Hyperfine Structure of Elements in Mercury Arc—II.

NUCLEAR MOMENT OF CAESIUM.

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BAINBRIDGE (*P.R.*, **36**, 1668, 1930) has confirmed the earlier results of Aston (*P.M.*, **42**, 436, 1921) regarding the isotopic constitution of cæsium, *viz.*, that it has only one isotope of mass number 133. The source of discrepancy between the simple isotopic constitution of cæsium and its chemical atomic weight cannot be definitely traced until the packing fraction is correctly determined. The hyperfine structure analysis, however, is greatly simplified by the fact that cæsium atoms are all of one class with mass number 133, and no complications arising from a mixture of isotopes are at all possible. Jackson (*P.R.S.*, **121**, 432, 1928) first surmised the nuclear spin moment of cæsium to be either $\frac{1}{2}$ or $\frac{3}{2}$ in units of $\frac{h}{2\pi}$. But according to Kopfermann (*Naturwiss.*, **19**, 676, 1931) the nuclear spin is $\frac{7}{2}$ or $\frac{9}{2}$, while Schutz (*Naturwiss.*, **19**, 1007, 1931) gives for the nuclear moment $\frac{5}{2}$ as the most probable value. Thus to the nucleus of cæsium atom have been ascribed by various observers all the half integral values ranging from $\frac{1}{2}$ to $\frac{9}{2}$. White (*P.R.*, **35**, 411, 1930) however concludes that $\frac{5}{2}$ is probably the correct value from the meagre evidence obtained from the equation

$$\frac{\Delta \nu_g}{\Delta \nu_f} = \frac{m_k}{4\, i\, m_e}$$

connecting the nuclear moment i with the gross structure separation $\Delta \nu_g$ of ^2P levels, the electronic mass m_e, the nuclear mass m_k, and the fine structure separation $\Delta \nu_f$ supposed to be equal for both the $^2P_{\frac{1}{2}, \frac{3}{2}}$ levels. Jackson gives that

$$\frac{\Delta \nu_f}{\Delta \nu_g} = \frac{1}{\frac{1}{2}Z} \frac{\mu_k}{\mu_e}$$

where μ_k and μ_e are the nuclear and electronic magnetic momenta respectively; whence it follows that the individual separations of the hyperfine levels of ^2P states are unresolvably small if we assume that $\frac{\mu_k}{\mu_e}$ is of the order of 10^{-3} after Kopfermann.

The value of the nuclear quantum number can be determined quite simply from the intensity ratio of the components of the hyperfine structure doublets. The CsI doublet $6^2S_{\frac{1}{2}} - 7^2P_{\frac{1}{2}, \frac{3}{2}}$ (4593 Å and 4555 Å) gives two components for each line and from their relative intensity the nuclear spin can be estimated. By applying Burger and Dorgelo's intensity rule for gross multiplets to fine multiplets by the substitution of f for j, and considering the fine structure levels of $^2P_{\frac{1}{2}, \frac{3}{2}}$ to have negligible separations, the intensity ratio of the two components becomes $\frac{i+1}{i}$ agreeing with the value obtained by Fermi from quantum mechanical considerations. In cæsium the two components have been found to be of very nearly equal intensity, so that the value of i must be high; Jackson (*Nature*, **127**, 924, 1931) says "it may well be $\frac{5}{2}$, or perhaps higher".

Since the normal atoms of cæsium can absorb $6^2S_{\frac{1}{2}} - m^2P_{\frac{1}{2}, \frac{3}{2}}$ the effect of absorption in the source on the relative intensity of the hyperfine components needs special mention. Since the ratio $\frac{\text{emission}}{\text{absorption}}$ is the same for both the components of any one line, the stronger component will be more suppressed than the weaker one and the intensity of the two components will be rendered nearly equal as a result of the existence of self-absorption in the source. Filippov and Gross (*Naturwiss.*, **17**, 121, 1929) mention that in their source as well as in the one used by Jackson the possibility of self-reversal is not ruled out. Hence arises the necessity for re-examining the structure in a source where the effect of self-reversal is considerably reduced if not entirely eliminated. With this end in view the radiation from a vertical cooled mercury arc lamp with a tungsten anode containing a small quantity of cæsium chloride is analysed. The source answered our expectations since the use of cæsium chloride in an atmosphere of mercury vapour resulted in the great reduction of normal cæsium atoms responsible for the absorption as compared with other modes of excitation. Again the influence of the inner atomic electric fields on the radiating atoms is more marked in cases where the neighbouring atoms are in the same spectroscopic state as the radiating atoms and belong to the same element. Since the mutual influence is thus great in like atoms, an atmosphere of mercury vapour will serve to greatly diminish the broadening effect. An analysis of the lines 4593 Å and 4555 Å by Hilger Lummer plates revealed each line as a doublet consisting of two sharp lines with a clear intensity difference. Fig. 1 shows

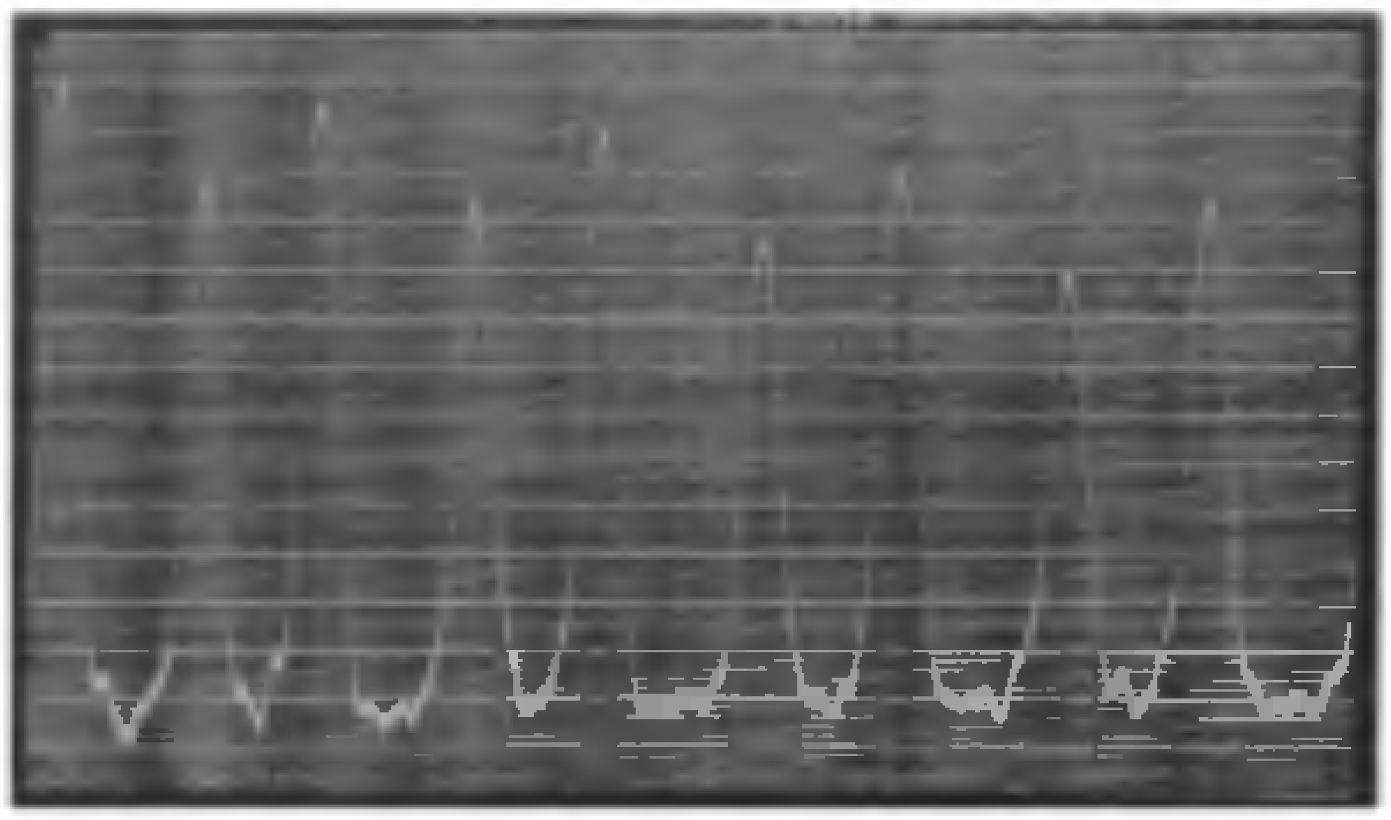

Fig. 1.

Microphotogram of the CsI Line λ 4555 Å, $6\ ^2P_{3/2} - 7\ ^2S_{1/2}$.

the densitometer curve of the Lummer plate pattern of the line 4555 Å taken on a Cambridge Microphotometer by Dr. A. L. Narayan of the Kodaikanal Solar Physics Observatory.

The intensity ratio of the components has been computed by using the Schwarzchild-Stark formula for the darkening D of a photographic plate that

$$D = \log k I^m t^n$$

where I is the absolute intensity of the radiation and t the time of exposure, k, m and n being constants depending only on the photographic plate and the wavelength of the radiation. Neglecting the wavelength difference between the components so far as its effect on the sensitiveness of the photographic plate is concerned, we obtain for the two components, whose darkenings are D and D′ and absolute intensities I and I′ that

$$\frac{I'}{I} = e^{\frac{D'-D}{m}}$$

the time of exposure for the two components being necessarily the same. The plate constant 'm' can next be evaluated by photographing the multiplet line with different slit widths for the same intervals of time, and assuming that the absolute intensities are proportional to the slit widths. An alternative method would be to determine 'm' from a hyperfine pattern of known intensity ratio obtained on the same plate, the wavelength of the line employed being as near as possible to that of the line under investigation. A calculation of the relative intensities of the two components from the densitometer curve has given a mean value of $1 \cdot 408 \pm 0 \cdot 018$. Hence the nuclear spin of cæsium can be estimated to be $\frac{5}{2}$; the theoretical value of the intensity ratio as given by the relation $\frac{i+1}{i}$ would then be 1·4. The neighbouring values of nuclear spin, *viz.*, $\frac{3}{2}$ or $\frac{7}{2}$ would give the theoretical ratio as 1·667 or 1·286 respectively, both of which are well outside the observed value. From measurements on the lines $6^2S_{\frac{1}{2}} - 7^2P$, the separation of the $6^2S_{\frac{1}{2}}$ term has been calculated to be 0·298 cm^{-1}, agreeing with value obtained by other observers. Fermi (*Z.P.*, **60**, 320, 1930) has shown that this separation

$$\Delta\nu = 146 \frac{\mu_k}{\mu_e} \frac{2i+1}{i}$$

whence $\frac{\mu_k}{\mu_e} \simeq \frac{1}{1180}$

in agreement with the assumption made by Kopfermann. Applying Nile's correction (*P.R.*, **38**, 375, 1931) to the Fermi formula, the Lande g (I) factor of the cæsium nucleus becomes 1·11. In the case of cæsium where the 6s optical electron alone is responsible for the term $^2S_{\frac{1}{2}}$, its relatively large separation as compared with that of ^2P terms is due to the extreme penetration of the 6s electron in consequence of which the coupling is very strong. The 6p electron is less penetrating, and hence the coupling is far weaker thereby producing only a very small separation in the ^2P levels.

Since the nuclear spin of cæsium has here been determined by applying the gross multiplet intensity rule for hyperfine structure components, it may be pointed out that the intensity ratio of the doublet lines 4555 Å and 4593 Å deviates considerably from the intensity rule for multiplets. Hagenow and Hughes (*P.R.*, **30**, 284, 1927) give ratios ranging from 2·3 : 1 to 3·8 : 1, the higher ratio being obtained with more attenuated sources where one would expect from Burger and Dorgelo's rule an asymtotic approach to the ratio 2 : 1. Filippov (*Z.P.*, **36**, 477, 1926) obtains an average intensity ratio of 3·81 : 1 for this doublet when the weakest possible concentration of the salt was used. Kohn and Jakob (*P.Z.*, **27**, 819, 1926) give ratios ranging from 3·43 : 1 to 4·25 : 1. Though the intensity rule is thus often violated in the gross structure multiplets, the hyperfine intensity rule has been applied with confidence to the patterns of those very lines that neither obey the intensity rules nor follow LS coupling. If a breakdown of the intensity rule in hyperfine structure should however occur in any single case, the estimate of the nuclear spin of cæsium will have to be established from entirely different considerations such as the Paschen-Back effect or the percentage polarisation of resonance radiation. The observed patterns of the two lines show a wing towards the shorter wavelength side of each component and if this wing be attributed to the small ^2P fine separations, it follows that the fine levels of $7^2P_{\frac{1}{2}, \frac{3}{2}}$ are possibly inverted, those of $6^2S_{\frac{1}{2}}$ remaining regular (Fig. 2). The wings of

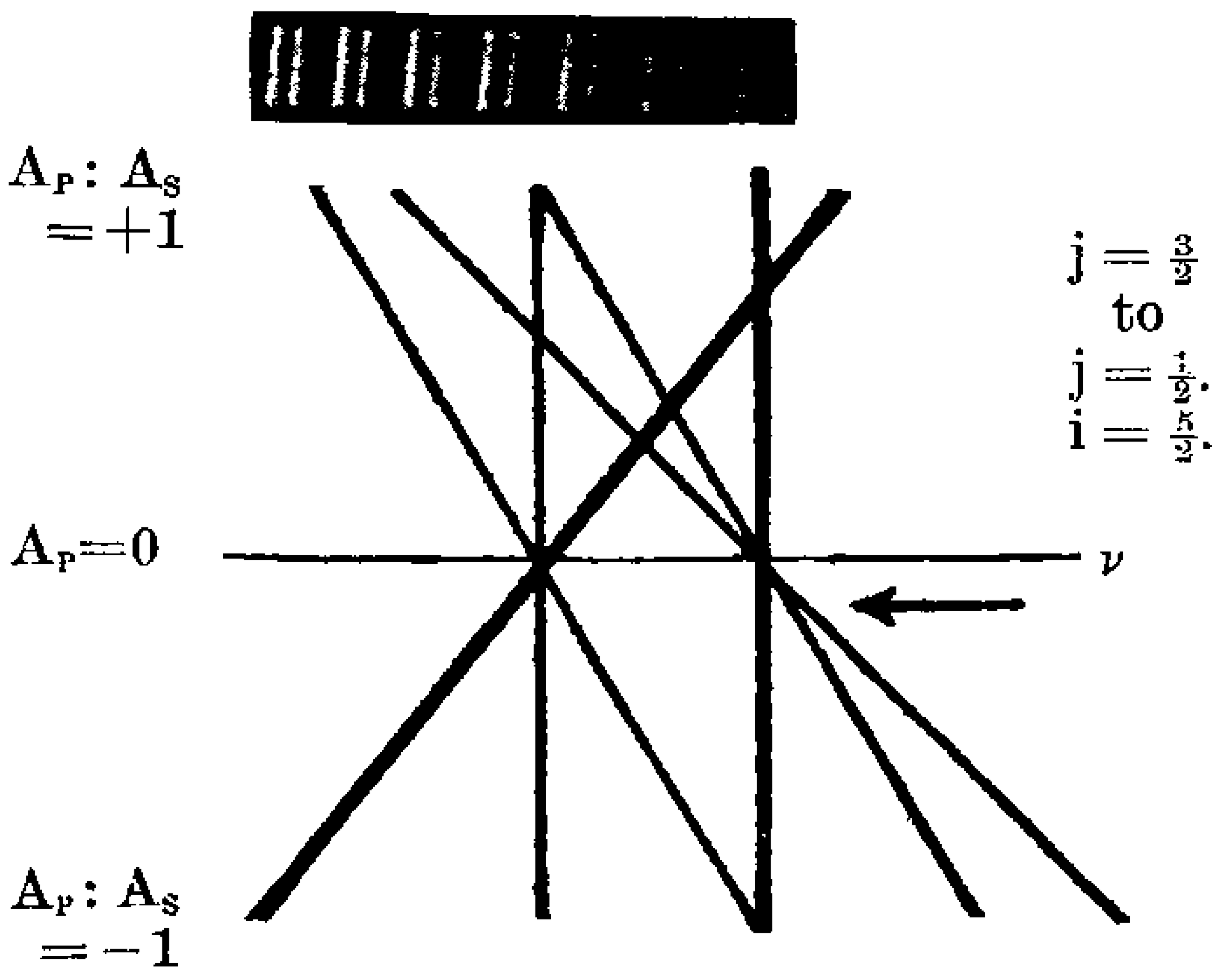

Fig. 2.

Graphical analysis of the structure of CsI 4555 Å, $6\ ^2S_{1/2} - 7\ ^2P_{3/2}$, showing that the observed pattern which fits into the diagram along the arrow is consistent with the inverted fine levels for the term $^2P_{3/2}$ with very small separation. A_P and A_S refer to the interval factors of the P and S states respectively.

the components of 4593 should then be expected to be more pronounced than those of 4555 Å, for according to Fermi

$$\frac{\Delta\, ^2P_{\frac{1}{2}}}{\Delta\, ^2P_{\frac{3}{2}}} = 2 \cdot 5$$

a relation which is however violated in the Tl I spectrum. Since in this investigation the chief point was the calculation of the relative intensity of the components, exposures for the patterns were necessarily insufficient to bring out the new faint satellites, if any, as in the case of cadmium or thallium (Venkatesachar and Sibaiya, *Cur. Sc.*, **1**, 264, 1933). Our earlier suggestion that such "faint satellites may be caused by isotopes present in such small relative abundance that the mass-spectrograph has not been able to reveal them" is further supported by the recent discovery of a large number of new isotopes for bismuth, lead and thallium by Miss Bishop and her collaborators (*P.R.*, **43**, 43, 1933) using a magneto-optic method.

Discussion on alkali nuclei :—The nuclear spin of cæsium from the intensity measurements on the hyperfine components is seen to be $\frac{5}{2}$. Using a source similar to the one described above in the case of sodium, each of the D lines have been found to be doublets with a separation of 0·058 cm^{-1} and an estimated intensity ratio of 3 : 1. This would mean that the nuclear spin of sodium is $\frac{1}{2}$, in entire agreement with the conclusions of Frisch and Ferchmin (*Naturwiss.*, **18**, 866, 1930) and Murakawa (*Tokyo Sc. Papers*). But the value $i = \frac{1}{2}$ gives theoretically 33·3% polarisation of resonance radiation, while Ellett's observed value (*P.R.*, **35**, 588, 1930) of 16·3% can only be explained if i is assumed to be equal to 1; again the band spectral data of Na_2 lead us to suspect that the nuclear spin is greater than 2. Thus the spin value determined by the intensity rule is not in agreement with that obtained by the polarisation of resonance radiation or by the band spectral calculations. In potassium also Loomis and Wood (*P.R.*, **38**, 854, 1931) point out that "the phenomenon of alternating missing lines not occurring disproves the assertion, based on the failure of certain observers to find hyperfine structure, that the nuclear spin of K 39 is zero." In rubidium, on the other hand, Jackson (*Nature*, **128**, 34, 1931), using an eye-estimate of the intensity ratio of the components as 2 : 1, gives the nuclear spin of Rb 85 as $\frac{3}{2}$, while it could well be 1 in agreement with theory; he attributes the wings of the hyperfine components towards the violet to the heavier isotope Rb 87. Kopfermann (*Naturwiss.*, **21**, 24, 1933) has concluded that the nuclear spin of Rb 85 is $\frac{5}{2}$, while that of Rb 87 is either $\frac{3}{2}$ or $\frac{9}{2}$, and shows that the magnetic moment of Rb 87 is 2·3 times greater than that of Rb 85. Li 6 has a nuclear moment of 0, while that of Li 7, according to the hyperfine structure data of Schüler and Brück (*Z.P.*, **58**, 735, 1929) and Schüler

(*Z.P.*, **66**, 431, 1930), is $\frac{1}{2}$; Harvey and Jenkins (*P.R.*, **35**, 789, 1930) conclude from band spectra that nuclear spin of Li 7 is $\frac{3}{2}$. It must be admitted with Gamow that "the results obtained from the band-spectra on the one hand and from hyperfine structure on the other do not always agree; these inconsistencies may be due to the uncertainty of the experimental data, or to the wrong interpretation of the observed facts."

It is suggested that the nucleus consists of a maximum number of α-particles, one proton or none, and neutrons with spin moments of $\frac{1}{2}\frac{h}{2\pi}$ arranged in shells (Venkatesachar and Subbaraya, *Cur. Sc.*, **1**, 120, 1932). The magnetic moment of a neutron being nearly equal to that of a proton, the hyperfine splitting will be of the right order of magnitude as compared with the multiplet splitting due to the magnetic moment of the spinning electron. This approximate equality of the magnetic moments of a neutron and a proton follows directly from the measurements of Granath (*P.R.*, **42**, 44, 1932) on lithium. The magnetic effect of the spin of a free proton in the nucleus will be masked by the magnetic effect of its motion in just the same way as for the electron, but for a neutron the conditions may be different. In the case of a neutron its magnetic moment is perhaps due only to its intrinsic spin moment, because the orbital magnetic moment may be negligible owing to the fact that the neutron is a particle carrying no net charge. The resultant spin quantum number of the theoretical normal term of the neutrons arranged just like the extra-nuclear electrons is here coupled with the proton spin for obtaining the nuclear spin moment. Since the nucleus of cæsium may be considered to be made up of 27 α-particles, 24 neutrons and 1 proton, the arrangement in shells of the 24 neutrons on the electronic model would give a normal term $3d^5 4s^1\ {}^7S_3$ corresponding to a spin value of 3. Combining this vectorially with a proton spin of $\frac{1}{2}$, the minimum energy configuration would give a spin moment of $\frac{5}{2}$ for the nucleus of the cæsium atom. This theoretical result is in conformity with our experimental value.

The Vertebral Column of Some South Indian Frogs.

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DR. H. K. MOOKERJEE has recorded in a note published in *Current Science* (Vol. I, No. 6, 1932), a case of *Rhacophorus maximus* in which the 8th. and 9th. vertebræ are procœlous, a condition which marks a departure from the well-known amphicœlous nature of the 8th. and 9th. having a boss in front and two behind such as occur in *Rana* generally. If it could be shown that the vertebræ are uniformly procœlous in this genus *Rhacophorus*, then its inclusion under the family Ranidæ, becomes a questionable procedure, since Nicholls has pointed out that the procœlous nature of the 8th. vertebra of *Bufo* may be used for diagnostic purposes. In view of the importance of the subject in its bearing on taxonomy I have examined the vertebral column of the following species:

Rhacophorus maculatus; Rh. eques; Rh. dubius; Rh. microtympanum; Ixalus chalazodes; I. sylvaticus; I. nasutus; I. oxyrhynchus; I. sp. (marked B in the museum collection); Micrixalus saxicola; Micrixalus sp. (marked A in the museum collection); Nyctibatrachus major; N. pygmœus; N. sanctipalustris; Nannobatrachus kempholensis (n. sp. Rao); Rana beddomii; R. bhagmandalensis; R. breviceps; R. brevipalmata; R. crassa; R. cyanophlyctis; R. curtipes; R. diplostichus; R. gracilis; R. intermedius; R. leithi; R. leptodactyla; R. limnocharis; R. malabarica; R. pantherina; R. parambiculamana (n. sp. Rao); R. sauriceps (n. sp. Rao); R. semipalmata; R. tennuilingua (n. sp. Rao).

Of the four species of Rhacophorus examined by me, I notice that the centrum of the 8th. vertebra is a variable structure. It is procœlous only in certain species such as *Rhacophorus maximus* (as reported by Mookerjee), *Rhacophorus dubius*, and *Rhacophorus microtympanum*, while it is amphicœlous in *Rhacophorus maculatus* and *Rhacophorus eques*. Possibly an examination of other species of this genus may reveal a similar divergence and if it be so, then we have clearly included in this genus *Rhacophorus*, two groups which, so far as the character of the 8th. and 9th. vertebræ is