kv bombardment the value 1.19σ if the values we have determined or adopted for Φ_K, w_K and c are correct. The total energy of nickel K series lines, as may be deduced from relative measurements[13] of line intensities, is $1.351\times10^{-8}n_\alpha$. Substituting $n_\alpha=1.19\sigma$ in this result, we have as the total energy of K radiation emitted by nickel subjected to electron bombardment at 70 kv the value $1.61\times10^{-8}\sigma$ ergs per bombarding electron. Again it is noted that σ must be small enough so that all depths of the target are subjected to substantially the incidence bombarding energy and so that the electrons experience, on the average, only small deviations within the target.

It is not difficult to compute the efficiency of x-ray production under these conditions. The energy loss suffered by an electron having the relative speed β in passing through a layer of surface density σ may, by a slight modification of the formula of Williams,[20] be stated in the form $-E=3.38\times10^{-6}Z\beta^{-1.4}\sigma/A$. Upon evaluating this loss for a 70-kv electron in nickel and dividing the result into the K radiation output of the preceding paragraph, we arrive at an efficiency of 0.0035 or 0.35 percent. This is not the efficiency of production of nickel K radiation from a *thick* target under 70 kv bombardment; in such a case the electron remains productive while its energy declines from the initial 70 kev to K-ionization energy at 8.35 kev. Evaluation of the radiant output and efficiency then requires knowledge of the variation of Φ_K with electron energy, a subject beyond the scope of this paper.

[20] E. J. Williams, Proc. Roy. Soc. **A130**, 310 (1932). A factor $2Z/A$ has been applied to Williams' expression, following the recommendation of D. L. Webster.

PHYSICAL REVIEW VOLUME 67, NUMBERS 5 AND 6 MARCH 1 AND 15, 1945

Forbidden Lines λ2967.5 and λ2269.8 of Mercury HgI

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(Received December 18, 1944)

The structure of the forbidden lines λ2967.5 ($6^1D_2\rightarrow6^3P^\circ_0$) and λ2269.8 ($6^3P^\circ_2\rightarrow6^1S_0$) of neutral mercury was studied with a high resolving power in order to get evidence for their perturbational nature. It was predicted some time ago by several authors that these lines should be emitted only by the odd isotopes of mercury. The emission would be of the electric dipole type, the selection rule $\Delta J=0, \pm1$ being partially invalidated by the weak interaction of the outer electrons with the nuclear magnetic moment. Only one line, namely λ2655.8 ($6^3P^\circ_0\rightarrow6^1S_0$) of mercury was analyzed in the past and definitely shown to belong to this category. The structure of the line λ2967.5 was fully resolved in the third order of a 30-foot Chicago grating. The structure of the line λ2269.8 was obtained by means of an aluminized Fabry-Perot etalon and a medium size quartz spectrograph. All components predicted for both cases were observed, except a very weak one for the line λ2269.8. The distances and intensities are in a very good agreement with theoretical predictions, hence establishing beyond doubt the nuclear perturbational nature of the forbidden transitions in the spectra of unperturbed atoms of zinc, cadmium, and mercury.

THERE is a certain ambiguity in the definition of a forbidden line. The definition that only the lines emitted by an unperturbed atom and obeying the selection rules for the electric dipole radiation should be called allowed, all the others—forbidden, is a very impractical one, since most of the quantum designations are approximate, the degree of approximation depending from the coupling conditions. It seems most convenient to call forbidden for the atom not perturbed by external forces all the lines not emitted at all or emitted with a transition probability not greater than about 10^{-4} of the highest transition probability found for the given atom in the optical region. Some forbidden lines appear only and acquire a considerable intensity in external fields—the so-called enforced dipole lines; they can be easily recognized by their considerable broadening if a spectrograph with a high resolving power is used. A large number of forbidden lines are caused by an electric dipole radiation enforced by internal interactions occurring between different electrons in atomic shells. These interactions are making approximate all quantum number designations, with the exception of the total angular momentum J and the even-odd symmetry relation. The remaining forbidden lines—likewise emitted spontaneously by an unperturbed atom—are violating one or both of the selection rules for the electric dipole radiation: (1) Laporte's odd$\rightleftarrows$even rule, and (2) angular momentum rule $\Delta J=0, \pm 1$ with $0\rightarrow 0$ excluded. The lines violating the first and some of them also at the same time the second rule are the electric quadrupole, and the lines violating only the first one are the magnetic dipole lines. All these lines were thoroughly investigated in the past, and it was shown that their type can be easily determined by study of their Zeeman effect or their hyperfine structure.[1]

There is, however, a whole group of forbidden lines known especially well in the spectra of HgI, CdI and ZnI, which are violating only the second rule, and therefore the corresponding radiation can be only (a) electric dipole or, (b) electric octopole (magnetic quadrupole). The second possibility (b) is very improbable. It has been therefore suspected for quite a long time, that the emission of these lines, among them of the two famous mercury lines, $\lambda 2655.8$ and $\lambda 2269.8$, is caused by coupling of the electronic shell with the nuclear magnetic moment I. The process of emission would be essentially similar to the electric dipole emission enforced by the interelectronic interactions. In the given case, the total angular momentum J of all electrons becomes only an approximate quantum number, the total angular momentum of the system being given by the quantum number F. Therefore, the rule $\Delta J=0, \pm 1$ is no more strictly valid and a violation can occur with a probability depending of the strength of interaction between J and I.

A direct evidence for the assumption was obtained in case of the mercury line $\lambda 2655.8$ ($6^3P^\circ_0 \rightarrow 6^1S_0$) by a direct observation of its hyperfine structure.[2] Two components are found with a separation indicating that they correspond to two mercury isotopes with masses differing by two units. There are two odd mercury isotopes 199 and 201 with nuclear spins of $\frac{1}{2}$ and $\frac{3}{2}$. The even isotopes 198, 200, 202 and 204 have no nuclear spin and no emission can take place in view of the rigorous application of the selection rule number 2. Opechowski[3] calculated the theoretical transition probabilities for those two isotopes and showed that the intensities of the two components should be in a ratio slightly different from the ratio of the concentration of isotopes. This seems to be in agreement with the observations. However, no measurements of intensities were performed at that time. Further it is not quite certain if the relative concentrations of metastable atoms are equal to the relative concentrations of isotopes in the mixture, since several processes of different kinds lead to the destruction and formation of metastable atoms, among others the refilling of the $6^3P^\circ_{10}$ state by collisions with metastable atoms of the even isotopes (infinite lifetimes). Finally the distance of the two components was calculated indirectly as the distance of centers of gravity of multiplets from the hyperfine structure pattern of the line $\lambda 2537$. It seemed therefore worthwhile to secure a still better check for the theoretical relations by studying the structure of the other forbidden line of mercury $\lambda 2269.8$ ($^3P^\circ_2 \rightarrow {}^1S_0$) and observe the positions and relative intensities of different components belonging not to two different, but to the same isotope.

Goudsmit and Bacher[4] discussed the source of the perturbation in the positions of the hyperfine levels of the 6^3D_1 and 6^1D_2 states for the odd isotopes of mercury and suggested that the very faint line $\lambda 2967.5$ observed next to the allowed line $\lambda 2967.3$ ($6^3D_1 \rightarrow 6^3P^\circ_0$) is caused by the interaction of the nuclear moment with the

[1] See the reviews on forbidden lines: W. Rubinowicz and J. Blaton, Ergeb. d. Exakt. Naturwiss. XI, 176 (1932); I. S. Bowen, Rev. Mod. Phys. **8**, 55 (1936); H. Niewodniczanski, Acta Phys. Polonica **5**, 111 (1936); S. Mrozowski, Bull. Polish Inst. Arts and Sci. Am. **2**, 200 (1943), or S. Mrozowski, Rev. Mod. Phys. in preparation.

[2] S. Mrozowski, Zeits. f. Physik **108**, 204 (1938).

[3] W. Opechowski, Zeits. f. Physik **109**, 485 (1938).

[4] S. Goudsmit and R. F. Bacher, Phys. Rev. **43**, 894 (1933).

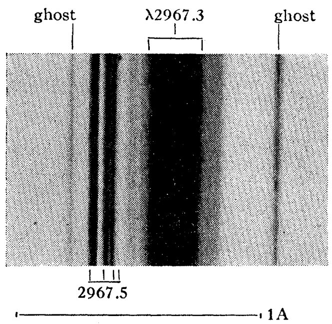

FIG. 1. Photograph of the forbidden line λ2967.5 obtained in the third order of a 30-foot grating (dispersion 0.2A/mm).

outer electrons. This line would be then in principle analogous to the line λ2269.8. Since the forbidden line λ2967.5 was only partially resolved by Wendt[5] (two components, one of them unsharp) it was decided first to study the structure of this line and after that to proceed with the much more difficult task of investigating the line λ2269.8. Only a big grating with a high dispersion can be used as a spectrograph for this purpose. The weak line λ2967.5 is so close to the strong line λ2967.3 that only for a very high dispersion the line is not disappearing in the halo surrounding the line λ2967.3. For the same reason a ghost free grating has to be used. The resolving power of the grating is not of such great importance, since the distances of the components are not very small (a resolving power of 160,000 is just sufficient). Wendt[5] used the fourth order of an excellent 21-foot Rowland grating and failed to split the short wave triplet because his source probably emitted too broad lines. Maybe also the temperature fluctuations in the grating room prevented him from obtaining the highest resolution in long exposures. In the experiments described in this paper the third order of a 30-foot, 30,000 lines per inch grating number 1 was used. This grating is giving a less intense spectrum and is possessing less resolving power than the grating number 3 used for most of other spectroscopic work in this laboratory, but is showing considerably weaker ghosts. Exposure times were relatively short (1–3 hours), so no special precautions had to be taken into consideration.

As a strong source of the forbidden line an all quartz high vacuum water-cooled mercury arc of a special design[6] in an end-on arrangement was used. The current was adjusted to a quite high level (10–12 amp), so as to weaken the line λ2967.3 by reabsorption, keeping at the same time the width of the components at a reasonably low value. It was found before[6] that this mercury arc provides very sharp lines even at such high density of current. A photograph of the line λ2967.5 obtained with this source is reproduced in Fig. 1. Between the line λ2967.3 (wide over-exposed dark band) and its long wave-length ghost a group of four components can be recognized with the relative positions: 0 (10), +0.553 (5), +0.828 (4) and 1.048 cm^{-1} (<1), the intensities given in parenthesis are, values estimated roughly on a scale of ten.

In Fig. 2 the level scheme for the two odd isotopes of mercury is presented after Goudsmit and Bacher.[4] On the outside are drawn the unperturbed hyperfine structure levels for the states 6^3D_1 and 6^1D_2, and towards the center the same levels are inserted after a correction for the mutual repulsion of the levels with the same quantum number F was introduced. Only perturbed levels of the 6^1D_2 state are combining with the $6^3P^\circ{}_{10}$ state, since they have an admixture of the eigenfunctions of the 6^3D_1 state, and are producing the structure of the forbidden line represented in the lower part of Fig. 2. The structure obtained experimentally is in excellent agreement with the predictions of Goudsmit and Bacher. Even the weakest component is well visible on Fig. 1. The calculated splittings of the levels deviate considerably from the distances obtained experimentally by Schüler and Jones.[7] This deviation induced Casimir[8] to express a pessimistic view about the ability of the perturbation theory to give an explanation for the observed interaction. According to the opinion of Goudsmit and Bacher,[4] however, Casimir[8] was overestimating the accuracy of the measurements of Schüler and Jones.[7] The results here reported show a very good agreement with the values of Goudsmit and Bacher and confirm their suspicions regarding the work of Schüler and Jones.

[5] G. Wendt, Ann. d. Physik **37**, 545 (1912).

[6] S. Mrozowski, Zeits. f. Physik **95**, 524 (1935).
[7] H. Schüler and E. G. Jones, Zeits. f. Physik **77**, 801 (1932).
[8] H. Casimir, Zeits. f. Physik **77**, 811 (1932).

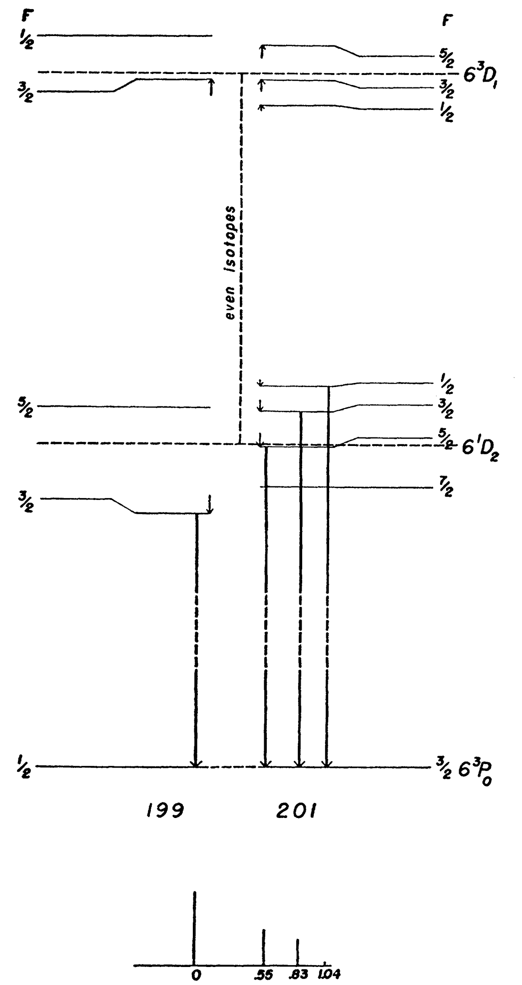

FIG. 2. The level scheme for the isotopes 199 and 201 of mercury. Unperturbed levels outside, levels after introduction of the mutual perturbational repulsion—closer to the center. Below the predicted structure of the forbidden line λ2967.5 according to Goudsmit and Bacher (reference 4) (corrected for isotope shift).

Schüler and Jones investigated the lines corresponding to allowed transitions from the states 6^3D_1 and 6^1D_2 to $6^3P^\circ_{2,1,0}$ and from their structures derived the level scheme. A careful inspection of the structures of these lines reveals however that most of the components corresponding to low values of the quantum number F are either very weak or are at least partly overlapped by other stronger components. Therefore any analysis must be in consequence of a relatively lower accuracy for the levels having low F-quantum numbers.

The forbidden line λ2269.8 has been obtained in a condensed discharge by Hansen, Takamine, and Werner[9] and later with a much higher intensity in a branched arc by Takamine and Fukuda.[10] Foote, Takamine, and Chenault[11] studied the optimum conditions for the excitation of this line and showed that a current of 0.25 amp/cm² gives the highest relative intensity of the line. Pure mercury vapor at a comparatively low density was used. As it became clear later, this condition was necessary in order to keep the number of collisional transfers to lower states $6^3P^\circ_{1,0}$ as low as possible. On the other hand, the current has to be kept low as to decrease the probability of destruction of metastable atoms by excitation to higher states. End-on observation of the above mentioned mercury arc showed that the line in question can be obtained with a considerable intensity if the current is kept low and the arc is well cooled. Although the intensity relative to other lines decreases above 0.25 amp per cm², however, the absolute intensity increases steadily to about 0.9 amp per cm². In order to have an intensity as high as possible without increasing too excessively the intensity of other lines and of the continuous background in the neighborhood of the line, a current of about 0.6 amp per cm² was maintained. At first an attempt was made to obtain a picture with the second order of the 30-foot aluminized grating number 3, however without success (48 hr. exposure did not reveal even the slightest traces of the line). Subsequently a quite heavily aluminized Fabry-Perot etalon in conjunction with a medium quartz spectrograph (Hilger E3) was tried. The greatest difficulty was encountered in the presence of a continuous background, which can be only partly avoided by a corresponding decrease of slit width. Photographs of the line were obtained with this arrangement in 2–3 hours. Longer exposures could not be made in view of the interference of the background. Three components were found with decreasing intensities: 0(5), 0.300(2) and 0.620 cm^{-1}(1), the distances being very uncertain in view of the haziness of the components. The photograph

[9] H. Hansen, T. Takamine, and S. Werner, Kgl. Danske Vid. Sels. Math.-Fys. Medd. V, 3 (1923).
[10] T. Takamine and M. Fukuda, Phys. Rev. **25**, 23 (1925).
[11] P. D. Foote, T. Takamine, and R. L. Chenault, Phys. Rev. **26**, 165 (1925).

cannot be reproduced here, since the pattern is very weak and of a low contrast (low reflection coefficient of aluminum for such a short wavelength).

If the assumption about the origin of the line λ2269.8 is correct and the emission of the line is caused by the interaction of the nuclear magnetic moment with the electrons, the case would be exactly analogous to the case of the line λ2967.5 with the slight difference, that the perturbing levels are below the perturbed levels and that the perturbation is much weaker in view of the great distance of perturbing levels (4630 cm^{-1} instead of 3 cm^{-1}, ratio of 1543 times). Four components are therefore expected with positions 0, 0.325, 0.613 and 0.793 cm^{-1}, the first belonging to the isotope 199 and the other three to the isotope 201. The relative intensities, as predicted by Einaudi[12] are 63.6, 23.0, 11.6 and 1.8 percent. The calculations are simplified in this case by the fact that the distance of all perturbing levels is practically the same (separation of $6^3P°_2$ and $6^3P°_1$ states). In Fig. 3 the predicted and observed patterns are represented. They are in a quite good agreement. The failure to observe the fourth component is easily explainable by its weakness.

The results obtained in this work are furnishing an additional evidence for the perturbational nature of the forbidden lines in the spectra of ZnI, CdI and HgI and are showing that the lines are emitted only by the odd isotopes of those elements. It is important to keep in mind that the relative intensities of components are not proportional to the concentrations of isotopes and for a given isotope not proportional to the statistical weights of the levels. Obviously in these spectra all the other forbidden lines, which violate the Laporte's rule and whose intensities increase proportional to the square of the current[13] are caused by the perturbing effect of the electric fields in the discharge. For one of these lines at least the evidence of its character was given by observation of its width and its Zeeman effect by Segrè and Bakker.[14]

In connection with these experiments it may be worth while to mention that the two other forbidden lines λ2536.04 and λ2379.45 mentioned by Goudsmit and Bacher[4] and presumably also of a nuclear perturbational type were carefully looked for and found not present in the spectrum of the mercury arc. The high intensity with which the line λ2967.5 can be obtained suggests that an investigation of the Zeeman

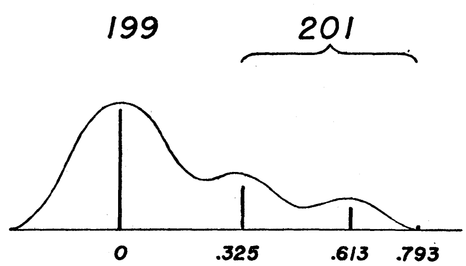

FIG. 3. Predicted and observed structures of the forbidden line λ2269.8.

effect in such a perturbational line, especially of the Paschen-Back transformation, can be of a considerable interest.

The author is very much indebted to Professor G. S. Monk for a loan of a Fabry-Perot etalon and for the kind permission to use his apparatus for aluminizing the plates.

[12] R. Einaudi, Rend. R. Acc. dei Lincei **17**, 552 (1933).

[13] M. Fukuda, Jap. J. of Phys. **3**, 139 (1924).

[14] E. Segrè and J. C. Bakker, Nature **128**, 1076 (1931).

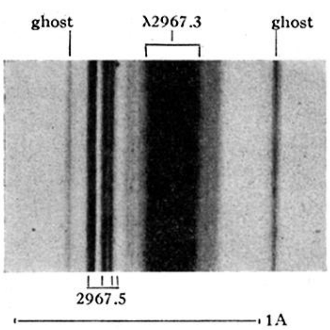

FIG. 1. Photograph of the forbidden line λ2967.5 obtained in the third order of a 30-foot grating (dispersion 0.2A/mm).