amplitudes $\bar{A}_\gamma/\bar{A}_\beta$ is 1.6. The shift of the centroids of the corresponding delay curves, taken without pulse height selection, was $(5\pm1)\times10^{-11}$ second.

Using next a light absorber (wire mesh) of the proper transparency between crystal B and its photomultiplier when measuring γ's, it was possible to adjust the γ amplitude distribution to that of the β's so that the rms of the differences between corresponding ordinates was 4.9 percent (curve 3, Fig. 3). The shift of the centroids of the corresponding delay curves (Fig. 2b) was $(0.5\pm1)\times10^{-11}$ second, i.e., within statistical accuracy. From this it appears that the equalization of amplitude distributions to within a few percent, permits one to make time measurements by the coincidence method with an accuracy of $\sim10^{-11}$ second.

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[1] Z. Bay, Phys. Rev. **77**, 419 (1950).
[2] Z. Bay, Rev. Sci. Instr. **22**, 397 (1951).
[3] Bay, Kanner, and Henri, Oak Ridge National Laboratory Technical Report ONR Contract 168(00), September, 1953; and to be published.
[4] Z. Bay, Phys. Rev. **83**, 242 (1951).
[5] Bay, Cleland, and McLernon, Phys. Rev. **87**, 901 (1952).
[6] Bay, Henri, and McLernon (to be published).
[7] Kanner, Bay, and Henri, Phys. Rev. **90**, 371 (1953).
[8] Bay, Henri, and McLernon, Phys. Rev. **90**, 371 (1953).
[9] R. F. Post and L. I. Schiff, Phys. Rev. **80**, 1113 (1950).
[10] V. F. Weisskopf, Phys. Rev. **83**, 1073 (1951).
[11] Aeppli, Frauenfelder, Heer, and Rüetschi, Phys. Rev. **87**, 379 (1952).
[12] M. Deutsch and W. E. Wright, Phys. Rev. **77**, 139 (1950).
[13] Gorodetzki, Knipper, Armbruster, and Gallmann, J. phys. et radium **14**, 550 (1953).

Inelastic Collision Cross Sections at 1.0-, 4.0-, and 4.5-Mev Neutron Energies

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In recent years, sphere transmission measurements have been used successfully to determine inelastic collision cross sections.[1–5] In this method the transmission of a spherical shell is measured by surrounding either the neutron detector or the neutron source. To minimize the difficulties caused by the highly anisotropic $T(p,n)He^3$ neutron source used in this experiment, the neutron detector was surrounded instead of the source. The maximum spread in neutron energies was 160 kev for the 1-Mev source and about 70 kev for the 4.0 and 4.5-Mev sources. A high-pressure hydrogen gas proportional counter detected the 1-Mev neutrons. At 4.0 and 4.5 Mev, the neutron detector was a hydrogen recoil scintillation counter consisting of nine spheres of plastic phosphor, 0.100 inch in diameter, separated by quartz to reduce gamma-ray sensitivity.[6] Each detector was positioned at about 30 inches from the tritium gas target in the forward direction. It was operated as a biased neutron detector with about ten energy thresholds allowing ten transmissions to be measured simultaneously. This procedure was adopted to obtain information concerning the energy spectrum of inelastic neutrons produced in the spheres.

When calculating inelastic cross sections from observed sphere transmissions, it is important to consider the probability of multiple neutron scattering. The errors which are made by not considering multiple scattering were not investigated accurately until a few years ago. At that time, Bethe[2–4] proposed a simple and accurate method of evaluating multiple scattering in a spherical geometry which agreed with both experimental observation and detailed Monte Carlo calculations of this effect.

We included the following effects in the numerical analysis of the experimental data: (1) the multiple scattering in the sphere, (2) the relative variation in energy and intensity of neutrons over the solid angle subtended by the sphere, (3) the effect of loss of energy in elastic collisions with resulting reduction in counting sensitivity, and (4) the effect of finite detector size inside the sphere. Corrections due to these effects can be computed using basically the Bethe method of analysis. Since the magnitude of the third correction is large for light elements and the higher energy thresholds, this effect was computed by the Monte Carlo method for increased accuracy. All corrections listed above depend to varying extents on the shape of the elastic scattering angular distributions and on the total neutron cross sections. The known angular distributions at 1 Mev[7] and the recently measured distributions at 4.1 Mev[8] were used. To speed up the numerical analysis the entire computing problem was coded for the Los Alamos Maniac Computer by E. D. Cashwell, C. J. Everett, and J. M. Kister.

The cross sections given in Table I for 1-Mev neutron energy were taken with the proportional counter biased at 750 kev. With the exception of gold and silver, the cross sections are relatively insensitive to the energy threshold of the detector and are probably the entire inelastic collision cross sections. This cross section for

Table I. Inelastic collision cross sections.

Element	1 Mev	4.0 Mev	4.5 Mev
Beryllium		0.62±0.05	
Carbon	−0.09±0.14	0.04±0.08	
Aluminum	0.04±0.08	0.75±0.05	0.72±0.06
Titanium		1.28±0.09	1.16±0.09
Iron	0.41±0.04	1.42±0.07	1.34±0.07
Nickel		1.35±0.09	1.50±0.09
Copper	0.21±0.05	1.60±0.07	1.60±0.06
Zinc	0.10±0.06	1.69±0.06	1.81±0.09
Zirconium		1.56±0.07	1.59±0.09
Silver	1.61±0.16	2.05±0.10	2.02±0.11
Cadmium	0.99±0.06	2.05±0.10	2.12±0.11
Tin	0.07±0.05	2.09±0.10	2.18±0.10
Tungsten		2.58±0.20	2.56±0.20
Gold	1.63±0.10	2.75±0.12	2.69±0.13
Lead	0.23±0.04	1.84±0.08	2.02±0.16
Bismuth	0.12±0.04	1.98±0.10	2.19±0.10

gold at 1 Mev is estimated to be about 1.8 barns. The 1-Mev data were compared with the inelastic cross sections obtained by Walt and Barschall.[7] For the majority of the elements, the agreement is within the experimental errors.

The cross sections given for 4.0- and 4.5-Mev neutron energies were obtained with the scintillation detector biased at 3.4 and 3.8 Mev respectively. The values do not change rapidly with the energy threshold of the detector. These data agree very well with inelastic collision cross sections recently determined at 4.1-Mev neutron energy in the elastic scattering angular distribution experiments.[8]

A more extensive report on the experimental procedure, numerical analysis, and results is being prepared.

[1] H. H. Barschall, Revs. Modern. Phys. **24**, 120 (1952).
[2] H. A. Bethe, Los Alamos Report LA-1428, 1952 (unpublished).
[3] Bethe, Beyster, and Carter, Los Alamos Report LA-1429 (unpublished).
[4] H. A. Bethe, Report of Second Conference on Medium Energy Nuclear Physics at University of Pittsburgh, 1953 (unpublished).
[5] Phillips, Davis, and Graves, Phys. Rev. **88**, 600 (1952).
[6] McCrary, Taylor, and Bonner, Phys. Rev. **94**, 808(A) (1954).
[7] M. Walt and H. H. Barschall, Phys. Rev. **93**, 1062 (1954).
[8] M. Walt and J. R. Beyster, Bull. Am. Phys. Soc. **29**, No. 8, 31 (1954).

Multiplicity of Neutrons from the Spontaneous Fission of Californium-252*

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THE neutron number distributions from the spontaneous fission of some of the transuranic elements are being measured with a neutron detector of high efficiency. The first data to be analyzed are from a sample of Cf^{252} with about 300 spontaneous fissions per minute.

The material was mounted in a fission chamber placed at the center of a cylindrical tank of cadmium-loaded liquid scintillator. The dimensions and construction of this detector are nearly identical with the design of the Los Alamos group.[1] A pulse from the fission chamber triggered the sweep of an oscilloscope. The fission neutrons were moderated in the toluene and captured in the cadmium with a mean lifetime of 20 microseconds, and some of the resulting γ rays produced pulses in the scintillator which were displayed on the scope trace and photographically recorded.

The numbers of fissions with 0, 1, 2, etc., *detected* neutrons are given in Table I. A correction has been made for a background of 0.75 percent. The average number of neutrons per spontaneous fission of this nucleus has been measured by Crane *et al.*[2] to be 3.10±0.18.[3] The 8494 fissions reported here gave an average of 1.43 neutrons, from which we conclude that our detection efficiency was 46.0±2.8 percent (probable error) for this measurement. A Monte Carlo calculation made at the Livermore laboratory indicates that this efficiency is constant over the energy interval in which nearly all the fission neutrons are expected to lie. Using this value of the efficiency we calculated the number of fissions *vs* the *true* numbers of neutrons per fission; the results are given in Table I.

TABLE I. Observed and calculated neutron multiplicities from the spontaneous fission of Cf^{252}.

No. of neutrons	0	1	2	3	4	5	6	7
Observed distribution	1596	3200	2445	1001	214	33	5	0
True distribution	−65 ±100	+999 ±340	+1407 ±770	+2970 ±950	+2763 ±1150	−107 ±600	+528 ±250	0

It is seen that there is a large probability that all Cf^{252} fissions emit at least one neutron, and the fraction of spontaneous fissions giving seven or more neutrons is certainly less than one percent.

The multiplicities of neutron production by spontaneous fission of natural uranium have been measured by Geiger and Rose,[4] using equipment with a neutron detection efficiency of three percent.

They were able to fit their data to a Poisson distribution, although other forms were not excluded. It can be shown that if the true distribution is binomial with a mean number of neutrons m, and the efficiency with which a single neutron is detected is e, then the observed

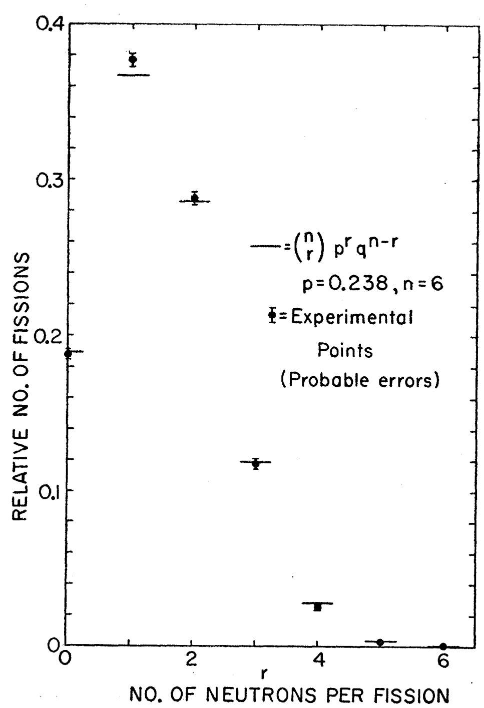

FIG. 1. Observed neutron number distribution arising from the spontaneous fission of Cf^{252}.