Letters to the Editor

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Stars and Slow Protons at 14,125 Feet

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A LARGE number of heavily ionizing particles appeared in a Wilson cloud chamber containing five horizontal lead plates each one cm thick. The plates were six cm apart and the gas in the chamber was argon at a pressure such that the range of a particle in the gas is approximately the same as that in dry air at 20°C and 76-cm Hg pressure.

Stars containing heavily ionizing particles appear both coming out of the lead and arising in the gas. Many of the particles start in one lead plate and stop in the next. If there were equilibrium in the chamber, then the ratio of the stars produced in the lead to those produced in the gas should be equal to the ratio of the particles stopping in the lead (i.e., traversing the space between the plates) to those stopping in the gas. These two ratios are found to be 14.7 and 13.2, respectively, which makes them equal to each other well within the experimental error. It can be concluded that equilibrium is established. By multiplying the average path of a particle in the gas, namely 7 cm, by this ratio, we find the average range of the particles to be 100 cm in air. This corresponds to a kinetic energy of about 10 Mev, which agrees closely with the maximum in the energy distribution curve for particles appearing in photographic emulsions left at high altitudes.[1]

The range in lead of a 10-Mev proton amounts to approximately 0.02 cm, and since the plates are one cm thick, the rays of only one star in fifty produced in the plate will appear leaving the lead plate. The average number of particles in a star in the gas is three, and there are probably as many neutrons as ionizing particles ejected. If we assume that it takes about eight Mev to eject a neutron or proton from the nucleus then the total energy necessary to produce an average star is a little over 100 Mev.

In a set of 19,000 pictures there appear 156 stars and 9840 penetrating particles. The penetrating particles make slightly more than two traversals per particle and thus are responsible for 2×10^4 traversals. Since there are fifty stars created inside the lead for one appearing leaving the lead, the total energy for all the stars at 100 Mev per star is $156\times50\times100$ Mev or 7.8×10^5 Mev. The penetrating particles lose approximately 13 Mev in traversing one lead plate. The total energy of all the traversals is $2\times10^4\times13$ Mev or 2.6×10^5 Mev. The startling fact appears that the energy used in creating stars is three times greater than the energy lost by the penetrating component in the same amount of material. If instead of using only the stars we make the same type of comparison with short range heavily ionizing particles which leave one lead plate and stop in the next one without penetrating a lead plate, we get dissipation of energy of the same order of magnitude.

Practically all of the stars are produced by non-ionizing radiation, and since they are hardly ever accompanied by cascade showers it seems reasonable to assume that the producing agent is neutrons. The average energy of the neutrons, as we found above, is in the neighborhood of 100 Mev. If their average angular distribution is similar to that for the penetrating particles, they will make two traversals of one cm of lead on the average. If the nuclear cross section is 3×10^{-24} cm^2 per lead atom and if they pass 6×10^{22} lead atoms in penetrating two cm of lead, then approximately five out of six neutrons will pass through the chamber without producing a star. This means that there are $156\times50\times6$ or 4.7×10^4 energetic neutrons while 9840 penetrating particles pass through the chamber. This is nearly a ratio of five to one in favor of neutrons.

There is a group of slow protons which stop in the chamber and at the same time have enough energy to penetrate one or more lead plates. On comparing these protons with the faster penetrating particles, it is at once apparent that the protons have a maximum range very nearly equal to five cm of lead. Only two protons out of 400 stopped with a range of five cm of lead, whereas a total of 40 particles would be expected to pass through the five plates on the basis of the geometry of the chamber and the statistics of more energetic penetrating particles. This indicates that the protons are of secondary origin and we should expect to find them in equilibrium. Actually we find that the ratio of protons created in the chamber to those stopped, instead of being one, was one to twenty. We are forced to conclude that for this group of protons capable of penetrating one or more cm of lead, equilibrium is not established. None of the usual assumptions can be applied with any satisfaction to explain this situation.

The explanation appears to lie in the action of the energetic neutrons. We have just seen that the neutrons have an average energy around 100 Mev. Inside the chamber there are no free protons. All the nuclei present are heavy. The neutrons produce disintegrations and low speed protons inside the chamber. On the other hand, outside the chamber there are free protons in the wood of the trailer-laboratory and in the observer. There the neutrons can transfer their energy to protons without degradation and the protons will appear passing through the lead plates of the chamber. One cm of wood in the neighborhood of the chamber bombarded by these neutrons would be sufficient to account for the number of fast protons observed. This explains completely the large number of fast protons entering the chamber and their maximum range, and at the same time reconciles this fact with the small number of fast protons produced inside the chamber.

I wish to take this opportunity to thank Professor

Oppenheimer for many valuable suggestions in interpreting the results, and to acknowledge the support of the Rumford Fund of the American Academy of Arts and Sciences, the Fund for Astrophysical Research, and the American Philosophical Society.

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[1] A. Widhalm, Zeits. f. Physik 115, 481 (1940).

On the Virtual State of the Deuteron

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In a previous paper[1] it was shown that

$$\frac{d^2\phi}{d\xi^2}+\left(a+b\frac{e^{-\xi}}{\xi}\right)\phi=0, \tag{1}$$

being the simplest possible form of the Schrödinger equation for the deuteron in the ^1S and ^3S states,[2,3] has no discrete eigenvalue, if $b<B_1=1.6798$, one eigenvalue a—i.e., one stable energy level—if $B_1<b<B_2=6.44_7$, etc.[4] Putting $b=B_1-\beta$, $|\beta|\ll B_1$, and supposing a to be of the same order of size as β^2, we can with great accuracy write the normalized solutions of (1) for the continuous spectrum $(a>0)$ as follows

$$\phi(\xi)=\frac{(1-e^{-\xi}-c(1-e^{-\xi})^2)}{(1-c)\pi^{\frac{1}{2}}a^{\frac{1}{4}}}\sin\,(a^{\frac{1}{2}}\xi+\delta) \tag{2}$$

with the constants c and δ $(=\delta_\infty)$ given by

$$c=0.3489-0.0296\beta,\quad \operatorname{tg}\delta=2.2655a^{\frac{1}{2}}/\beta.$$

A natural definition of the virtual eigenvalues for an equation like (1) is obtained by requiring the average of the potential energy to be minimum for the state in question. Thus, in our case, a is a virtual eigenvalue, if it makes the expression

$$S(a)=b\int_0^\infty\frac{e^{-\xi}}{\xi}\phi^2d\xi \tag{3}$$

a maximum. An equivalent definition, quite analogous to the definition of the discrete eigenvalues, is given by the condition: $\operatorname{tg}^2\delta=1$.

For small β we then get

$$a_{\text{virt}}=0.1948_4\beta^2 \tag{4}$$

for positive *and* negative β. From a purely mathematical point of view there is in general an infinite number of virtual eigenvalues for equations of the type considered here, but in our case even the second maximum is far too flat to possess any physical importance. Moreover, the first and lowest virtual state is strongly pronounced only when b is very close to one of the critical values B_1, B_2, etc.

For small negative β there exists a discrete eigenvalue a_1:

$$a_1=-0.1947_9\beta^2. \tag{5}$$

The obvious symmetry of (4) and (5) with respect to the zero level seems to be a general feature of problems of this kind: exact validity has been verified for the rectangular potential well and the potential function $e^{-\xi}/(1-e^{-\xi})$.

Although the virtual state of a system described by an equation like (1) can thus be calculated exactly, one cannot, of course,—apart from the question of the strict validity of (1) for the deuteron—expect any corresponding accuracy in experiments, because the breadth of the energy level is of the same order of size as the energy itself.

As (4) agrees surprisingly well with the relation suggested by Belinfante,[5] the determination of the fundamental constants g_1 and g_2 of the meson theory is not appreciably influenced by the results presented here.[1,3,6]

Further details will be published elsewhere.

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[4] Cf. also Wilson, reference 2, besides R. Sachs and M. Goeppert-Mayer, Phys. Rev. 53, 991 (1938).
[5] F. J. Belinfante, Dissertation (1939), p. 45.
[6] C. Møller, Danske Vidensk. Selsk. math.-fys. Meddelelser 18, No. 6 (1941).

Secondary Scattering of Electrons in Silicon

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In electron diffraction patterns of polycrystalline CuCl Germer[1] finds the (222) ring roughly 200 times as strong as it should be, though the (200) ring has its expected very low intensity. He explains this anomaly by supposing that most of the electrons reaching the (222) ring have actually suffered two successive first-order (111) reflections in the same crystal. His experiments show, in support of this view, that the (222) ring is practically absent if the crystals are sufficiently small, and increases in relative prominence with increasing crystal size until it is approximately as strong as the (400) ring.

We can offer, as another instance of the same effect, our observation that the (222) ring appears prominently in electron diffraction patterns of polycrystalline silicon, where it should be not merely weak but entirely absent. We have examined transmission samples made by settling powdered Si from air suspension onto Formvar films, and reflection samples prepared by rubbing bulk polycrystalline Si on emery paper—here the diffracting microcrystals are in a dust layer adherent to but not continuous with the bulk Si crystals. In every pattern the (222) ring has the same intensity, estimated by eye, as the adjacent (400) ring. Contrastingly, no trace of a (200) ring can be found.

The (222) ring, in our patterns, contains several distinct spots, each spot arising from a single crystal of the sample. We find that every prominent (222) spot is associated with a prominent spot on the (111) ring, while the reverse correspondence is not nearly complete. This fact seems to us to speak decisively in favor of Germer's explanation, and against the alternative view that the diamond type extinction rule is here for some reason relaxed with respect to (222). If the observed (222) spots were true second-order reflections from (111) planes, the correspondence either should be complete in both directions or should fail as often in one direction as in the other. On the other hand, if the (222) spots are actually due to twice-reflected electrons, each pseudo-(222) ray should be accompanied by its parent (111) ray, though (because some crystals are too