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A REVIEW OF EVALUATED CROSS SECTION DATA FOR AIR AND GROUND CONSTITUENTS*

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ABSTRACT

During the past few years the Defense Nuclear Agency has sponsored a radiation transport program that has the goal of substantially reducing uncertainties in predictions of radiation environments. Important aspects of the program have been to provide new cross section measurements directed particularly at areas of ignorance in the data for several important materials and to maintain up-to-date cross section evaluations that fully incorporate the new experimental information. As a result, significant improvements have been made in recent years in the availability and accuracy of evaluated data for a number of materials, particularly in the area of gamma ray production.

In the present paper a review is given of the status of evaluated cross section data for common air and ground constituents including C, N, O, Al, Si, Ca, and Fe. Particular emphasis is given to the air materials and to recent improvements in gamma ray production data. Comparisons of presently available evaluated data with the results of extensive new experimental measurements are given, and summaries of estimated errors in the evaluated data are presented. The increased accuracy of cross sections for other processes, such as neutron inelastic scattering and charged-particle production, that results from the improved gamma ray data is discussed. In addition, likely future trends in the evaluated data sets for air and ground constituents are outlined.

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For the past few years the Defense Nuclear Agency (DNA) has sponsored a radiation transport program that has the goal of substantially reducing uncertainties in predictions of radiation environments. The program, which is described schematically in Fig. 1, includes coordinated measurements, calculations, and evaluations of neutron-induced cross sections, measurements of integral quantities chosen to test important aspects of evaluated data, calculation of integral epxeriments, and sensitivity studies that can be used together with error estimates by evaluators to help establish the adequacy of the data sets. When significant problems are discovered in the evaluated data, new measurements are made that are directed specifically at solving the difficulties. Particular evaluators have been made responsible for certain materials so that new information can be rapidly assimilated into the data sets and therefore into the testing apparatus. The evaluations are provided in ENDF/B format, and the distribution of the data sets is handled by the Radiation Shielding Information Center (RSIC) at Oak Ridge.

A number of materials that are of interest for EMP calculations are included in the DNA library. These include common air and ground constituents such as N, O, C, Al, Si, Ca, and Fe. Regarding the status of these materials, each has gone through at least one evaluation iteration in the loop shown in Fig. 1, and some of the materials have been through more than one iteration. There is still significant experimental input, both microscopic and integral, that is needed for several of the materials; however, substantial progress has already been made at upgrading the evaluations and providing relevant data that was previously not available. Versions of the DNA-supported evaluations for each of these materials are included in the ENDF/B(3) nuclear data library.

Because of the time limitation, it is not possible to describe even one of the evaluations in any detail, so instead I will attempt to outline some of the more important general improvements that have been made, particularly for EMP applications, and I will show a few specific examples.

A very major improvement has been the addition of evaluated gamma-ray-production data to the neutron cross section evaluations in a self-consistent fashion; that is, the neutron cross sections and the secondary gamma-ray data are evaluated together, and both are required to be consistent with the available physics information. Furthermore, the availability of comprehensive new gamma-ray-production measurements, many of which were supported by the DNA in this program, has greatly increased the quality of the evaluated data.

Figure 2 shows a comparison between such a measurement made on ^{14}N at Oak Ridge with ORELA[1] and the nitrogen evaluation[2] as it existed at that time. In this case, the gamma ray response in a NaI detector was measured at 125° for incident neutron energies between 12 and 14 MeV, and the results were unfolded to obtain the gamma ray spectrum. The evaluated data shown in Fig. 2 have been averaged over the same neutron energy group and smeared with the NaI resolution function. In that measurement, data were obtained for neutron energies between 1 and 20 MeV for both 90° and 125°.

A similar measurement[3] for ^{27}Al is shown in Fig. 3 for the neutron energy bin 12-14 MeV, together with the existing evaluated data.[4] In this case, the differences between the experiment and the evaluation are more apparent, and a revision of the evaluation that includes these data is nearly complete.

Measurements such as these shown in Figs. 2 and 3 have greatly improved the quality of evaluated gamma ray data. In the case of ^{14}N, we feel that the uncertainty in the total γ-ray production cross section at 14 MeV has been reduced from greater than 20% to about 10%, and we estimate that the average γ-ray energy is now known to within a few percent. These measurements have had the additional effect of substantially improving other parts of the data files, for example, the inelastic neutron and charged-particle production cross sections that lead to the gamma rays. In this context, a special effort has been made in recent evaluations to include charged-particle production information wherever it is known in order that local energy deposition calculations can be accurately performed. There are frequent cases where charged-particle processes occur with significant cross sections. One such example is given in Fig. 4 where the $^{14}N(n,\alpha_1)$ cross section to the 2.124-MeV state in ^{11}B is shown from 7 to 20 MeV, together with the $(n,\alpha\gamma)$ cross section for production of the 2.124-MeV gamma ray. At these energies, the (n,α) cross section for ^{14}N represents a significant source of local energy deposition. Other examples of charged particle production processes that have frequently been ignored in the past are the (n,nx) reactions where x represents one or more charged-particles. Such reactions have commonly been lumped into the inelastic neutron files in the past. The ENDF format has been modified to allow more adequate representation of these processes, and this type information is now available in many of the evaluated files.

Another important improvement in evaluated data has been made possible in recent years by the availability of very accurate total cross section measurements that utilize time-of-flight and continuous neutron sources such as electron linear accelerators. Figure 5 compares several older ^{14}N total cross section measurements[17-19] to the three time-of-flight measurements of Heaton et al.,[14] Carlson and Cerbone,[15] and Foster and Glasgow[16] which were used to derive the ENDF/B(III) curve.[2] While there is considerable difference between some of the results, the three time-of-flight measurements are in excellent agreement, better than 0.5% on the average after allowance for differences in resolution, and have substantially reduced the uncertainty in the cross section.

In order to determine the differences caused by introduction of the new air data sets, time-dependent ANISN calculations have been performed by Engle and Mynatt at Oak Ridge[20] for the transport of neutrons and secondary gamma rays in infinite homogeneous air, using both the newer ENDF/B(III) N and O evaluations and an older, commonly used multigroup set by Straker and Gritzner.[21] Figure 6 shows the neutron ionization in silicon as a function of time at a range of 500 meters for a "typical" thermonuclear source. The most significant difference that occurs is for early times, where the newer results are higher. At times past 50μs there is little difference. Figure 7 shows a similar calculation of the time-dependent gamma-ray kerma in silicon from the Engle and Mynatt report.[20] In this case more significant differences are observed. The calculations with the newer data are almost a factor of two lower at early times than those made with the Straker data. This difference is due to the fact that the γ-ray production cross section near 14 MeV is a factor of 2 lower in the newer data set. Substantial differences also occur at later times.

At least one EMP study has been made utilizing cross sections from the DNA library. These results are available in a DNA report by Sargis et al.[22] from Science Applications. The report, which is unclassified, describes several calculations of ionization rates and electric currents in air and ground resulting from a typical thermonuclear source and presents comparisons between calculations made with the newer DNA evaluations and with older ENDF/B and United Nuclear Corporation data.[23] Figure 8 shows a calculation of the total ionization rate as a function of time from a burst at 480 meters using both the older and newer data sets. The calculations are for infinite air, using the one-dimensional, time-dependent discrete ordinates code TDA. The total ionization rate computed from the newer data is substantially lower at early times than is predicted from the older evaluation, again due to the fact that the gamma-ray-production cross sections for 14 MeV neutrons are substantially lower in the newer data set. Conversely, at late times the newer data predict a higher ionization rate, which is primarily due to differences in the neutron cross sections. In the time region following the arrival of the neutron front at 9μs until about 40μs, the two data sets give similar results. In actual fact, there is some cancellation in this region between neutron-and gamma-ray-induced ionization.

Regarding future developments in the evaluated data sets, it is likely that each of the air and ground materials will go through at least one or two revisions over the next two years as more experimental information, both microscopic and integral, becomes available. However, in most cases the revisions will be less dramatic than in the past as more and more of the important problems are worked out. There is presently an effort underway to add error information to the evaluated data files, including limited correlation data both with energy and reaction type, and this information will become available approximately in the summer of 1974. This information is needed for coupling with sensitivity calculations to assess the adequacy of the data files for various applications.

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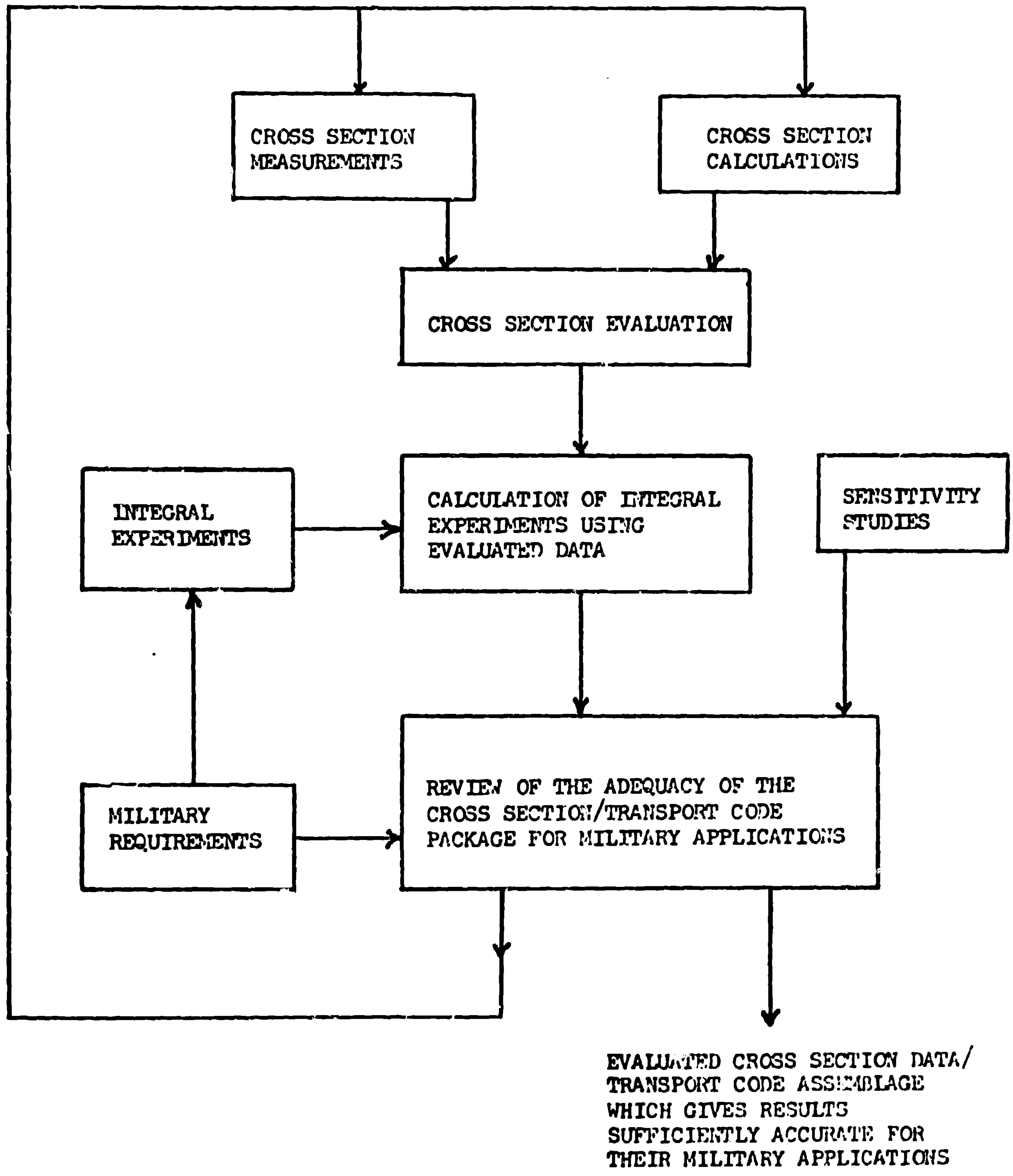

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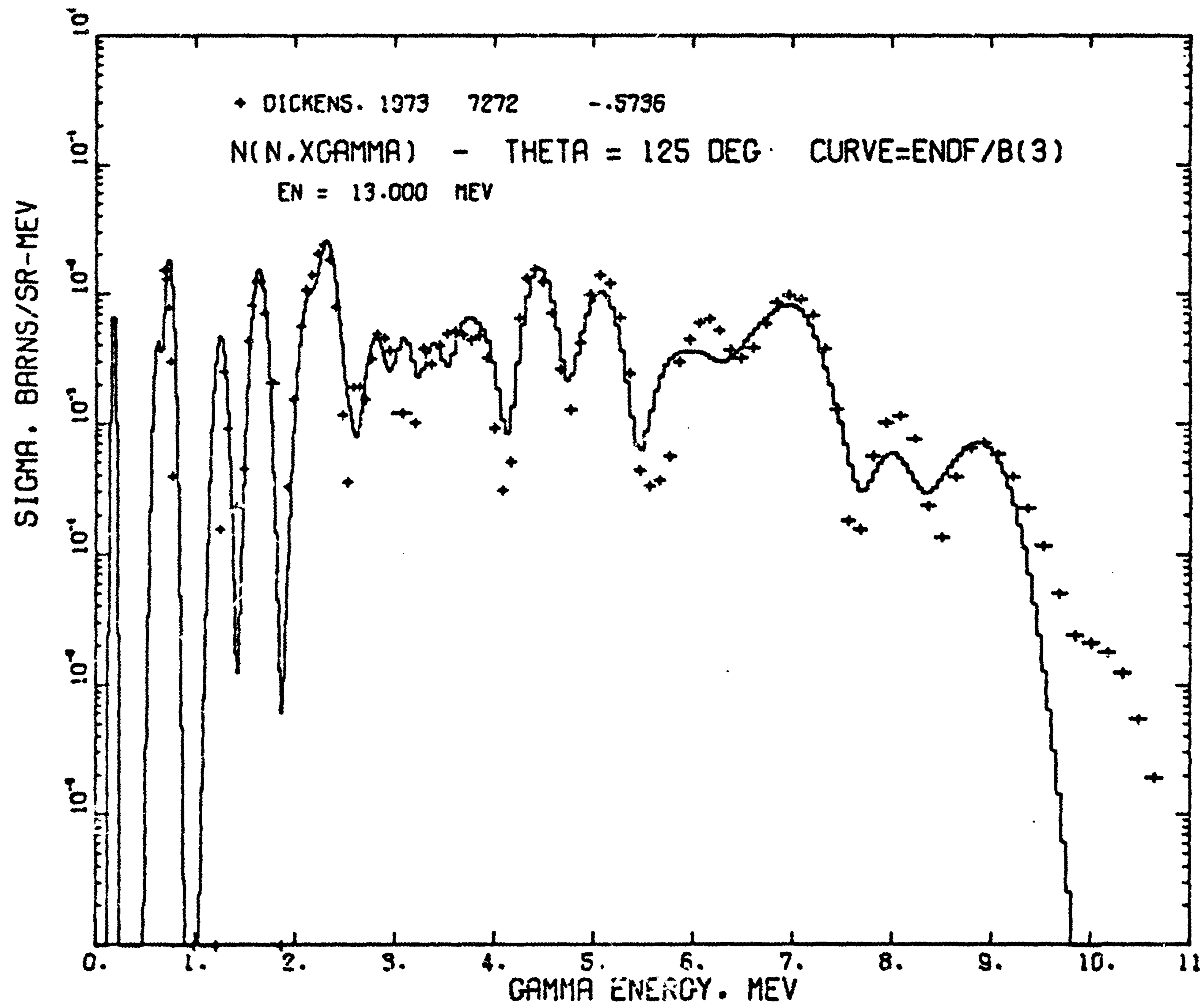

Fig. 2. Secondary gamma-ray spectrum at $\theta = 125°$ from the $^{14}N(n,x\gamma)$ reaction with neutrons of energy 12-14 MeV. The curve is the ENDF/B(3) evaluation,[2] and the crosses represent the experimental data of Dickens et al.[1]

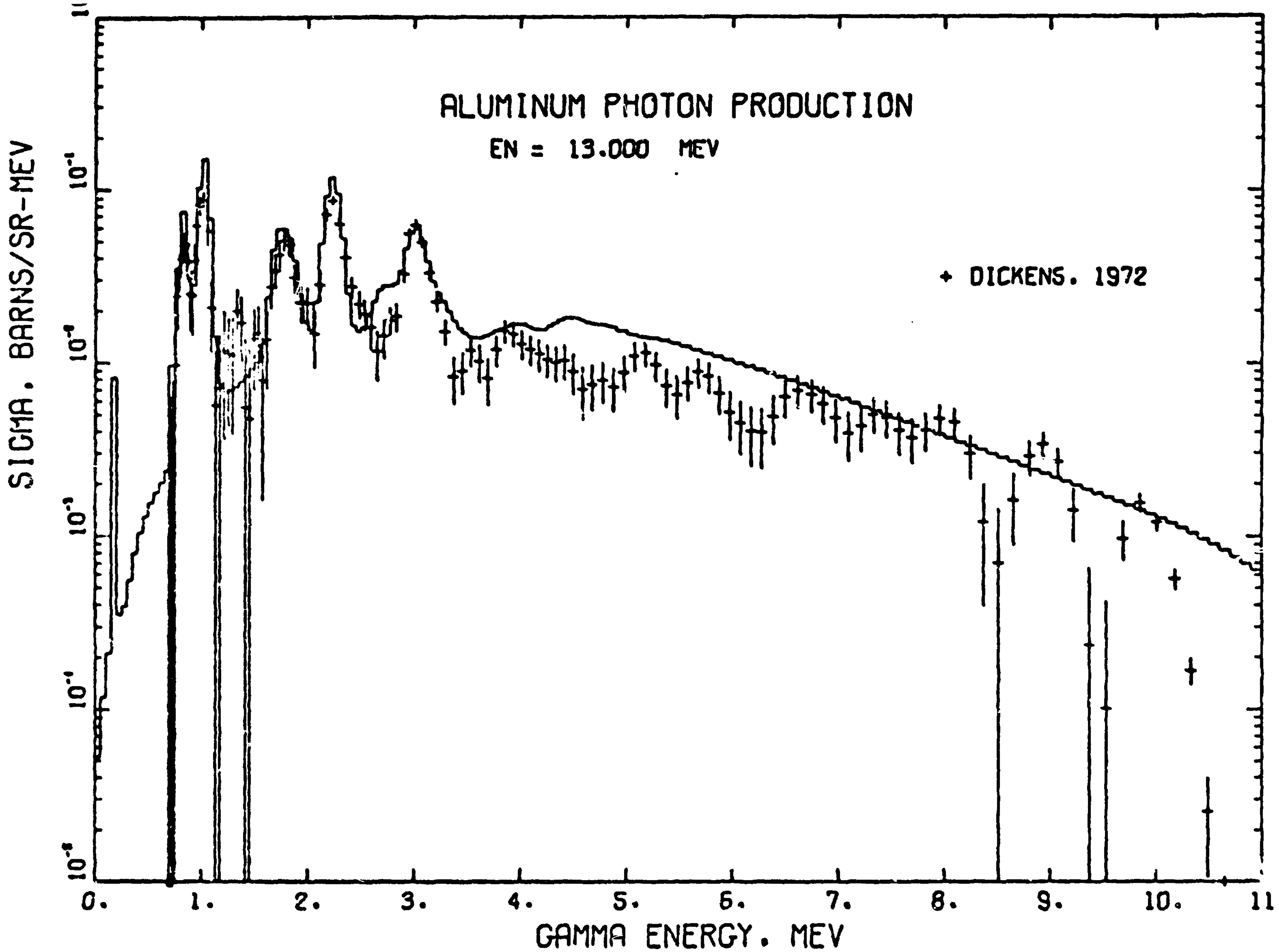

Fig. 3. Secondary gamma-ray spectrum at θ = 125° from the $^{27}Al(n,x\gamma)$ reaction with neutrons of energy 12-14 MeV. The curve is the ENDF/B(3) evaluation,[4] and the crosses represent the experimental data of Dickens et al.[3]

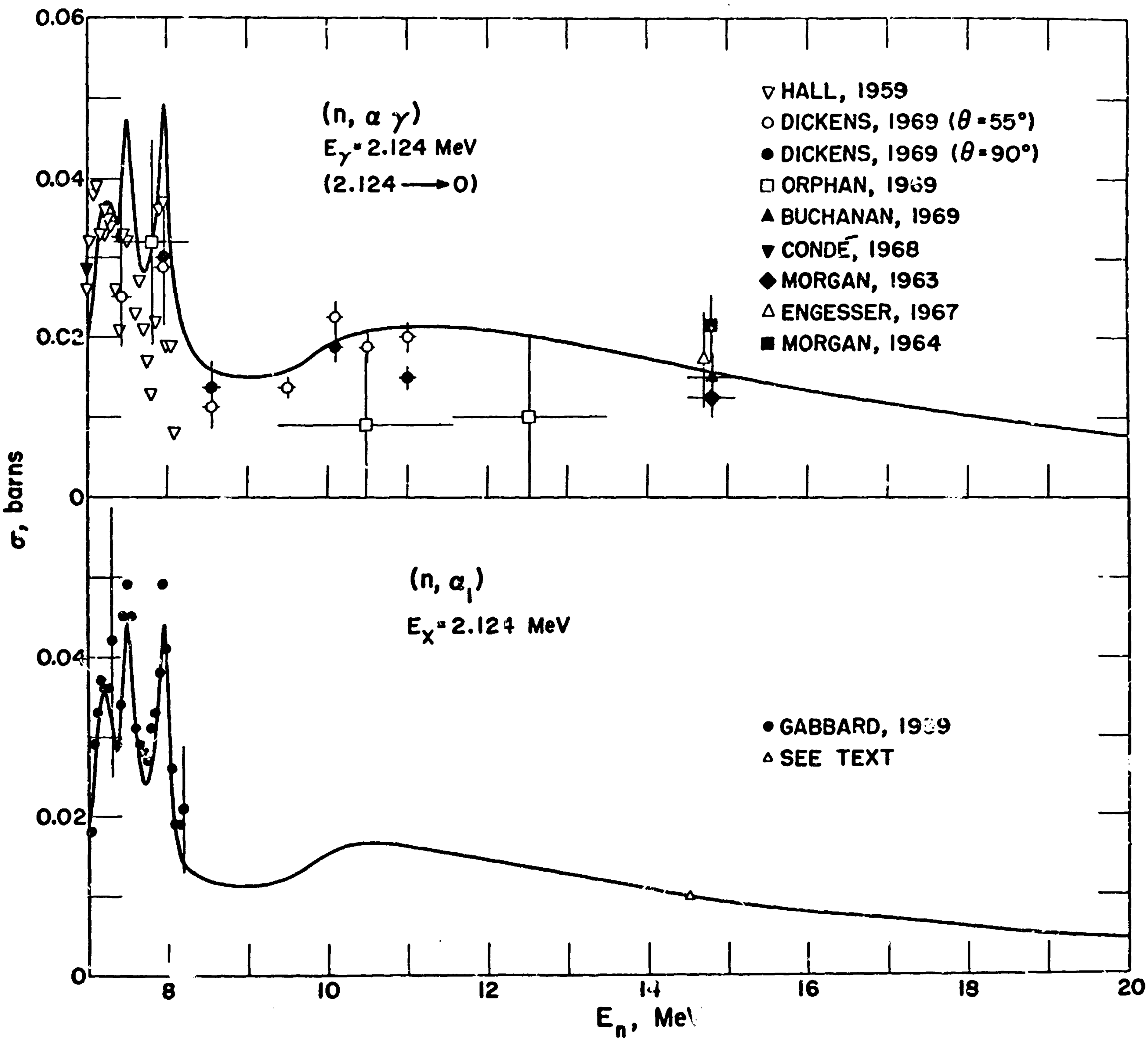

Fig. 4. Measured and evaluated $^{14}N(n,\alpha_1)^{11}B$ and $^{14}N(n,\alpha\gamma)^{11}B$ cross sections for the 2.124-MeV level of ^{11}B. The experimental data of Hall,[5] Dickens,[6] Orphan,[7] Buchanan,[8] Condé,[9] Engesser,[11] Morgan,[10,12] and Gabbard[13] are compared to the ENDF/B(3) evaluation.[2] The 14.5-MeV (n,α_1) datum is a composit of four measurements.

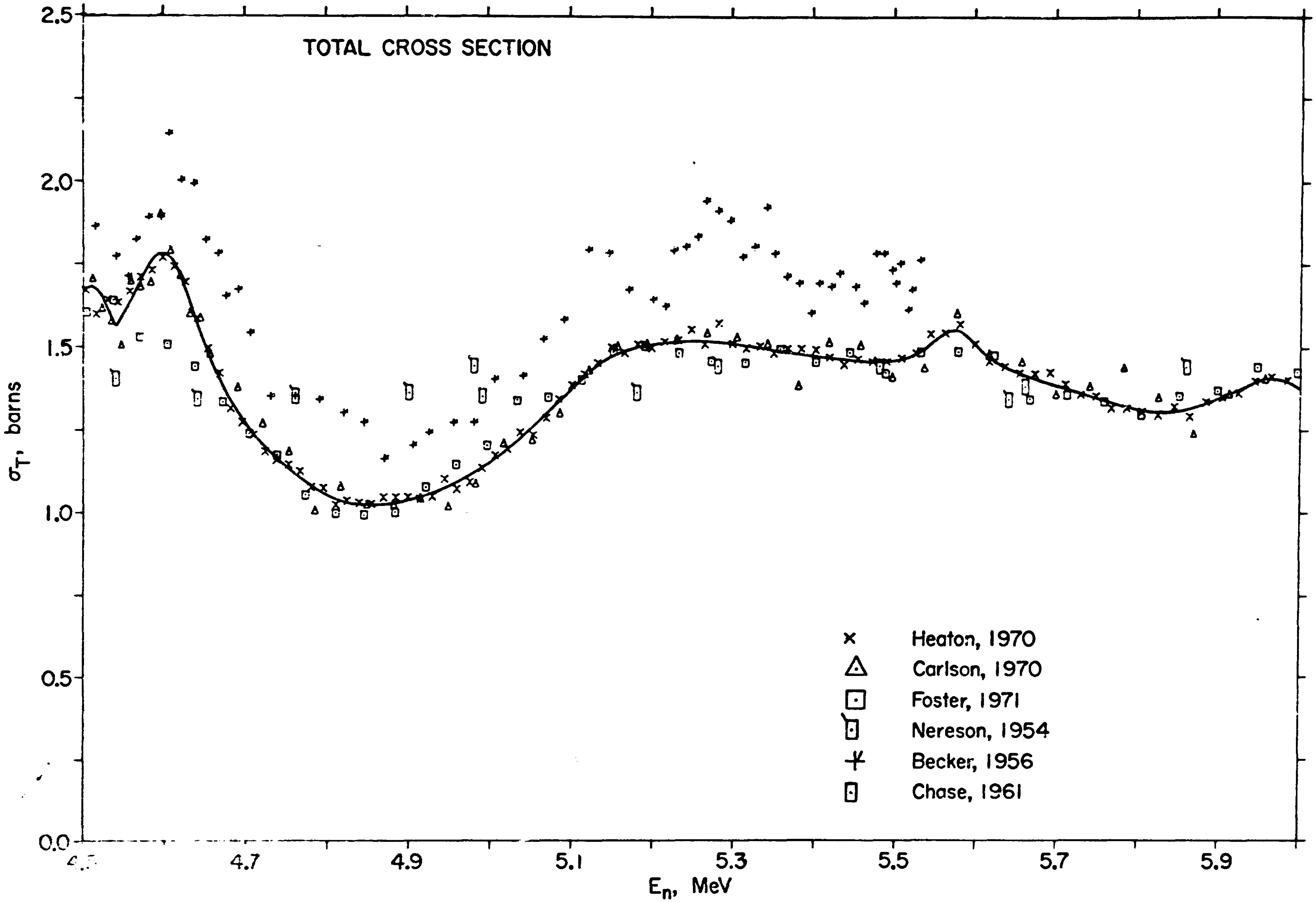

Fig. 5. Measured and evaluated ^{14}N total cross section from 4.5 to 6.0 MeV. The experimental data of Heaton,[14] Carlson,[15] Foster,[16] Nereson,[17] Becker,[18] and Chase[19] are compared to the ENDF/B(3) evaluation.[2]

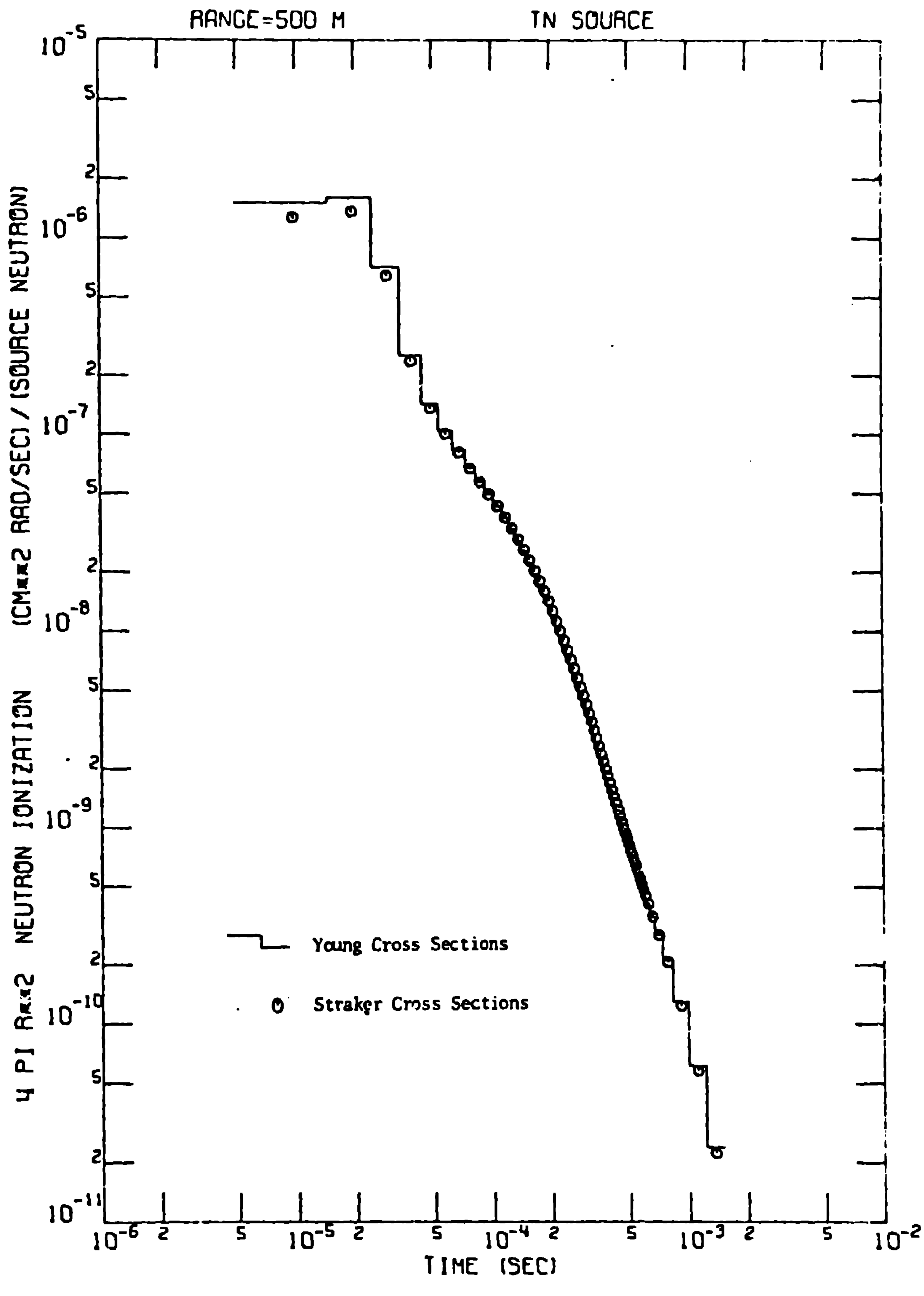

Fig. 6. Time-dependent neutron ionization in silicon at a range of 500m from a thermonuclear source as calculated by Engle and Mynatt.[20] ^{14}N and ^{16}O evaluations by Young and Foster[2,24] and by Straker and Gritzner[21] were used in the calculations.

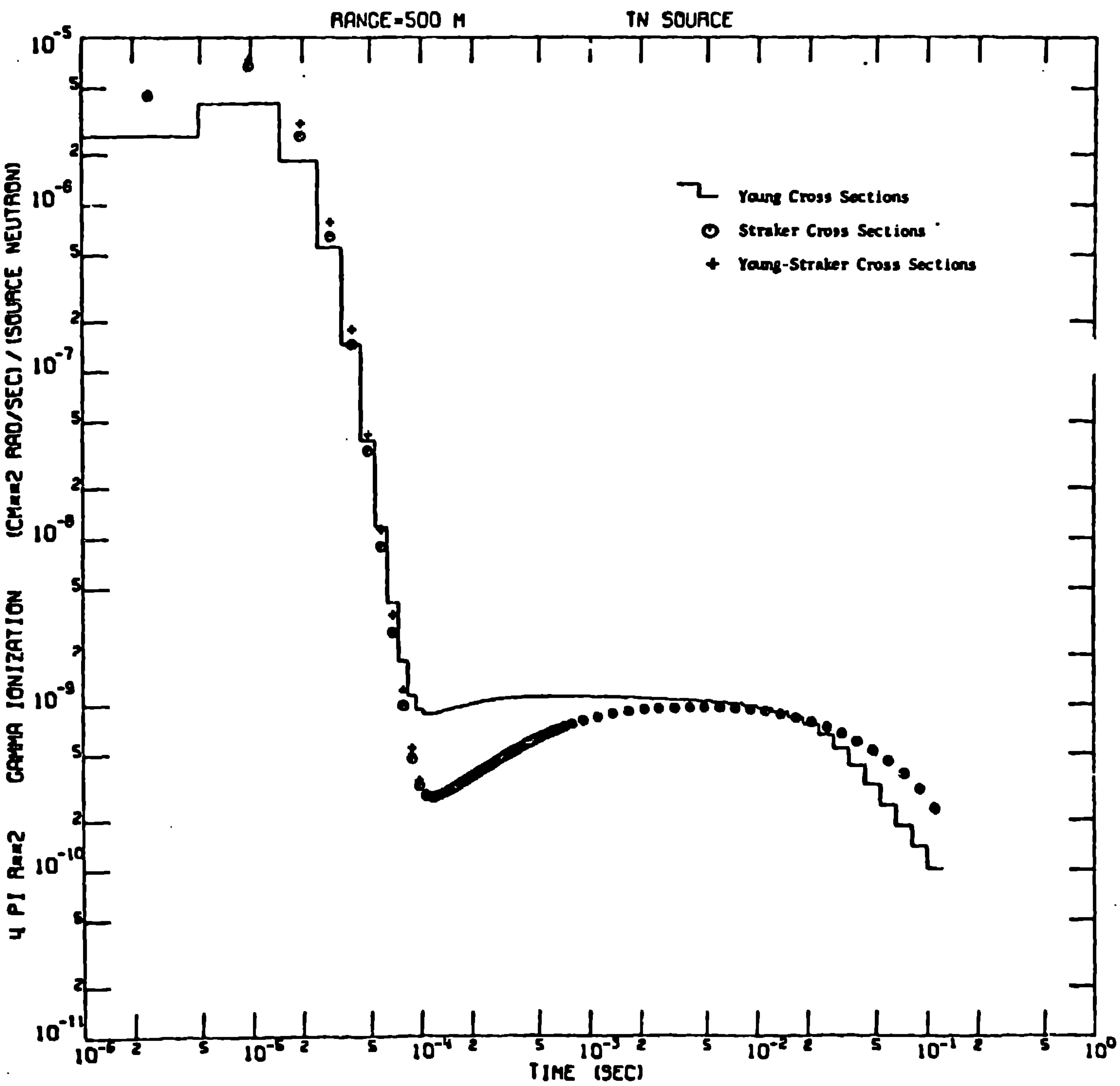

Fig. 7. Time-dependent gamma-ray kerma in silicon at a range of 500m from a thermonuclear source as calculated by Engle and Mynatt.[20] The calculations were performed using data evaluations by Young and Foster,[2,24] Straker and Gritzner,[21] and a hybrid set consisting of the neutron data from Young and Foster and the gamma-ray production data from Straker and Gritzner.

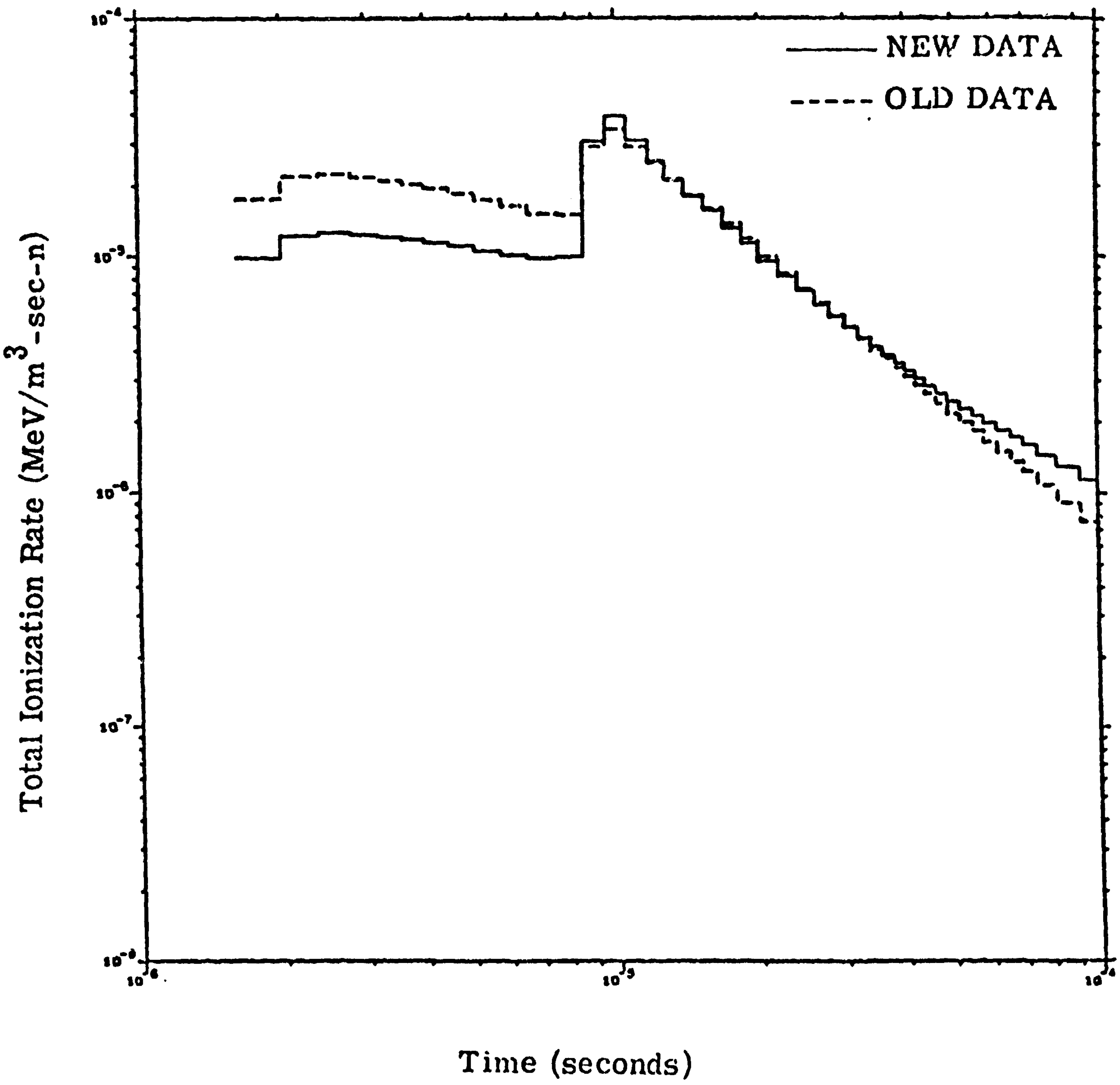

Fig. 8. Calculation by Sargis et al.[22] of the total neutron and gamma-ray ionization rate at 480m from a thermonuclear source. The calculations were performed using an older ENDF/B evaluation of the neutron cross sections combined with gamma-ray production data from the United Nuclear Corp.[23] and with the more recent ENDF/B(3) evaluations of Young and Foster.[2,24]