## A-VII. Corrections Applied to the Spectra

When one measures neutrons with the time-of-flight (TOF) technique, to ensure an acceptable energy resolution of the data, the neutron detectors cannot be placed too close to the target (see Appendix IV). In this experiment the flight path varied from 1.14 to 2.42 m. Necessarily, then neutrons detected in a detector have first passed through various materials like the 1/8" steel chamber wall, approximately 1.5 m of air, the 6 mm NE102A proton veto paddle, the 1/8" aluminum detector housing, and the 1/8" glass cell wall. Hence the neutron spectra contain distortions due to absorption and scattering, and these distortions should be corrected for. It is useful to divide the correction into an absorption and outscattering effect and an inscattering effect, as depicted in Fig. A-19. Outscattering means that neutrons created in the nuclear reaction and initially traveling towards a detector are scattered out of their path and are not detected in that detector. Fig. A-4 shows the telescope arrangement inside the chamber. The shaded regions represent the solid angles subtended at the target by the two neutron detectors at $\pm 10^{o}$, i.e., the regions of outscattering due to the telescopes.

Inscattering, on the other hand, means that neutrons not initially moving towards a given detector are by some sequence of scattering (off the floor, chamber wall, detector housing) detected in that detector. Inscattered neutrons are typically called background neutrons, and the standard technique for

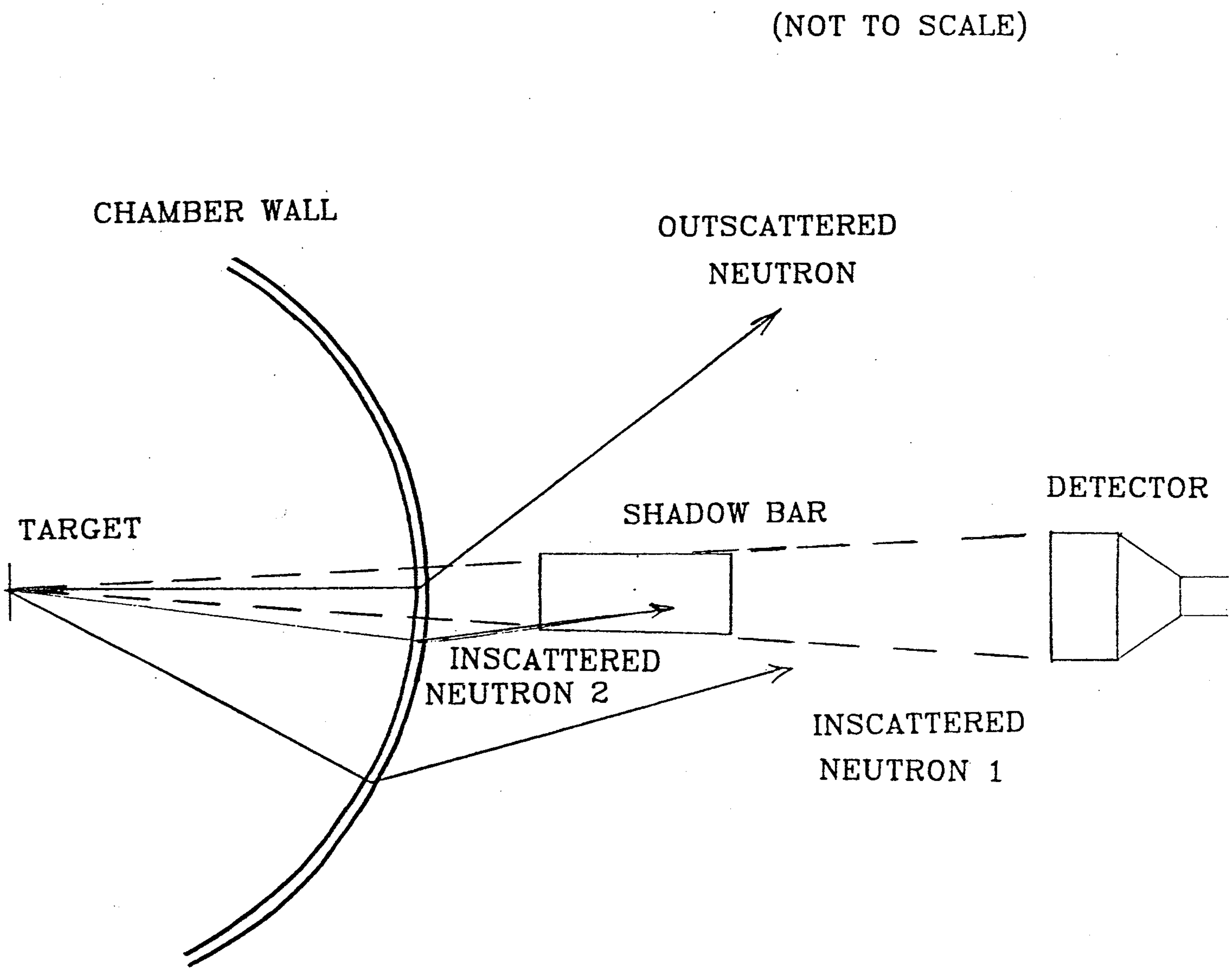



Figure A-19. Outscattered and inscattered neutrons dealing with them is through the use of shadow bars. The placement of all shadow bars was approximately midway between the target and the detector in an attempt to minimize the added distortions the shadow bar itself can introduce to the neutron spectra. Transmission through the shadow bar as a function of neutron energy was studied (see the discussion below) and found to be negligible for the thicknesses of brass and steel chosen. The shadow bars used were 30 cm long by 7.62 cm diameter brass cylinders except at the forward angles where we had 41 cm long brass cylinders at ±30° and 46 cm long tapered steel cylinders at ±10°.

To make correct positioning of the shadow bar possible, the diameter of the bar was chosen such that at the target it subtended a solid angle slightly larger than that of the neutron detector. This "overshadowing" is greatest at the end of the shadow bar nearest to the target and smallest at the end nearest to the neutron detector. Due to "overshadowing" some of the "bad" or inscattered neutrons were also shadowed and not recorded during the shadow bar run of the experiment. Therefore, when the shadow bar data is subtracted from the raw data, these scattering events will not be subtracted out. The data must be corrected for these events, then, with a calculation.

The starting point for both the outscattering and inscattering correction calculations is the relation

$$N = N_0 \, e^{-n\sigma_T x} \qquad \text{(A-5)}$$

where $N_o$ is the number of neutrons/sec incident upon a thickness x of material and N is the number/sec transmitted. Here n is equal to the number of nuclei/$cm^3$ in the material and $\sigma_T$ is the total neutron interaction cross section. Equation A-5 can be derived as follows. Let N neutrons/sec be incident upon a thickness dx of material, and let dN neutrons/sec undergo any type of interaction. Then the defining relation for total cross section, $\sigma_T$, is

$$dN = -\frac{N}{A}(ndxA)\sigma_T$$

$$= -Nndx\sigma_T$$

where A is the cross sectional area of the bombarded material, and N/A is the incident flux of neutrons (i.e., number/(sec-$cm^2$)). Then (n dx A) is the total number of target nuclei that "see" the beam. The negative sign is to show that dN neutrons/sec are removed from the incident flux, not added to it. Rearranging the above relation gives

$$\frac{dN}{N} = -n\sigma_T dx \qquad ,$$

and integrating over the thickness, x, of the scattering material gives

$$\ell nN = -n\sigma_T x + const$$

After some rearranging this then gives the desired relation:

$$N = e^{-n\sigma_T x + const}$$

or

$$N = N_0 \; e^{-n\sigma_T x} \qquad \text{(A-5)}$$

where $N_o$ corresponds to the incident neutrons/sec.

First the outscattering correction calculation will be discussed. Using eq. A-5, one can write down the neutrons/sec undergoing any type of interaction in thickness x of material as

$$N_{int} = N_0(1 - e^{-n\sigma_T x})$$

But of those neutrons that interact,

$$N_{e\ell} = N_0(1 - e^{-n\sigma_T x})(\Delta\sigma_\ell/\sigma_T)$$

are the neutrons that elastically scatter through such a shallow angle that they still enter the detector. Here $\Delta\sigma_{e\ell}$ is given by

$$\Delta\sigma_{e\ell} = \int_{\theta=0}^{\theta_0} \frac{d\sigma_{e\ell}(\theta)}{d\Omega} 2\pi sin\theta d\theta$$

and $\theta_o$ is the angle subtended by the edge of the neutron detector at the scattering material in question. To simplify the notation, we define F and f as

$$F = N/N_0$$

$$f = e^{-n\sigma_T x}$$

where N corresponds to the actual neutrons/sec detected and $N_o$ to ideally what should have been detected had there been no scattering or absorption. Considering both those neutrons transmitted through thickness x with no interaction and those elastically scattered through a small angle $\theta \leq \theta_o$, one can write down the fraction of neutrons detected as

$$F = f + (1 - f)(\Delta\sigma_{el}/\sigma_T) \quad \text{(A-6)}$$

If the scattering material is close to the neutron detector, it is possible that a neutron can inelastically scatter or undergo an (n,n), (n,2n), (n,nα), or (n,p) interaction and still create a signal in the detector with a time-of-flight nearly the same as that of the original neutron. So the above cross sections, where available, have been included, and entered into the equation as follows:

$$F = f + (1 - f)\Delta\sigma_{el}/\sigma_T + \Sigma(1 - f)\Delta\sigma_i/\sigma_T$$

where the sum over i runs over the above interactions for a scattering material close to the detector. This, so far, is for only a single outscattering material and considers only the outscattering correction. If there were J outscattering materials in the path of the neutrons going to a given detector, then the final result would be the product of their individual fractional contributions, i.e.,

$$F = \pi_{j=1}^{J} F_j$$

where $F_j$ would be the fraction detected if there existed only the jth outscattering material.

The derivation for the inscattering contribution develops in a similar fashion. One has to calculate the inscattering effect from objects which are not included in subtraction of the shadow bar data due to overshadowing. The inscatterers contained in the overshadowed region are relatively far from the detectors. So inelastic scattering can be neglected and only elastic scattering need be considered.

Consider first just a single such inscatterer. If $N_o$ is the neutron flux contained in the solid angle subtended at the target by the neutron detector, then let $AN_o$ be the flux contained in the solid angle subtended by the inscatterer, where A is a scaling parameter. If the angular distribution of the incident neutrons is neglected, then A is just the ratio of the solid angle subtended by the inscatterer to the solid angle subtended by the neutron detector. If the inscatterer in question is of thickness x, has n nuclei/cm$^3$, and total cross section $\sigma_T$, then

$$N_{int} = AN_0(1 - e^{-n\sigma_T x})$$

is the number of neutrons undergoing any type of interaction. The probability that an interacting neutron elastically scatters into the detector can be written as $\Delta\sigma_{el}/\sigma_T$ , where

$$\Delta\sigma_{el} \approx \frac{d\sigma_{el}(\theta_0)}{d\Omega}\Delta\Omega$$

Here $\theta_o$ is the angle through which the neutrons must scatter from the inscatterer to move on a path towards the neutron detector, and $\Delta\Omega$ is the solid angle subtended by the detector at the inscatterer. So

$$N_{e\ell} = AN_0(1 - e^{-n\sigma_T x})\Delta\sigma_{e\ell}/\sigma_T$$

gives those neutrons that scatter elastically from the inscatterer on a path towards the neutron detector. Finally, let $F_{attn}$ be the attenuation factor resulting from the material between the target and the inscatterer and between the inscatterer and the neutron detector. $F_{attn}$ is calculated in the same way as F in the outscattering calculation. The fraction of $N_0$ neutrons detected at the detector due to inscattering can then be written as

$$F_{in} = N_{e\ell}/N_0$$

$$= F_{attn}A(1 - e^{-n\sigma_T x})(\Delta\sigma_{e\ell}/\sigma_T)$$

So far this assumed a single inscatterer. For J inscatterers, the total fraction inscattered is just the sum of the individual contributions, i.e.,

$$(F_{in})_{total} = \sum_{j=1}^{J}(F_{in})_j$$

where $(F_{in})_j$ is the fraction due to the jth inscatterer.

If $F_{in}$ is the total fraction of $N_0$ neutrons arriving at the detector due to inscattering, then the final equation for the fraction of $N_0$ neutrons detected in the detector is

$$N/N_0 = F + F_{in} \quad .$$

N is the detected neutron flux and $N_o$ is the desired undistorted flux. So the neutron energy spectra (after subtraction of shadow bar and accidental coincidence data) have to be multiplied by the energy dependent scaling factor

$$scaling\ factor = \frac{1}{F + F_{in}}$$

This calculation was carried out for each of the ten neutron detectors, and the results are displayed in Fig. A-20. Detectors 1, 3, 5, 7 and 9 in the figure titles refer to angles of 10°, 30°, 70°, 110° and 160°, respectively on the left side of the beam (when facing downstream). Detectors 2, 4, 6, 8 and 10 refer to the same angles on the right side of the beam. The scaling factors are energy dependent but typical values range from 80% detected for the low energy neutrons to 94% for the high energies for all the detectors except at ±10°. The largest corrections were for the two detectors at ±10°, with the results ranging from about 50% for low energy neutrons to 80% for high energy neutrons. Outscattering is the major contribution to the correction calculation, as can be seen in Fig. A-21 for the neutron detectors at 10° to the left of the beam. In this figure the squares are the correction calculation neglecting inscattering and the circles are the final results when both outscattering and inscattering are considered.

The basic shape of the correction curves can be understood by examining the total cross section curve. All neutrons detected have passed through at least the 1/8" steel

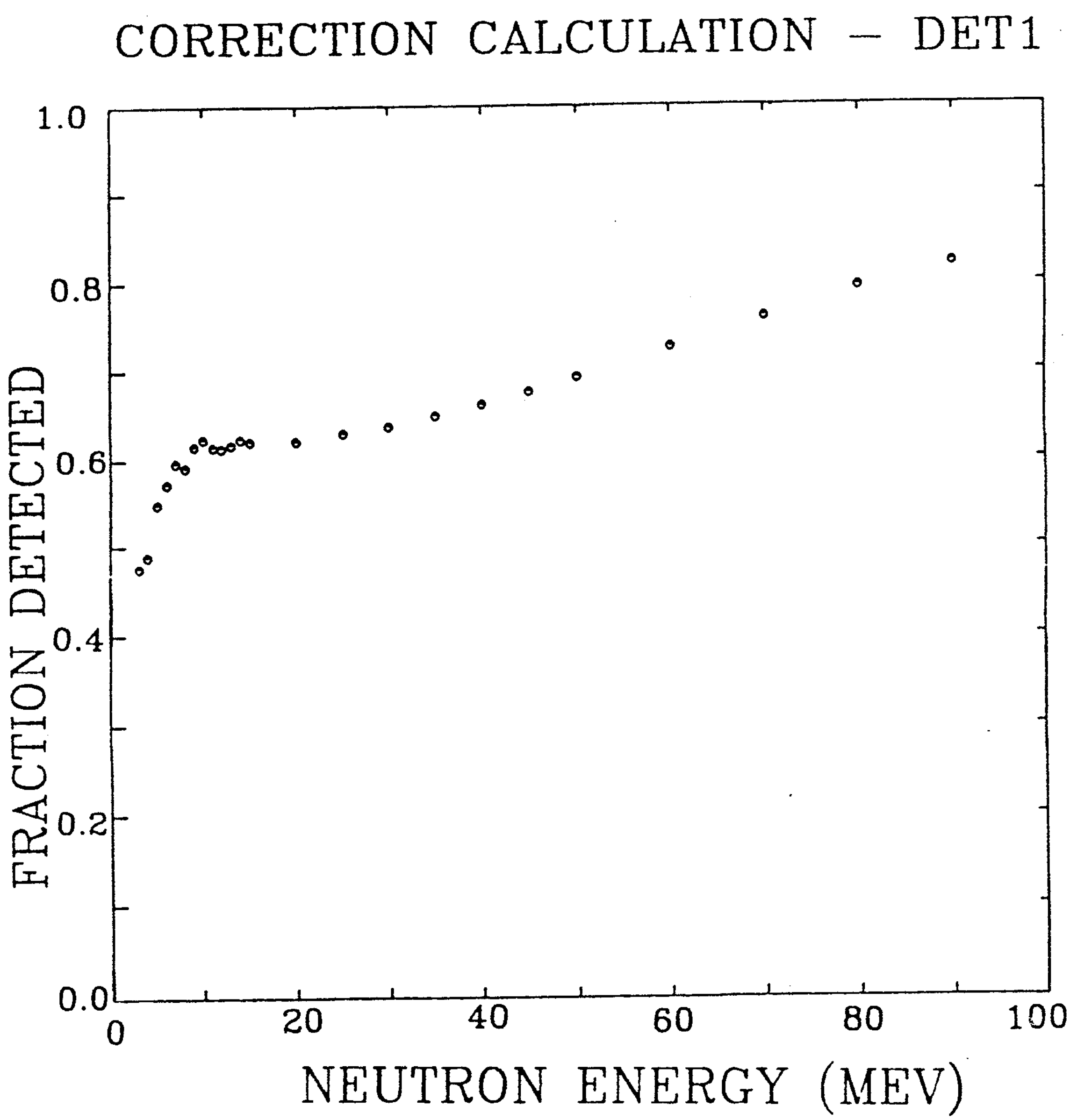
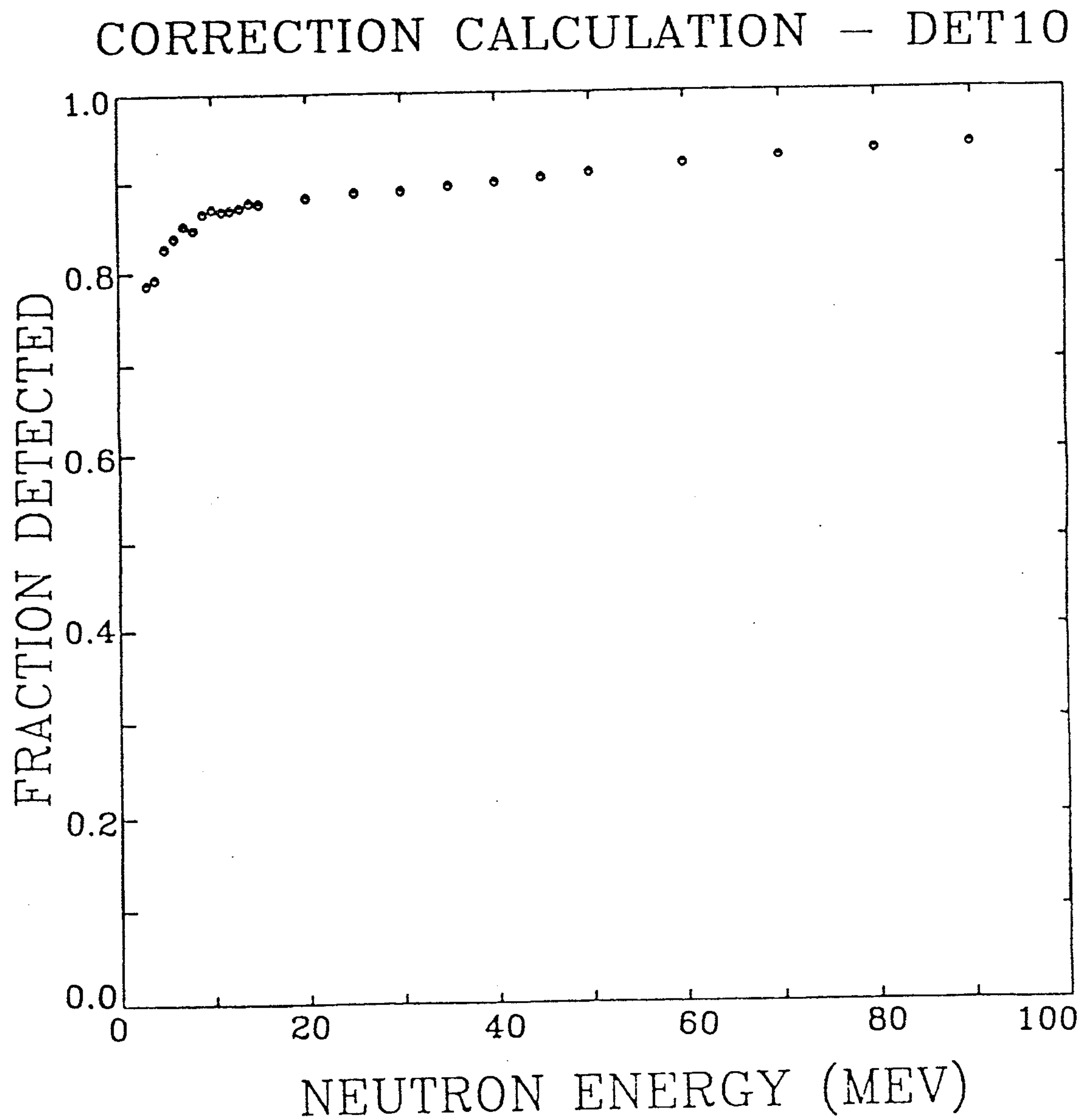



Figure A-20. Correction calculations for the ten neutron detectors

Figure A-20. (continued)



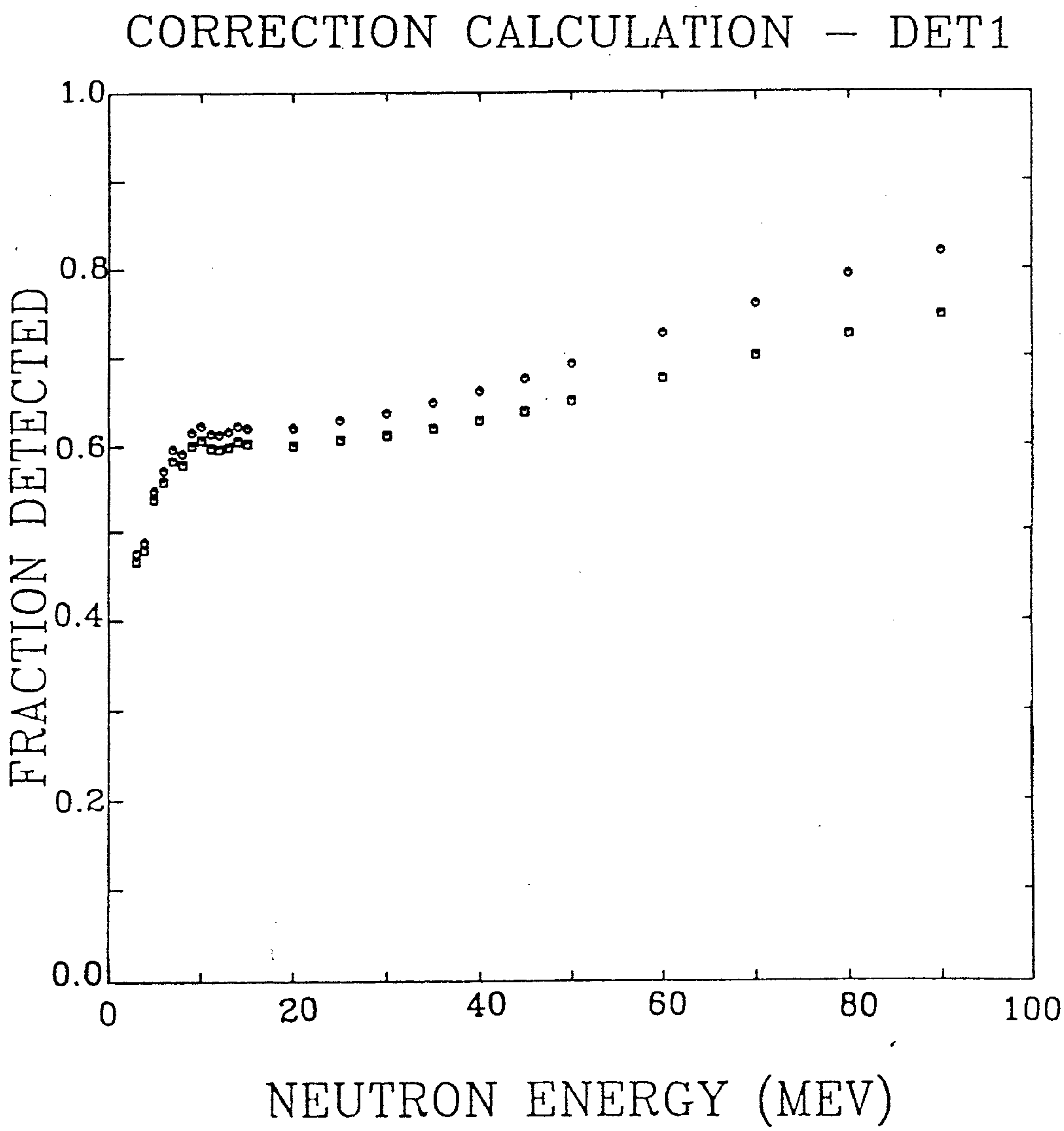



Figure A-21. Correction calculation with and without inscattering chamber wall and the 6 mm thick NE102A proton veto detector. Figure A-22 displays total cross section and its elastic and nonelastic components for iron and carbon. The overall rise of the correction curve is the result of the overall decrease in total cross section as a function of energy exhibited by all of the scattering materials. The bumps in the correction curve at low energies arise from the resonances in the total cross section at those energies, especially from carbon. And the sharp increase of the correction curve from 0 to about 10 MeV arises from the sharp decrease in the total cross section. This is seen in Fig. A-22 to be due mainly to the elastic scattering component of the total cross section.

In using shadow bars to measure the background neutrons detected in the detectors, one needs to consider whether there is any transmission of neutrons through the shadow bar. One way of estimating this is to assume that the shadow bar is divided up into, say, four separate pieces and do an "outscattering/inscattering" calculation as described above. Another method is to assume that neutrons traveling through the shadow bar undergo enough interactions that a multiple scattering calculation can be used. For 84 MeV neutrons traveling through copper (Br 50), the average number of collisions is about six, suggesting that a multiple scattering calculation might be worth trying. Both approaches were tried, but before discussing the results, the multiple scattering relationship will be developed.

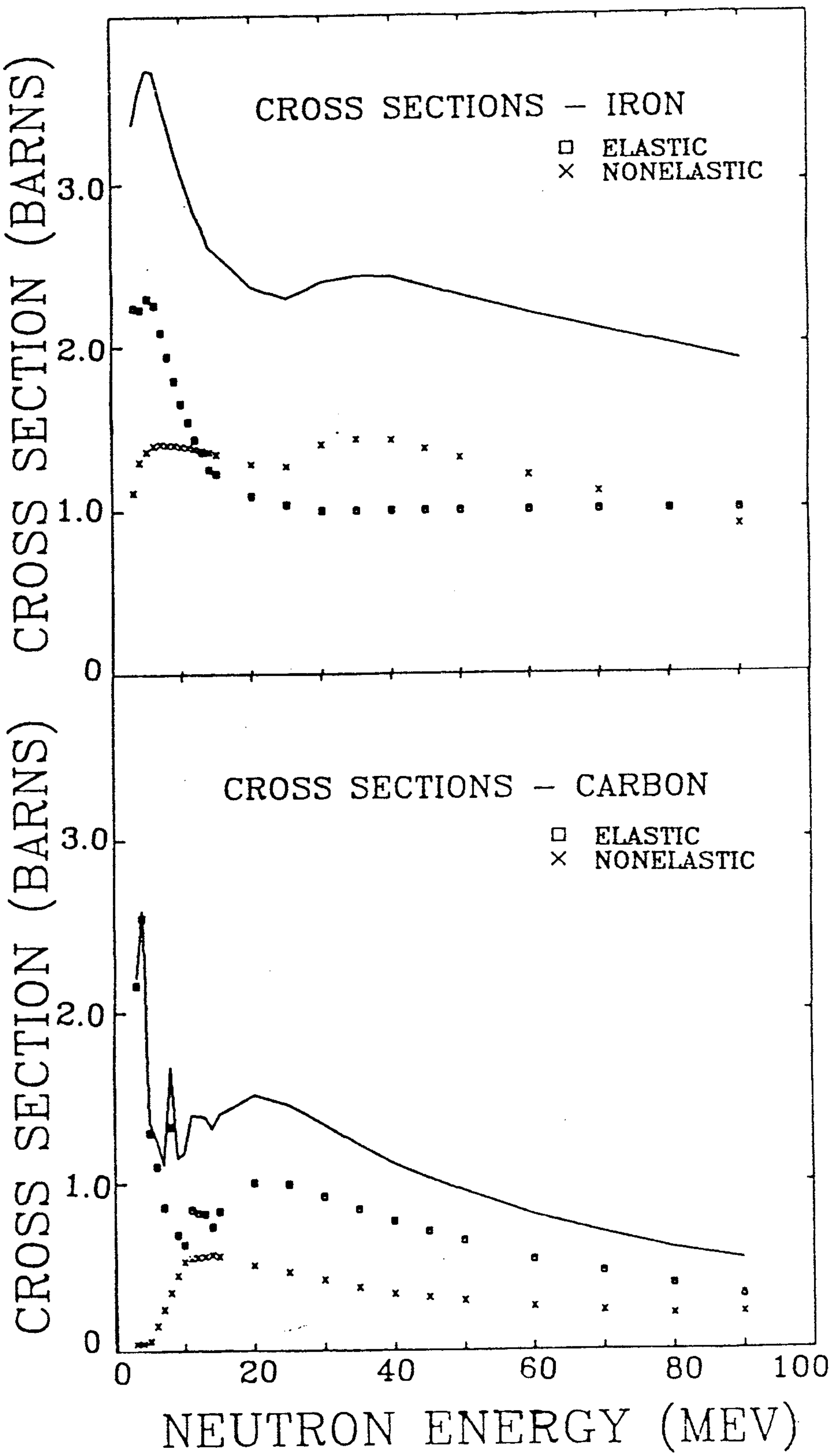



Figure A-22. Cross sections for iron and carbon

The multiple scattering relation can be derived as follows. The probability that a neutron undergoing multiple scattering is deflected through an angle of θ is given by

$$P_{(\theta)}d\Omega = \frac{1}{\pi < \theta^2 >} e^{-\theta^2/<\theta^2>}\, d\Omega$$

where $\langle\theta^2\rangle$ is the average squared deflection angle due to multiple scattering (equation 2-7.9 in Ref. Se 77). But $\langle\theta^2\rangle$ can be related to $\langle\theta^2_{single}\rangle$, where $\langle\theta^2_{single}\rangle$ is the average squared deflection angle due to single scattering. Let θ and α represent the angles of deflection arising from multiple scattering and single scattering, respectively. Then

$$< \theta^2 > = < \sum_{i=1}^{N} \alpha_i^2 >$$

where the average is taken over independent particles incident upon the scatterer, and the sum is taken over the N collisions each such particle undergoes. If one assumes each of the N collisions is independent of all the others, i.e., if one assumes incoherent collisions, then

$$< \theta^2 > = \sum_{i=1}^{N} < \alpha_i^2 >$$

$$= \sum_{i=1}^{N} < \alpha^2 >$$

$$= N < \alpha^2 >$$

$$= N < \theta^2_{single} >$$

where N is the number of collisions. So by using the measured angular distribution for 84 MeV neutrons on copper (Br 50), one can obtain $\langle\theta^2_{single}\rangle$, hence $\langle\theta^2\rangle$ and then $P(\theta)d\Omega$. The fraction of neutrons multiply scattered through a small enough angle that they still enter the neutron detector is given by

$$F_{ms} = \int_{\theta=0}^{\theta_0} P(\theta) 2\pi sin\theta d\theta$$

where $\theta_0$ is the angle subtended by the neutron detector at the shadow bar. Then the fraction of the neutrons incident upon the front face of the shadow bar that reach the detector is given by

$$F_{trans} = e^{-n\sigma_T x} + F_{ms}$$

Both the multiple scattering calculation and the "outscattering/inscattering" calculation were done assuming a Cu shadow bar 11.625" long, and the results are presented in Fig. A-23. The transmission through the shadow bar is less than 5% for all but the highest neutron energies. For a 100 MeV neutron, there is about 10% transmission. At $\theta_n \geq 70^o$, though, there were no 100 MeV neutrons and at smaller $\theta_n$ longer shadow bars were used, as mentioned above. So in subtracting the shadow bar data from the raw data, the effect of transmission through the shadow bar was neglected.

It should be noted that all cross sections used were the most recent values available and were obtained upon request from the neutron cross section data bank maintained at the National Nuclear Data Center at Brookhaven National Laboratory (BNL 84).

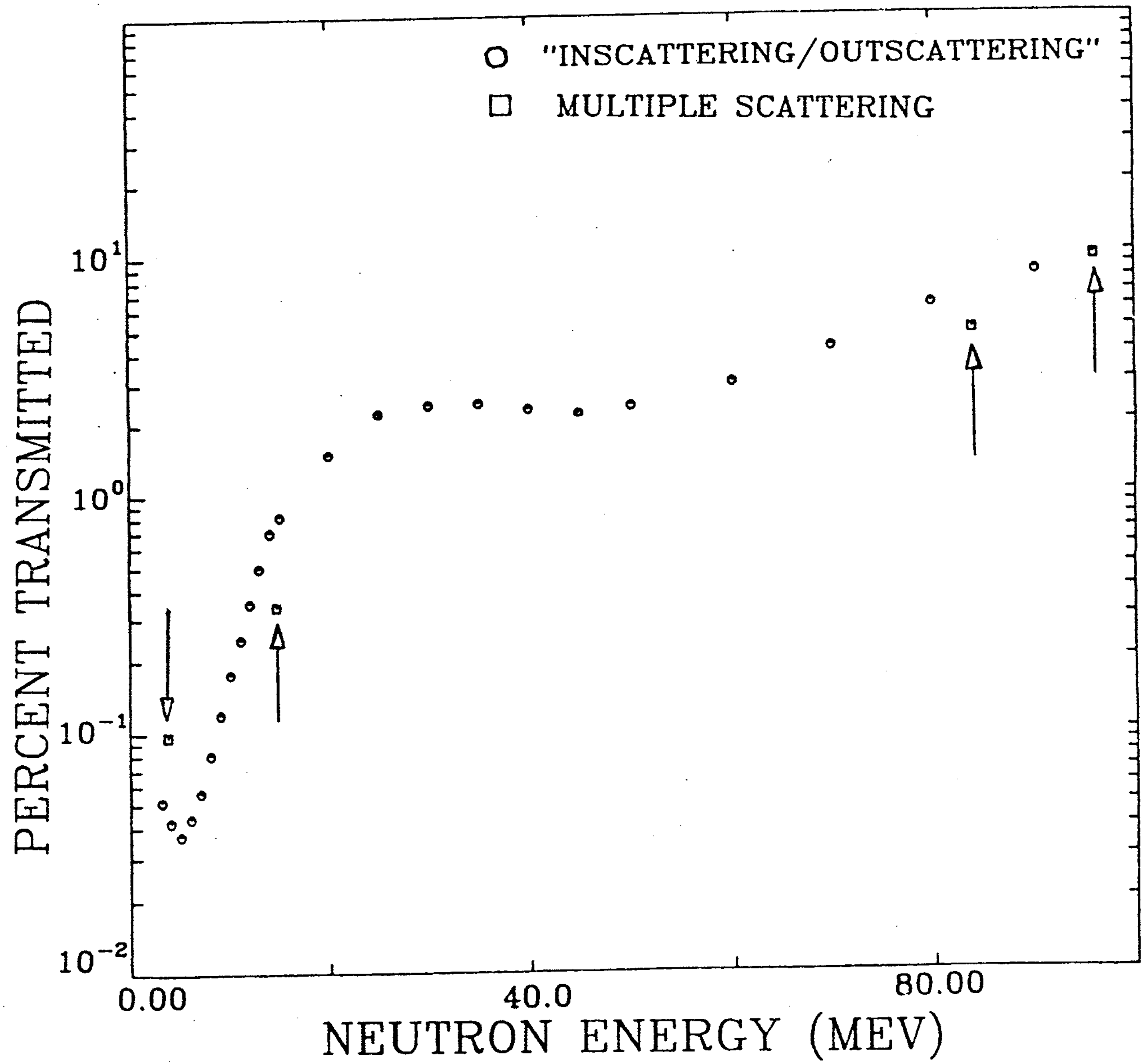



Figure A-23. Neutron transmission through the shadow bar