However, expressions for secondary yields and energy losses based upon this cross section actually vanish since, in this approximation, $\sigma_{\mathbf{q}}$ is zero, a fact not recognized in previous theories. This is an immediate consequence of the orthogonality relation between the lattice eigenfunctions belonging to $\mathbf{k}$ and $\mathbf{k}+2\pi\mathbf{q}/a$,

$$\int \psi_{\mathbf{k}}\psi_{\mathbf{k}+2\pi\mathbf{q}/a}^{*}\,d\tau=0. \tag{7}$$

Substitution of Eq. (3) into Eq. (7) yields

$$\frac{1}{V}\Sigma_{\mathbf{m},\mathbf{n}}a_{\mathbf{n}}(\mathbf{k})a_{\mathbf{m}}^{*}(\mathbf{k}+2\pi\mathbf{q}/a)\int\exp[(2\pi i/a)(\mathbf{n}-\mathbf{q}-\mathbf{m})\cdot\mathbf{r}]d\tau$$
$$=\Sigma_{\mathbf{m}}a_{\mathbf{m}+\mathbf{q}}(\mathbf{k})a_{\mathbf{m}}^{*}(\mathbf{k}+2\pi\mathbf{q}/a)=0. \tag{8}$$

Substitution of Eq. (8) into Eq. (6) yields a zero cross section. In order to obtain a finite result, it is necessary to take into account the variation of $a_{\mathbf{m}}(\mathbf{k}')$ with $\mathbf{K}'$. This can be accomplished by a Taylor series expansion of $a_{\mathbf{m}}(\mathbf{k}')$ about the point $\mathbf{k}'=\mathbf{k}+2\pi\mathbf{q}/a$. This results in a cross section which for sufficiently high energies has the same form as that obtained by Bethe[3] for the ionization of atoms, namely,

$$\sigma_{\mathbf{q}}=(A/E)\ln(E/E'), \tag{9}$$

where E is the energy of the primary electron and A and E' are parameters characteristic of the medium. A similar expression is obtained for the rate of energy loss by electrons passing through solids. These results are entirely different from those obtained on the basis of Eq. (4), which have previously been interpreted[1,2] to mean that both the rate of production of secondaries and the rate of energy loss should be practically independent of the energy of the primary. Actually, these quantities are zero in the approximation leading to Eq. (4), and as indicated by Eq. (9) and the equivalent expression for the energy loss, they decrease rapidly with energy.

It should be pointed out that the above considerations do not apply to the case of free electrons ($\mathbf{q}=0$), which has been treated by Baroody[4] and by Dekker and van der Ziel[2], since values of $\mathbf{S}$ in the neighborhood of $\mathbf{S}_{\min}$ are forbidden because they correspond to transitions to occupied states.

The questions outlined here will be treated in more detail in a forthcoming paper.

* Supported by the ONR.

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Alpha-Particle Ionization in Mixtures of the Noble Gases

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DURING the course of experiments to determine for polonium alpha-particles the absolute value of W, the average energy required to produce an ion pair in various gases, erratic results soon showed that the effect of minute gaseous impurities in such measurements is much greater than is commonly recognized. Accordingly, experiments have been carried out where a contaminant in measured quantities could be added to the gas under investigation and the effect of the impurity on the total ionization observed. Preliminary experiments on helium and neon have shown rather striking results.

In the measurements a short collimating system directed the polonium alpha-particles along the axis of a long cylindrical ionization chamber. The effective path length was about 20 cm. The ions produced by each alpha-particle were collected and measured by a method already described.[1] From a knowledge of the capacity of the system and the change of potential of the system produced by the ionization from each alpha-particle, the absolute number of ion pairs produced may be determined. The average energy W to produce an ion pair is, of course, the energy of the polonium alpha-particle (5.298 Mev) divided by this number.

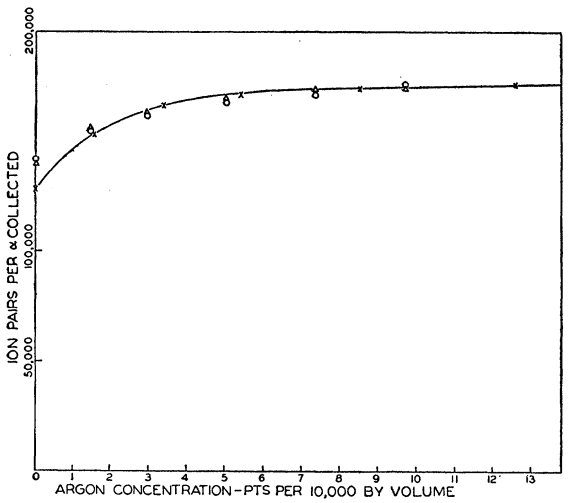

FIG. 1. Ion pairs collected per alpha-particle as a function of argon concentration in helium. Runs △ and ○ represent commercial "spectroscopically pure" He. Run × represents this He after further purification.

The ionization chamber was pumped and baked for twelve hours at a temperature above 200°C at the beginning of the measurements, and extreme care was taken to minimize gaseous impurities from the system.

The graph in Fig. 1 shows the effect on the ionization produced per alpha-particle of adding extremely small quantities of argon to pure helium. The ionization per alpha-particle at first increases rapidly with increasing argon concentration and then more slowly, apparently approaching finally a saturation value. The points on the curve may be indefinitely repeated by adding argon in measured quantities and then removing it by repeated passage over coconut charcoal at liquid air temperature.

The addition of argon to pure neon gives a curve of the same type as that shown in Fig. 1, but with higher ionization values throughout. Data for helium and neon with argon as an impurity are shown in Table I.

TABLE I. Polonium alpha-ionization measurements in helium and neon.

Gas	Ion pairs per Po alpha-particle	W = average energy per ion pair, ev/ion pr
Purest helium used	128,300	41.3
Helium +0.13% argon	178,400	29.7
Purest neon	146,000	36.3
Neon +0.12% argon	203,000	26.1

It is of interest to note that, for the purest gases used here, the number of ion pairs produced per alpha-particle is much smaller, and the W correspondingly larger, than the results heretofore given in the literature. In fact, the value of W for helium commonly given in the literature, about 30 ev/ion pair, is in much closer agreement with the above value for helium saturated with argon as an impurity. This suggests the presence of impurities in previous determinations.

Experiments with a small radium source placed in a standard position with regard to the chamber show a similar increase in gamma-ray ionization as the argon concentration in helium is increased. Here the total relative current through the chamber was measured, rather than the effect of single gamma-rays.

A plausible explanation[2] for the increase in ionization observed, both for alpha-particles and gamma-rays, is that this increase results from a transfer of energy from the metastable states in

helium (or neon) when an excited atom of helium encounters an argon atom. In the process the argon atom is ionized and a pair of ions collected in the chamber. Thus for helium, we have

$$He^*+A \rightarrow He+A^++e^-.$$

Any additional energy imparted by the metastable helium atom He* to the argon atom A, above that energy to produce an ion pair, is carried off as kinetic energy in the ejected electron e^-. The above reaction has already been studied[3,4] under quite different experimental conditions in connection with metastable atoms.

Krypton and carbon dioxide as contaminants in helium have been found to yield results, in general, similar to argon. However, no significant increase in ionization is observed when neon is added to helium. This is in accord with the explanation above, since the energy available in the metastable state for helium (19.8 ev) is insufficient to ionize the neon atom with an ionization potential of 21.5 ev.

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The Reaction $Li^6(\gamma,d)He^4$ at 2.76 Mev

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A SEARCH has been made for the $Li^6(\gamma,d)He^4$ reaction using 2.76-Mev γ-rays from Na^{24}. Ilford C2 nuclear emulsions loaded with enriched Li^6 were used. Using fused NaF irradiated in the Argonne heavy water pile, the Li^6 plates were exposed to approximately 10 r using $\frac{1}{8}$ in. of Al to filter out the beta-rays from Na^{24}. Using the accepted mass values[1] for Li^6, He^4, and H^2, the reaction threshold is found to be 1.48 Mev and there is 1.28 Mev available for the reaction products. From the kinetics of the problem, neglecting γ-ray momentum, the alpha-particle receives $\frac{1}{3}$ and the deuteron receives $\frac{2}{3}$ of this energy. These correspond to ranges of 2 and 8 microns, respectively, in the emulsions used.

During preliminary investigations, one example of the reaction was found. Searching was continued on a plate which had the maximum exposure, but with a tolerable gamma-background. In 7500 fields of view, corresponding to $\frac{3}{4}$ cm^2, only two possible events were found. Figure 1 shows the first example to be found. The ranges for the alpha and the deuteron tracks are 2 and 8 microns, respectively, as predicted, and the track density shows the two-body nature of the event. The photograph does not show the two tracks and the point of disintegration as clearly as they appear under the microscope.

On the basis of this evidence, an upper limit for the cross section for the reaction can be placed at

$$\sigma[Li^6(\gamma,d)He^4]_{2.76\ Mev}=(4\pm4)\times10^{-30}\ cm^2.$$

The only other work reported[2] on this reaction was done using a mixture of 14.8-Mev and 17.6-Mev γ-rays from the $Li^7(p,\gamma)$ reaction.

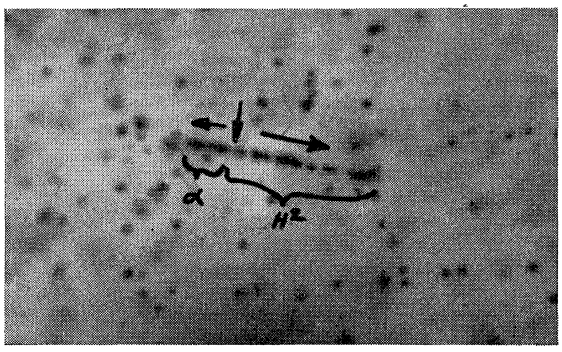

FIG. 1. Example of the reaction $Li^6(\gamma,d)He^4$.

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Mean Free Paths of Electrons in Evaporated Metal Films

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RECENT work on the evaporation of metals, particularly Cu and Ag, has made available thin films of these metals, in the thickness range from about 100–2000 angstroms, which have resistivities and resistance-temperature coefficients predictable from existing theories. These results suggest approximate values for the mean free paths l of the conduction electrons in these metals at room temperatures.

It is well known that the resistivity ρ' of a thin metallic film is greater than ρ for the bulk metal, and that the ratio ρ'/ρ increases with decrease in film thickness t. Thomson[1] was the first to suggest a theory of this effect involving the mean free path and the film thickness. Subsequently, this theory has been modified and extended by others, including Fuchs[2] and Dingle.[3] A comprehensive review of this subject has been given recently by Sondheimer.[4] Andrew,[5] working with Sn and Hg using relatively thick layers $>3\mu$ and wires $>6\mu$ in diameter, has obtained experimental confirmation of this theory at low temperatures. Similar results appear lacking in the literature for thinner layers and for higher temperatures. In general, thin metallic films exhibit wide variations in properties with method of preparation and have much larger resistivities than would be predicted from theory. Our recent work has been successful in minimizing these variations by selection and control of the rate of evaporation and residual gas pressure. Optimum conductivity is obtained by using fast rates of evaporation, for example, 500–1000 angstroms per second, and low residual gas pressure, for example, 10^{-5} mm. At these rates and pressures satisfactory films can be obtained in the thickness range previously mentioned. Films deposited at much slower rates and/or higher pressures show considerable departure from calculated values.

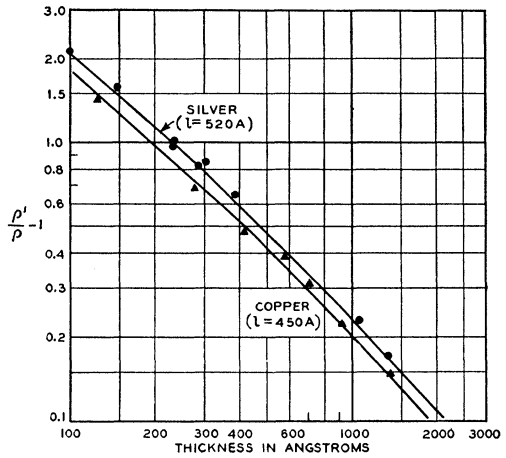

FIG. 1. Experimental points involving resistivity measurements of Cu and Ag films at room temperature, shown with curves calculated from theory to obtain approximate values of mean free paths.