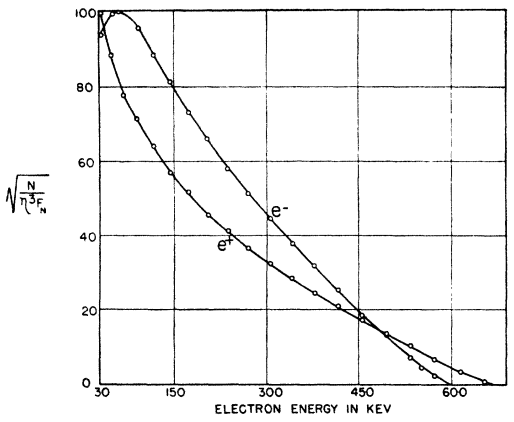

FIG. 3. Kurie plots of Cu^{64} electron and positron spectra from BeO of 11 mg/cm².

We wish to thank Professor W. E. Stephens for his kindness in sharing his radioactive $Be^{10}O$ with us. The constant interest and encouragement of Dr. L. J. Rainwater, Dr. W. W. Havens, Jr. and Professor J. R. Dunning are greatly appreciated.

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Photoelectric Disintegration of the Deuteron

J. S. LEVINGER
Cornell University, Ithaca, New York
July 18, 1949

THE cross section for the photoelectric disintegration of the deuteron has been calculated by many authors, with various assumptions as to the size, shape, and exchange character of the neutron-proton potential.[1] Recent measurements on neutron-proton scattering at high energies are consistent with a Yukawa potential of range $\mu^{-1}=1.18\times10^{-13}$ cm, about half exchange force, and half ordinary force.[2] The combination of half exchange and half ordinary force gives no force on states of odd orbital quantum number, thus greatly simplifying the calculation of the photoelectric cross section.

In this note we shall further simplify the calculation by assuming central forces, and by using an approximate wave function for the Yukawa potential.[3] The calculation is then very similar to the derivation of the Bethe-Peierls formula[4] for zero range of nuclear forces. We shall follow Bethe's notation.[4]

The cross section for the dipole term of the photoelectric effect is

$$\sigma=8\pi^3\nu|M_{OE}|^2/c, \tag{1}$$

where the electric dipole moment between ground state 0 and excited state E is

$$M_{OE}=\tfrac{1}{2}e\int U_O z U_E d\tau. \tag{2}$$

For the ground state of the deuteron we use the wave function[3]

$$U_O=[\alpha\beta(\alpha+\beta)/2\pi(\alpha-\beta)^2]^{\frac{1}{2}}[\exp(-\alpha r)-\exp(-\beta r)]/r. \tag{3}$$

For the excited state, we use the free wave function

$$U_E=\frac{3^{\frac{1}{2}}}{2\pi\hbar}\cos\theta\left(\frac{M}{k}\right)^{\frac{1}{2}}\frac{1}{kr^2}(\sin kr-kr\cos kr). \tag{4}$$

In Eq. (1), $\alpha=(M\epsilon)^{\frac{1}{2}}/\hbar$, where ϵ = binding energy of the deuteron. We shall use $\beta/\alpha=5.476$[3] corresponding to $\mu^{-1}=1.18\times10^{-13}$ cm, or effective range[5] $b=2.5\times10^{-13}$ cm; k is the wave number of the emitted proton.

The only changes from the Bethe-Peierls derivation are in the wave function for the ground state. Our Eq. (3) as compared to Bethe's Eq. (44c)[4] $U_O=(\alpha/2\pi)^{\frac{1}{2}}\exp(-\alpha r)/r$ has the extra term $\exp(-\beta r)$ and a different normalization factor. Our 4 equations give us

$$\sigma=\left[\frac{\beta(\alpha+\beta)}{(\alpha-\beta)^2}\right]\left[1-\left(\frac{\alpha^2+k^2}{\beta^2+k^2}\right)^2\right]^2\left[\frac{8\pi}{3}\frac{e^2}{\hbar c}\frac{\hbar^2}{M}\frac{\epsilon^{\frac{1}{2}}E^{\frac{3}{2}}}{(E+\epsilon)^3}\right]$$
$$=20.4\left[1-\left(\frac{\gamma}{29+\gamma}\right)^2\right]^2(\gamma-1)^{\frac{3}{2}}\gamma^{-3}\text{ millibarns}. \tag{5}$$

Here γ = photon energy/binding energy of the deuteron.

The term $\beta(\alpha+\beta)/(\alpha-\beta)^2$ in Eq. (5) represents our use of a different normalizing factor[6] for the bound wave function from that used by Bethe. The term $[1-(\alpha^2+k^2)^2/(\beta^2+k^2)^2]^2=[1-\gamma^2/(29+\gamma)^2]^2$ represents the effect of the $\exp(-\beta r)$ term in the wave function for the ground state. This interference term, due to the finite range of nuclear forces, greatly reduces the cross section at high energies. For $\gamma\gg29$, the cross section varies as $\gamma^{-7/2}$, instead of as $\gamma^{-\frac{3}{2}}$ in the Bethe-Peierls formula. The interference effect is very small for $\gamma\ll29$, or photon energy much less than 65 Mev. The term $(8\pi/3)(e^2/\hbar c)(\hbar^2/M)[\epsilon^{\frac{1}{2}}E^{\frac{3}{2}}/(E+\epsilon)^3]$ in Eq. (5) is the Bethe-Peierls formula for zero range of nuclear forces.

In Fig. 1, we show the photoelectric cross section as a function of photon energy, both as given by Eq. (5), and as given by the Bethe-Peierls formula. This dipole term for the photoelectric cross section should be a fair approximation to the total photo-disintegration cross section between photon energies of about 6 Mev and about 100 Mev. At energies near the threshold for photo-disintegration the photomagnetic cross section is of importance.

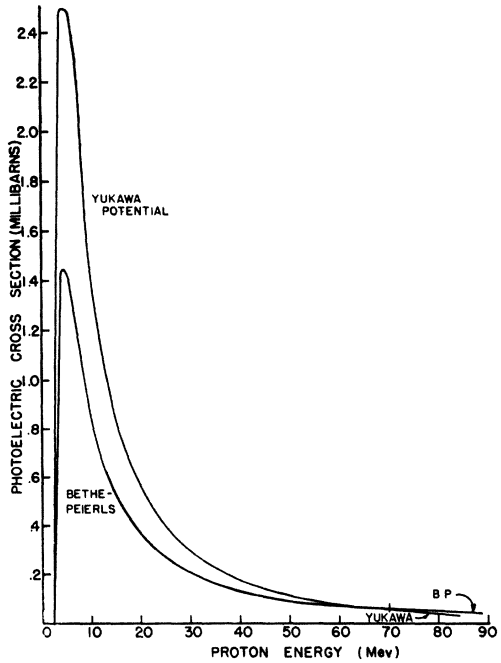

FIG. 1.

At high energies quadrupole and higher multipoles must be considered; and at very high energies relativistic and mesonic effects are important. Also our approximation of central forces may give poor results at moderately high energies.[7]

This work was done while the author was employed under an ONR contract.

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[7] Hu and Massey, reference 1, compare total cross sections for central *vs.* non-central forces. For a square well of range 2.62×10^{-13} cm, and symmetrical meson theory ($\frac{1}{2}$ exchange $+\frac{1}{2}$ ordinary force) non-central forces cause only a 4 percent decrease in the photoelectric cross section for photons of 17.5 Mev, but a 40 percent increase in the cross section for photons of 28.8 Mev.

Evidence on Nuclear Moments of Stable Ge and Si Isotopes from Microwave Spectra*

C. H. Townes, J. M. Mays, and B. P. Dailey
Columbia University, New York, New York
July 12, 1949

A previous letter[1] reported measurements on the $J=1\rightarrow2$ rotational transition of SiH_3Cl and the $J=2\rightarrow3$ transition of GeH_3Cl. Absorption lines due to the eight stable isotopes of Si and Ge were found, and a sizable nuclear quadrupole coupling noted in the case of Ge^{73}. An examination of hyperfine structure in the spectra of these molecules allows a determination of the spins of the even Ge isotopes, Ge^{70}, Ge^{72}, Ge^{74}, and Ge^{76} as zero, the spin of Ge^{73} as 9/2, and the nuclear quadrupole moment of Ge^{73} as $-0.21\pm0.10\times10^{-24}$ cm^2. Less certain evidence is obtained that the spins of the even isotopes of Si, Si^{28} and Si^{30}, are zero, and the spin of Si^{29} is $\frac{1}{2}$.

Hyperfine structure of the $J=2\rightarrow3$ transition of $Ge^{73}H_3Cl$ near 1 cm wave-length is rather complex because both Ge^{73} and the Cl nuclei show quadrupole coupling and spectra for $K=0$, 1, and 2 are superimposed. Consequently the considerably simpler transition $J=0\rightarrow1$ transition at 3.6 cm wave-length was studied in order to obtain the Ge^{73} spin and quadrupole coupling. Observed hyperfine structures were fitted by theoretically calculated patterns assuming the Ge^{73} has a spin of 9/2 and a quadrupole coupling constant $eqQ=-95\pm3$ mc. Coupling constants for Cl^{35} and Cl^{37}, obtained from measurements of hyperfine structure of lines due to GeH_3Cl molecules with even isotopes of Ge, were taken as -46 ± 1 and -36 ± 1 mc, respectively. These are consistent with and more accurate than the value -34 mc previously given for Cl^{37}. Both relative intensities and positions of lines were calculated.[2] The line positions agree well as shown in Fig. 1. The lowest frequency Cl^{35} line was partially obscured by the adjoining $Ge^{74}H_3Cl^{35}$ pattern and thus its measurement is somewhat uncertain. Although relative intensities could not be accurately measured, they agreed with theoretical expectations within experimental errors. Hyperfine patterns computed for spins of 3/2, 5/2, and 7/2 for several different assumed values of the Ge^{73} coupling constant show that these values of spin cannot give a reasonable fit of the observed patterns. Calculations for a spin of 11/2 have not yet been completed, but this value of spin is very improbable.

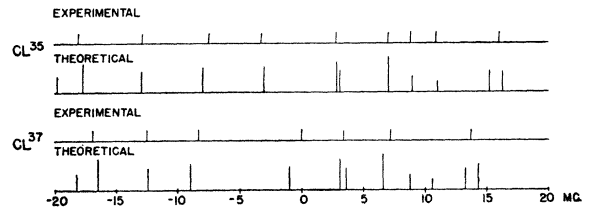

Fig. 1. Experimental and theoretical hyperfine structure patterns for $J=0\rightarrow1$ transition of $Ge^{73}H_3Cl^{35}$ and $Ge^{73}H_3Cl^{37}$. Origins correspond to position of unsplit transition, $Ge^{73}H_3Cl^{35}$ 8700 mc and $Ge^{73}H_3Cl^{37}$ 8389 mc.

It can be shown[3] that the value of q or $(\partial^2V/\partial z^2)$ for an atom in a molecule depends principally upon the number of "unbalanced" p electrons along the molecular axis. The GeCl bond has been assigned[1] 45 percent ionic and 15 percent double bond character. In the single and double bond structures the three p orbitals of the Ge atom are assumed to be equally populated by bonding electrons and thus not to contribute appreciably to q. The ionic structure $H_3Ge^+Cl^-$, however, corresponds to a deficiency of $0.75p$ electrons and thus produces a q equal to 0.34 of that for GeII. This latter quantity can be calculated[3] using the doublet separation $\Delta\nu=1768$ cm^{-1} [4] for GeII. The resulting value of the Ge^{73} nuclear quadrupole moment is $-0.21\pm0.10\times10^{-24}$ cm^2. The large limits of error allow for uncertainties in the GeH_3Cl structure, as well as errors in the approximations involved.

The spin of Ge^{73}, which has 41 neutrons and an even number of protons, is the same as the spin of Cb^{93} which has 41 protons and an even number of neutrons. Furthermore Ge^{73} is the lightest nucleus with a known spin as large as 9/2. These facts fit very well into the nuclear shell scheme proposed by Mayer,[5] where the first neutron or proton which goes into the $5g9/2$ shell is the 41st. The Ge^{73} spin can also fit into other[6,7] nuclear shell schemes.

No evidence of a quadrupole moment for the Ge^{70}, Ge^{72}, Ge^{74}, or Ge^{76} nuclei was observed. A rough calculation based on the observed line widths and the splitting to be expected for various spin values shows that the quadrupole moments of these nuclei must be less than 1/30 of the Ge^{73} quadrupole moment, or $Q=0.007^{-24}$ cm^2. This appears to be very good evidence that the spins of the even Ge isotopes are zero, since then no quadrupole moment is observable.

In the case of Si moments the spectrum of SiH_3Cl has so far given less clear-cut evidence. No hyperfine structure due to Si nuclei has been observed, which suggests the Si^{28} and Si^{30} spins are zero and the Si^{29} spin is $\frac{1}{2}$. It is possible, however, that these spins are not correct and that the nuclei have very small quadrupole coupling constants. It is hoped that projected work with a high resolution microwave spectrometer and with other silane derivatives will make certain the assignment of spins for the Si nuclei.

The authors are indebted to Mrs. Zelda Droshnicop for assistance in calculation of the theoretical hyperfine patterns.

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