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Neutron Yields from Alpha-Particle Bombardment

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Thick-target (α,n) *neutron yields have been measured for* $^{6,7,NAT}Li$, ^{9}Be, $^{10,11,NAT}B$, $Pb^{19}F_2$ *and* $Zn^{19}F_2$, ^{NAT}Mg, ^{27}Al, ^{NAT}Si, *and* $^{28}Si^{NAT}O_2$. *From the* $Pb^{19}F_2$ *and* $Zn^{19}F_2$ *data, we have extracted the neutron yield that would result from the* (α,n) *reaction on a thick target of pure fluorine. Using the* $^{28}Si^{NAT}O_2$ *data, we have extracted the yield that would result from the* (α,n) *reaction on a thick target of pure* $^{NAT}O_2$ *and the* $^{NAT}O(\alpha,n)$ *cross section at alpha-particle energies above those for which measurements previously existed. In addition, we have remeasured the thin-target oxygen cross section to obtain a correction to the previously measured values. Thick-target yields are calculated from the cross-section values for carbon and oxygen and are compared to the experimental thick-target data. Thick-target yields for* $^{238}U^{NAT}O_2$ *and for* $^{238}U^{NAT}C$ *are calculated from the thin-target cross sections. Results are compared to existing experiment and calculations.*

INTRODUCTION

In recent years, there has been a reawakening of engineering interest in the neutron yields produced when alpha particles bombard light elements. Unfortunately, very little of the desired data was available; even worse, some of the existing data were incorrect. When we attempted to use our[1] published $^{13}C(\alpha,n)$ thin-target cross sections to calculate the neutron yield from an infinitely thick target of natural isotopic carbon, the calculated result differed from the published[2] infinitely thick target work by a very large error. This discovery led to our remeasurement of the infinitely thick carbon yield. This new measurement,[3] estimated to be accurate to ±5%, led to the discovery of an error in the processing of the earlier thick-target yield data.[2] In a similar way, when we calculated the neutron yield from $^{238}PuO_2$ using the thin-target ^{17}O and $^{18}O(\alpha,n)$ cross-section data,[1,4] we found that the result was about one-third lower than the precision value[5] of the yield from a high-purity $^{238}PuO_2$ source. This discrepancy was surprising, but not impossible, in view of the stated 23% error in the cross section and the ±5% uncertainty in the values of the alpha-particle energy loss. Our interest in these discrepancies, together with recent requests for thick-target (α,n) yields for various target materials, culminated in the present series of measurements.

EXPERIMENTAL METHOD

The alpha-particle beams used in the present series of measurements were produced by the Oak Ridge National Laboratory Tandem Van de Graaff. Energies are known to better than 0.2%. The neutrons were detected by means of the graphite sphere neutron detector.[6] This detector consists of a 1.5-m (5-ft)-diam sphere of reactor-grade graphite with eight ^{10}B-enriched BF_3 counters imbedded near the surface. It was last calibrated against the National

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[1] J. K. BAIR and F. X. HAAS, *Phys. Rev.*, **C7**, 1356 (1973).

[2] R. L. MACKLIN and J. H. GIBBONS, *Nucl. Sci. Eng.*, **31**, 337 (1968).

[3] J. K. BAIR, *Nucl. Sci. Eng.*, **51**, 83 (1973).

[4] J. K. BAIR and H. B. WILLARD, *Phys. Rev.*, **128**, 299 (1962).

[5] J. K. BAIR and H. M. BUTLER, *Nucl. Technol.*, **19**, 202 (1973).

[6] R. L. MACKLIN, *Nucl. Instrum.*, **1**, 335 (1957).

Bureau of Standards NBS-II source in June 1970. The calibration has been recently checked by use of a local Ra-γ-Be source, which had been compared directly to NBS-II during the 1970 calibration. This detector and its use are discussed further in Ref. 7. In the present usage, the target is placed on the end of a 1-m-long vacuum beam pipe extension of the accelerator; the carriage on which the graphite sphere rests is then moved so that the target is positioned in the center of the sphere during bombardment.

This detector, like many or most other neutron detectors, has the undesirable attribute that the neutron detection efficiency falls off for high-energy neutrons. For the graphite sphere, this effect is well understood. If the energy spectrum of the neutrons being measured is known, it is possible to use the efficiency curve given in Ref. 6 to make a suitable correction. Since detailed neutron energy spectra are not available for all the reactions studied in this paper, we have not made the correction although estimates are given. If suitable spectra become available in the future, the present data can be corrected at that time.

Since the graphite sphere detects neutrons with no discrimination as to the reaction that produced them, our measured yields, while mainly (α,n) neutron yields, may in some cases include other reactions; for example, the threshold for the $^{6}\mathrm{Li}(\alpha,np)$ reaction is 6.3 MeV, and that for the $^{10}\mathrm{B}(\alpha,np)$ reaction is only 1.2 MeV. Such neutrons are, of course, neutrons produced by the alpha-particle bombardment of the target material and should be counted as such. However, an error would occur if the data presented here were used to determine, for example, the yield of the residual nucleus.

CARBON

In the paper giving our $^{13}\mathrm{C}(\alpha,n)$ thin-target cross-section data,[1] we estimated our error as ±20%, but in a footnote we stated that the data must be reduced by 15 to 20% to match smoothly with our thick-target measurements,[3] which, at that time, had not yet been published. Reference 3 again stated that the thin-target data must be reduced by 15%. This reduction is in excellent agreement with that which Johnson[8] found necessary in his detailed analysis of the $(^{16}\mathrm{O} + n)$ reactions. When these cross sections and the energy loss values given by Whaling[9] are used to calculate the yield from an infinitely thick carbon target, the results join smoothly with the precision (±5%) thick-target measurements of Ref. 3. As pointed out in a footnote to Ref. 3, those data were in good agreement with the older data of Ref. 2 when the older data were reanalyzed. Thus, the infinitely thick carbon neutron yield is given by Ref. 3 to an accuracy of ±8% below ~5 MeV and ±5% above that value.

Liskien and Paulsen[10] recently published a paper in which they have surveyed the existing data and calculated thick-target (α,n) yields from various targets. They stated that their uncertainties are, in general, ±20 to ±30%, although these values may be surpassed in some cases. In the case of carbon, they used our thick-target data above ~5.25 MeV and calculated the yield below that energy from the thin-target data of Sekharan et al.[11] and of Bair and Haas.[1] They state the the latter data gave results ~30% high but that the Sekharan et al. data agreed well in the region of overlap with the high-energy thick-target data. This is in disagreement with our results.

It is difficult to compare our thin-target carbon cross sections with those of Sekharan et al. because our target thickness was some 20 times less than that of Sekharan et al.; however, it is apparent that their cross sections are lower than ours even after our published values are reduced by 15%, as they should be (see above). For example, in the flat region between 4.7 and 4.8 MeV, we measured ~40 mb, whereas the value read from the Sekharan et al. curve is ~22 mb. Thus, even reducing our value by the above 15%, the Sekharan et al. value is only about two-thirds of ours.

Liskien and Paulsen[10] used the energy loss data of Ziegler and Chu[12] below 4 MeV. Above 4 MeV, they used the values of Williamson et al.[13] normalized at 4 MeV to the values of Ref. 12. When we follow this prescription, we obtain, in the region from 3 to 9 MeV, values 17% lower than those of Whaling,[9] which we had used. At the present time, we use the more modern energy loss data of Ref. 14, which agree with Whaling's data to within ±3% in the above energy region. Note that the use of the low energy loss values tends to raise the calculated integral yield and thus to compensate for the use of low cross-section values. This result is that the calculated carbon

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[7] E. L. ROBINSON, J. K. BAIR, and J. L. DUGGAN, *Health Phys.*, **28**, 205 (1975).

[8] C. H. JOHNSON, *Phys. Rev.*, **C7**, 561 (1973).

[9] W. WHALING, in *Handbuch der Physik*, Vol. 34, S. FLUGGE, Ed., Springer-Verlag, Berlin (1958).

[10] H. LISKIEN and A. PAULSEN, *Atomkernenergie*, **30**, 1 (1977).

[11] K. K. SEKHARAN, A. S. DIVATIA, M. K. MEHTA, S. S. KEREKATTE, and K. B. NAMBIAR, *Phys. Rev.*, **156**, 1187 (1967).

[12] J. F. ZIEGLER and W. K. CHU, *At. Data Nucl. Data Tables*, **13**, 463 (1974).

[13] C. F. WILLIAMSON, J. P. BONJOT, and J. PICARD, "Tables of Range and Stopping Power of Chemical Elements for Charged Particles of Energy 0.5 to 500 MeV," CEA-R-3042, Commissariat à l'Energia Atomique, Saclay (1966).

[14] L. C. NORTHCLIFFE and R. F. SCHILLING, *Nucl. Data Tables*, 7, 233 (1970).

yields of Liskien and Paulsen are only 13% lower than ours in the flat region between 3.5 and 4 MeV.

OXYGEN, THIN TARGETS

We have recently obtained a new value for the absolute cross section of the $\mathrm{O}(\alpha,n)$ reaction. Measurements were made using a tantalum disk that had been anodized in water containing natural isotopic ratio oxygen. The anodized layer contained a carefully weighed amount of oxygen (50.5 μg/cm^2). Yield measurements taken for 4.62 MeV $< E_\alpha <$ 4.8 MeV, where the cross section is fairly flat, together with background measurements taken with a plain tantalum blank, resulted in a cross section for $^{18}\mathrm{O}(\alpha,n)$ 1.35 times the value given in Ref. 4, slightly outside the sum of the errors of the two measurements. Since the $^{17}\mathrm{O}(\alpha,n)$ and $^{18}\mathrm{O}(\alpha,n)$ measurements of Ref. 1 are based on the value given in Ref. 4, the ^{17}O and ^{18}O cross-section values of both Refs. 1 and 4 should be multiplied by 1.35 and have a new error assigned of about ±7%.

OXYGEN, INFINITELY THICK TARGETS

Measurements were made on targets of SiO_2 in which the silicon had been isotopically enriched to 99.85% ^{28}Si and contained only 0.11% ^{29}Si and 0.04% ^{30}Si. Since the $^{28}\mathrm{Si}(\alpha,n)$ reaction has a negative Q value of over 8 MeV, there is no contribution to the neutron yield from that reaction for the bombarding energies used here.

The points shown in Fig. 1 are the present experimental values for $^{28}\mathrm{SiO}_2$ uncorrected for the falloff of detector efficiency with increasing neutron energy. This correction is known[5] to be (+1.9 ± 0.2)% at a 5.5-MeV alpha-particle energy. Since the energy distribution of the emitted neutrons is not known at other bombarding energies, it is not possible to make the correction at this time. One would expect it to be always less than perhaps 4%. Other than that, the overall absolute error is ±3%. The dashed line in Fig. 1 gives an estimate of the neutron yield from the ^{29}Si and ^{30}Si impurity in the target.

OXYGEN, CALCULATIONS

Using the revised $^{17}\mathrm{O}(\alpha,n)$ and $^{18}\mathrm{O}(\alpha,n)$ cross sections and the energy loss values of Northcliffe and Schilling,[14] we have calculated the neutron yield to be expected from the alpha-particle bombardment of infinitely thick targets of $^{28}\mathrm{SiO}_2$. These calculated values are given by curve marked "x5" in Fig. 1. Since the cross-section data available do not extend above ~5.15 MeV, neither do the calculated yield curves. Since the calculations use energy loss data with an estimated error of ±5% and the revised cross sections have an error of ±7%, we believe that the calculated yields are reliable to ±9%. The agreement of the calculated curves and experimental points in Fig. 1 tends to verify this.

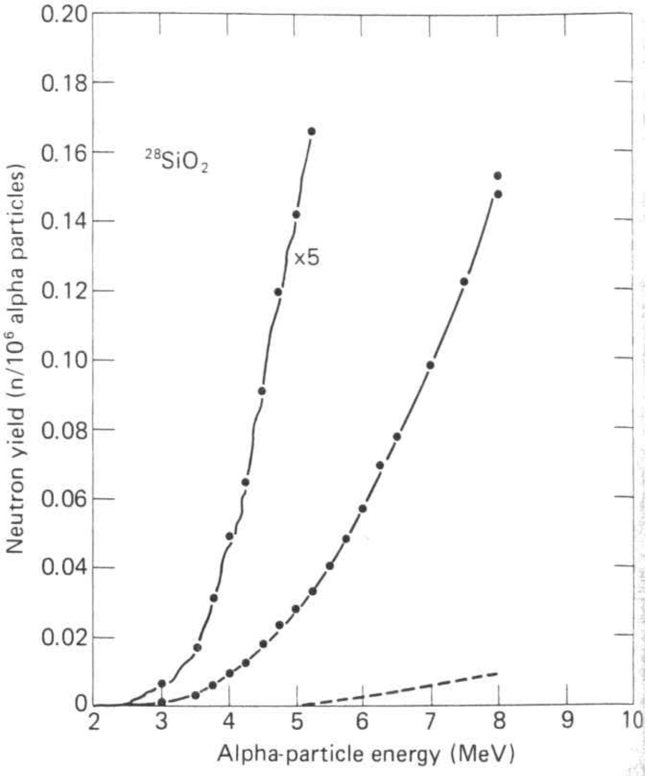

Fig. 1. The curve marked "x5" shows the calculated yield of neutrons to be expected from the alpha-particle bombardment of an infinitely thick target of $^{28}\mathrm{SiO}_2$ (having the natural isotopic ratio of oxygen) as calculated from our measured thin-target cross sections. The data points shown are from the current thick-target measurements. The smooth curve *not* marked x5 is merely a guide to the eye. The dashed line is an estimate of the neutron yield from ^{29}Si and ^{30}Si impurities.

Liskien and Paulsen[10] have recently published a yield curve for alpha particles on $^{\mathrm{NAT}}$O, which they derived from our old thin-target cross-section data.[1,4] These are just the data that the current work finds low and thus should be multiplied by a factor of 1.35. If this is done, their data then range from 20% higher than what we calculate at 3 to 4 MeV to agreement at 5 MeV. Perhaps this discrepancy may be due to the use of different alpha-particle stopping powers.

Above 5 MeV, reliable cross-section data have not been available. As a result, we have used our $^{28}\mathrm{SiO}_2$ yield data of Fig. 1 to calculate cross-section values for natural isotopic oxygen from 5 to 8 MeV. These results are given in Fig. 2. They are estimated to have an overall error of <10%. It must be noted that these data are obtained from smooth curves fitted to $^{28}\mathrm{SiO}_2$ yields obtained at 0.25- to 0.5-MeV intervals of

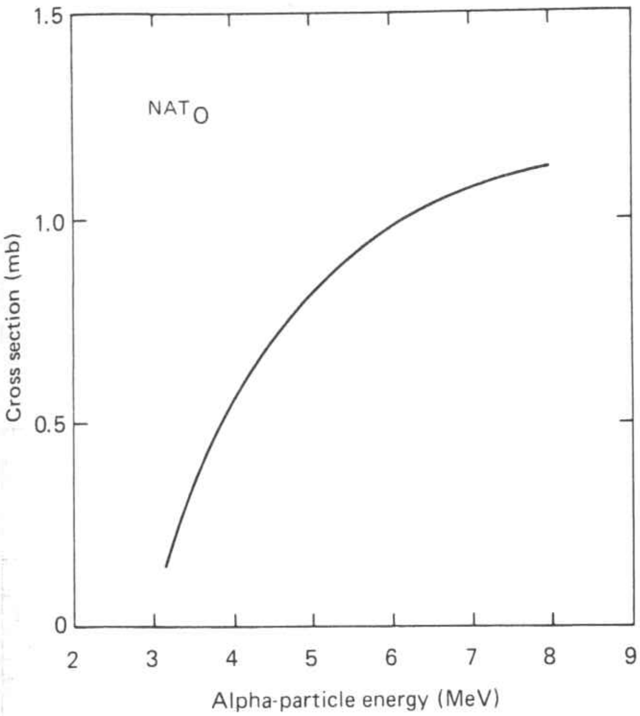

Fig. 2. The neutron production cross section for the reaction of alpha particles on a thin target of oxygen of natural isotopic content. These data are calculated from the thick-target data of Fig. 1. The averaging interval is 250 keV.

bombarding energy; thus, they are averaged over a much wider ΔE than our thin-target data of Ref. 4. While the oxygen yields calculated from these averaged cross sections agree with those calculated from the thin-target data to better than 10%, the use of the thin-target cross section is much to be preferred in the region (below 5.1 MeV) where they exist and where the cross section is known to fluctuate rapidly as a function of bombarding energy.

Using the thin-target cross sections where they exist and the cross sections of Fig. 2 above ~5 MeV, we have calculated the neutron yield for ^{238}Pu alpha particles in $^{238}PuO_2$ to be 0.0240 neutrons per 10^6 alpha particles. This is 5.7% higher than the value given in Ref. 5 for a high-purity $^{238}PuO_2$ source after correcting the source value for spontaneous fission.

Liskien and Paulsen[10] used the only cross-section information available, the very low resolution data of Hansen et al.,[15] to calculate the yield from 5 to 7 MeV, normalizing the data to our old thin-target cross sections at 4.7 MeV. We have used our calculated cross sections of Fig. 2 to extend the yield from pure oxygen to 8 MeV. These data are shown in Fig. 3. The yield based on the Hansen et al.[15] data, as reported by Liskien and Paulsen (corrected by 1.35), is approximately equal to ours at 5.5 MeV and 7% lower at 7 MeV.

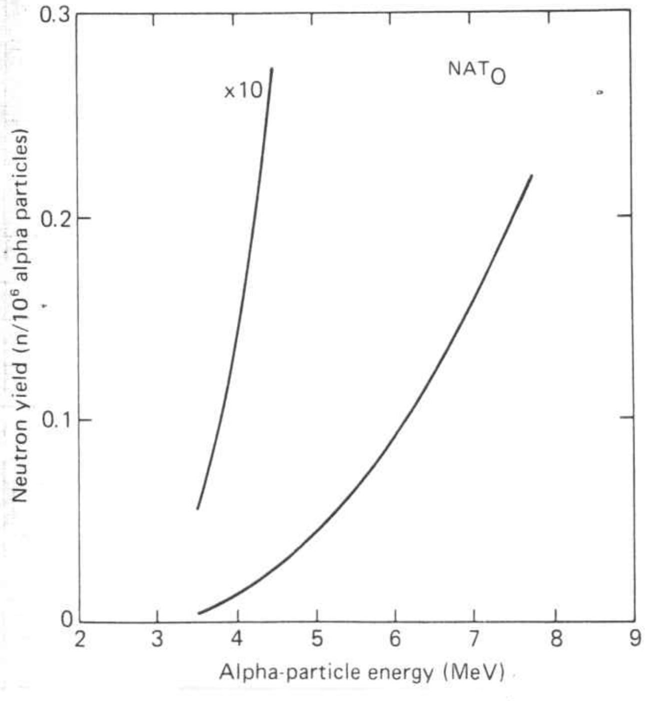

Fig. 3. The curves show the yield of neutrons from an infinitely thick target of oxygen of natural isotopic content calculated from the measured yield from an infinitely thick target of $^{28}SiO_2$. The points are the same results calculated from thin-target cross sections.

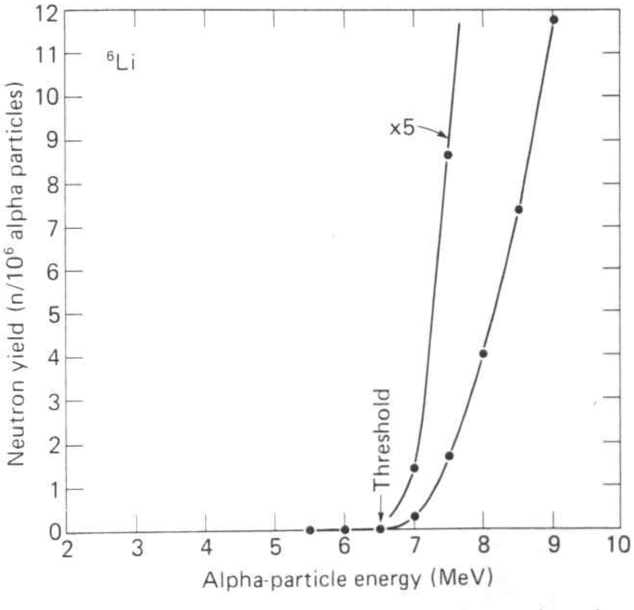

Fig. 4. The experimental yield of neutrons resulting from the alpha-particle bombardment of an infinitely thick target of ^{6}Li. The data have been corrected for the small amount of ^{7}Li in the enriched target. The smooth curves are merely guides to the eye.

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[15] L. F. HANSEN et al., *Nucl. Phys.*, **A98**, 25 (1967).

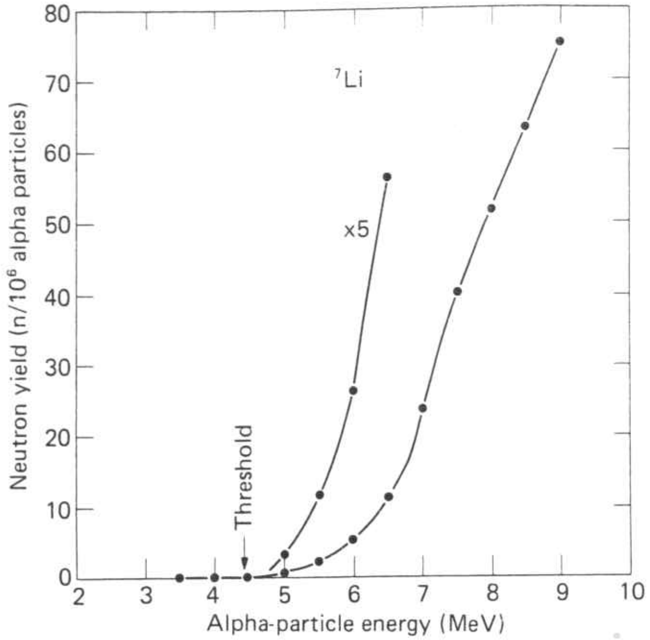

Fig. 5. The experimental yield of neutrons resulting from the alpha-particle bombardment of an infinitely thick target of ^{7}Li. The data have been corrected for the small amount of ^{6}Li in the enriched target. The smooth curves are merely guides to the eye.

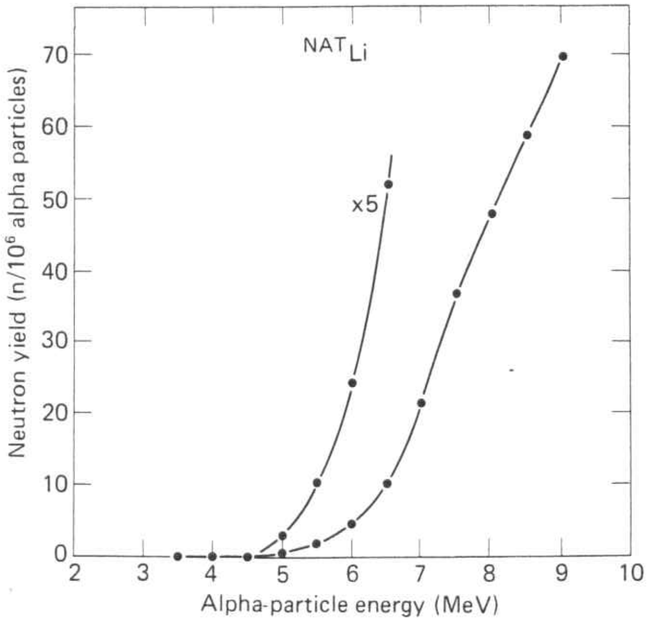

Fig. 6. The data points show the yield of neutrons resulting from the alpha-particle bombardment of an infinitely thick target of lithium of natural isotopic concentration as calculated from the measured yields (Figs. 4 and 5) of the separated isotopes. The smooth curves are merely guides to the eye. A comparison of these results with those measured using an infinitely thick target of natural isotopic lithium indicates that the calculated results are lower by 3% below 7.5 MeV and by 0.6% for alpha particles above that energy.

TABLE I

The Yield of Neutrons per 10^6 Alpha Particles from Infinitely Thick Targets of Various Materials as a Function of the Initial Energy of the Bombarding Alpha Particle

(See text for details of certain corrections not included in these data.)

Energy (MeV)	^{6}Li	^{7}Li	^{NAT}Li	^{9}Be	^{10}B	^{11}B	^{NAT}B	^{19}F	^{NAT}Mg	^{27}Al	^{NAT}Si	^{238}U^{NAT}O$_2$	^{238}U^{NAT}C
3.00				9.790								0.00091	0.00468
3.50		0.001	0.001	12.97	0.331	3.803	3.150	0.31		0.0012		0.00208	0.00810
4.00		0.002	0.002	19.88	0.758	7.618	6.238	0.879	0.077	0.0169		0.00593	0.00842
4.50		0.030	0.028	33.27	1.924	12.64	10.63	2.159	0.263	0.0802	0.016	0.0107	0.00943
5.00		0.680	0.629	49.43	3.552	18.43	15.64	4.394	0.644	0.2643	0.052	0.0164	0.0119
5.50		2.325	2.150	71.81	5.674	24.05	20.59	7.746	1.262	0.6967	0.114	0.0236	0.0193
6.00	0.000	5.268	4.873	99.16	8.578	29.24	25.35	12.26	2.141	1.438	0.231	0.0321	0.0295
6.50	0.000	11.26	10.41	126.2	12.29	33.92	29.85	17.95	3.250	2.780	0.385	0.0416	0.0423
7.00	0.294	23.42	21.68	154.8	16.78	37.52	33.62	24.84	4.600	4.657	0.602	0.0520	0.0574
7.50	1.733	40.03	37.16	185.5	20.67	42.27	38.21	32.95	6.352	7.131	0.872	0.0631	0.0747
8.00	4.054	51.71	48.14	221.3				42.17	8.349	10.13	1.226		0.0939
8.50	7.428	63.32	59.13	259.1					10.55	13.77	1.666		0.114
9.00	11.80	74.99	70.25	302.5					13.29	17.99	2.191		0.136

LITHIUM

We have measured the infinitely thick target neutron yield from ^{6}Li, ^{7}Li, and "natural isotopic" lithium. The results for ^{6}Li and ^{7}Li are shown in Figs. 4 and 5. Modern natural isotopic lithium is always suspect. Thus, Table I and Fig. 6 give the yield for natural lithium as calculated from the measured results for separated ^{6,7}Li. This calculated ^{NAT}Li yield, when compared to our measurements on a natural isotopic sample, was 3% low below 7.5 MeV and 0.6% low above 7.5 MeV. The correction for the falloff of detector efficiency is negligible. No data on ^{6}Li or ^{7}Li were previously available. The new data on lithium, when compared to the old data of Macklin and Gibbons,[16,17] as converted to yields and reported by Liskien and Paulsen,[10] are 32% lower at 4.5 MeV, 13% lower at 5.0 MeV, 21% lower at 5.5 MeV, and are within ±4% between 6 and 7 MeV.

BERYLLIUM

Figure 7 shows the experimental yield of neutrons resulting from the alpha-particle bombardment of an infinitely thick target of high-purity beryllium metal. This reaction produces a very high percentage of high-energy neutrons. Thus, the correction for the falloff of detector efficiency with neutron energy is unusually large. No such correction has been made. Using the Anderson[18] spectrum for 5.5-MeV alpha

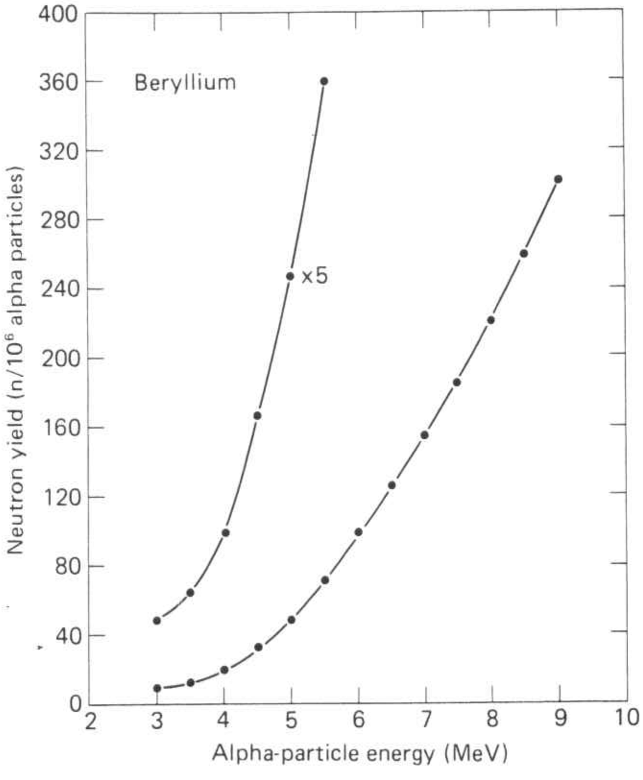

Fig. 7. The experimental yield resulting from the alpha-particle bombardment of an infinitely thick target of high-purity beryllium metal. This reaction produces a very high percentage of high-energy neutrons. Thus, the correction for the falloff of detector efficiency with neutron energy is unusually large; no such correction has been made (see text). The smooth curves are merely guides to the eye.

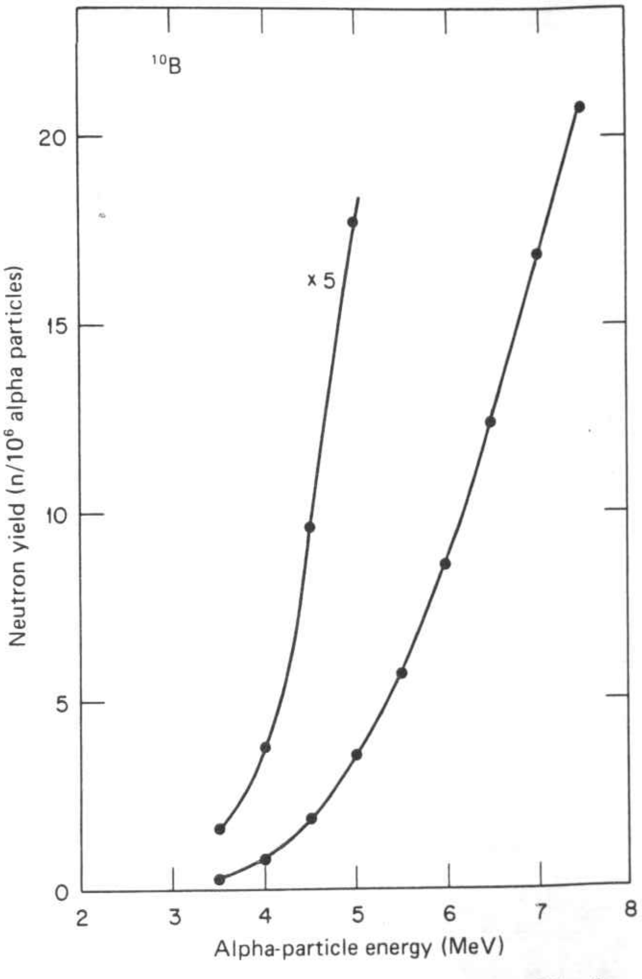

Fig. 8. The experimental yield of neutrons resulting from the alpha-particle bombardment of an infinitely thick target of enriched elemental ^{10}B. The data have been corrected for the small amount of ^{11}B in the target. The smooth curves are merely guides to the eye.

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[16] R. L. MACKLIN and J. H. GIBBONS, *Phys. Rev.*, **165**, 1147 (1968).

[17] J. H. GIBBONS and R. L. MACKLIN, *Phys. Rev.*, **114**, 571 (1959).

[18] M. E. ANDERSON, "Neutron Energy Spectra of ^{239}PuBe, ^{238}PuF, and ^{238}Pu^{18}O (α,n) Sources," MLM 1422, Monsanto Research Corporation, Mound Laboratory (1967).

particles, we derive a correction of (+6.9 ± 2)% at that energy. We might estimate a correction at 9 MeV of perhaps (+10 ± 4)%. The beryllium target used in these measurements was, for mechanical reasons, considerably thicker than the range of the alpha particles; thus, a small correction is needed to account for neutrons produced by the $^{9}\text{Be}(n,2n)$ reaction. This correction depends on the energy spectrum of the primary $^{9}\text{Be}(\alpha,n)$ neutrons and is −1.4% at $\sim$5.15 MeV, where the neutron spectrum[18] is known. No such correction has been applied to the data, since it is not known at other neutron energies. The uncertainty, other than the above, is estimated to be ±4%.

Runnalls and Boucher[19] have obtained thick-target yields from measurements made on actinide-beryllium alloys. Their results are $\sim$7% higher than ours in the region from 5 to 6 MeV. Anderson and Hertz[20] have obtained a value at polonium-alpha-particle energy (5.3 MeV) that is 11% higher than ours. Anderson and Hertz[20] also calculated the thick-target yield using the data of Gibbons and Macklin[21] and Bader et al.,[22] and normalizing the result to their source value at 5.3 MeV. These results run 10 or 11% above our results uncorrected for the graphite sphere efficiency, a

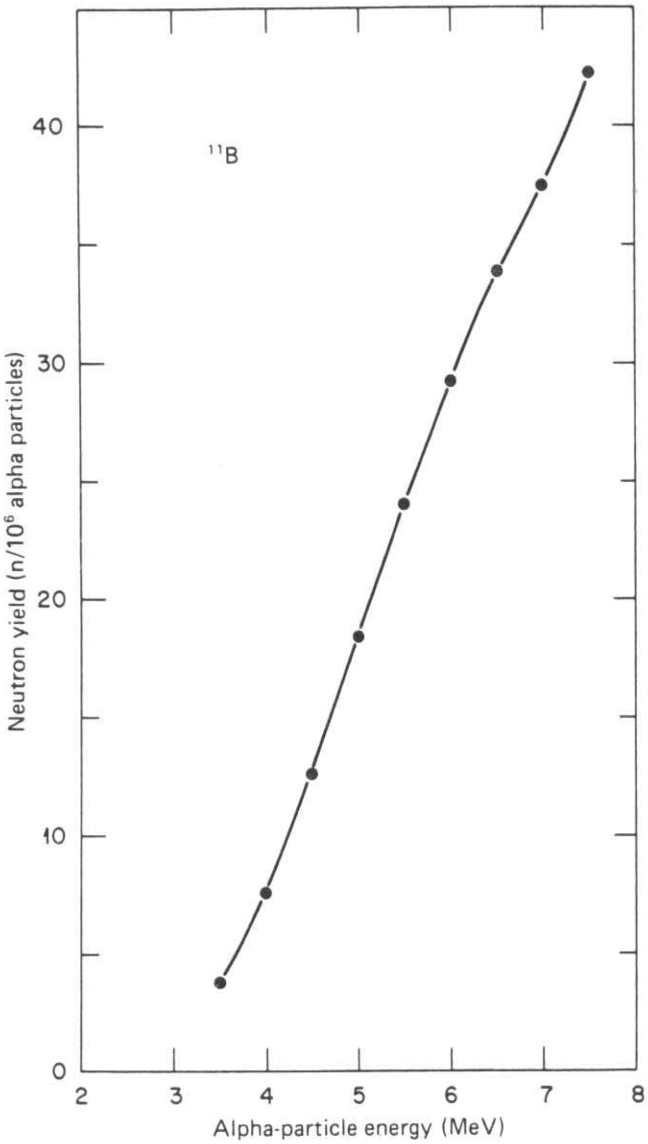

Fig. 9. The experimental yield of neutrons resulting from the alpha-particle bombardment of an infinitely thick target of enriched elemental ^{11}B. The data have been corrected for the small amount of ^{10}B in the target. The smooth curve is merely a guide to the eye.

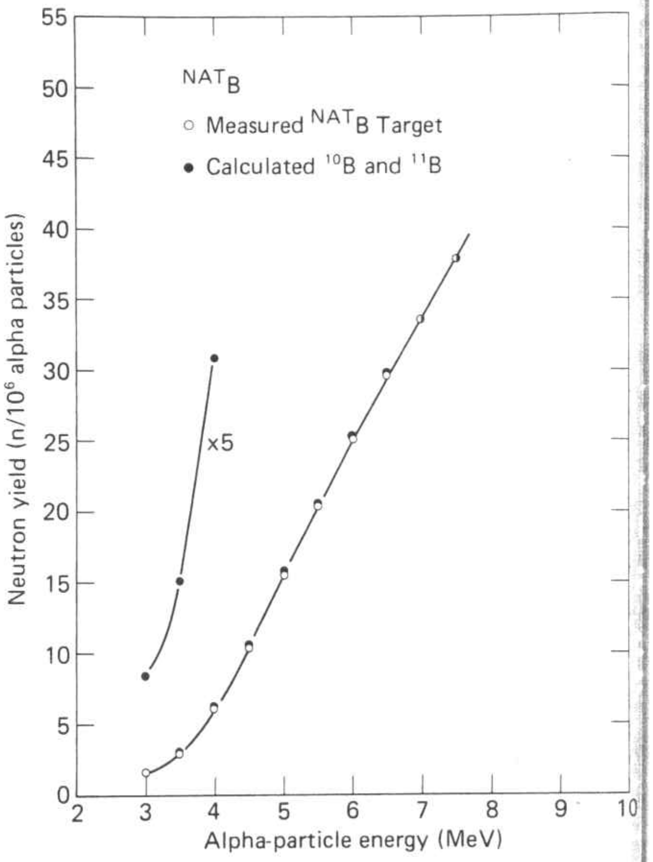

Fig. 10. The experimental yield of neutrons, shown by open circles, resulting from the alpha-particle bombardment of an infinitely thick target of elemental boron having the natural isotopic mixture. The closed circles are calculated from the measurements made on the separated isotopes. The smooth curves are merely guides to the eye.

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[19] O. J. C. RUNNALLS and R. R. BOUCHER, *Can. J. Phys.*, **34**, 949 (1956).

[20] M. E. ANDERSON and M. R. HERTZ, *Nucl. Sci. Eng.*, **44**, 437 (1971).

[21] J. H. GIBBONS and R. L. MACKLIN, *Phys. Rev.*, **137**, B1508 (1965).

[22] M. BADER, R. E. PIXLEY, F. S. MOZER, and W. WHALING, *Phys. Rev.*, **103**, 32 (1956).

correction that would make our results in excellent agreement with theirs. The Liskien and Paulsen[10] results, based on a cross-section evaluation of Geiger and Van der Zwan,[23] run 30 to 40% higher than ours in the region of overlap (3 to 7 MeV).

BORON

We have measured the thick-target (α,n) yield from ^{10}B, ^{11}B, and the natural isotopic mixture. These data, shown in Figs. 8, 9, and 10, have not been corrected for the falloff of detector efficiency with neutron energy. Using the neutron spectrum of polonium alpha particles on ^{NAT}B obtained by Cochran and Henry,[24] we determined this correction to be (+3 ± 1)%. At a 7-MeV alpha-particle energy, we estimate this correction might be (+5 ± 2)%. This correction for ^{11}B would be expected to be similar. No neutron spectra seem to be available for ^{10}B. Exclusive of this uncertainty, the overall error is estimated to be ±4%. The values for ^{NAT}B calculated from our results for ^{10}B and ^{11}B average ~3.5% higher than the measured results for ^{NAT}B. The data of Walker[25] for natural boron as converted to yields and reported by Liskien and Paulsen[10] are 65 to 53% higher than the present work in the energy region from 3.5 to 5 MeV.

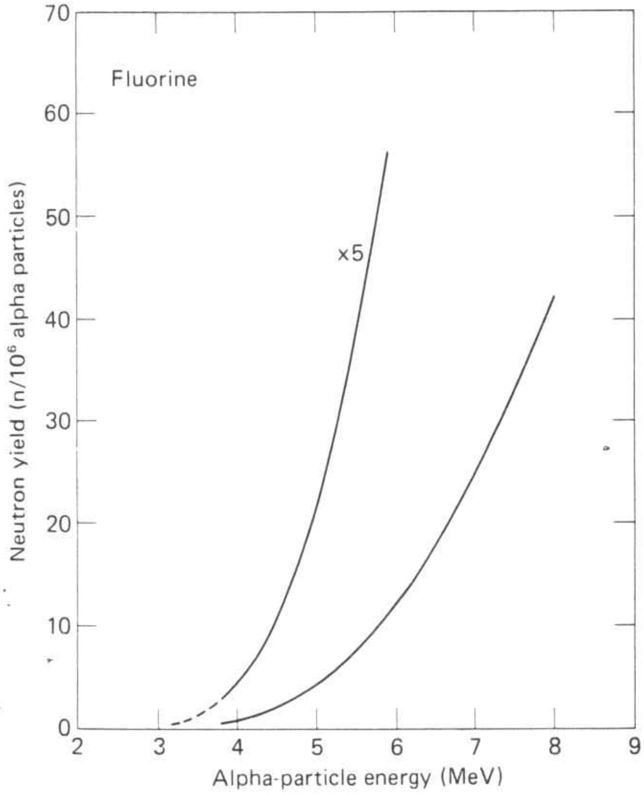

Fig. 11. The yield of neutrons that would result from the alpha-particle bombardment of an infinitely thick fluorine target. The data shown are derived from our measured yields from infinitely thick targets of high-purity lead fluoride and zinc fluoride. The fluorine results derived from each of the two fluorides differ from their average (shown here) by <3%.

FLUORINE

Figure 11 shows the yield of neutrons that would result from the alpha-particle bombardment of an infinitely thick fluorine target. The data shown are derived from our measured yields from infinitely thick targets of lead fluoride and zinc fluoride. The fluorine results derived from each of the two fluorides differ from their average (shown here) by <3%.

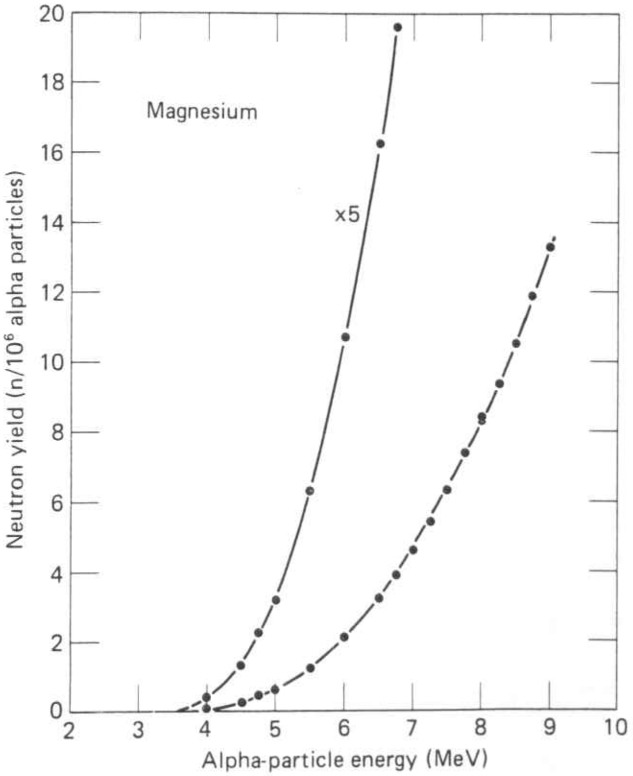

Fig. 12. The experimental yield of neutrons resulting from the alpha-particle bombardment of an infinitely thick target of magnesium metal of normal isotopic ratio. The smooth curves are merely guides to the eye.

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[23] K. W. GEIGER and L. VAN DER ZWAN, "An Evaluation of the ^{9}Be(α,n) Cross-Section," PXNR-2404, Document No. 15303 of the National Research Council of Canada (1976).

[24] R. C. COCHRAN and K. M. HENRY, *Rev. Sci. Instum.*, **26**, 757 (1955).

[25] R. L. WALKER, *Phys. Rev.*, **76**, 244 (1949).

Since this difference also involves errors in the energy loss values used in the computations, the agreement is considered to be quite satisfactory. The yield below 3.8 MeV is obtained from an extrapolation of cross-section data (calculated from the lead and zinc fluoride data) to the threshold and thus is subject to an extra uncertainty ranging from perhaps 15% at low energies to perhaps 5% at 3.8 MeV. The correction for the falloff of detector efficiency has not been made but, using the neutron spectra of Anderson,[18] is calculated to be +0.9% at 5.5 MeV, decreasing to zero at low alpha-particle energies. Spectral data are not available at high alpha-particle energies; however, we estimate that the correction at 9 MeV would be (+2 ± 1)%. With the above exceptions, the overall accuracy is estimated to be ±7%. No other data for fluorine are known.

MAGNESIUM

Figure 12 shows the yield of neutrons from a target of high-purity magnesium metal. Since no neutron energy spectra are available, no graphite sphere efficiency correction has been made. This correction can be roughly estimated as (+5 ± 3)%. The overall error, exclusive of this uncertainty, is ±5%. The data of Halpern,[26] as used by Liskien and Paulsen,[10] are 30% higher than the present data at 4 MeV, 3% higher at 4.5 MeV, and 10% lower at 5 MeV.

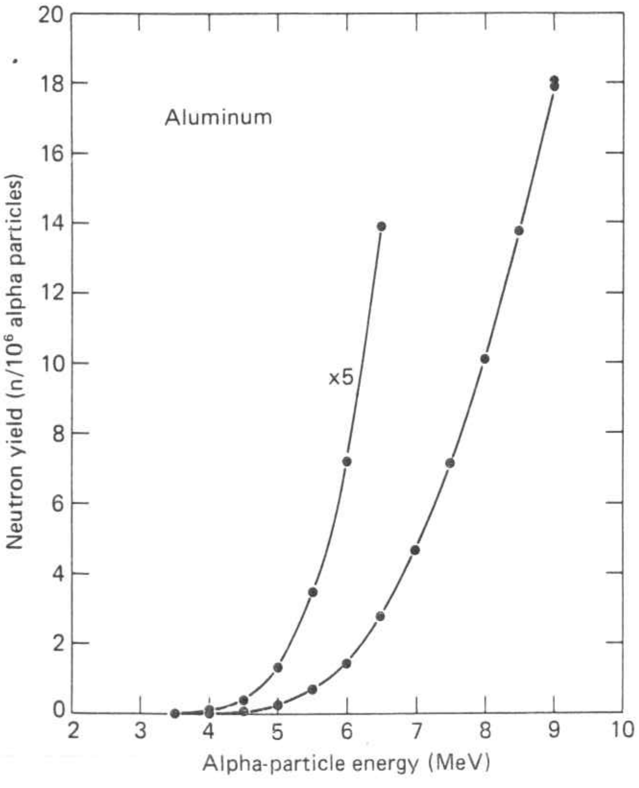

Fig. 13. The experimental yield of neutrons resulting from the alpha-particle bombardment of an infinitely thick target of aluminum. The smooth curves are merely guides to the eye.

ALUMINUM

Figure 13 shows the yield of neutrons from a target of high-purity aluminum metal. We have made no sphere efficiency correction due to lack of suitable neutron energy spectra. We roughly estimate that this correction might be (+4 ± 3)%. Exclusive of this, the overall error is ±3%. Liskien and Paulsen[10] have published an Al(α,n) yield based on the measurements of Stelson and McGowan[27] above 5.2 MeV and on the

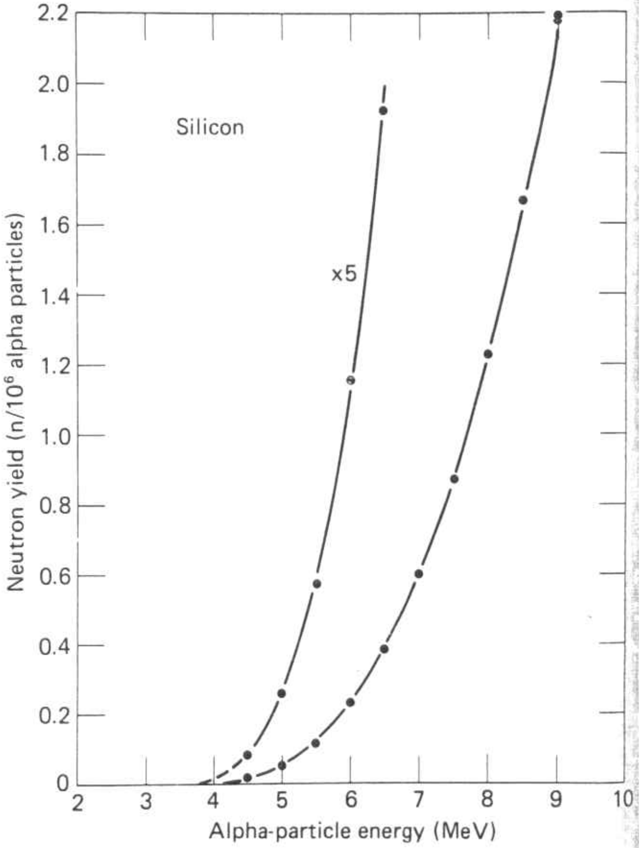

Fig. 14. The experimental yield of neutrons resulting from the alpha-particle bombardment of an infinitely thick target of elemental silicon of normal isotopic ratio. The smooth curves are merely guides to the eye.

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[26] I. HALPERN, *Phys. Rev.*, **76**, 248 (1949).

[27] P. H. STELSON and F. K. McGOWAN, *Phys. Rev.*, **133**, B911 (1964).

measurements of Howard et al.[28] below 6.1 MeV. Our new results are ~4% lower than those of Ref. 27, and those of Ref. 10 in the region from 5.2 and 7.0 MeV, while at 9 MeV, the new results are 9% lower. In the region from 3 to 5 MeV, the new data are ~10% lower than the results quoted by Liskien and Paulsen.[10] Thus, all the data are in agreement well within the various errors stated by the authors. In particular, the published results of Stelson and McGowan[27] are now known to be 2% high due to a better calibration of the graphite sphere neutron detector: by making this correction, the new results agree within 2% from 5.2 to 7 MeV.

SILICON

Figure 14 shows the measured yield of neutrons from an infinitely thick target of natural isotopic elemental silicon. No sphere efficiency corrections have been made, since no suitable neutron energy spectra are available. We would roughly estimate such a correction to be (+5 ± 3)%. Exclusive of this uncertainty, we estimate the overall error to be ±5%. The calculated values given by Liskien and Paulsen[10] are almost a factor of 2 higher than our measurement. We have integrated the recent thin-target data of Flynn et al.[29] for ^{29}Si and ^{30}Si to obtain the thick-target yield for ^{NAT}Si. The values so obtained are ~30% higher than ours in the region of overlap, 4.5 to 6.0 MeV. This discrepancy is somewhat surprising in view of their stated error of ±8% and an error of not more than ±5% for the energy loss values used in the calculation and an error of ~5% in our measurement.

URANIUM COMPOUNDS

As indicated earlier, we believe that the present carbon and oxygen cross sections combined with the best of the existing energy loss values permit the calculation of thick-target (α-n) yields to an accuracy of ~10%. We have therefore calculated the yield to be expected from the alpha-particle bombardment of infinitely thick targets of $^{238}U^{NAT}O_2$ and $^{238}U^{NAT}C$ (assuming zero alpha particles are emitted from the ^{238}U).

Figure 15 shows the yield calculated for $^{238}U^{NAT}O_2$. As a check on the reliability of this calculation, we note that $^{238}PuO_2$ is, from the standpoint of energy loss per atom, very similar to $^{238}UO_2$. The measured[5] yield of neutrons per gram of ^{238}Pu in

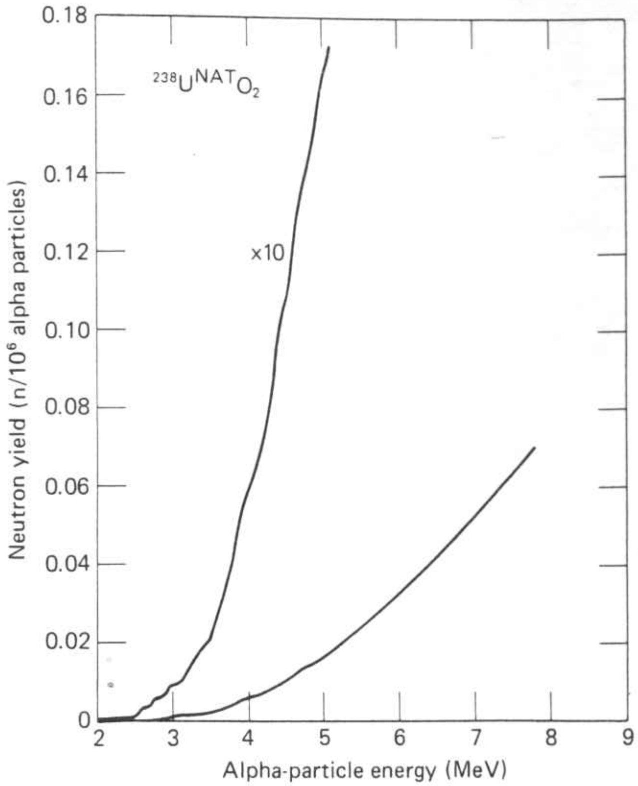

Fig. 15. The calculated yield of neutrons to be expected from the alpha-particle bombardment of an infinitely thick target of $^{238}UO_2$ whose oxygen has the normal isotopic ratios.

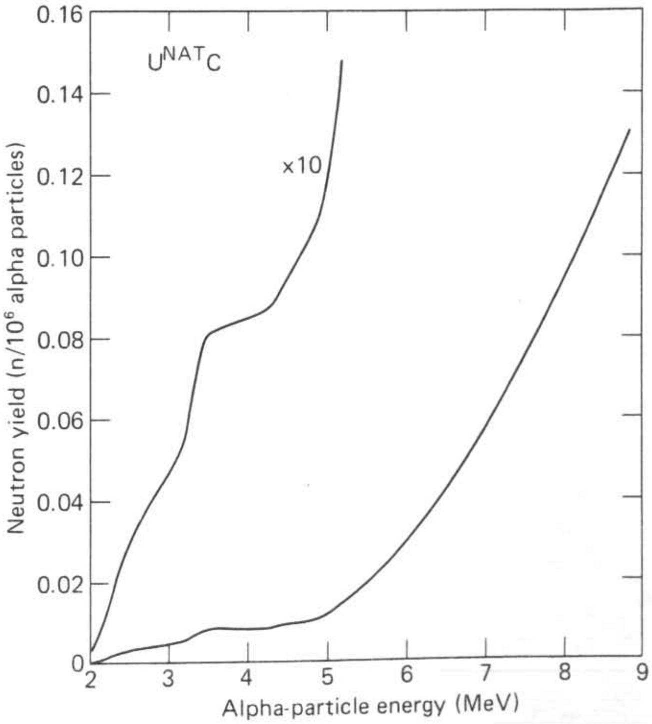

Fig. 16. The calculated yield of neutrons to be expected from the alpha-particle bombardment of an infinitely thick target of ^{238}UC whose carbon has the normal isotopic ratio.

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[28] A. J. HOWARD, H. B. JENSEN, M. RIOS, W. A. FOWLER, and B. A. ZIMMERMANN, *Astrophys. J.*, **188**, 131 (1974).

[29] D. S. FLYNN, K. K. SEKHARAN, B. A. HILLER, H. LAUMER, J. L. WEIL, and F. GABBARD, to be published in *Phys. Rev. C* (1978).

a $^{238}PuO_2$ source converts to 0.0227 neutrons per 10^6 ^{238}Pu alpha particles, corrected for spontaneous fission. The value from Fig. 15 for alpha particles of the same energy is 0.0236 or 4% higher. At this same energy, the results of Liskien and Paulsen[10] are 33% lower than ours, with the discrepancy increasing to a factor of 2 lower at 7 MeV.

Figure 16 shows the neutron yield calculated for $^{238}U^{NAT}C$ using our thin-target carbon cross sections below ~5 MeV and the carbon cross section extracted from our thick-target neutron yield above ~5 MeV. We know of no measurements with which to compare these results. Liskien and Paulsen[10] have also calculated this yield; their results are ~60% of our yields in the region of overlap below 5.5 MeV.

CONCLUSIONS

New precision data on (α,n) neutron yields have been presented. Correlations between measured thick-target yields and those calculated from thin-target cross-section data have been made that indicate that the calculations, using good energy loss values and good thin-target cross-section data, agree with the measured values to within 5 to 10%, not only for thick elemental targets but also for compounds.

ACKNOWLEDGMENT

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