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Informal Report

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Hydrogen Scattering Cross Section, $^1H(n,n)\,^1H$

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by

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ABSTRACT

The status of the hydrogen scattering cross section is reviewed with particular emphasis on standards applications. The ENDF/B-V evaluation is described in detail and compared with experimental data.

I. DESCRIPTION

The hydrogen scattering cross section is the only standard which presently satisfies acceptable criteria for standards applications above 100 keV. That is, it has no structure and is known with sufficient accuracy to be used as a reference cross section. This cross section is highly recommended for the range from a few keV to 20 MeV and, when used in conjunction with a 1/v cross section up to a few keV, the energy range for applied programs can be well covered. The total cross section is often referred to as "the standard". This is not the case, since the total cross section can only be used to check the integral of the elastic scattering angular distributions.

The recoil proton is usually the detected particle. If used in a proton-telescope arrangement, some kind of radiator is employed whose thinkness limits the recoil-proton range (and therefore the neutron energy to be investigated). Whenever a telescope is used, the angular distribution of the protons becomes the dominant factor in setting the accuracy to be associated with the use of this standard. This is particularly important when the observed solid angle is small.

II. STATUS

The total cross section for hydrogen is essentially equal to the elastic scattering integral above a few hundred eV. The total cross section is well known, but the angular distributions of the neutrons (and recoil protons) are not well determined experimentally on an absolute scale at any incident neutron energy up to 20 MeV.

The ^{1}H evaluation for ENDF/B-V (MAT 1301) is basically the same as Version III and Version IV, except for the changes in interpolation rules and the addition of correlated error data in MF=33. This evaluation is well documented in LA-4574-MS (1971), LA-6518-MS (1976), and LA-7663-MS (1979).

A. General Description of ENDF/B-V

For an extensive summary of the status of the hydrogen cross section including historic advances, see the report to the INDC by C. A. Uttley.[1] The only comment which requires updating in that report refers to a lower 180° cross section between 23 and 29 MeV reported by Drosg.[2] Actually, Drosg's data were "inferred" rather than "measured" and were later found to be in reasonable agreement with the Hopkins-Breit analysis.

Since the ENDF file has been highly recommended for international use since 1972 and Uttley finds the Hopkins-Breit analysis gives excellent shape agreement with a recent Harwell angular distribution measurement at 27.3 MeV[3] when combined with the Wisconsin results,[4] only the ENDF evaluations are compared in the following sections.

The theoretical analysis of fast-neutron measurements by Hopkins and Breit[5] was used to generate the scattering cross section and angular distributions of the neutrons for the ENDF/B-V file.[6] The code and the Yale phase shifts[7] were obtained from Hopkins[8] in order to obtain the data on a fine-energy grid. Pointwise angular distributions were produced to improve the precision over that obtained from the published Legendre coefficients.* The phase shifts were also used to extend the energy range down below 200 keV as represented in the original paper.[5]

*For E_n = 30 MeV, the difference in the 180° cross section is ~1% as calculated from the Legendre coefficients[5] compared to that calculated from the phase shifts.

At 100 eV, the elastic cross section calculated from the phase shifts is 20.449 barns, in excellent agreement with the thermal value of 20.442 ± 0.023 barns derived by Davis and Barschall.[9] Therefore, for the present evaluation, the free-atom scattering cross section is assumed to be constant below 100 eV and equal to the value calculated from the Yale phase shifts at 100 eV giving a thermal cross section of 20.449 b.

B. Total Cross Sections

Total cross-section measurements are compared with the evaluation in Fig. 1 for the energy range from 10 eV to 0.5 MeV. Similarly, Figs. 2 and 3 compare the evaluation with measured data from 0.5 to 20 MeV. The agreement with the earlier experiments shown in Fig. 2 is quite good over the entire energy range. The 1969 data of Schwartz[10] included in Fig. 3, however, lie slightly below the evaluation over most of the energy range even though agreement with the 1972 results of Clement[11] is quite acceptable. The Wisconsin data[12] are compared from 1.5 to 20 MeV with ENDF/B-V in Fig. 4 along with the very precise value[13] at 2.533 ± 0.003 MeV of 2.536 ± 0.0015 barns. Data from KFK and Harwell which are not shown in these figures also tend to support the ENDF curve reasonably well. At the same time, it would be useful to have a few points measured with excellent precision as further checks on the phase-shift analysis.

At this time, no attempt has been made to estimate the effect of errors on the energy scale in ENDF/B. It is clear, however, that a small energy shift would produce a large change in the cross section, especially at low energies. For example, a 50-keV shift in energy near 1 MeV would produce a change in the standard cross section of approximately 2½%. Therefore, precise determination of the incident neutron energy and the energy spread could be very important in employing hydrogen as a cross-section standard, depending upon the experimental technique.

C. Angular Distributions

Unfortunately, few absolute values of the angular dependence of the neutrons (or recoil protons) exist and even the relative measurements are often restricted to less than half of the angular range. The experiment of Oda[14] at 3.1 MeV is not atypical of the earlier distributions which, as shown in Fig. 5, does not agree with the phase-shift predictions. Near 14 MeV, the T(d,n) neutron source has been employed in many experiments to determine the angular distributions. A composite of these measurements is compared with ENDF/B-V in Fig. 6 Note that most of the experiments are in reasonable agreement on a relative scale, but 10% discrepancies frequently appear among the data sets. The measurements of Cambou[15] average more than 5% lower than the predicted curve and differences of 5% or more are occasionally apparent among the data of a single set. Figure 7 shows the measurements of Galonsky[16] at 17.9 MeV compared with the evaluation. Again, the agreement on an absolute basis is quite poor.

Elastic scattering angular distributions at 0.1, 5, 10, 20, and 30 MeV are provided in Ref. 3 as Legendre expansion coefficients. Using the Hopkins-Breit phase-shift program and the Yale phase shifts, additional and intermediate energy points were calculated for the present evaluation.[6] As shown in Figs. 4 and 5, the angular distributions are neither isotropic below 10 MeV nor symmetric about 90° above 10 MeV as assumed in earlier evaluations. In this evaluation, the angular distribution at 100 keV is assumed to be isotropic since the calculated 180°/0° ratio is very nearly unity, that is, 1.0011. At 500 keV, this ratio approaches 1.005. Therefore, the pointwise normalized probabilities as a function of the center-of-mass scattering angle are provided at the following energies: 10^{-5} eV (isotropic), 100 keV (isotropic), 500 keV, and at 1-MeV intervals from 1 to 20 MeV.

Certainly the Hopkins-Breit phase shifts reproduce reasonably well the measured angular distributions near 14 MeV. It is important, however, that experiments be made at two or three energies which would, hopefully, further corroborate this analysis. Near 14 MeV, the energy-dependent total cross section is presently assumed to be known to ~1% and the angular distribution to 2-3%. At lower energies where the angular distributions approach isotropy, the error estimate on the angular distribution is less than 1%.

III. CONCLUSIONS AND RECOMMENDATIONS

A. Measurements

1. Precision total cross section measurements are needed at a few energies. (Experiments are currently under way by W. P. Poenitz, ANL).
2. Angular distributions on an absolute basis are needed at a few energies. This experiment should be performed near 14 MeV using T(D,n) or D(t,n) neutrons when the associated alpha particle will provide the absolute flux monitor. Other energy points would also be useful.

B. Evaluations

Several years have passed since the Hopkins-Breit phase-shift analysis was performed. Recent phase-shift analyses carried out by Bohannon et al.[57] in 1976 and by Arndt et al.[58] in 1977 agree reasonably well with each other and with Hopkins-Breit and the LLL constrained set. These analyses emphasize the need for precise angular distribution measurements which cover a wide angular range in order to improve the precision obtainable for the value of $\delta(^1P_1)$.

It is very doubtful whether a new phase-shift analysis using the existing relative angular distribution measurements would provide data with better accuracy than already quoted for the Yale phase-shift analysis. It may be worthwhile, however, to perform a simultaneous charge-independent analysis of the n-p and p-p systems since p-p experimental data cover a wide energy range and the charged-particle measurements have very small associated errors.

C. Standard's Use

It should be pointed out that errors involved in using hydrogen as a standard depend upon the experimental techniques employed and therefore may be significantly larger than the errors placed on the standard cross section itself. The elastic angular distribution measurements of neutrons scattered by hydrogen, which are available today, seem to indicate that $\sigma(\theta)$ is difficult to measure with the precision ascribed to the reference standard. If this is the case, then the magnitude of the errors in the $\sigma(\theta)$ measurements might be indicative of error assignments which should be made on hydrogen flux monitors. That is, it is difficult to assume that hydrogen scattering can be implemented as a standard with much higher precision than it can be measured. Even though better agreement with many past measurements can be reached by renormalizing the absolute scales, such action may not always be warranted.

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REFERENCES

1. C. A. Uttley, A.E.R.E., Harwell (1977), contribution to INDC Standards.

2. M. Drosg, "180° n-p Cross Sections for Counter Telescopes in Fast Neutron Work," Proc. Intrn. Conf. on the Interactions of Neutrons with Nuclei, Lowell (1976) Vol. 11, p. 1383, CONF-760715-P2, and private communication.

3. J. A. Cookson, J. L. Fowler, M. Hussain, R. B. Schwartz, and C. A. Uttley, Angular Distribution of Neutron Scattering From Hydrogen at 27.3 MeV," Nucl. Phys. A299, 365 (1978).

4. T. W. Burrows, "Angular Distribution of 24.0- and 27.2-MeV Neutrons Scattered by Protons," Phys. Rev. C7, 1306 (1973).

5. J. C. Hopkins and G. Breit, "The H(n,n)H Scattering Observables Required for High Precision Fast-Neutron Measurements," Nuclear Data A9, 137 (1971) and private communication prior to publication (1970).

6. L. Stewart, R. J. LaBauve, and P. G. Young, "Evaluated Nuclear Data for Hydrogen in the ENDF/B-II Format," LA-4574 (1971). Neither the cross sections nor the angular distributions have been changed since Version II except to add one more significant figure to the total cross section.

7. R. E. Seamon, K. A. Friedman, G. Breit, R. D. Haracz, J. M. Holt, and A. Prakash, Phys. Rev. 165, 1579 (1968).

8. J. C. Hopkins, private communication to L. Stewart (1970).

9. J. C. Davis and H. H. Barschall, "Adjustment in the n-p Singlet Effective Range," Phys. Lett. 27B, 636 (1968).

10. R. B. Schwartz, R. A. Schrack, and H. T. Heaton, "A Search for Structure in the n-p Scattering Cross Section," Phys. Lett. 30, 36 (1969).

11. J. M. Clement, P. Stoler, C. A. Goulding, and R. W. Fairchild, "Hydrogen and Deuterium Total Neutron Cross Sections in the MeV Region," Nucl. Phys. A183, 51 (1972).

12. J. C. Davis and H. H. Barschall, "Fast-Neutron Total Cross Section of Deuterium," Phys. Rev. C3, 1978 (1971).

13. J. C. Davis, K. A. Weaver, D. Hilscher, H. H. Barschall, and A. B. Smith, "Total Cross Section of Protons for 2.5 MeV Neutrons," Phys. Rev. C4 1061 (1971).

14. Y. Oda, J. Sanada, and S. Yamabe, "On the Angular Distribution of 3.1-MeV Neutrons Scattered by Protons," Phys. Rev. 80, 469 (1950).

15. F. Cambou, "Amelioratin des Methods de Spectrometrie des Neutrons Rapids," Thesis - U. of Paris, CEA-N-2002 (1961).

16. A. Galonsky and J. P. Judish, "Angular Distribution of n-p Scattering at 17.9 MeV," Phys. Rev. 100, 121 (1955).

17. "ENDF/B Summary Documentation," ENDF-201, Compiled by D. Garber, (October 1975).

18. E. Melkonian, "Slow Neutron Velocity Spectrometer Studies of O_2, N_2, A, H_2, H_2O, and Seven Hydrocarbons," Phys. Rev. 76, 1950 (1949).

19. D. H. Frisch, "The Total Cross Sections of Carbon and Hydrogen for Neutrons of Energies from 35 to 490 keV," Phys. Rev. 70, 589 (1946).

20. W. D. Allen and A. T. G. Ferguson, "The n-p Cross Section in the Range 60-550 keV," Proc. Phys. Soc. (London) 68, 1077 (1955).

21. E. Bretscher and E. B. Martin, "Determination of the Collision Cross-Section of H, Deuterium, C and O for Fast Neutrons," Helv. Phys. Acta 23, 15 (1950).

22. C. E. Engleke, R. E. Benenson, E. Melkonian, and J. M. Lebowitz, "Precision Measurements of the n-p Total Cross Section at 0.4926 and 3.205 MeV," Phys. Rev. 129, 324 (1963).

23. C. L. Bailey, W. E. Bennett, T. Bergstralh, R. G. Nuckolls, H. T. Richards, and J. H. Williams, "The Neutron-Proton and Neutron-Carbon Scattering Cross Sections for Fast Neutrons," Phys. Rev. 70, 583 (1946).

24. E. E. Lampi, G. Frier, and J. H. Williams, "Total Cross Section of Carbon and Hydrogen for Fast Neutrons," Phys. Rev. 76, 188 (1949).

25. W. E. Good and G. Scharff-Goldhaber, "Total Cross Sections for 900-keV Neutrons," Phys. Rev. 59, 917 (1941).

26. S. Bashkin, B. Petree, F. P. Mooring, and R. E. Peterson, "Dependence of Neutron Cross Sections on Mass Number," Phys. Rev. 77, 748 (1950).

27. R. E. Fields, R. L. Becker, and R. K. Adair, "Measurement of the Neutron-Proton Cross Section at 1.0 and 2.5 MeV," Phys. Rev. 94, 389 (1954).

28. C. L. Storrs and D. H. Frisch, "Scattering of 1.32 MeV Neutrons by Protons," Phys. Rev. 95, 1252 (1954).

29. D. G. Foster, Jr. and D. W. Glasgow, "Neutron Total Cross Sections, 2.5-15 MeV, Part 1 (Experimental)," Nucl. Instr. and Methods, 36, 1 (1967).

30. R. E. Fields, "The Total Neutron-Proton Scattering Cross Section at 2.5 MeV," Phys. Rev. 89, 908 (1953).

31. G. Ambrosina and A. Sorriaux, "Total Cross Section Efficiency for Carbon, Fluorine and Vanadium," Comptes Rendus 260, 3045 (1965).

32. W. H. Zinn, S. Seely, and V. W. Cohen, "Collision Cross Sections for D-D Neutrons," Phys. Rev. 56, 260 (1939).

33. N. Nereson and S. Darden, "Average Neutron Total Cross Sections in the 3- to 12- MeV Region," Phys. Rev. 94, 1678 (1954).

34. E. M. Hafner, W. F. Hornyak, C. E. Falk, G. Snow, and T. Coor, "The Total n-p Scattering Cross Section at 4.75 MeV," Phys. Rev. 89, 204 (1953).

35. W. Sleator, Jr., "Collision Cross Sections of Carbon and Hydrogen for Fast Neutrons," Phys. Rev. 72, 207 (1947).

36. A. Bratenahl, J. M. Peterson, and J. P. Stoering, "Neutron Total Cross Sections in the 7- to 14-MeV Region," UCRL-4980 (1957).

37. A. H. Lasday, "Total Neutron Cross Sections of Several Nuclei at 14 MeV," Phys. Rev. 81, 139 (1951).

38. L. S. Goodman, "Total Cross Sections for 14-MeV Neutrons," Phys. Rev. 88, 686 (1952).

39. H. L. Poss, E. O. Salant, and L. C. L. Yuan, "Total Cross Sections of Carbon and Hydrogen for 14-MeV Neutrons," Phys. Rev. 85, 703 (1951).

40. M. Tanaka, N. Koori, and S. Shirato, "Differential Cross Sections for Neutron-Proton Scattering at 14.1 MeV," J. Phys. Soc. (Japan) 28, 11 (1970).

41. M. E. Battat, R. O. Bondelid, J. H. Coon, L. Cranberg, R. B. Day, F. Edeskuty, A. H. Frentrop, R. L. Henkel, R. L. Mills, R. A. Nobles, J. E. Perry, D. D. Phillips, T. R. Roberts, and S. G. Sydoriak," Total Neutron Cross Sections of the Hydrogen and Helium Isotopes," Nucl. Phys. 12, 291 (1959).

42. J. C. Allred, A. H. Armstrong, and L. Rosen, "The Interaction of 14-Mev Neutrons with Protons and Deuterons," Phys. Rev. 91, 90 (1953).

43. C. F. Cook and T. W. Bonner, "Scattering of Fast Neutrons in Light Nuclei," Phys. Rev. 94, 651 (1954).

44. H. L. Poss, E. O. Salant, G. A. Snow, and L. C. L. Yuan, "Total Cross Sections for 14-MeV Neutrons," Phys. Rev. 87, 11 (1952).

45. P. H. Bowen, J. P. Scanlon, G. H. Stafford, and J. J. Thresher, "Neutron Total Cross Sections in the Energy Range 15 to 120 MeV," Nucl. Phys. 22, 640 (1961).

46. J. M. Peterson, A. Bratenahl, and J. P. Stoering, "Neutron Total Cross Sections in the 17- to 29-MeV Range," Phys. Rev. 120, 521 (1960).

47. D. E. Groce and B. D. Sowerby, "Neutron-Proton Total Cross Sections Near 20, 24, and 28 MeV," Nucl. Phys. 83, 199 (1966).

48. M. L. West II, C. M. Jones, and H. B. Willard, "Total Neutron Cross Sections of Hydrogen and Carbon in the 20-30 MeV Region," ORNL-3778, 94 (1965).

49. R. B. Day, R. L. Mills, J. E. Perry, Jr., and F. Schreb, "Total Cross Section for n-p Scattering at 20 MeV," Phys. Rev. 114, 209 (1959).

50. R. B. Day and R. L. Henkel, "Neutron Total Cross Sections at 20 MeV," Phys. Rev. 92, 358 (1953).

51. M. E. Remley, W. K. Jentschke, and P. G. Kruger, "Neutron-Proton Scattering Using Organic Crystal Scintillation Detectors," Phys. Rev. 89, 1194 (1953).

52. J. D. Seagrave, "Recoil Deuterons and Disintegration Protons from the n-d Interaction, and n-p Scattering at E_n = 14.1 MeV," Phys. Rev. 97, 757 (1955).

53. S. Shirato and K. Saitoh, "On The Differential Cross Section for Neutron-Proton Scattering at 14.1 MeV," J. Phys. Soc. (Japan) 36, 331 (1974).

54. T. Nakamura, "Angular Distribution of n-p Scattering at 14.1 MeV," J. Phys. Soc. (Japan) 15, 1359 (1960).

55. A. Suhami and R. Fox, "Neutron-Proton Small Angle Scattering at 14.1 MeV," Phys. Lett. 24, 173 (1967).

56. I. Basar, "Elastic Scattering of 14.4 MeV Neutrons on Hydrogen Isotopes," Few Body Problems Light Nuclei/Nucl. Interactions, Brela, 867 (1967).

57. G. E. Bohannon, T. Burt, and P. Signell, "Phase-Shift Analysis of the 20-30-MeV pp and np Scattering Data, Including New High-Precision np P(θ) Measurements," Phys. Rev. C13, 1816 (1976).

58. R. A. Arndt, R. H. Hackman, and L. D. Roper, "Nucleon-Nucleon Scattering Analyses, II. Neutron-Proton Scattering From 0 to 425 MeV and Proton-Proton Scattering From 1 to 500 Mev," Phys. Rev. C15, 1002 (1977).

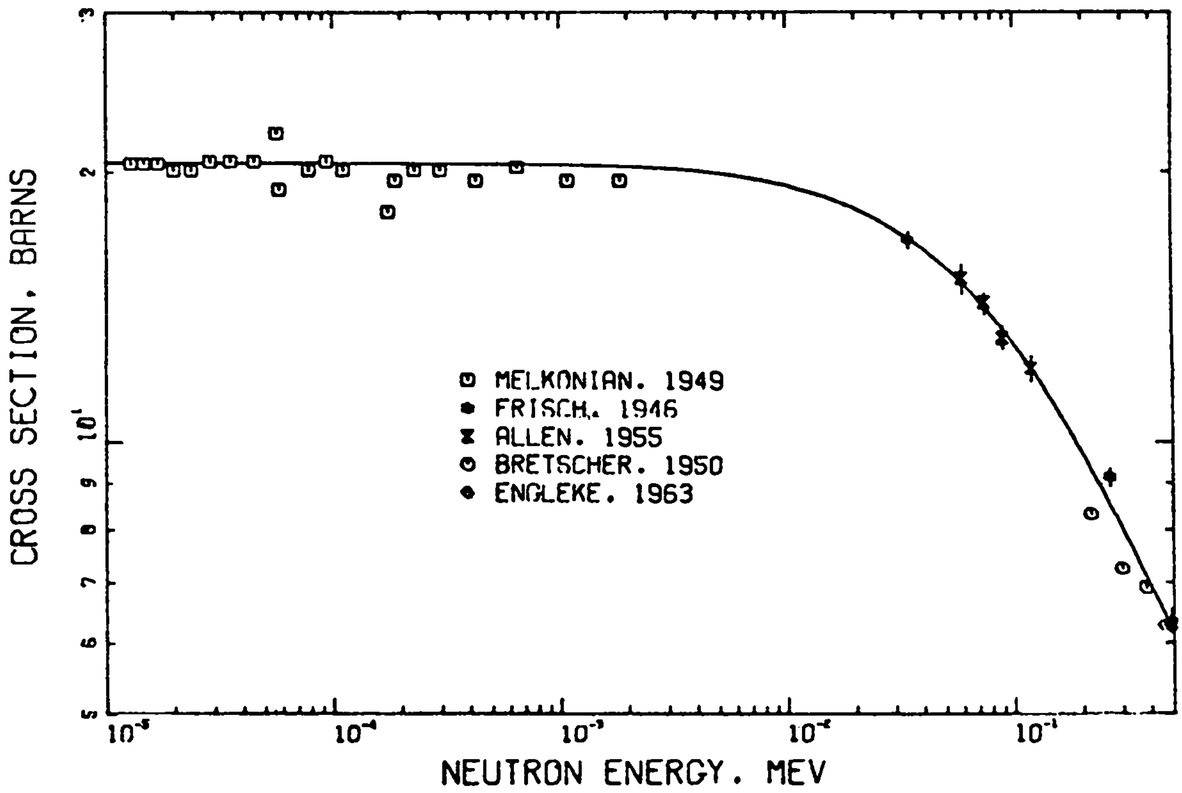

Fig. 1.
Total cross section for hydrogen from 1 x 10^{-5} eV to 500 keV. The ENDF/B-V evaluation is compared to the measurements of Refs. 18-22.

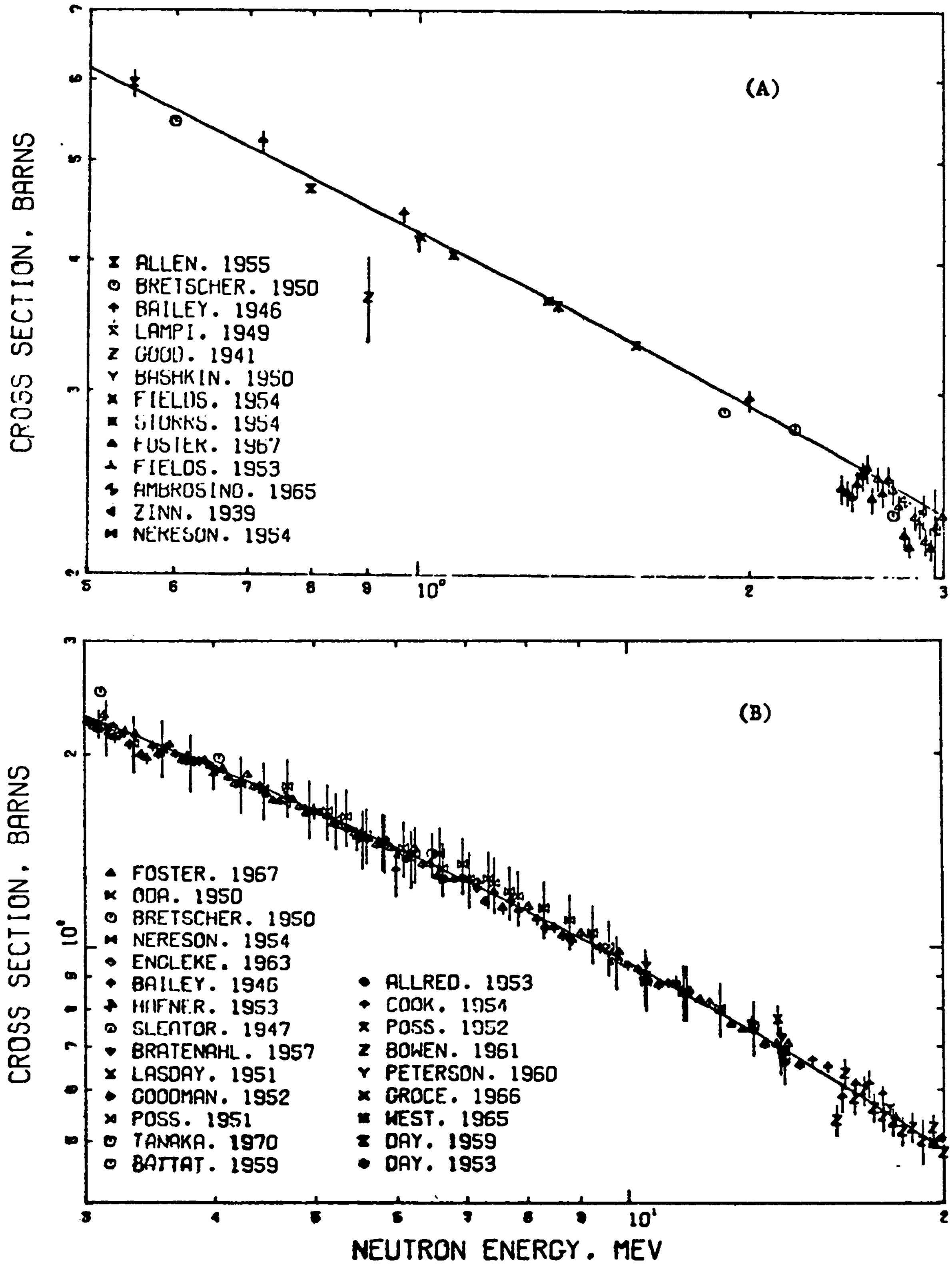

Fig. 2.
Total cross section for hydrogen from 500 keV to 20 MeV. The ENDF/B-V evaluation is compared to measurements reported in Refs. 14, 20-50.

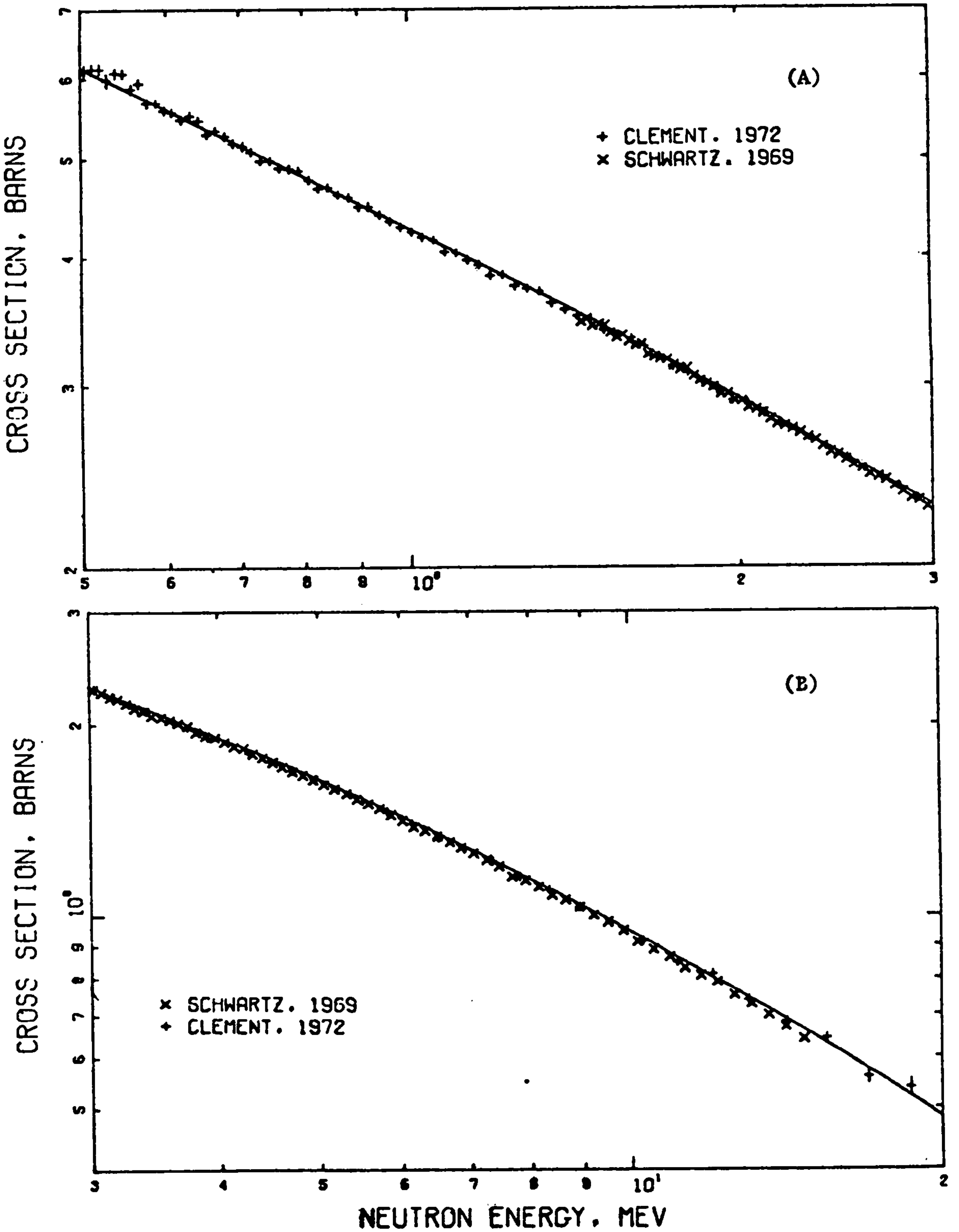

Fig. 3.
Total cross section for hydrogen from 500 keV to 20 MeV. The ENDF/B-V evaluation is compared to measurements reported in Refs. 10 and 11.

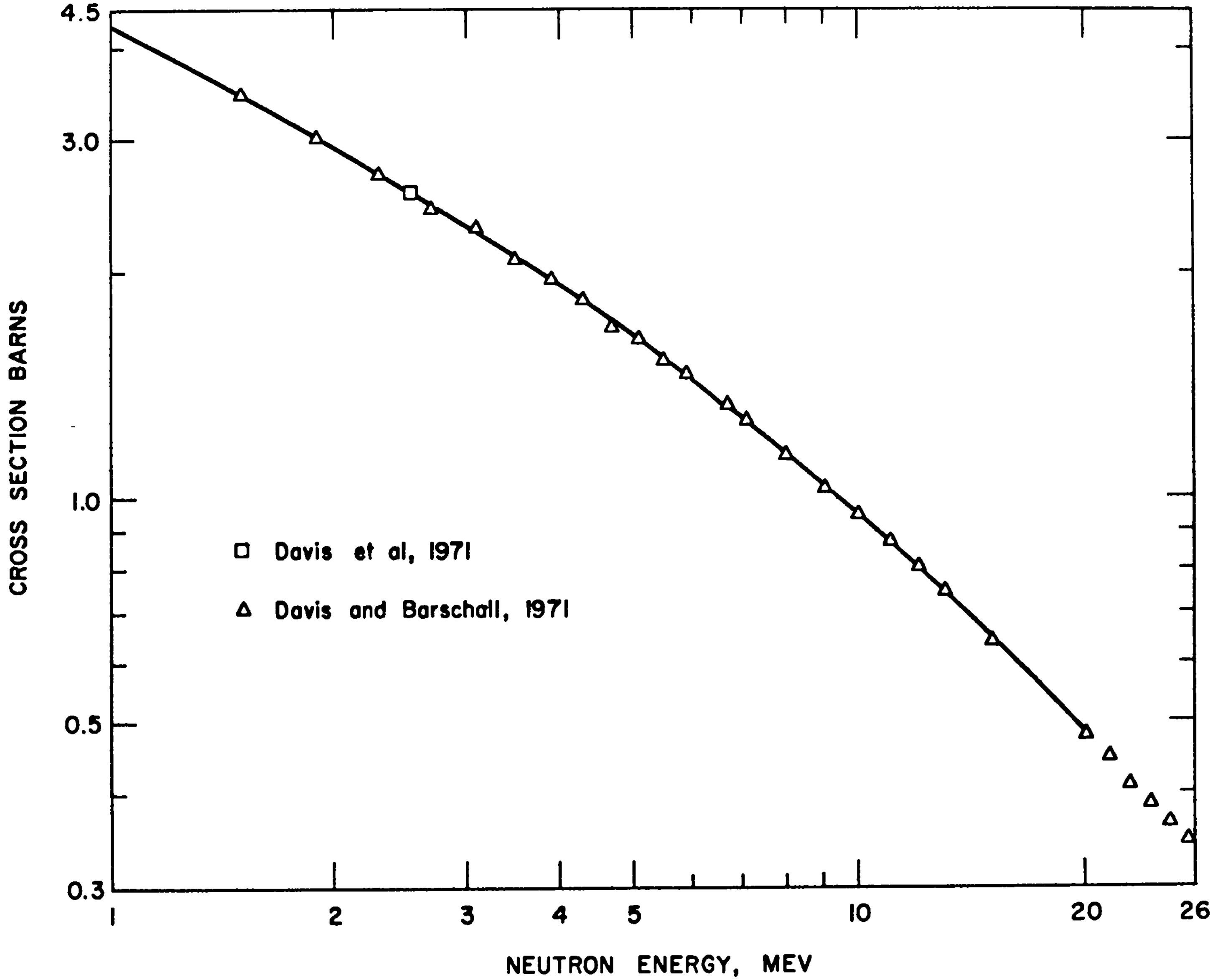

Fig. 4.

Total cross section for hydrogen from 1 to 26 MeV. The ENDF/B-V evaluation is compared to the Wisconsin measurements of Refs. 12 and 13. (Note that the symbols are larger than the experimental errors on these very precise measurements).

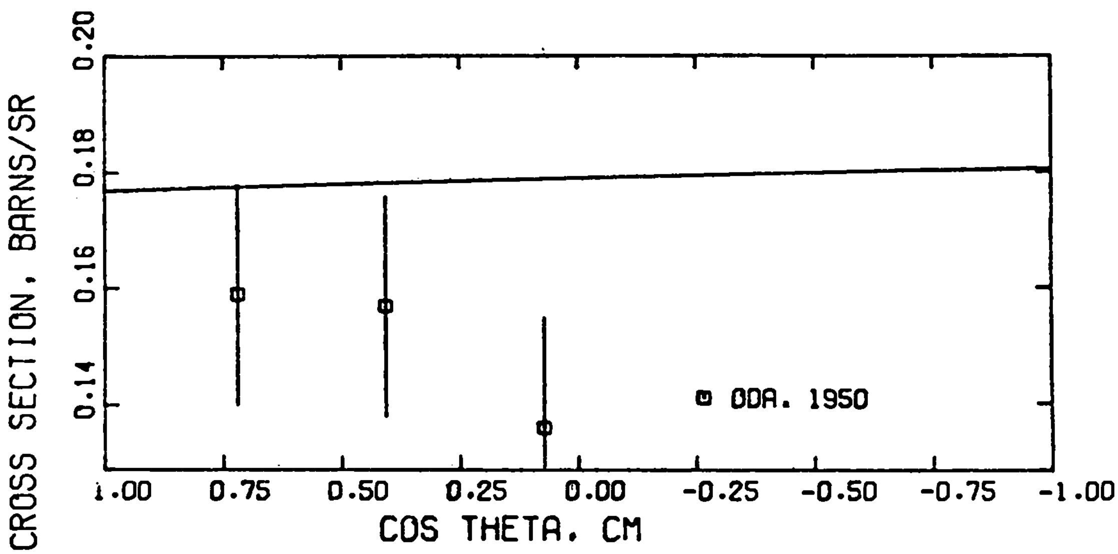

Fig. 5.
Angular distribution of the neutrons elastically scattered from hydrogen at 3.1 MeV. ENDF/B-V is compared with the experimental values of Oda.[14]

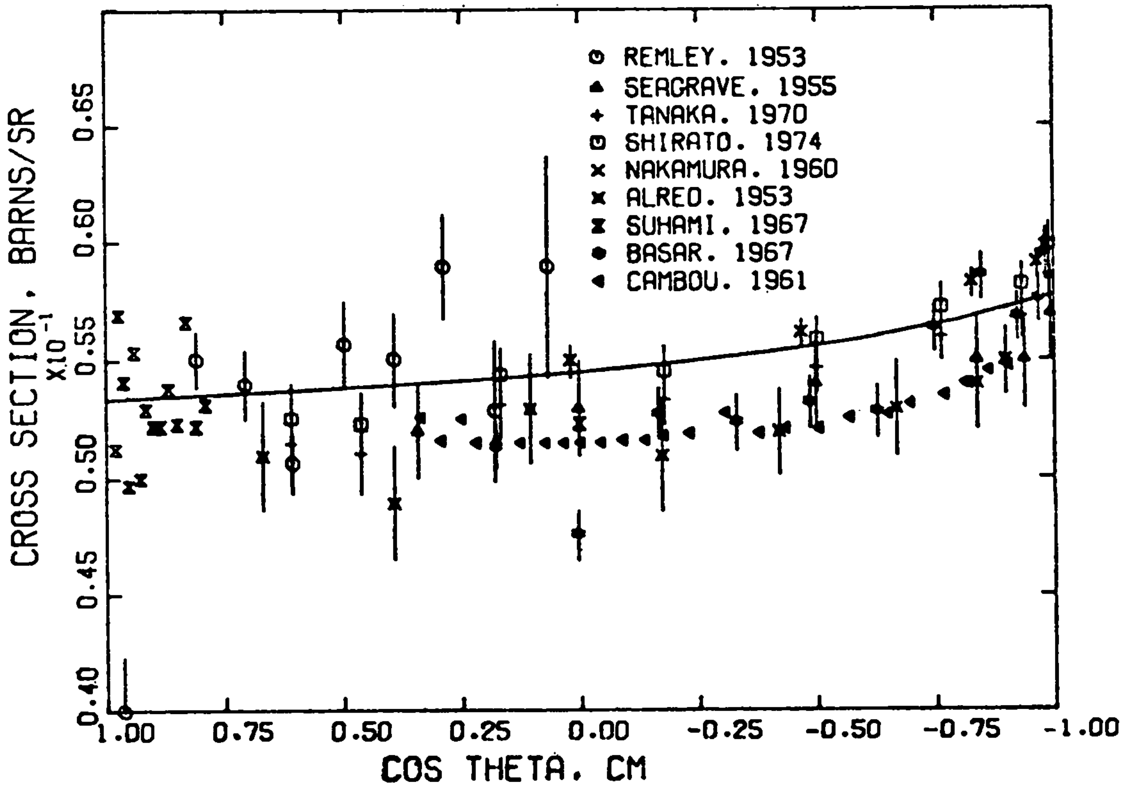

Fig. 6.
Angular distribution of the neutrons elastically scattered from hydrogen at energies near 14 MeV. The experimental data shown were reported in Refs. 15, 40, 42 and 51-56.

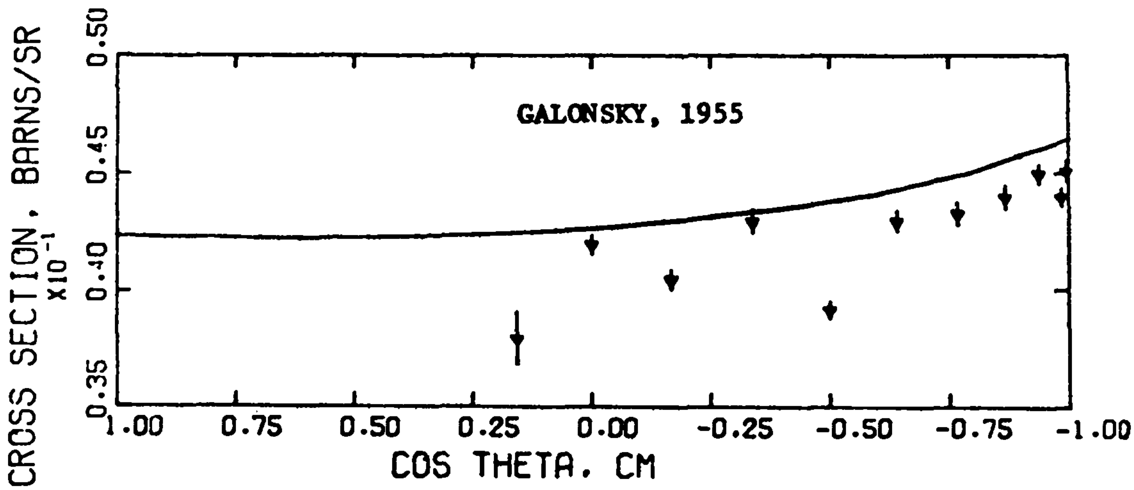

Fig. 7.
Angular distribution of the neutrons elastically scattered from hydrogen at energies near 17.8 MeV. The experimental data shown were reported in Ref. 16.

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