$4p$ electron will be excited to the continuum as a result of the nuclear charge alteration, and that the summed probabilities for like processes in the other shells amount to 9.9%. An extension to the outer electron shells of the calculations based upon the sudden-perturbation theory is being undertaken by A. E. S. Green, and preliminary results appear to indicate a reasonably satisfactory agreement with the numbers just cited. Dr. Green will doubtless communicate his complete results in the near future.

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Precision Determination of the Low-Lying Energy Levels of W^{182}, W^{183}, W^{184}, and W^{186}†

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The low-lying energy levels in the wolfram isotopes have been studied by using the 3.7-Mev proton beam of the A-48 high-current linear accelerator at the University of California Radiation Laboratory, Livermore, to excite the nuclei. The large beam currents available make it possible to use a bent-quartz-crystal spectrograph to observe the resultant γ rays. With such an instrument, a resolution of better than 0.1% is possible. The following γ rays have been observed: W^{182}, 100.07±0.05 kev; W^{183}, 46.508±0.030 kev and 52.612±0.030 kev; W^{184}, 111.13±0.06 kev; W^{186}, 122.48±0.08 kev. (Energies relative to W K-series x-rays.) The isotopic assignments are known from previous work on these lines. Known wavelengths of the K-series x-rays of wolfram and certain nuclear lines were used to calibrate the plate.

I. A-48 ACCELERATOR

THE A-48 accelerator[1] at the University of California Radiation Laboratory, Livermore is a resonant-cavity linear accelerator designed to accelerate large quantities of protons to 3.7 Mev and deuterons to 7.5 Mev. The maximum current of both species of particles which has been obtained so far is roughly 30 milliamperes. The energy spread of the beam is of the order of several hundred kilovolts because of the large phase acceptance of the machine. The beam at the target is well collimated, having a diameter of approximately 4 inches. The beam distribution on the target has a strong central maximum and is therefore very nonuniform under normal operating conditions.

The limitation on the maximum beam current available from A-48 is the power which can be dissipated on the target. The standard probe which is in use at present consists of a metal plate mounted in such a way that a high-pressure water flow of roughly 30 gallons per minute is maintained across the back. With copper targets it is possible to maintain heat loads of the order of 30 kw per square inch on $\frac{1}{8}$-in. copper plates. In the case of other materials, the heat load is usually smaller. Two wolfram targets were used in these experiments. One consisted of $\frac{1}{16}$-in. wolfram plate which was hard-soldered onto a $\frac{1}{8}$-in. copper plate. The other target was a $\frac{1}{16}$-in. wolfram plate mounted directly on the probe holder. Both of these targets were able to sustain heat loads of the order of 5 kw per square inch. The wolfram plate shattered completely toward the end of the second run. It is possible that the wolfram was weakened (i.e., made brittle) by the large amount of hydrogen deposited on the plate during the run.

II. ELECTRIC EXCITATION

The electric multipole (or Coulomb) excitation[2] of nuclei has been studied extensively during the last three years. Over one hundred energy levels in as many isotopes have been observed. The cross section for the excitation of most of the low-lying energy levels in the heavy nuclei is something of the order of several millibarns at the available proton energy. This process is particularly suited for the study of nuclear spectra because there are no unpleasant background radiations (i.e., neutrons) and it is therefore possible to observe the emitted γ rays very readily.

When a thick wolfram target is bombarded with 3.7-Mev protons, approximately 10^{-7} nuclear γ rays are emitted per proton. The W targets which have been developed for the A-48 can be bombarded with proton beams up to 5 milliamperes. It is possible therefore to obtain equivalent γ-ray sources at the target of the order of 10^{10} γ rays per second from electric excitation reactions. Such sources (~300 millicuries) are strong enough to make feasible the use of a bent-quartz-crystal spectrograph for the precision measurement of these γ rays.

III. BENT-QUARTZ-CRYSTAL FOCUSING γ-RAY SPECTROGRAPH

The bent-quartz-crystal focusing γ-ray spectrograph has been described in the literature.[3] The geometry of

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† Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] E. O. Lawrence, Science **122**, 1127 (1955).

[2] Alder, Bohr, Huus, Mottelson, and Winther, Revs. Modern Phys. 28, 432 (1956).

[3] Jesse W. M. DuMond, in *Ergebnisse der Exakten Naturwissenschaften* (Springer-Verlag, Berlin, 1955), Vol. 28, p. 232. (The

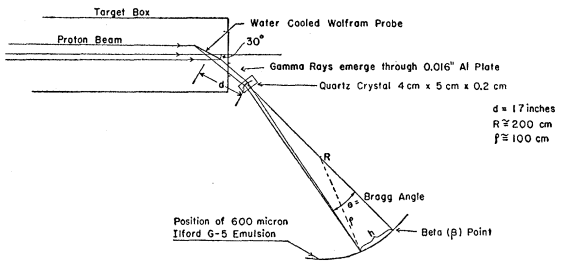

FIG. 1. Experimental geometry. The bent-crystal spectrograph is mounted on a shockproof platform in order to prevent line broadening from spatial motion of the platform.

the photographic-recording instrument used in these experiments is shown in Fig. 1. The quartz crystal is bent in such a way that the (310) planes in the crystal point to a spot 2 meters away from the center of the crystal. The different wavelengths are focused at different points along a focal circle 1 meter in radius. With the source irradiating the convex side of the crystal, as shown in Fig. 1, it is not necessary to have a point source since the crystal will focus monochromatic radiations emitted from an extended source to the same point on the focal circle.

The quartz crystal used in this series of experiments had an aperture of 4×5 cm and was 0.2 cm thick. In order to determine whether the use of such an instrument is feasible, some estimate of the efficiency of the spectrograph must be made. The efficiency of the instrument is determined by three factors: (1) The acceptance angle, $\delta\theta$, around the Bragg angle within which the quartz lattice will accept radiation from any point in the source. (Since the source is not on the focal circle of the crystal, there is only a very small range of angles, $\delta\theta$, around the Bragg angle within which any given point in the source can emit radiation which will be selectively reflected by the planes of the bent lattice. For a quartz crystal of high quality, such as the one used for this work, $\delta\theta$, is of the order of a few seconds of arc.) (2) The reflection coefficient of the (310) planes in quartz. (3) The efficiency of the detector placed on the focal circle of the spectrograph. The first two numbers have been determined with some precision by DuMond and his co-workers.[4] With the geometry shown in Fig. 1, the ratio of the number of photons (N) of energy $\sim$100 kev emitted into a line on the focal circle to the total number of photons of the same energy emitted by the source (N_0) is

$$N/N_0=5\times10^{-8}.$$

The total efficiency of the spectrograph at this photon energy is then this ratio multiplied by the efficiency of the detection device.

The proper detection device to use for these experiments should have a high efficiency. If 10^{10} γ rays per second are emitted by the source and the efficiency of the crystal is 5×10^{-8}, then 500 γ rays per second are collected in the focused line. Since approximately 10^7 photons are necessary in order to make a measurable line, an exposure time of roughly 2×10^4 seconds or approximately 10 hours at 5 milliamperes should be sufficient provided that the film is 100% efficient. Actually, for γ rays of the order of 100 kev, ordinary no-screen x-ray film has an efficiency of the order of 10^{-3} which would therefore raise the exposure time to 10^4 hours. Such exposure times are not feasible with the accelerator and it is therefore necessary to search for a more efficient detector.

There are several solutions to this problem. One is to build a scintillation counter with a suitable slit arrangement which can be scanned across the line profile. Such an arrangement has several advantages—the NaI detector is essentially 100% efficient, and pulse-height analysis in the detector can be used to reduce the background. On the other hand, it is doubtful whether the same resolution can be obtained in reasonable running times since a slit of the order of 0.05 mm must be used to equal the resolution of the film (a line on the film is $\sim$0.25 mm wide). With a single-slit counting arrangement it also would be necessary to look at only one line at a time, whereas with the film all lines are exposed at once. For the survey experiments described in this work, it was therefore decided to look for a more efficient film.

Ilford G-5 nuclear emulsions are available up to a thickness of several hundred microns. These emulsions are only slightly less sensitive to 100-kev radiations than no-screen film but are of the order of 200 times thicker. The efficiency of a 600-micron nuclear emulsion is thus of the order of 200 times larger than no-screen film and it is therefore possible to reduce the necessary exposure time to approximately 50 hours which is reasonably easy to achieve. It was therefore decided to use these nuclear emulsions as the detection device. Several problems had to be overcome: (1) The emulsion has to be mounted on a backing which is sufficiently rigid so that line positions can be measured with a precision consistent with the resolution of the instrument. (2) The mounting must be flexible enough so that the emulsion can be bent to conform with the focal circle of the spectrograph. It was found that 600-micron emulsions could be mounted on 30-mil glass plates which fulfilled both of the above conditions. Several experiments were carried out with such plates, accurately known templates being used to shield the plates during the irradiations. It was found that the displacement of the image on the plate from the markings on the template was less than 1 mil which corresponds to a shift in energy of approximately 10 ev out of 100 kev. It was also found that the 30-mil glass plates on which the emulsions were mounted could be bent to the 1-meter radius with only a negligible breakage rate.

Figure 2 is a print of the nuclear emulsion obtained

photographic recording spectrometer described in the present article corresponds to the arrangement shown at *I* in Fig. 6 of this reference.)

[4] Watson, West, Lind, and DuMond, Phys. Rev. **75**, 505 (1949); Lind, West, and DuMond, Phys. Rev. **77**, 475 (1950).

from the W target after an exposure of approximately 300 milliampere-hours. Twelve lines are readily visible on the plate of which five are nuclear γ rays from the wolfram isotopes, six belong to the K-series x-rays of wolfram which are emitted when the target is bombarded with protons and one is a nuclear line[5] ($\sim$122 kev) from Co^{57} which was put on the film after the run and will be used for calibration. It will be noted that the x-ray lines on the film are wider than the γ-ray lines. This is not entirely an effect of overexposure but is in large part the result of the natural spectral widths of the x-ray lines which are within the range of resolution of the quartz crystal. The γ-ray lines have widths which are far too narrow ($\sim 10^{-5}$ ev) for resolution, and these lines should therefore be taken as an indication of the instrumental resolution.

IV. ANALYSIS OF RESULTS

The wavelengths of the lines on the negative are determined in principle by Bragg's law. If one refers to the geometry of Fig. 1, this can be written

$$\lambda/(2d)=\sin(h/R), \tag{1}$$

where λ is the wavelength of the line; d, the grating constant of the (310) planes of quartz used for the reflection; h, the line position measured from the β point along the focal circle; and R, the diameter of the focal circle which is also the radius of curvature of the neutral axis of the bent crystal. The wavelengths, λ, expressed in x units (Siegbahn scale) are then converted into energies, E, in kev by using the conversion constant given by DuMond and Cohen[6] in the formula

$$E=(12\,372.44\pm 0.16)/\lambda. \tag{2}$$

It can be shown[3] that no correction for the refractive index of the radiation in the quartz is required for this case of transmission through the quartz plate and reflection therein by atomic planes normal to its bent surfaces. The grating constant, d, has been determined for the (310) planes of quartz with considerable precision,[7] but in the present instance this datum is not used. Instead, the plate has been calibrated by using the known wavelengths of the x-ray lines of wolfram and the γ-ray line of W^{182}. There are two reasons for choosing this method: (a) The determination of the true diameter of the focal circle of the crystal and the location of the center of the rather thick nuclear emulsion with respect to that circle are subject to some uncertainty. (b) The determination of the length of the arc, h, of the focal circle measured from the β-point to a given line (or the difference, h_1-h_2, between two such lines) is subject to further uncertainty because the glass plates are bent while being exposed but must be measured after they have sprung back flat. The neutral axis of the combination of glass plate and emulsion is ill-defined as is also its precise radius of curvature when bent. Part of the latter uncertainty arises from the fact that the plate is enclosed in an opaque black paper envelope and a moisture-proof Pliofilm wrapper before clamping it in the curved plate-holder of the spectrograph.

It would admittedly have been more precise if the positions of the calibration lines could have been recorded *on both sides* of the β point [by reflection from two opposite sides of the (310) planes]. In the present very simple spectrometer design no provision for this was made. To do this would require (a) two separate exposures and (b) either a very long unwieldy nuclear emulsion plate capable of spanning the long arc $2h$ between the two images of the longest wavelength calibration line or else a very precise method of measuring the arc or angle between two fiducial points on two separate plates or for two positions of the same plate, one on either side of the β point. None of these refinements are by any means impossible, but they were felt to be unjustified in the present exploratory and preliminary stage of this work in which it was not even

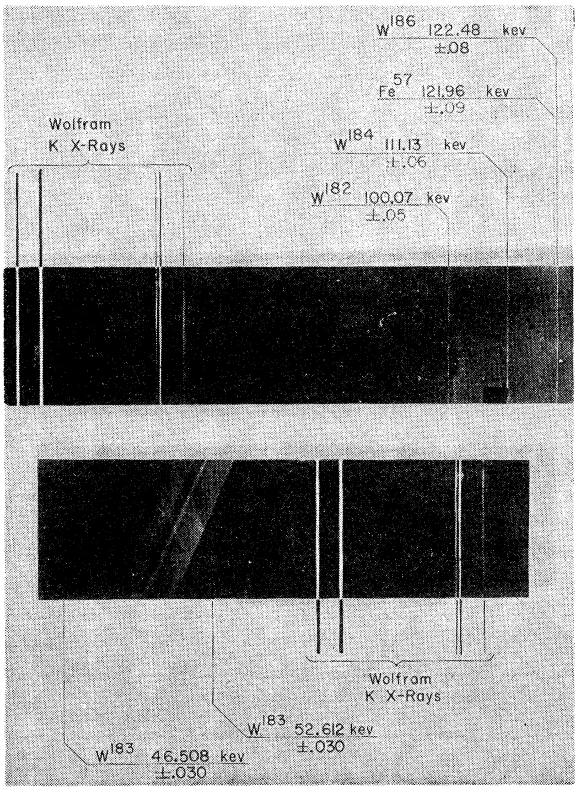

FIG. 2. The x-ray and γ-ray lines from a wolfram target bombarded with 3.7-Mev protons for 300 milliampere hours. The errors in the energies are shown.

[5] B. Craseman and D. L. Manley, Phys. Rev. **98**, 66 (1955); J. Bellicard and A. Moussa, Compt. rend. **241**, 1202 (1955).

[6] J. W. M. DuMond and E. Richard Cohen, Revs. Modern Phys. **27**, 363 (1955) and **25**, 691 (1953).

[7] The quantity $2d$ for the (310) planes of quartz has been determined by a number of observers.[4] We have used the value at 20°C, $2d=2355.34\pm 0.04$.

certain whether Coulomb-excited lines could be recorded at all.

If λ_1, λ_2, and λ_3 are respectively the known wavelengths of two calibration lines and the unknown wavelength of a third line appearing on the plate, the respective positions of these lines measured from the β point being h_1, h_2, and h_3, then

$$\frac{h_3-h_2}{h_1-h_2}=\frac{\arcsin(\lambda_3/2d)-\arcsin(\lambda_2/2d)}{\arcsin(\lambda_1/2d)-\arcsin(\lambda_2/2d)}, \quad (3)$$

in which the instrument parameter, R, does not appear.

The unknown wavelength, λ_3, can obviously be computed from this equation in which all the other quantities are given. Since all the Bragg angles involved in measurements with this spectrometer are small, the wavelength scale on the emulsion is nearly linear and it is therefore quite easy to simplify the computations by using power expansions of the sine or arcsine. Thus, for example, one can write to good approximation

$$\lambda_3-\lambda_2=\frac{h_3-h_2}{h_1-h_2}(\lambda_1-\lambda_2) \times\left[1-\frac{1}{6}\left(\frac{\lambda_3-\lambda_1}{2d}\right)\left(\frac{\lambda_1+\lambda_2+\lambda_3}{2d}\right)\right]. \quad (4)$$

The correction term in the brackets will usually be of order 0.1% or less and hence need not be evaluated with great precision. A first approximation to λ_3 may therefore be computed by using only the linear part of the formula and this approximate value will then be sufficiently accurate for use in the correction term.

It is clear from (3) or (4) that, to apply this method, the measured distance, h_1-h_2, between two calibration lines of known wavelength is one essential quantity for determining the wavelength of every other line on the spectrum. Formula (4) shows clearly that the essential factors whose relative errors determine the relative precision with which the wavelength difference, $\lambda_3-\lambda_2$, can be computed are the differences, h_3-h_2 and h_1-h_2, measured on the photographic plate and the wavelength difference, $\lambda_1-\lambda_2$, determined from other sources of information. Since they are statistically independent measurements, the relative errors of these three factors are to be combined by the familiar square-root-of-sum-of-squares rule[8] to find the relative error in $\lambda_3-\lambda_2$. The absolute error in λ_3 is then the square root of the sum of squares of the absolute error in the calibration wavelength, λ_2, and the absolute error in the difference, $\lambda_3-\lambda_2$. Clearly the most accurate results will be obtained for λ_3 if the spatial and wavelength intervals, h_1-h_2 and $\lambda_1-\lambda_2$, between the pair of calibration lines are large.

Four distinct pairs of calibration lines have been chosen from the wolfram K-series x-ray lines registered on our single plate. These calibration pairs were $(K_{\alpha 1}-K_{\beta 1})$, $(K_{\alpha 2}-K_{\beta 1})$, $(K_{\alpha 1}-K_{\beta 3})$, and $(K_{\alpha 2}-K_{\beta 3})$. In determining the wavelength of the 100-kev line of W^{182}, for example, eight separate measurements were made for each of the four calibrating pairs, or a total of 32 separate measurements, to determine the energy of this line. Figure 3 shows these results and their mean value, which is seen to agree satisfactorily with a more precise measurement of this wavelength made with the Mark I instrument in Pasadena. Figure 4 shows the data obtained in the same way for the 111-kev W^{184} line. The wavelengths and energies of all the nuclear lines on the plate were determined by using the x-ray lines for calibration in this way.

The estimates of the "standard" (or rms) error of the mean value of each wavelength were based both on "external" and "internal" consistency. The error of the mean value by external consistency is based on the

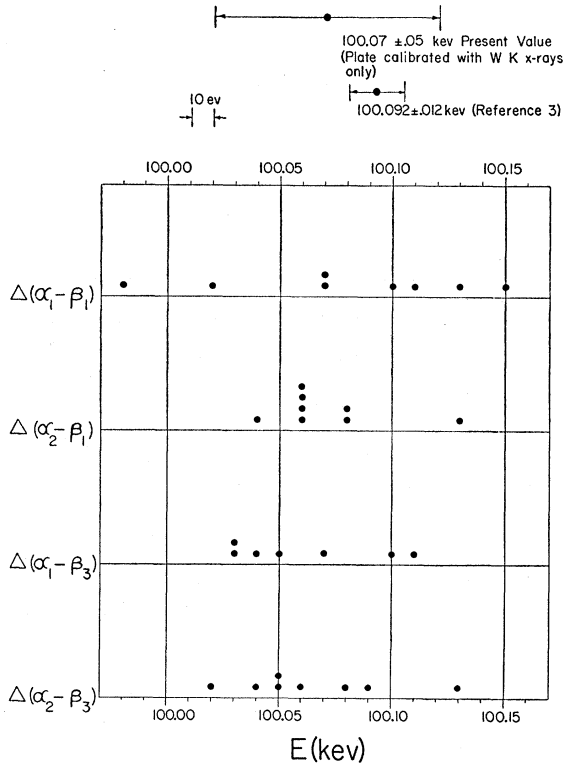

FIG. 3. Energy determination of the 100-kev line in W^{182} The individual energy determinations using each of the separate calibration distances are shown to five significant figures. The calibration distances between the various x-ray lines [i.e., $\Delta(\alpha_1-\beta_1)$, etc.] are shown on the ordinate. The error on the mean energy is obtained by the methods described in the text. The energy of this line obtained by DuMond and his co-workers is also shown.

[8] An exception to this statement should be noted. The *ratio* $(h_3-h_2)/(h_1-h_2)$, clearly does not suffer from any error ascribable to systematic deviation of the mean pitch of the comparator screw from its stated value. Random errors from the comparator do affect the ratio, however. In determining R by comparator measurements on calibration lines for check comparison with the directly measured R by means of machinists' gauges (see below), such a systematic error in comparator screw pitch *does* affect the comparison on the other hand.

deviations from the mean exhibited by the eight determinations of $(h_2-h_3)/(h_1-h_2)$ which were averaged to find the mean for each calibration pair. These errors are then combined with the errors[9,10] in the calibration lines $\lambda_1-\lambda_2$ to find the standard error in $\lambda_3-\lambda_2$. An error in λ_3 can therefore be calculated for each of the four sets of calibration lines $\lambda_1-\lambda_2$. The estimated error by internal consistency was calculated by a method based on error estimates of the three component factors of Eq. (4), h_1-h_2, h_2-h_3, and $\lambda_1-\lambda_2$, and their propagation through the calculation. The error estimate based on "internal" consistency is somewhat larger than the one obtained from "external" consistency.

The energies of the three high-energy nuclear lines (W^{182}, W^{184}, and W^{186}) together with the standard (rms) errors based on "internal" consistency are shown in Table I. It is clear that there are slight systematic differences between the energies obtained from the various calibration pairs. [That is, the set from $\Delta(\alpha_1-\beta_1)$ is uniformly high by $\sim$10 ev, the sets from $\Delta(\alpha_1-\beta_3)$ and $\Delta(\alpha_2-\beta_1)$ are in essential agreement, and the set from $\Delta(\alpha_2-\beta_3)$ is low by $\sim$10 ev.] The final energy for each line quoted in Table II is computed by taking the mean of the values obtained from each calibration pair. Because of the systematic differences pointed out above, it is not legitimate to compute the errors by using the standard error formulas since these apply only to random distributions around the mean. The errors quoted in Table II have therefore been estimated from the "internal" consistency computations based on the eight separate measurements of h_1-h_2 and h_2-h_3 for each calibration pair.

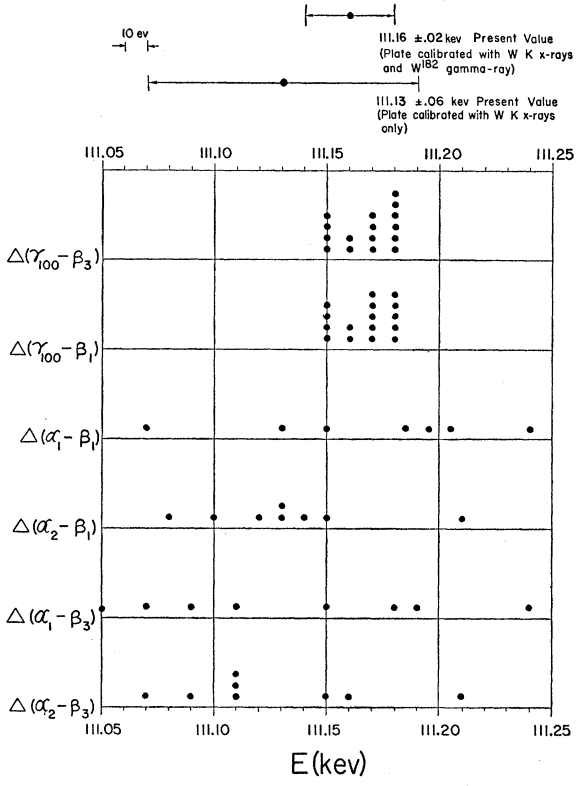

FIG. 4. Energy determination of the 111-kev line in W^{184}. The energy determination of the 111-kev line using the x-ray lines and also the 100-kev line in W^{182} is shown in this figure. This figure illustrates graphically the gain in precision when the distance between calibration lines is increased.

TABLE I. The energies of the three high-energy nuclear lines obtained from each of the four x-ray calibration distances are shown in this table. The errors quoted in these values are the result of an internal consistency computation based on eight separate measurements of the distances. The systematic error referred to in the text is clearly shown. The values quoted in this table are *not* the final energy values.

Calibration pair	W^{186}	W^{184}	W^{182}
$(K\alpha_1-K\beta_1)$	122.49±0.08	111.14±0.06	100.08±0.05
$(K\alpha_1-K\beta_3)$	122.47±0.08	111.13±0.06	100.07±0.05
$(K\alpha_2-K\beta_1)$	122.48±0.07	111.13±0.05	100.07±0.04
$(K\alpha_2-K\beta_3)$	122.46±0.07	111.12±0.05	100.07±0.04

In addition, determinations of the wavelengths of the nuclear lines have been made using calibrating pairs in which the 100-kev W^{182} line was used as one of the members. The wavelength of this line has been measured elsewhere[3,11] with considerable accuracy. These results are shown in the upper part of Fig. 4. The spread in these last results is much smaller than for the case where the x-ray lines alone were used for calibration, a result to be expected because of the much more favorable calibrating interval. A still more precise measurement (than the one given by Bellicard and Moussa[5]) of the Co^{57}-line wavelength is soon to be attempted with the Mark I instrument in Pasadena using a concentrated source to be prepared by bombardment of an iron target in the A-48 Livermore accelerator. This, it is hoped, will furnish a very valuable datum for future calibrations.

It has been pointed out that the wavelengths determined by the above method do not require a direct measurement of the instrument parameter, R. It is nevertheless instructive to measure R directly and to compare this value with the value which can readily be calculated from the equation for a pair of known calibration lines:

$$h_1-h_2=R\{\arcsin[\lambda_1/(2d)]-\arcsin[\lambda_2/(2d)]\}. \quad (5)$$

In the transmission-type curved-quartz-crystal spectrograph the focal circle is, strictly speaking, a circle tangent to the neutral axis of the bent quartz crystal at its center.* Its diameter is determined by the radius

[9] Y. Cauchois and H. Hulubei, *Longueurs d'onde des émissions X et des discontinuités d'absorption X* (Hermann et Cie, Paris, 1947).

[10] E. Inglestam, Nova Acta Regiae Soc. Sci. Upsaliensis 4, No. 5 (1936).

[11] Murray, Boehm, Marmier, and DuMond, Phys. Rev. **97**, 1007 (1955).

* It can readily be shown that the compression of the grating space of the atomic reflecting planes on the concave side of the neutral axis and the elongation of the same on the convex side should modify the Bragg angles of reflection from these regions in such a way as to cause all reflected radiation of a given wavelength to converge to one and the same point on the focal circle. This is a consequence of the elastic (rather than plastic) way in

TABLE II. This table shows the final wavelength and energy values of the nuclear lines obtained by using both x-rays and the 100-kev line in W^{182} for calibration. The errors are calculated by using the methods described in the text.

Isotope	Energy (kev) relative to W^{182} γ ray and W $K\beta$ x-rays	Energy (kev) relative to W K x-rays	Best previous value of energy (kev) and reference	Wavelength (Siegbahn x-units) relative to W^{182} γ ray and W $K\beta$ x-rays	Wavelength (Siegbahn x-units) relative to W K x-rays
W^{186}	122.52 ±0.02	122.48 ±0.08	124 ±4[a]	100.98±0.02	101.02±0.06
W^{184}	111.16 ±0.02	111.13 ±0.06	112 ±4[a]	111.30±0.02	111.33±0.06
W^{182}	...	100.07 ±0.05	100.092±0.012[b,c]	...	123.64±0.06
W^{183}	52.607±0.020 46.502±0.020	52.612±0.030 46.508±0.030	52.59 ±0.01[b,c] 46.48 ±0.01[b,c]	235.18±0.09 266.06±0.11	235.16±0.13 266.03±0.17

[a] McClelland, Mark, and Goodman, Phys. Rev. 93, 904 (1954); T. Huus and J. H. Bjerregard, Phys. Rev. 92, 1579 (1953).
[b] See reference 3.
[c] See reference 11.

of curvature of the neutral axis. For best focus, this circle should pass through the exact center of the thickness of the photographic emulsion while it is held in the curved plate-holder. This condition is fulfilled only approximately in this instrument but is certainly met better than is needed to insure that the lines shall be essentially well-focused over the entire working range. The distance between the center of the concave face of the crystal and a point on a glass plate in the film-holder corresponding to β in Fig. 1 was measured with a set of precision rods. This measurement must be corrected for the thickness of the quartz crystal, the thickness of the nuclear emulsion, and the opaque paper cover of the nuclear plate. In addition, the radius of the film holder was also measured from a pivot point on the line between β and the center of the crystal. The best estimated value of the instrument parameter R from these data is 199.05±0.05 cm. This is to be compared with the average value of R computed from (5) using all the known calibration pairs. After a correction for the fact that h_1-h_2 as measured on the plate is about 0.3% too large (because the neutral axis of the emulsion-glass sandwich is in the glass and hence the emulsion stretches by about this amount when removed from the curved holder), this calculated value of R is 199.04±0.10 cm.

V. CONCLUDING COMMENTS

The levels in the even-A (W^{182}, W^{184}, and W^{186}) isotopes of tungsten have already been investigated[12] by scintillation methods with less resolution, and the remarkable fact that adding of two neutrons seems to raise the energy of the first excited level by almost precisely the same amount (11.1 kev) is here again observed.

The results obtained with this first exposure can only be regarded as preliminary and chiefly of interest for indicating the possibilities that further development of such a technique promises. A further gain either in luminosity of the spectrometer or sensitivity of the detecting agency, or both, is much to be desired. Some sacrifice of the high resolving power of quartz could well be afforded if in return a corresponding increase could be obtained in the intensity selectively reflected into the lines.

For the study and precise verification of the predictions of the already very successful "collective nuclear model" of Bohr and Mottelson,[13] precision determination of many nuclear energy levels in a wide variety of isotopes is very important. Many of these can probably be studied with requisite precision only by some such technique as the one here attempted for the first time.

The authors wish to thank R. C. Jopson, D. H. Birdsall, and P. V. Livdahl for their valuable help in performing these experiments and Dr. R. S. White and his group for processing the emulsions. We are also indebted to Dr. F. Boehm and Dr. A. H. Wapstra for their valuable criticisms of the manuscript. Finally we would like to thank Dr. C. M. Van Atta for his continued support of this work.

which the quartz lamina bends. Quartz laminae which have been under strain for over a year by bending to a radius one thousand times the thickness are found to spring back so that their originally optically flat surfaces return to optical flatness when the strain is released by removing them from their curved holders.

[12] McClelland, Mark, and Goodman, Phys. Rev. 93, 904 (1954); and T. Huus and J. H. Bjerregard, Phys. Rev. 92, 1579 (1953).

[13] A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. 27, No. 16 (1953).

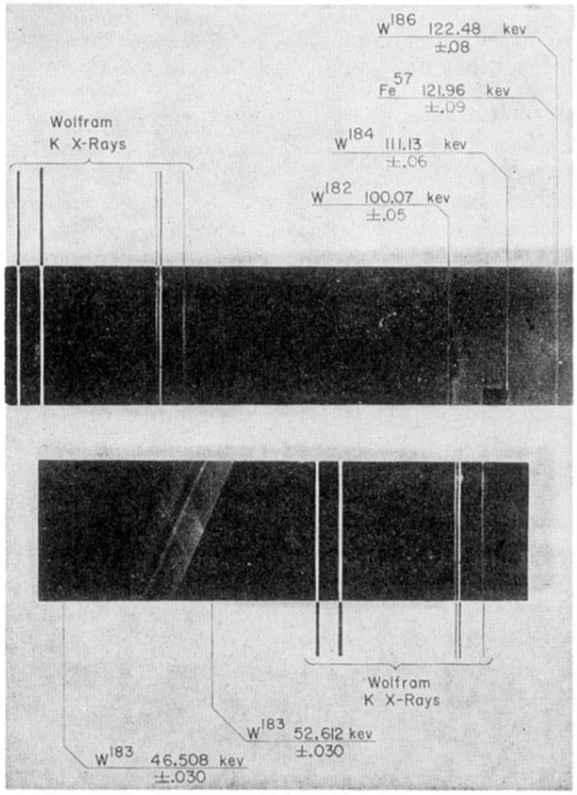

FIG. 2. The x-ray and γ-ray lines from a wolfram target bombarded with 3.7-Mev protons for 300 milliampere hours. The errors in the energies are shown.