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Shape of the Positron Spectrum of Rb^{84}†

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The shape of the positron distribution in the decay of Rb^{84} was studied in a magnetic spectrometer. Using both proportional counter and solid-state detectors, it was possible to obtain data which permitted the subtraction of the outer group from the total spectrum without obliterating the subtle details of the inner group. The outer group is fitted very well with the ***unique*** once forbidden shape factor. However, an additional empirical factor of $1+0.2/W$ yields an even better fit to the data. The inner group has a distribution which is slightly but measurably different from the statistical shape. This shape cannot be accounted for by an empirical factor of the form $1+b/W$ alone. The end-point energies are found to be 1.657 ± 0.003 MeV and 0.780 ± 0.006 MeV, in good agreement with the weighted average of 0.880 MeV for the gamma ray between the first excited and ground states of Kr^{84}.

I. INTRODUCTION

A DETAILED investigation of the positron spectrum of Rb^{84} was undertaken with particular emphasis on the shape of the inner β^+ group. Previous investigators[1] have reported a once-forbidden, *unique* shape for the highest energy $2-$ to $0+$ group, and a statistical shape for the inner $2-$ to $2+$ group. The combination of a statistical shape and the observed β-γ circular polarization[2] and β-γ angular correlation[3] appear to be incompatible with a theoretical description[4,5] in terms of either the ξ approximation, the B_{ij} approximation, or the modified B_{ij} approximation. Since improved techniques have made it possible to detect subtleties[6,7] in the shapes of β spectra, this study was undertaken in an attempt to determine whether any deviations might be measurable in the positron spectra of Rb^{84}. Furthermore, the previous determinations of the end-point energies of the inner and outer positron groups were not in good agreement with the observed energy of the gamma transition between the first excited and ground states of Kr^{84}. It was felt that a more detailed analysis of the shapes of the positron distributions might result in a self consistent decay scheme.

The β^+ decay of Rb^{84} is also of particular interest because it is quite similar to the β^- decay of Rb^{86}, which has been extensively investigated both experimentally and theoretically.[5,8,9] In neither the case of Rb^{86} or Rb^{84} has there been a completely satisfactory explanation of all of the experimental facts.

It is found that a once-forbidden, *unique* shape fits the data for the outer positron group of Rb^{84} quite well. However, an additional empirical correction of the form $1+0.2/W$ is in somewhat better agreement with the data. The shape of the inner group is found to deviate measurably from that of a statistical spectrum, and cannot be accounted for by a $1+b/W$ correction factor alone. The analysis of our data results in maximum positron energies of 1.657 ± 0.003 MeV and 0.780 ± 0.006 MeV which are quite consistent with the gamma energy of 0.880 MeV.

The decay rate at several points in the positron distribution was measured in the magnetic spectrometer. The half-life was found to be 33 ± 1 days.

II. EXPERIMENTAL PROCEDURES

Usually the method of subtracting off the outer group in order to determine the spectrum of an inner group results in uncertainties which make any detailed shape analysis of the inner group ambiguous, if not impossible. In most cases, the inner group and outer group are not of comparable intensity and, as a result, the statistical accuracy degenerates after the subtraction process. Also, any uncertainty in the exact shape of the outer group will be propagated into the analysis of the inner group. In this particular case of Rb^{84}, the two groups are of almost equal intensity, and the outer group is expected to have the unique once-forbidden shape. For these reasons, it was felt that the subtraction process might prove successful in yielding a definitive spectral shape for the inner group.

The same experimental methods were employed to measure the shape of the β^+ distribution emitted from the Rb^{84} nuclei as have been employed successfully in the past[6,7] to measure properties of very low intensity β groups. The reason for such extreme criteria to measure the shapes of the relatively more intense groups resides in the fact that the shape of the outer group, which is expected to be once forbidden, *unique* must not be distorted by instrumental effects in order that it can be

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† Supported by the U. S. Office of Naval Research.

[1] N. Benczer-Koller, Columbia University Report CU-177, 1958 (unpublished); W. O. Doggett, University of California Report, UCRL-3438, 1956 (unpublished); C. M. Huddleston and A. C. G. Mitchell, Phys. Rev. **88**, 1350 (1952).

[2] F. Boehm and J. D. Rogers, Nucl. Phys. **45**, 392 (1963).

[3] See references quoted in F. Boehm and J. D. Rogers, Nucl. Phys. **45**, 392 (1963).

[4] T. Kotani, Phys. Rev. **114**, 795 (1959).

[5] J. Eichler and S. Wahlborn (private communication).

[6] D. E. Wortman and L. M. Langer, Phys. Rev. **131**, 325 (1963).

[7] L. M. Langer and D. E. Wortman, Phys. Rev. **132**, 324 (1963); L. M. Langer, E. H. Spejewski, and D. E. Wortman, Phys. Rev. **132**, 2616 (1963).

[8] R. L. Robinson and L. M. Langer, Phys. Rev. **112**, 481 (1958).

[9] Z. Matumoto, M. Yamanda, I. T. Wang, and M. Morita, Phys. Rev. **129**, 1308 (1963).

subtracted unambiguously from the total spectrum. Only then may a meaningful shape-factor analysis of the inner group be made.

Magnetic Spectrometer

The Rb^{84} positron spectrum was studied in detail in the high-resolution, 40-cm radius-of-curvature shaped magnetic-field spectrometer.[6,10] This instrument was operated at a resolution of about 0.6% with source and detector widths of 0.4 cm.

An end-window proportional counter with a 0.9-$\mathrm{mg/cm^2}$ aluminized Mylar window was used for all low-energy spectrum measurements. Previous work has shown that such a window thickness should not distort the β^+ distributions in the energy regions of interest. An integrally biased solid-state radiation detector, of the silicon surface barrier type, was employed in the magnetic spectrometer for the accurate determination of the shape of the distribution at higher energies.[6] The reason for using the solid-state detector is that its small size and its inherent low sensitivity to gamma radiation yields a smaller background and, thus, makes possible more significant measurements in the higher energy region. It has been demonstrated[6] that the solid-state detector has the same energy response as the proportional counter in the region in which it was operated. However, the sensitivity of the solid-state detector is not independent of energy over the lower energy region. Thus, for measurements extending to lower energies, the end-window proportional counter, which is not energy dependent in the lower energy regions, was used.[11] The data obtained with the different counters were normalized to the same intensity in the energy region where the measurements overlapped.

Sources

One mCi of Rb^{84} was obtained carrier-free in the form of RbCl from the Nuclear Science and Engineering Corporation. From this activity two sources were prepared. Source 1 was a thin source ($<10\ \mu\mathrm{g/cm^2}$) and was somewhat less intense than source 2, which was $<100\ \mu\mathrm{g/cm^2}$ in thickness. To prepare source 1, approximately $\frac{1}{10}$ of the activity was quite uniformly liquid-deposited onto a 1 $\mathrm{cm^2}$ insulin-defined[12] area on a 0.9 $\mathrm{mg/cm^2}$ aluminized Mylar backing. Source 2 was similarly prepared with the remainder of the activity. Each RbCl source was dried and covered with a thin ($\sim 20\ \mu\mathrm{g/cm^2}$) Zapon film. The appearance of both sources was such that, on the basis of previous experience, one would not expect any distortions arising from the thickness or backing to be evident at energies above ~150 keV. Nevertheless, the purpose of the two sources was to obtain an experimental check on just this point.

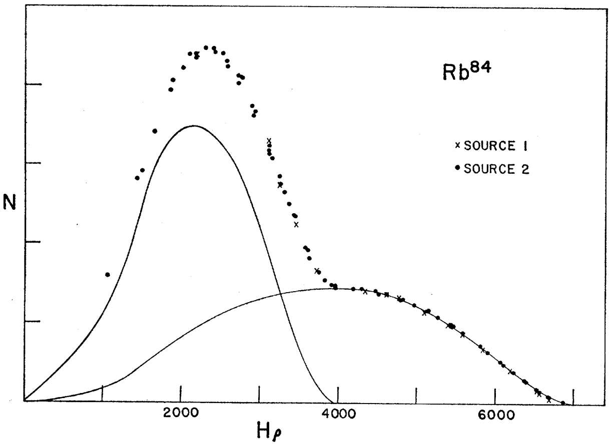

FIG. 1. Positron momentum distribution of Rb^{84}. The resolution into groups is based on the shape factor analyses shown in Figs. 3 and 4.

III. DATA AND RESULTS

The data obtained in the investigation of Rb^{84} were taken over a period of 35 days. Several runs were made through the spectrum using each Rb^{84} source. The majority of the data, however, was taken when employing the more intense source 2. From these data, the half-life was determined to be 33 ± 1 days, which is in agreement with the half-life value determined by Welker *et al.*[13] After the data were corrected for decay, the positron distribution which is shown in Fig. 1 was determined. The statistical accuracy of each datum point is better than 1%. The circles represent the data obtained with source 2 and the crosses represent points obtained with source 1. It is significant to note the agreement between the distributions obtained with the thick and thin sources. This agreement gives assurance that the spectrum was not being distorted by scattering in the source over most of the energy regions of interest. Hence, the statistically more accurate data obtained with the more intense source could be utilized with confidence. It would have been desirable to extend this source thickness check to the lowest energy region

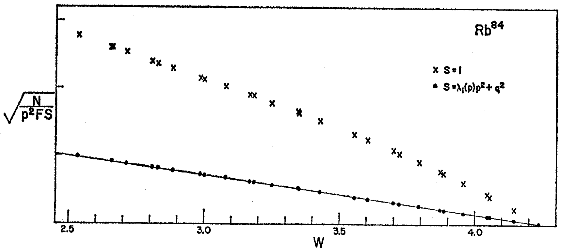

FIG. 2. F–K plot for the highest energy positron group in the decay of Rb^{84}. The lower curve shows the linear plot of the highest energy spectrum using the theoretical shape factor, S, that best fits the data in Fig. 3.

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[10] L. M. Langer and C. S. Cook, Rev. Sci. Instr. **19**, 257 (1948).

[11] J. H. Hamilton, L. M. Langer, and W. G. Smith, Phys. Rev. **112**, 2010 (1958).

[12] L. M. Langer, Rev. Sci. Instr. **20**, 216 (1949).

[13] J. P. Welker and M. L. Perlman, Phys. Rev. **100**, 74 (1955).

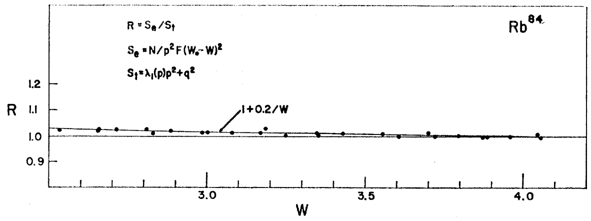

FIG. 3. Shape factor plot for Rb^{84}. The ratio of the experimental shape factor, $N/p^2F(W_0-W)^2$, to the theoretical once-forbidden, *unique* shape factor, $\lambda_1 p^2+q^2$, is plotted as ordinate. The influence of a possible $1+0.2/W$ empirical correction to the highest energy group is also shown.

covered by the proportional counter run. However, experimental difficulties precluded such measurements while source 1 was sufficiently active to be useful.

The solid curves in Fig. 1 represent positron spectra determined from shape factor analyses. The higher momentum group consists of 45% of the β^+ decays as determined on the basis of the theoretical once-forbidden, *unique* shape factor which is compatible with the experimental shape for the outer group as shown in Fig. 3. The inner group represents 55% of the β^+ decays, and the shape of the distribution corresponds to the shape-factor plot shown in Fig. 4. These relative intensity values are essentially the same as the average of the values reported by others.[14]

The Fermi-Kurie (F-K) plot of the highest energy group is shown in Fig. 2. The lower curve shows how well the *unique* shape factor of the form[15] $\lambda_1(p)p^2+q^2$, which fits the data in Fig. 3, linearized the F-K plot. λ_1 is a function of p, the electron momentum, and q represents the neutrino momentum. The data corrected for screening is indistinguishable from the uncorrected data in this energy range. An end-point energy of 1.657 MeV is consistent with an extrapolated curve through the data.

Figure 3 is a plot of the ratio of the experimental shape factor, $S_e = N/p^2F(W_0-W)^2$, to the theoretical once-forbidden, *unique* shape factor, $S_t = \lambda_1(p)p^2+q^2$. The end-point energy is determined to be 1.657 ± 0.003 MeV on the basis that the shape factor should remain finite as the end-point energy is approached. The exact determination of an end point in this manner can be very dependent upon uncertainties in the correction for background, scattering, bremsstrahlung and, in the case of positron emission, annihilation radiation produced in the neighborhood of the detector. The low sensitivity of the silicon surface barrier detector to gamma radiation is a great improvement in helping reduce the significance of these interferences to a minimum. In this investigation, the total background was only ~2 counts/min, whereas the peak counting rate was ~1200 counts/min.

Figure 3 also shows that the possible existence of an empirical correction factor of the form $1+b/W$ cannot be denied and, indeed, that such a factor with $b=0.2$, appears to yield a better fit to the data. Such an empirical factor has been found to be necessary, or possible, for other beta spectra.[16,17] It is perhaps of interest to note that a value of $b=0.2$, which is somewhat lower than the average value that has given the best fit for most other spectra, is the same as that which was needed in the case of the spectrum in the decay of Y^{90}, another once-forbidden, *unique* transition.[17]

The lower part of Fig. 4 is an F-K plot of the inner group found by subtracting the outer group from the total spectrum with the inclusion of the empirical correction factor, $1+0.2/W$, applied to the theoretical *unique* shape. Screening is also considered here. The same points not corrected for screening are shown, for comparison, by the triangles. Above approximately $W=1.7$, the uncorrected points are indistinguishable from the points corrected for screening, and, therefore, are not shown. The end-point energy of the inner group is again determined on the basis of the shape factor plot shown as the upper part of Fig. 4. The end-point energy

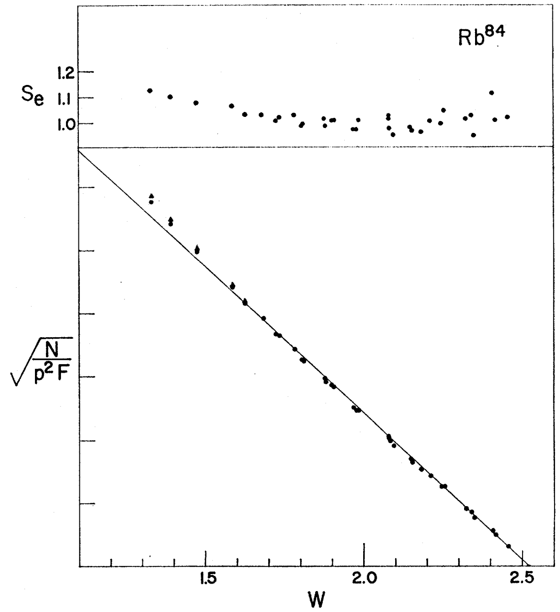

FIG. 4. F-K and shape factor plots for the inner β^+ group in the decay of Rb^{84}. The lower F-K plot shows the points obtained after subtracting the outer group from the total spectrum on the basis of the empirical correction factor, $1+0.2/W$, applied to the theoretical *unique* shape with screening considered. The triangles are the same points if screening corrections are not included. The upper shape factor plot corresponds to the lower F-K plot.

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[14] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences-National Research Council, Washington 25, D. C.) NRC 5-2-11.

[15] T. Kotani and M. Ross, Phys. Rev. **113**, 662 (1959).

[16] See references, for example, in D. C. Camp and L. M. Langer, Phys. Rev. **129**, 1782 (1963).

[17] O. E. Johnson, R. G. Johnson, and L. M. Langer, Phys. Rev. **112**, 2004 (1958).

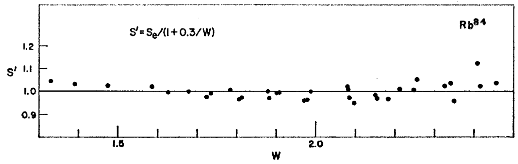

FIG. 5. Shape factor plot of the inner β^+ group of Rb^{84}. This shape is obtained if the data are corrected for screening, if the empirical correction factor, $1+0.2/W$, is considered in conjunction with the *unique* shape factor in subtracting the outer group from the total spectrum, and if the resulting inner group is further corrected by an empirical factor of the form $1+0.3/W$.

obtained by requiring that the shape factor tends to a finite value as the end point is approached is found to be $E_0=0.780\pm0.006$ MeV. If the empirical correction factor were not considered in subtracting the outer group from the total spectrum, the end-point energy determined in the same way would be 0.786 ± 0.006 MeV. The value obtained by including the empirical correction factor is more consistent with the values reported[14] previously for the energy of the first excited state in Kr^{84}, which is ~0.880 MeV.

The upper curve in Fig. 4 clearly shows that the shape of the inner group is not that of the statistical distribution as has been reported. There is a significant positive slope from $W=2.1$ to the end point. Also, there is a negative slope from $W=1.3$ to 2.0. It was felt that the data below $W=1.3$ might be influenced by source thickness effects and for that reason they were not considered in the analysis. It is thus seen that a nonstatistical shape factor might be fitted to the experimental data. However, the exact shape of this group is still somewhat ambiguous as an empirical correction factor of the form $1+0.3/W$, which has been consistent with other such spectra, cannot arbitrarily be excluded from consideration. If the empirical factor $1+0.3/W$ is invoked, the experimental shape factor is that shown in Fig. 5. It is to be noted that even after considering such a correction term the shape shows a deviation from the allowed shape which corresponds to the straight line shown for comparison in Fig. 5. Thus, a definite deviation from the statistical shape is found for the inner, 780-keV β^+ group. The numerical data, without normalization, corresponding to the shape factor plots (Figs. 4 and 5) are shown in Table I.

TABLE I. Shape Factor Data for Inner Positron Group of Rb^{84}.

W	S	$S'=S/(1+0.3/W)$
1.330	0.929	0.758
1.391	0.911	0.749
1.474	0.895	0.743
1.586	0.881	0.741
1.626	0.856	0.723
1.678	0.855	0.726
1.724	0.834	0.711
1.734	0.845	0.720
1.783	0.854	0.732
1.806	0.818	0.701
1.812	0.824	0.707
1.878	0.842	0.726
1.882	0.818	0.706
1.901	0.835	0.721
1.908	0.837	0.723
1.970	0.806	0.700
1.978	0.806	0.700
1.987	0.836	0.727
2.080	0.849	0.742
2.082	0.840	0.735
2.085	0.809	0.707
2.097	0.790	0.691
2.150	0.815	0.715
2.155	0.802	0.704
2.183	0.799	0.702
2.212	0.834	0.734
2.248	0.827	0.729
2.256	0.866	0.764
2.325	0.840	0.744
2.341	0.850	0.753
2.350	0.787	0.698
2.408	0.920	0.818
2.417	0.835	0.743
2.456	0.844	0.752

IV. DISCUSSION

Previous experimental measurements suggested that the inner positron group of Rb^{84} had a statistical shape. Such a shape would follow immediately from the ξ approximation. The β-γ circular polarization measurements, however, cannot be explained in terms of the simple ξ approximation. Any efforts to explain the β-γ circular polarization in terms of the B_{ij} or the modified B_{ij} approximations have run into difficulty in attempting to account for the statistical shape of the spectrum. It was our hope in undertaking this investigation that a more definitive spectrum shape might be obtained. This might prove valuable in any further attempts at a theoretical explanation which might be compatible with the experimental measurements of the shape factor, the β-γ circular polarization, and the small β-γ directional correlation.

Previous investigations reported that the highest energy group exhibited the once-forbidden *unique* shape. The results of this investigation show that although the shape of the 1.657-MeV group is represented quite well by the once-forbidden, *unique* shape factor, it is better to apply further an empirical correction factor of the form $1+b/W$. This is in agreement with correction factors which have been found necessary in other well-measured decays. Although the average value of b has been found to be approximately 0.3, the other once-forbidden, *unique* shape which has been studied in detail, that of Y^{90}, required $b=0.2$ to fit the data. There may be some significance in the fact that this group also requires b equal to only 0.2 for a good fit to the data.

The inclusion of this correction factor results in a more consistent decay scheme. If it is not taken into account in the subtraction process, an end-point energy of 0.786 ± 0.006 MeV is obtained for the inner group. This would imply that the first excited state of Kr^{84} is at 871 keV, which is not in good agreement with the value of 880 keV which results from γ-ray measurements.

However, including the $1+0.2/W$ term in the shape factor of the outer group gives an end-point energy of 0.780 ± 0.006 MeV for the inner group. This yields a value of 877 keV for the excited level of Kr^{84}, which is in much closer agreement.

Whether the correction factor is applied to the outer group or not, however, the shape of the inner group deviates from that of an allowed spectrum. This deviation cannot be accounted for by an empirical correction factor of the form $1+0.3/W$ alone. Such a factor has been found compatible with the shapes of other well-measured spectra. Hence, it is reasonable to expect that it should apply in this case also. Thus, the inner β^+ transition does appear to have a shape which is slightly, but measurably, different from the statistical shape. Although this small deviation from the statistical shape may not be sufficient to permit an explanation in terms of the modified B_{ij} approximation, it should be taken into account in any attempt at a detailed analysis involving all of the matrix elements.[18]

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[18] Such an explanation is being attempted by S. Wahlborn (private communication).

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Photoneutron Cross Sections for Natural Cu, Cu^{63}, and Cu^{65}†

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Using monochromatic gamma rays obtained from the annihilation-in-flight of fast positrons, the (γ,n) and $(\gamma,2n)$ cross sections for samples of natural Cu, Cu^{63} enriched to 99.3% and Cu^{65} enriched to 99.7% were measured. The (γ,n) cross sections for natural Cu, Cu^{63}, and Cu^{65} were found to have maximum values of 71 ± 7, 70 ± 7, and 75 ± 7 mb, respectively, while the maximum $(\gamma,2n)$ cross sections are 15.4 ± 2, 13.5 ± 1, and 28 ± 3 mb, respectively. The corresponding values for the (γ,n) integrated cross sections up to 28 MeV are 525 ± 52, 523 ± 52, and 437 ± 43 MeV-mb, and the $(\gamma,2n)$ integrated cross sections are 110 ± 11, 80 ± 8, and 195 ± 19 MeV-mb.

The (γ,n) cross section of copper has been used extensively as a standard for the measurement of photonuclear cross sections. The 9.8-min half-life of Cu^{62}, resulting from $Cu^{63}(\gamma,n)$ reaction, is convenient for measurement. The activity of the 12.8-h Cu^{64} can also be easily measured. Thus, the copper (γ,n) cross section may be measured either by activation or neutron detection, and the results of many experiments have been presented relative to it. The activation technique has the advantage that the cross section for a single isotope is determined. To achieve this advantage in experiments which detect neutrons, separated isotopes must be used.

Previous measurements on (γ,n) and (γ,p) reactions in copper have been performed using photons from charged-particle reactions and electron bremsstrahlung. For those measurements using bremsstrahlung, either activation curves or neutron-yield curves were obtained and these were unfolded by standard techniques in order to obtain the cross sections. In the work described herein, cross sections for (γ,n) and $(\gamma,2n)$ reactions in natural Cu, Cu^{63}, and Cu^{65} were measured by use of nearly monoenergetic photons obtained from the annihilation-in-flight of fast positrons. The $(\gamma,2n)$ cross section was determined by counting those cases in which one, two, or three neutrons were detected following a pulse of photons.

EXPERIMENTAL METHOD

Positrons were created in a thick tungsten target located at the end of the first section of a two-section linear electron accelerator. They were then accelerated to the desired energy by adjusting the rf power and phase in the second section. The positrons were energy analyzed by a magnet and a two-jaw slit. The nearly monochromatic positrons then passed through a thin LiH target in which some annihilated in flight by two-photon annihilation. In this process, the photon moving in the forward direction has about 0.76 MeV more energy than the positron. Multiple scattering in the LiH target caused a photon energy spread of approximately 3%. Those positrons which penetrated the target were swept away by a strong magnet. The photon flux was measured by use of a transmission ion chamber filled with xenon to a pressure of 1 atm. This chamber was calibrated with a gamma-ray spectrometer having a 6-in.-long×5-in.-diam NaI(Tl) crystal.

The photons were incident (in 2-μsec pulses) on copper samples placed in a 4π neutron detector having an efficiency of about 20%. This paraffin-moderated neutron detector contained 24 BF_3 proportional counters filled to 120 cm Hg with 96% enriched B^{10}. The gating

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