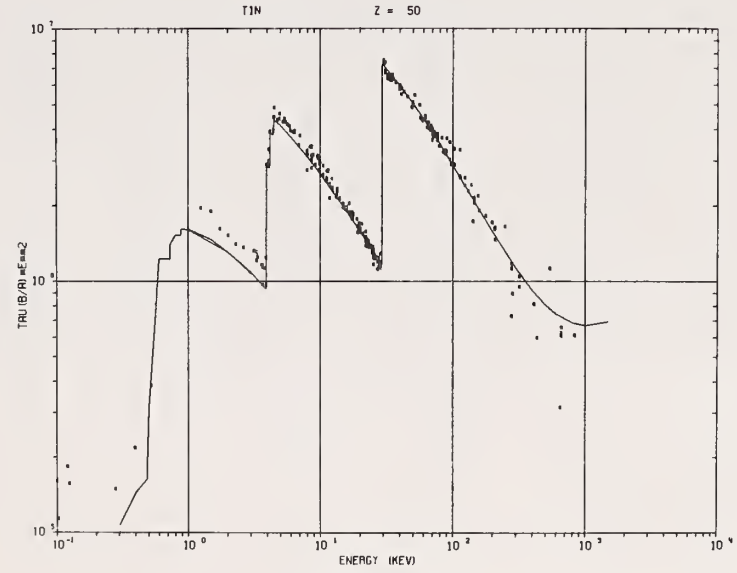


Figure 51

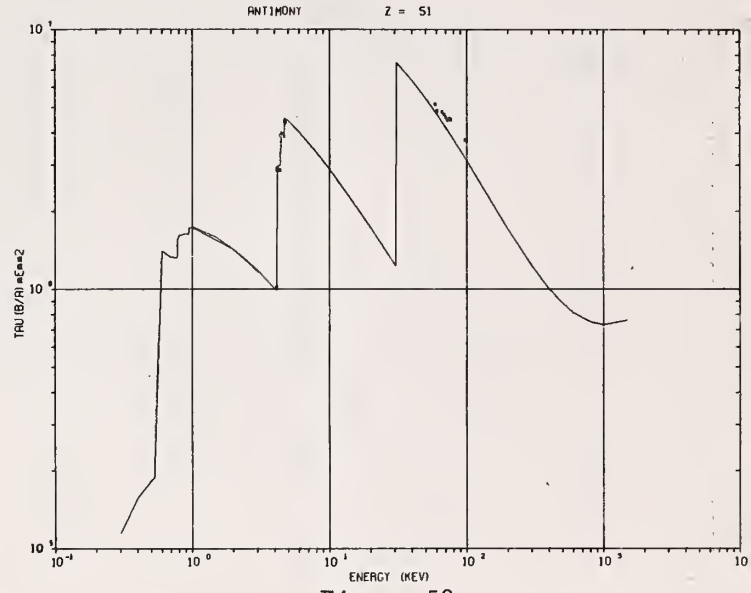


Figure 52

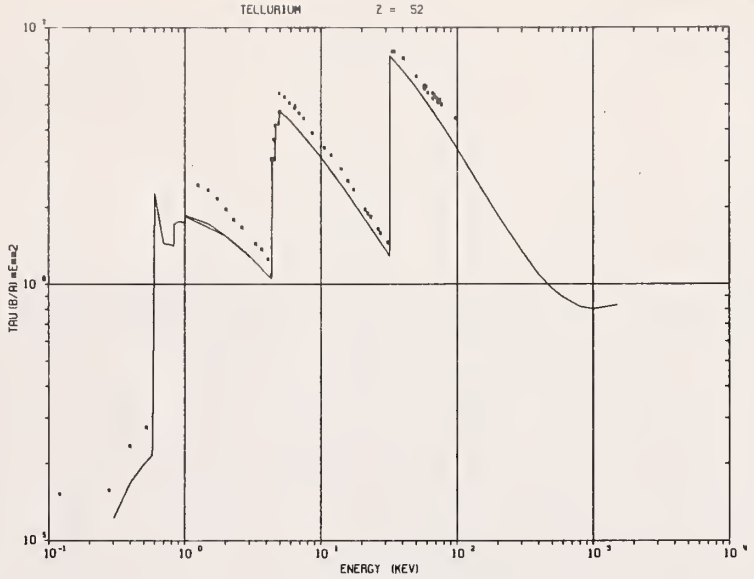


Figure 53

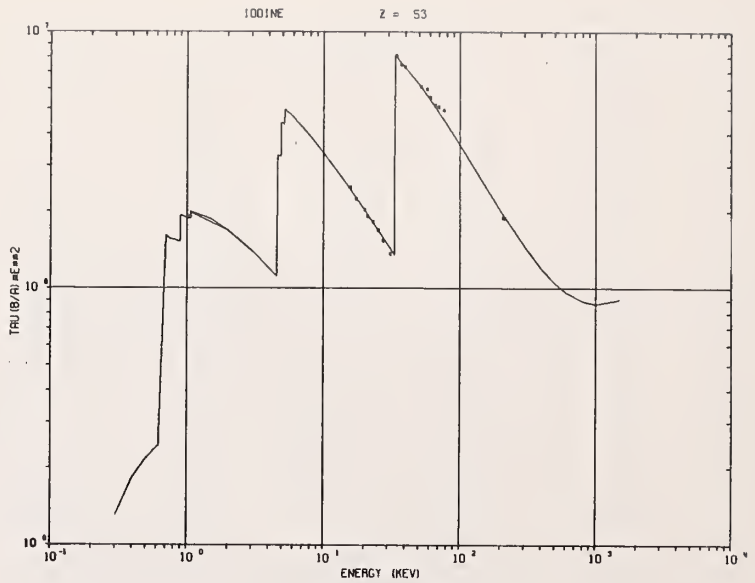


Figure 54

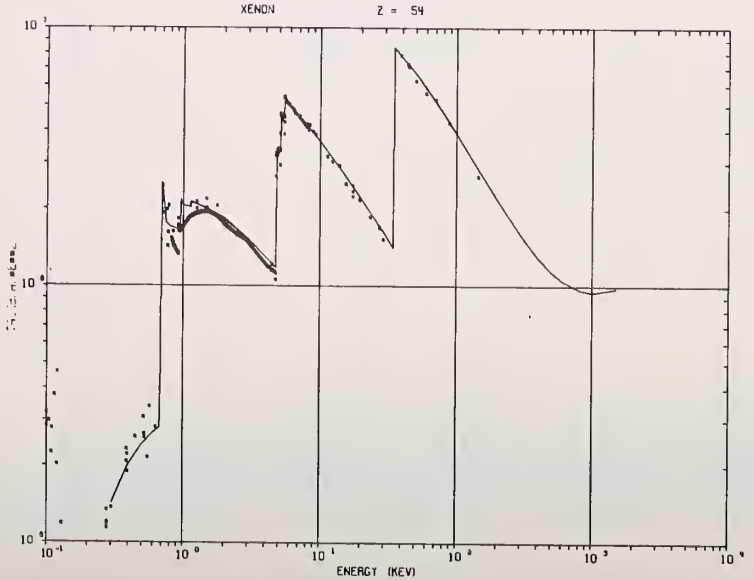


Figure 55

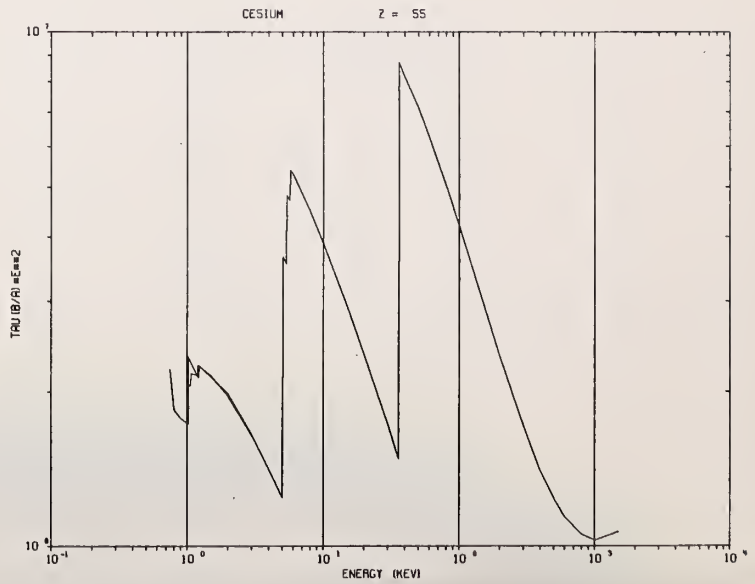


Figure 56

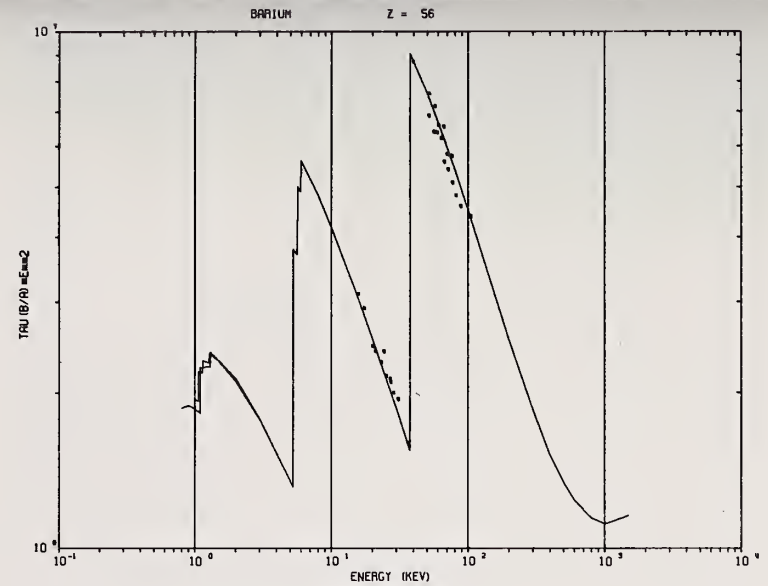


Figure 57

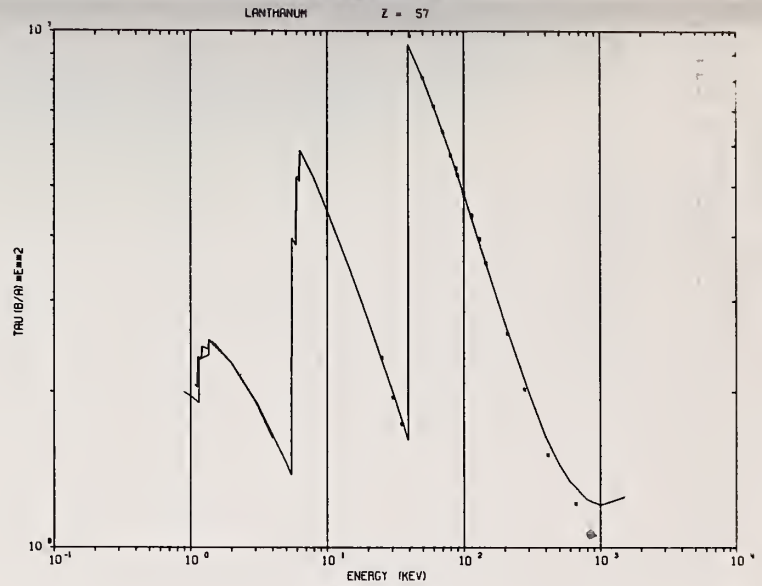


Figure 58

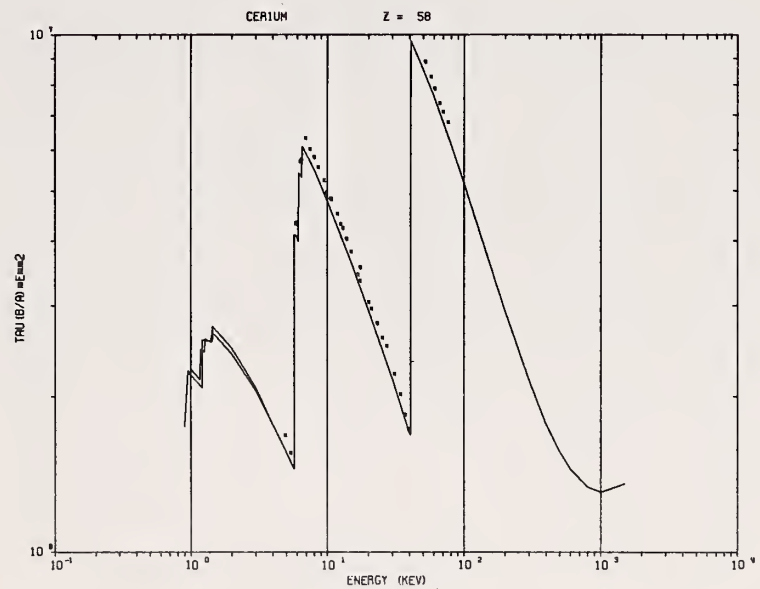


Figure 59

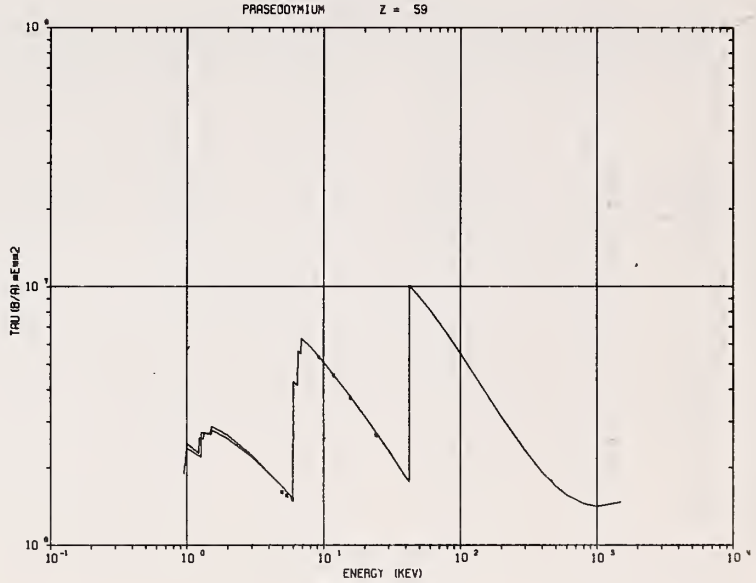


Figure 60

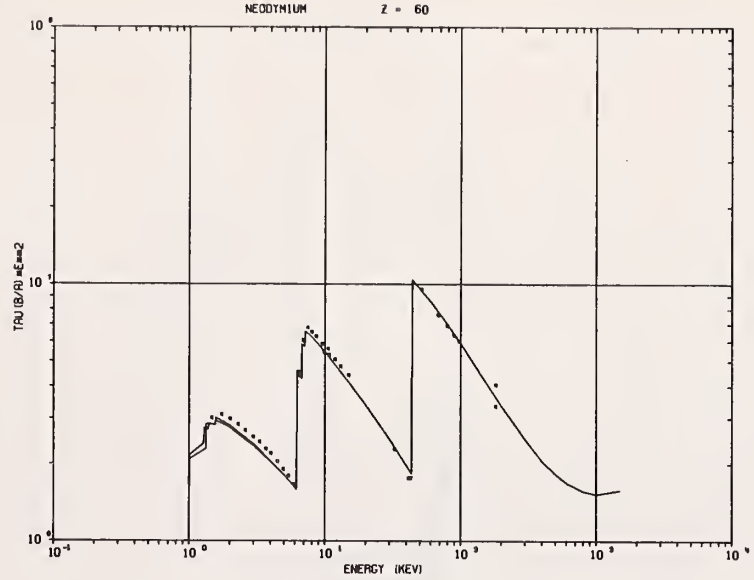


Figure 61

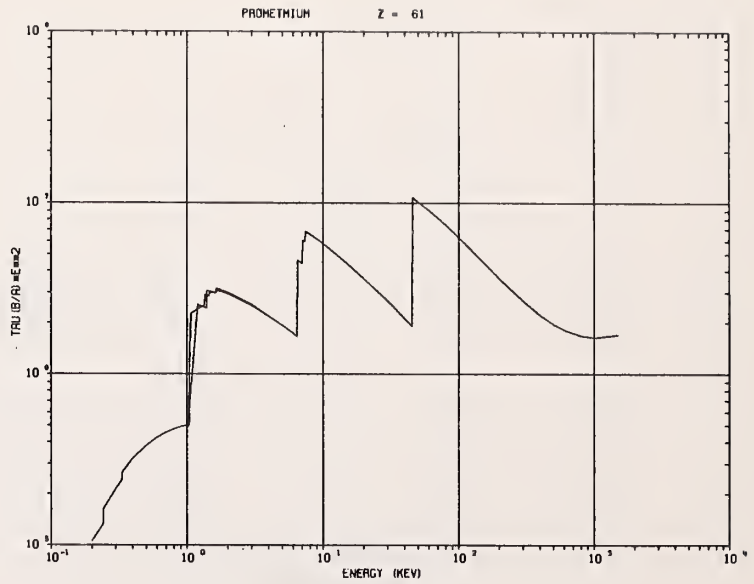


Figure 62

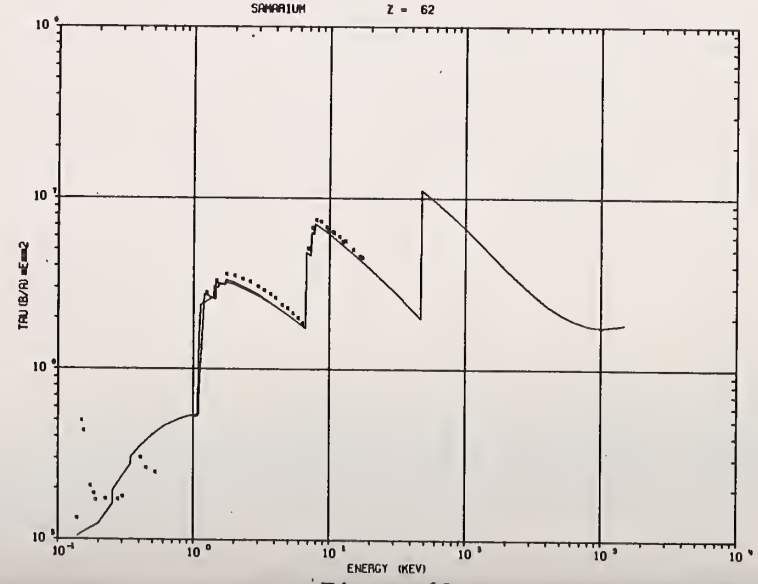


Figure 63

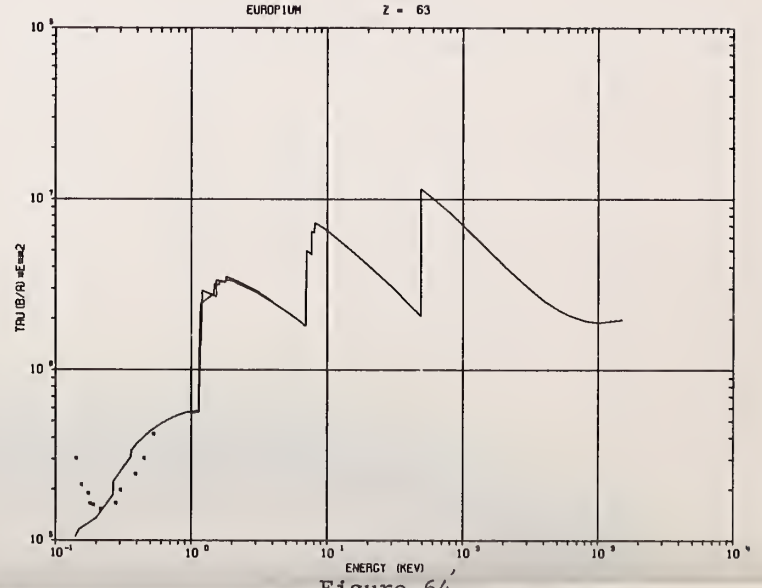


Figure 64

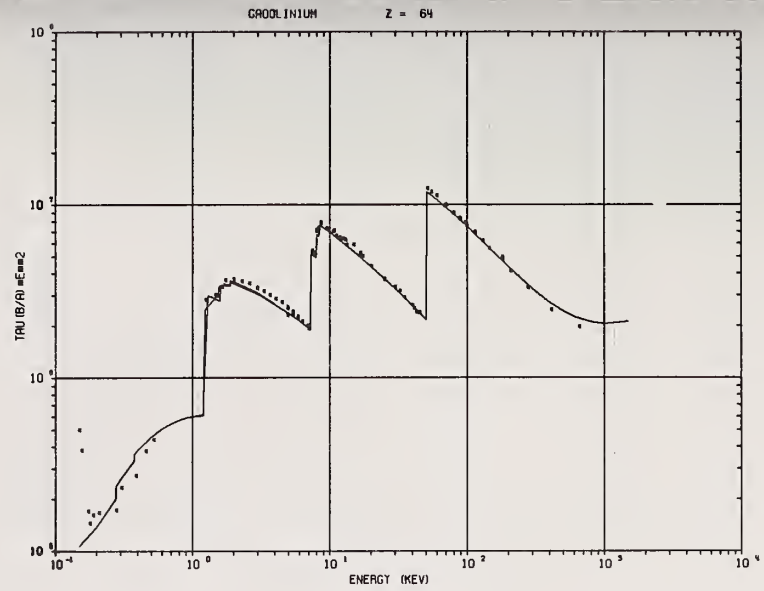


Figure 65

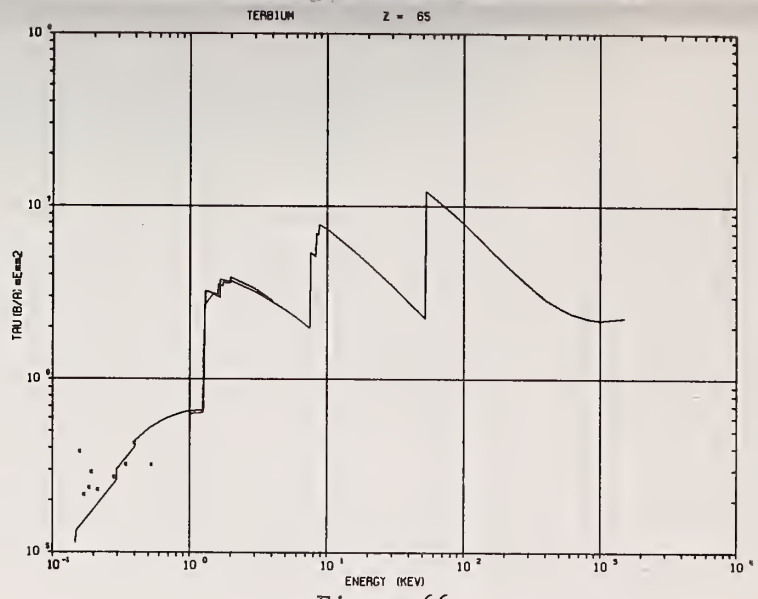


Figure 66

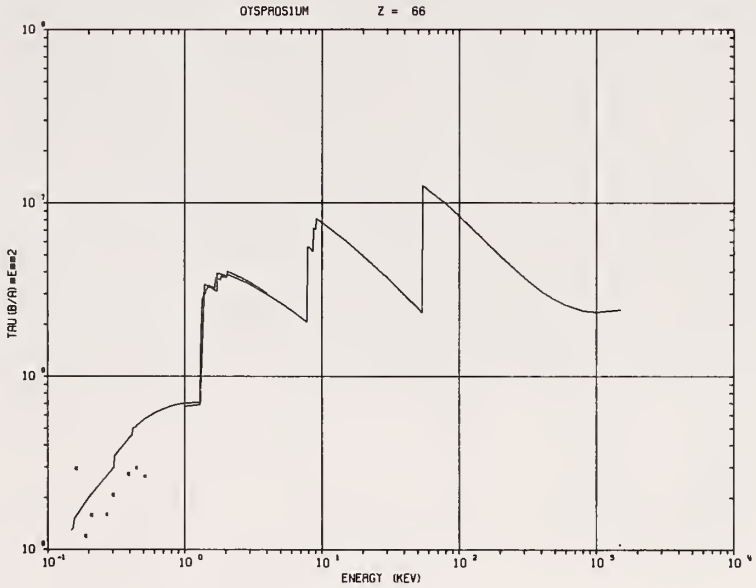


Figure 67

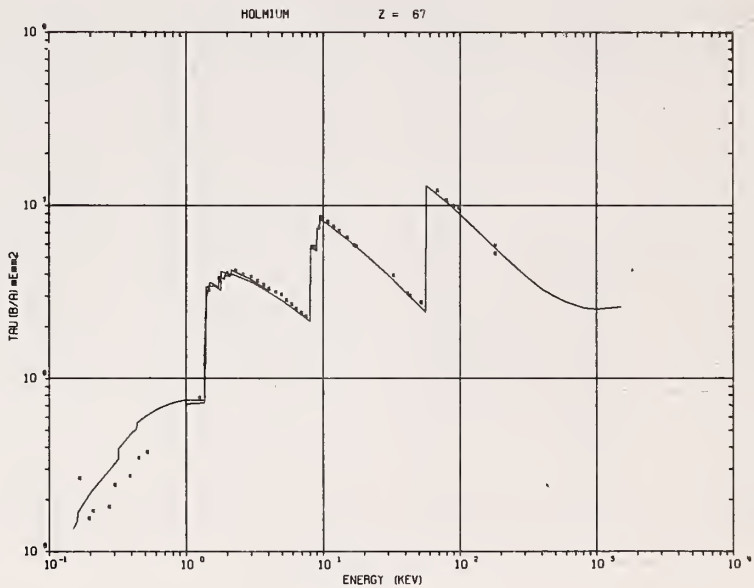


Figure 68

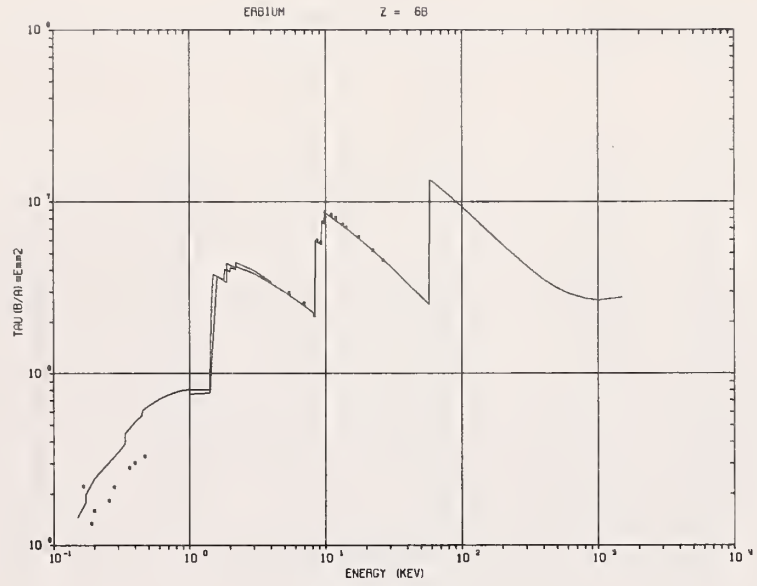


Figure 69

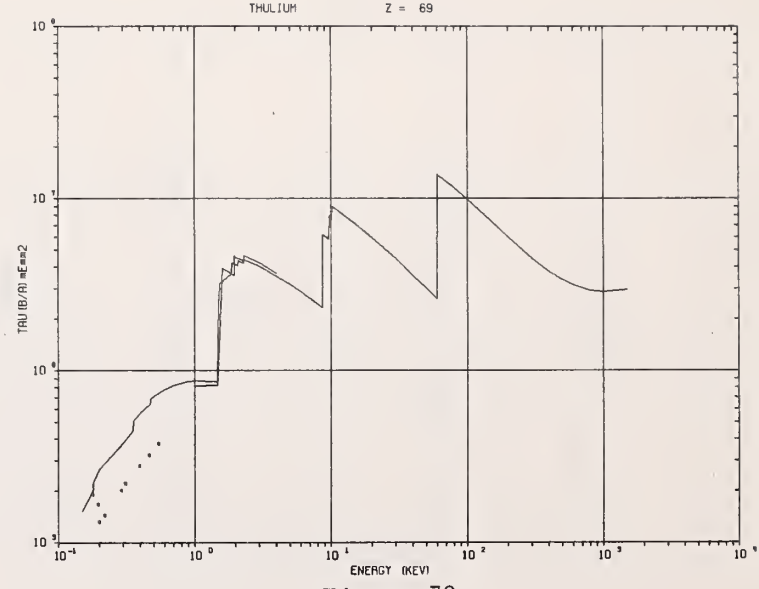


Figure 70

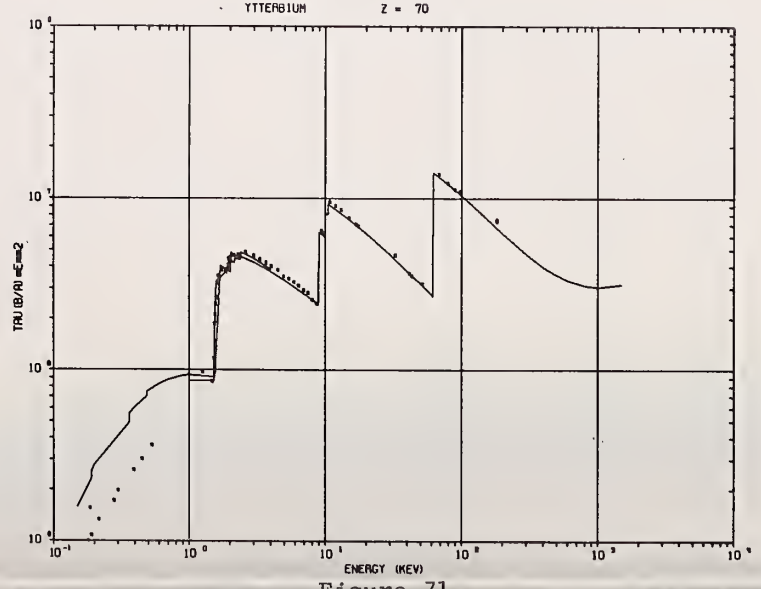
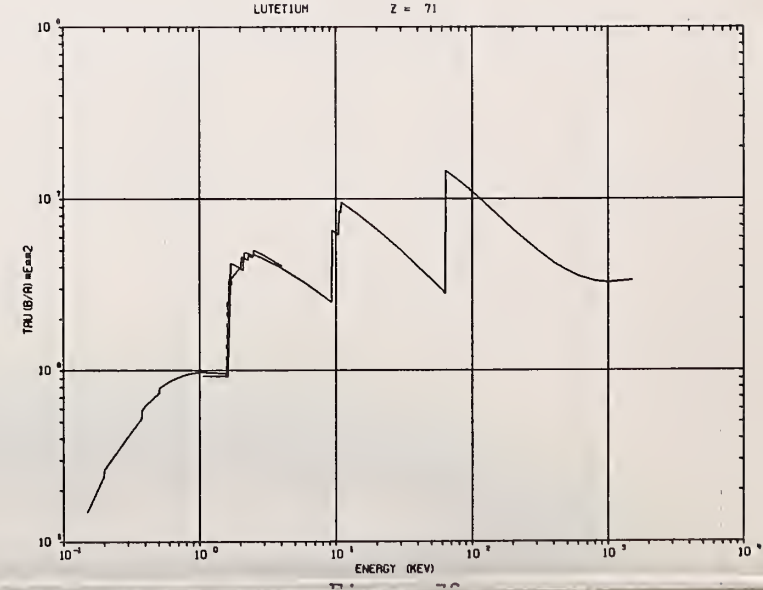


Figure 71



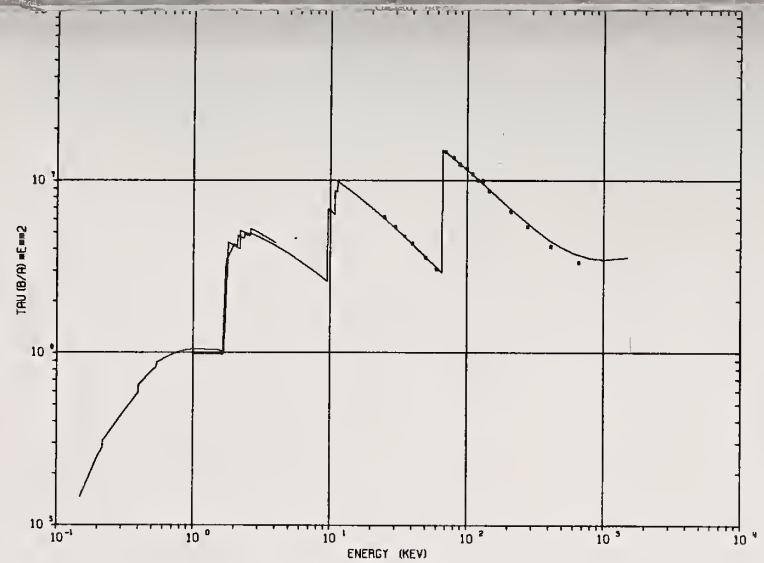


Figure 73

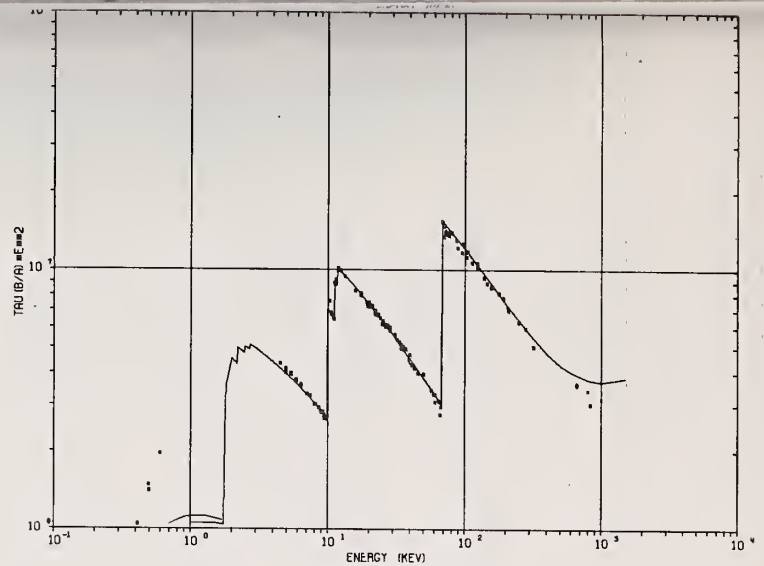


Figure 74

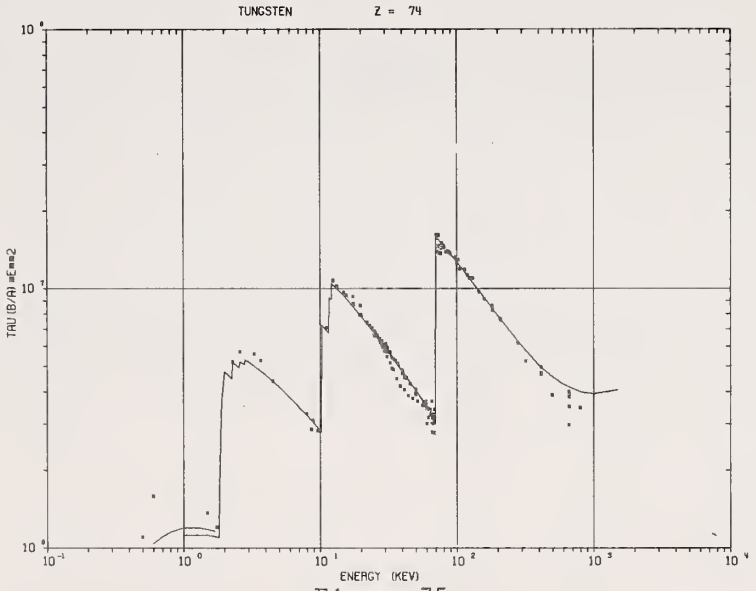


Figure 75

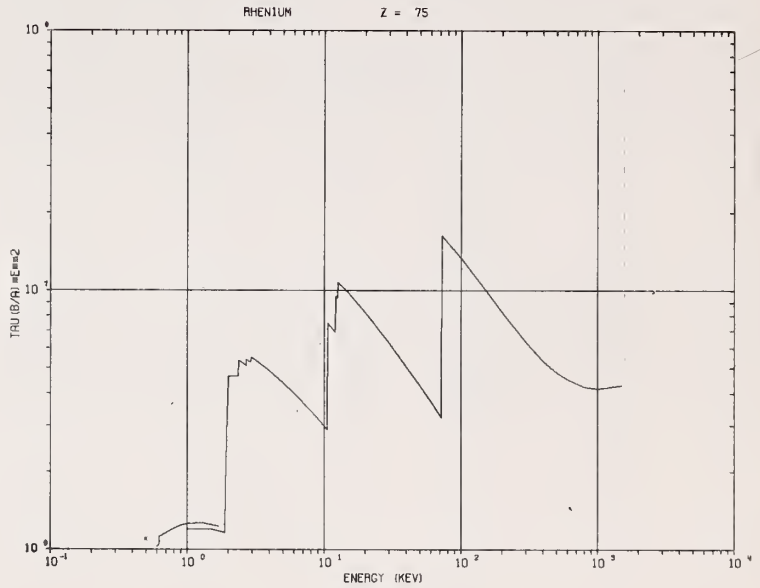


Figure 76

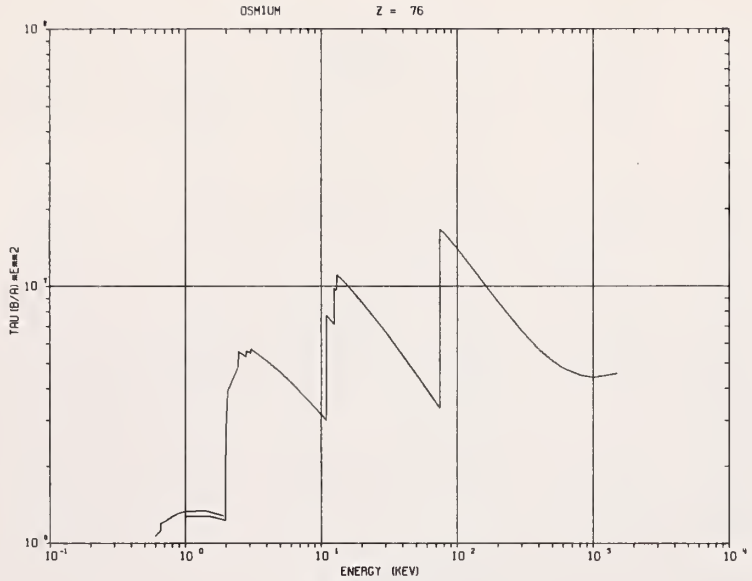


Figure 77

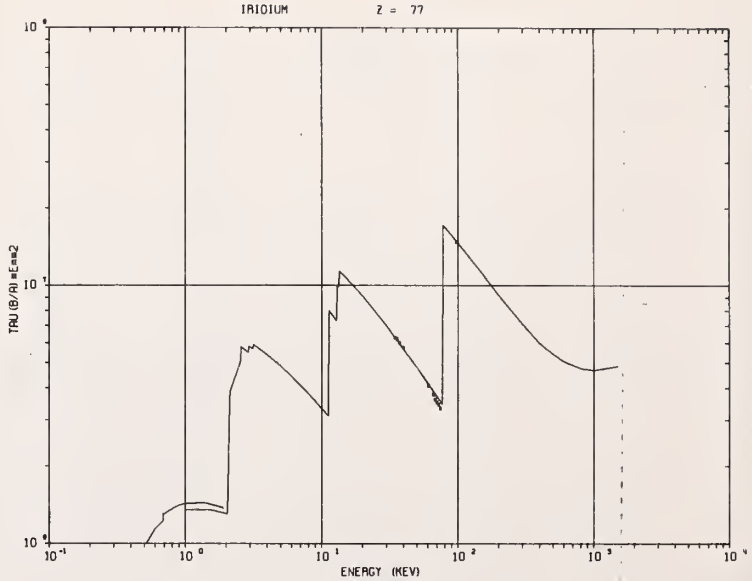


Figure 78

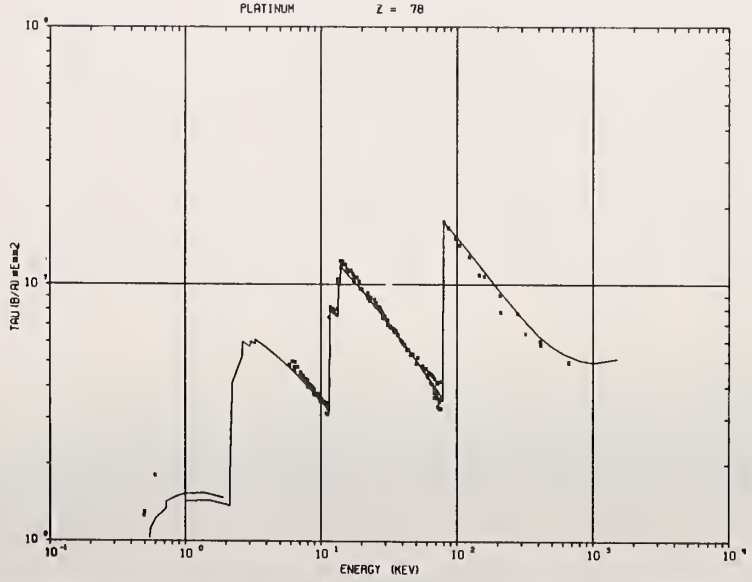


Figure 79

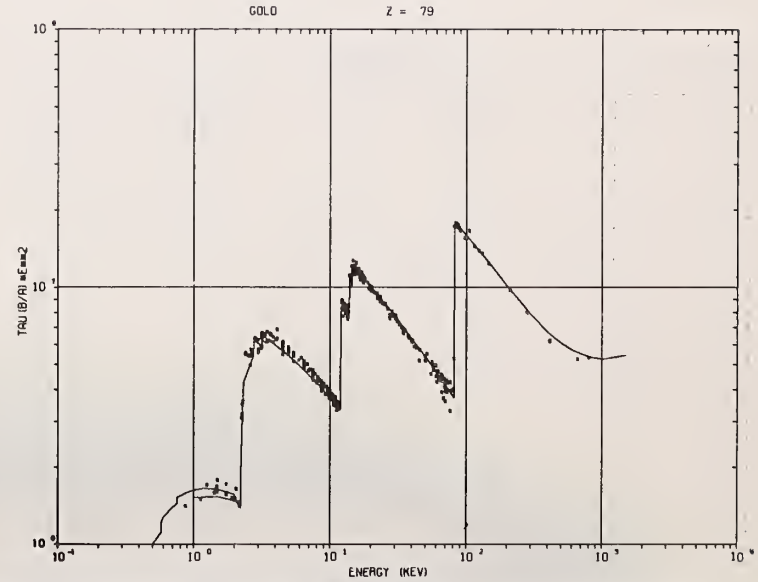


Figure 80

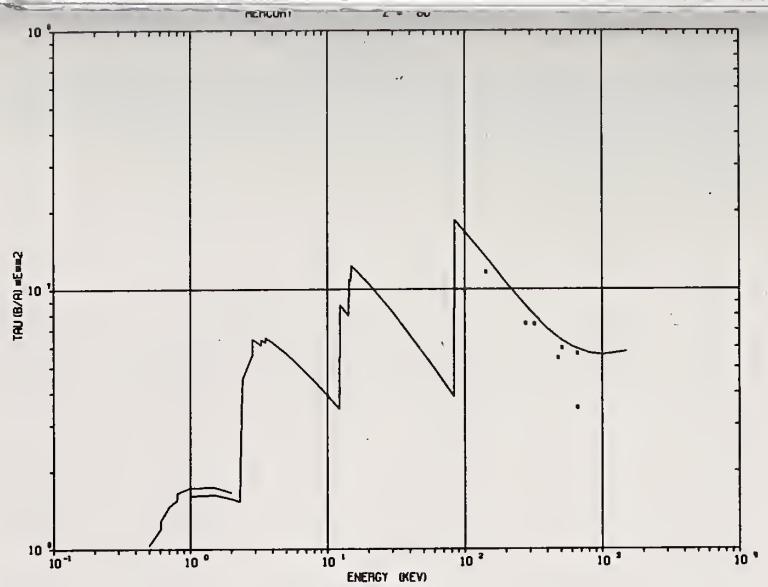


Figure 81

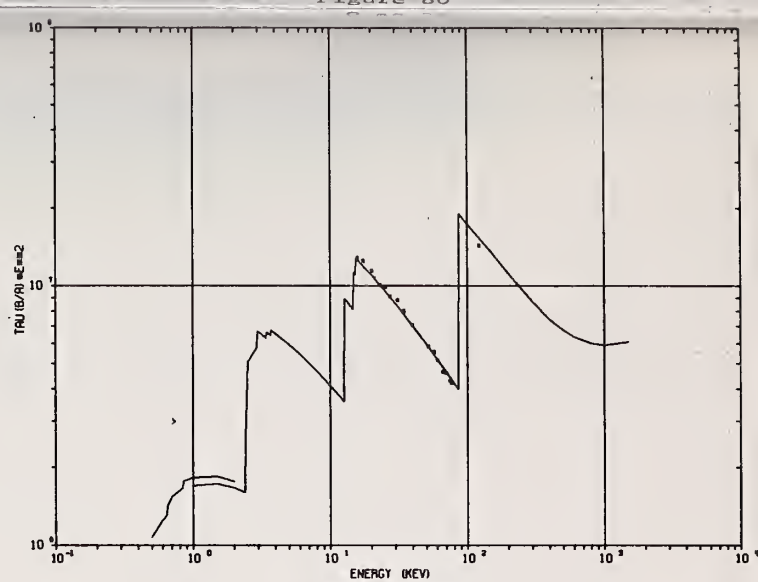


Figure 82

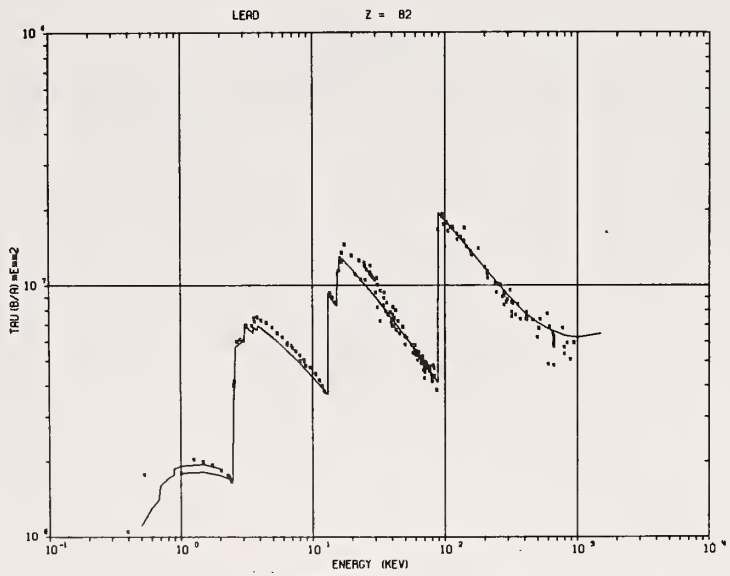


Figure 83

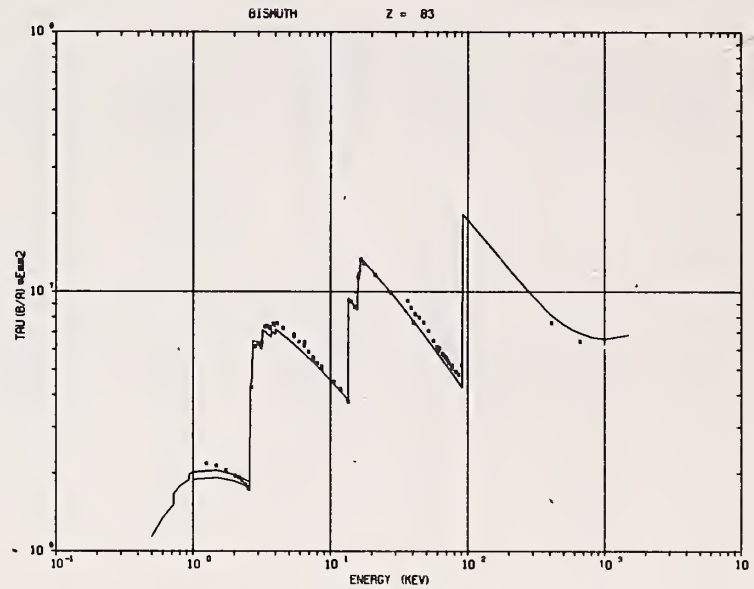


Figure 84

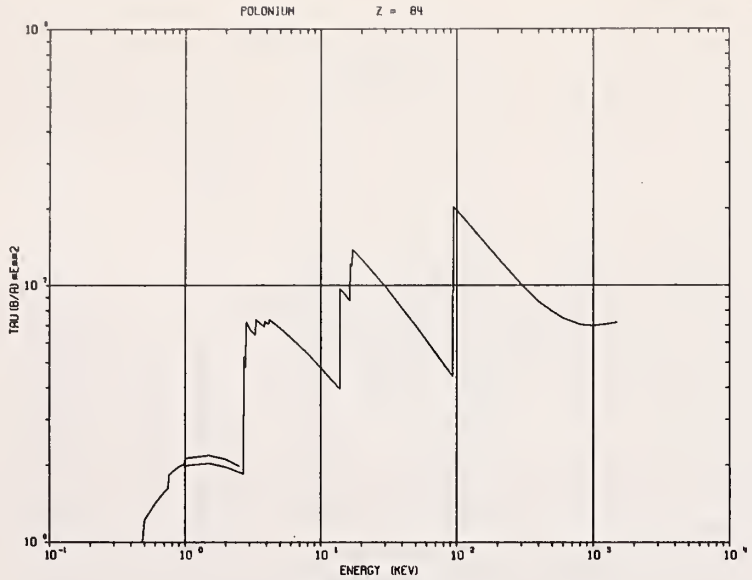


Figure 85

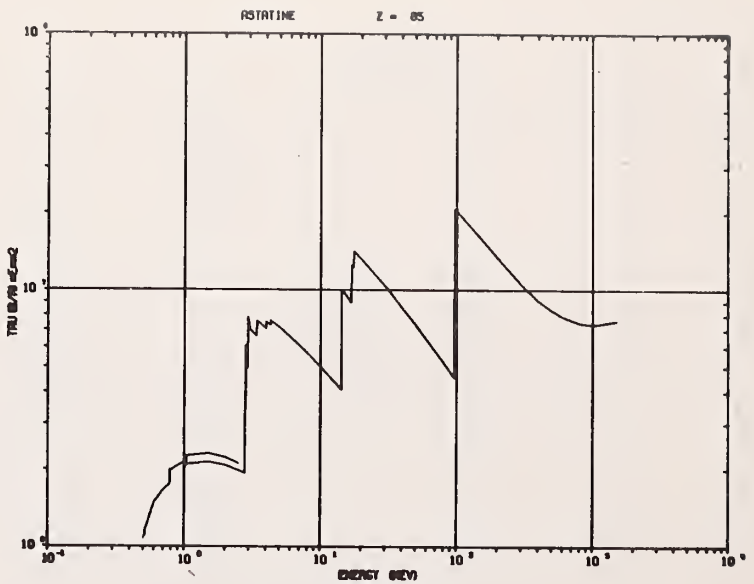


Figure 86

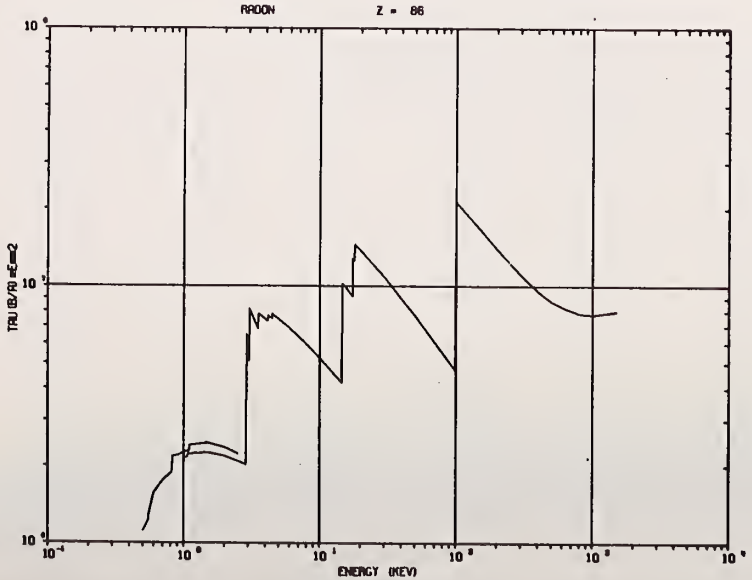


Figure 87

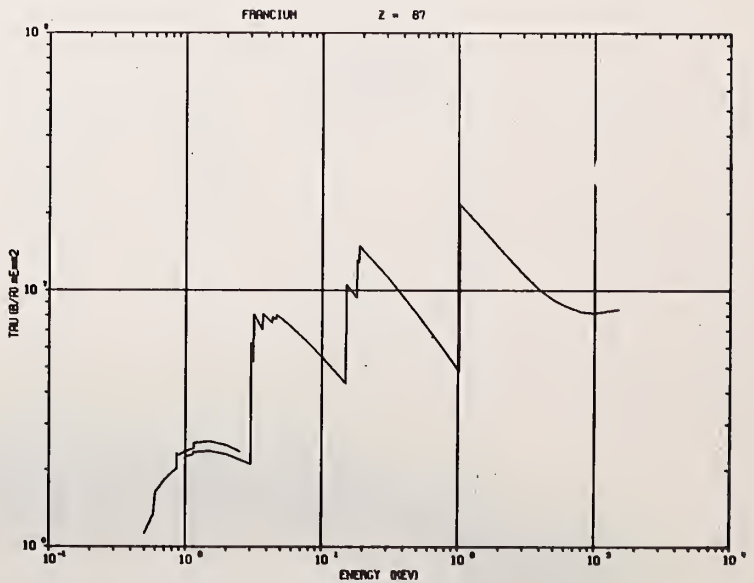


Figure 88

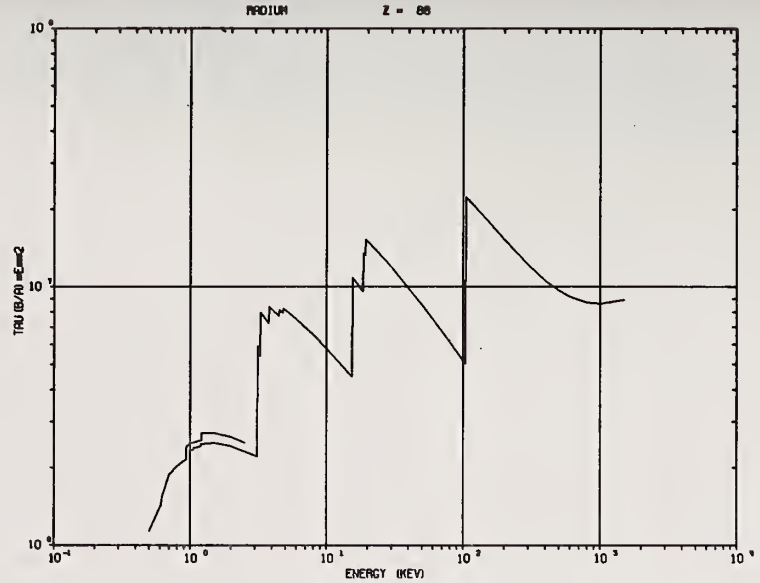


Figure 89

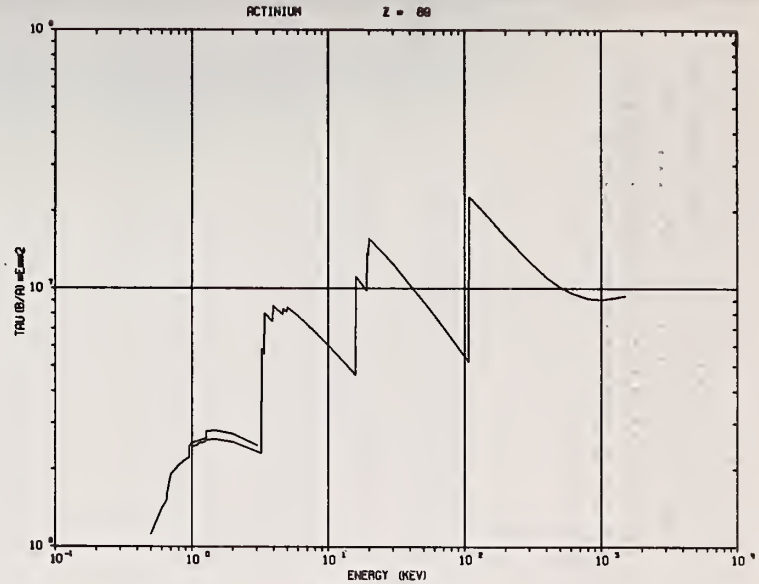


Figure 90

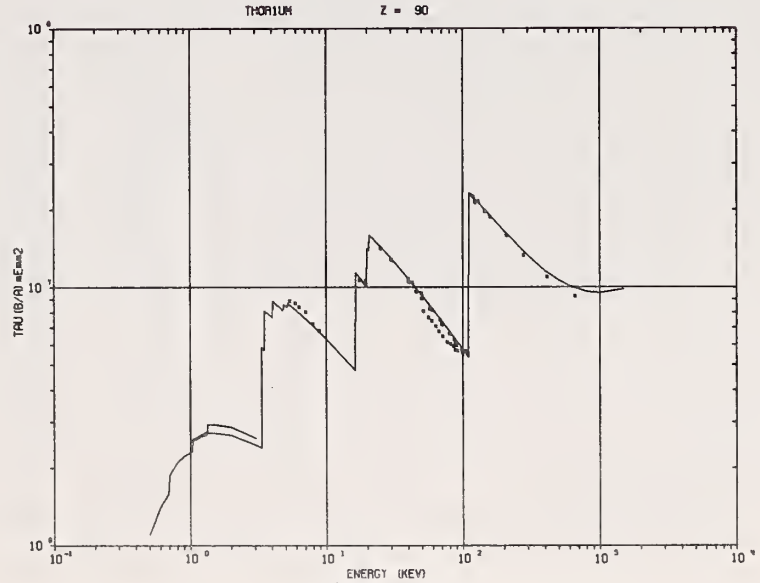


Figure 91

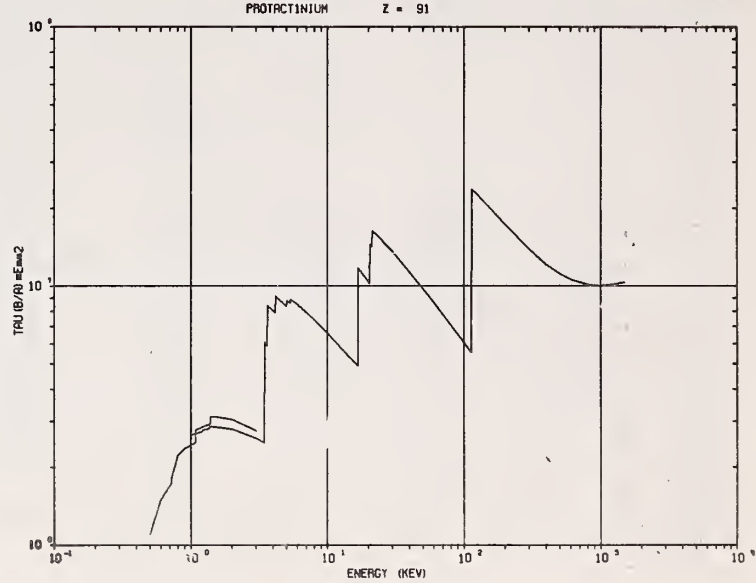


Figure 92

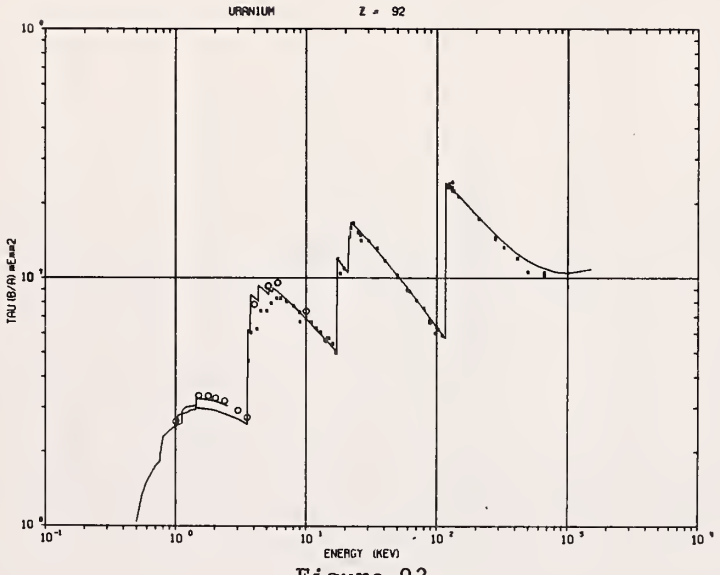


Figure 93

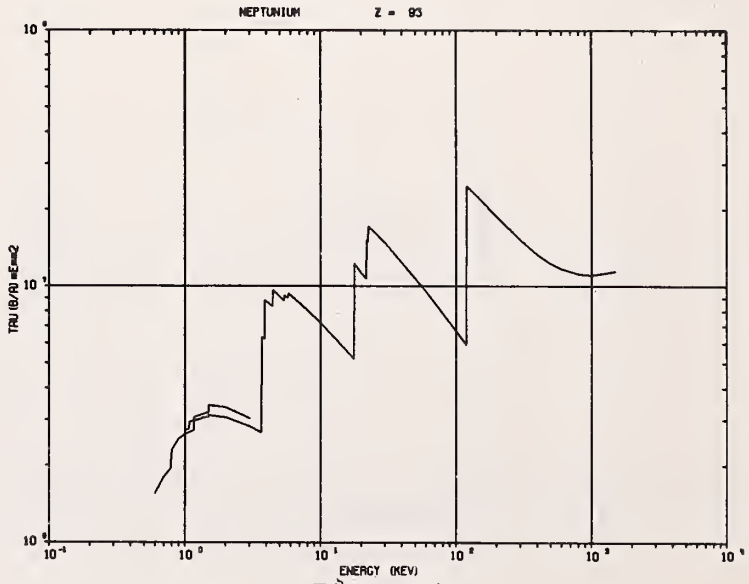
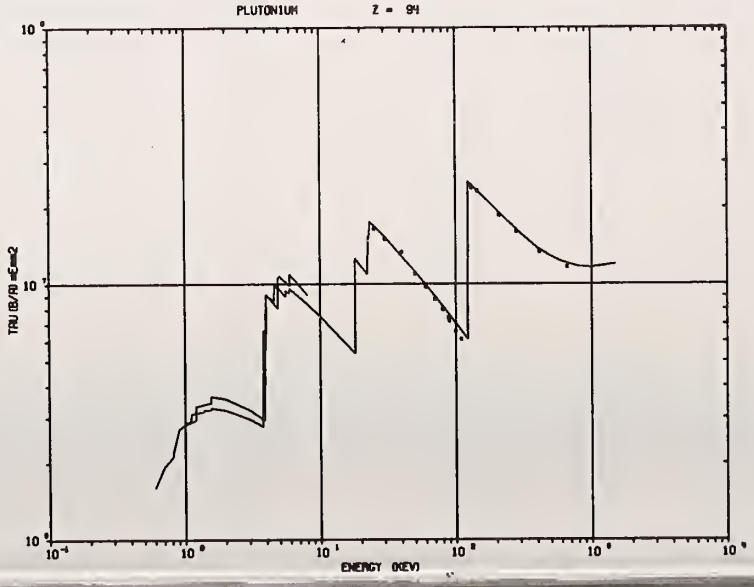


Figure 94



NBS-114A (REV. 7-73)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET	1. PUBLICATION OR REPORT NO. NBS TN-901	2. Gov't Accession No.	3. Recipient's Accession No.

4. TITLE AND SUBTITLE

Comparison of Theoretical and Experimental Photoeffect Data 0.1 keV to 1.5 MeV

5. Publication Date April 1976

6. Performing Organization Code

7. AUTHOR(S)

J. H. Hubbell and Wm. J. Veigele

8. Performing Organ. Report No.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

10. Project/Task/Work Unit No. 2400105

11. Contract/Grant No.

12. Sponsoring Organization Name and Complete Address *(Street, City, State, ZIP)*

NBS Office of Standard Reference Data
Washington, D. C. 20234
The Defense Nuclear Agency, Washington, D. C. 20305

13. Type of Report & Period Covered

14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Graphs of calculated and experimental atomic photoeffect cross sections as a function of photon energy 0.1 keV to 1.5 MeV are presented for all elements Z = 1 to 94. The calculated results presented are (a) the non-relativistic Hartree-Fock self-consistent-field (SCF) results of Veigele, Henry, et al., over the range 0.1 keV to between 1.0 and 8.0 keV for all elements Z = 1 to 94 and (b) the relativistic Hartree-Slater SCF results of Scofield over the range 1.0 keV to 1.5 MeV for all elements Z = 1 to 101. The "experimental" data-points are derived by subtracting theoretical scattering cross sections from total attenuation coefficient measurements in the literature. Differences between theoretical and experimental photoeffect data are typically a factor of two from 0.1 to 1.0 keV, 5-10% from 1.0 to 5.0 keV and 1-5% from 5.0 keV up to energies, ranging from 20 keV for carbon up to 500 keV for lead, above which the photoeffect cross section becomes fractionally too small to be accurately determined from the total attenuation coefficient.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Attenuation coefficients; cross sections; gamma rays; photoelectric effect; photons; x-rays.

18. AVAILABILITY [X] Unlimited

[ ] For Official Distribution. Do Not Release to NTIS

[ ] Order From Sup. of Doc., U.S. Government Printing Office Washington, D.C. 20402,

[ ] Order From National Technical Information Service (NTIS) Springfield, Virginia 22151

19. SECURITY CLASS (THIS REPORT) UNCLASSIFIED

21. NO. OF PAGES 43

20. SECURITY CLASS (THIS PAGE) UNCLASSIFIED

22. Price

USCOMM-DC 29042-P74

☆ U.S. GOVERNMENT PRINTING OFFICE: 1976— 210-801/206

NBS TECHNICAL PUBLICATIONS

PERIODICALS

JOURNAL OF RESEARCH reports National Bureau of Standards research and development in physics, mathematics, and chemistry. It is published in two sections, available separately:

• **Physics and Chemistry (Section A)**

Papers of interest primarily to scientists working in these fields. This section covers a broad range of physical and chemical research, with major emphasis on standards of physical measurement, fundamental constants, and properties of matter. Issued six times a year. Annual subscription: Domestic, $17.00; Foreign, $21.25.

• **Mathematical Sciences (Section B)**

Studies and compilations designed mainly for the mathematician and theoretical physicist. Topics in mathematical statistics, theory of experiment design, numerical analysis, theoretical physics and chemistry, logical design and programming of computers and computer systems. Short numerical tables. Issued quarterly. Annual subscription: Domestic, $9.00; Foreign, $11.25.

DIMENSIONS/NBS (formerly Technical News Bulletin)—This monthly magazine is published to inform scientists, engineers, businessmen, industry, teachers, students, and consumers of the latest advances in science and technology, with primary emphasis on the work at NBS. The magazine highlights and reviews such issues as energy research, fire protection, building technology, metric conversion, pollution abatement, health and safety, and consumer product performance. In addition, it reports the results of Bureau programs in measurement standards and techniques, properties of matter and materials, engineering standards and services, instrumentation, and automatic data processing.

Annual subscription: Domestic, $9.45; Foreign, $11.85.

NONPERIODICALS

Monographs—Major contributions to the technical literature on various subjects related to the Bureau's scientific and technical activities.

Handbooks—Recommended codes of engineering and industrial practice (including safety codes) developed in cooperation with interested industries, professional organizations, and regulatory bodies.

Special Publications—Include proceedings of conferences sponsored by NBS, NBS annual reports, and other special publications appropriate to this grouping such as wall charts, pocket cards, and bibliographies.

Applied Mathematics Series—Mathematical tables, manuals, and studies of special interest to physicists, engineers, chemists, biologists, mathematicians, computer programmers, and others engaged in scientific and technical work.

National Standard Reference Data Series—Provides quantitative data on the physical and chemical properties of materials, compiled from the world's literature and critically evaluated. Developed under a world-wide program coordinated by NBS. Program under authority of National Standard Data Act (Public Law 90-396).

NOTE: At present the principal publication outlet for these data is the Journal of Physical and Chemical Reference Data (JPCRD) published quarterly for NBS by the American Chemical Society (ACS) and the American Institute of Physics (AIP). Subscriptions, reprints, and supplements available from ACS, 1155 Sixteenth St. N. W., Wash. D. C. 20056.

Building Science Series—Disseminates technical information developed at the Bureau on building materials, components, systems, and whole structures. The series presents research results, test methods, and performance criteria related to the structural and environmental functions and the durability and safety characteristics of building elements and systems.

Technical Notes—Studies or reports which are complete in themselves but restrictive in their treatment of a subject. Analogous to monographs but not so comprehensive in scope or definitive in treatment of the subject area. Often serve as a vehicle for final reports of work performed at NBS under the sponsorship of other government agencies.

Voluntary Product Standards—Developed under procedures published by the Department of Commerce in Part 10, Title 15, of the Code of Federal Regulations. The purpose of the standards is to establish nationally recognized requirements for products, and to provide all concerned interests with a basis for common understanding of the characteristics of the products. NBS administers this program as a supplement to the activities of the private sector standardizing organizations.

Federal Information Processing Standards Publications (FIPS PUBS)—Publications in this series collectively constitute the Federal Information Processing Standards Register. Register serves as the official source of information in the Federal Government regarding standards issued by NBS pursuant to the Federal Property and Administrative Services Act of 1949 as amended, Public Law 89-306 (79 Stat. 1127), and as implemented by Executive Order 11717 (38 FR 12315, dated May 11, 1973) and Part 6 of Title 15 CFR (Code of Federal Regulations).

Consumer Information Series—Practical information, based on NBS research and experience, covering areas of interest to the consumer. Easily understandable language and illustrations provide useful background knowledge for shopping in today's technological marketplace.

NBS Interagency Reports (NBSIR)—A special series of interim or final reports on work performed by NBS for outside sponsors (both government and non-government). In general, initial distribution is handled by the sponsor; public distribution is by the National Technical Information Service (Springfield, Va. 22161) in paper copy or microfiche form.

Order NBS publications (except NBSIR's and Bibliographic Subscription Services) from: Superintendent of Documents, Government Printing Office, Washington, D.C. 20402.

BIBLIOGRAPHIC SUBSCRIPTION SERVICES

The following current-awareness and literature-survey bibliographies are issued periodically by the Bureau:

Cryogenic Data Center Current Awareness Service

A literature survey issued biweekly. Annual subscription: Domestic, $20.00; foreign, $25.00.

Liquefied Natural Gas. A literature survey issued quarterly. Annual subscription: $20.00.

Superconducting Devices and Materials. A literature survey issued quarterly. Annual subscription: $20.00. Send subscription orders and remittances for the preceding bibliographic services to National Bureau of Standards, Cryogenic Data Center (275.02) Boulder, Colorado 80302.

Electromagnetic Metrology Current Awareness Service Issued monthly. Annual subscription: $24.00. Send subscription order and remittance to Electromagnetics Division, National Bureau of Standards, Boulder, Colo. 80302.

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Washington, D.C. 20234

OFFICIAL BUSINESS

Penalty for Private Use, $300

POSTAGE AND FEES PAID
U.S. DEPARTMENT OF COMMERCE
COM-215

U.S.MAIL

SPECIAL FOURTH-CLASS RATE
BOOK