this case is not so complete as in the analogous problem in the pseudoscalar theory. This fact will probably explain the apparent discrepancy between my result and conclusions drawn by Van Hove at the end of his work.

When dealing with scalar mesons we get a strong spin-orbit coupling as indicated recently by many experiments.

I will now outline the method used.

The equations of meson field theory, e.g.,

$$(\Box-\mu^2)\,\varphi=-4\pi g\delta(\bar{x}-\bar{\xi}(t)),$$

can be solved by assuming that there exists a development of the function φ according to the successive orders of time derivatives i.e., in a power series of a parameter $\lambda=1/c$ (absorbed in the φ's) and such that differentiation with respect to time raises the order by one.

So we assume:

$$\varphi=\sum_{l=0}^{\infty}{}_{2l}\,\phi\lambda^{2l}=\sum_{l=0}^{\infty}{}_{2l}\varphi.$$

$1/c\;\partial_{2l}\varphi/\partial t={}_{2l}\dot{\varphi}$ is of the same order as ${}_{2l+1}\varphi$.

We now have

$$(\Delta-\mu^2)\Sigma\,{}_{2l}\varphi=-4\pi g\delta_3(\bar{r})+\Sigma\,{}_{2l}\ddot{\varphi}$$

$$\bar{r}=\bar{x}-\bar{\xi}(t),$$

and after reordering the terms we obtain an infinite set of equations

$$(\Delta-\mu^2)_0\varphi=-4\pi g\delta_3(\bar{r})$$

$$(\Delta-\mu^2)_{2l}\varphi={}_{2l-2}\ddot{\varphi}\quad\text{for}\quad l\geqslant 1.$$

A general formula for ${}_{2l}\varphi$ satisfying this set can be given. The first three terms have the form (we put $c=1$):

$$\varphi={}_0\varphi+{}_2\varphi+{}_4\varphi+\cdots$$
$$=g\left[\frac{e^{-\mu r}}{r}-\frac{1}{2\mu}\frac{\partial^2}{\partial t^2}e^{-\mu r}+\frac{1}{8\mu^3}\frac{\partial^4}{\partial t^4}(\mu r+1)e^{-\mu r}+\cdots\right].$$

The full solution can be written symbolically:

$$\varphi=g\int\frac{\exp[-r(\mu^2+d^2/dt^2)^{\frac{1}{2}}]}{r}\delta(t-t_0)dt.$$

The above formalism can be easily extended to cases of more complicated sources. If in the development of φ we restrict ourselves to the retardation correction of the second order we get:

$$\varphi=g\frac{e^{-\mu r}}{r}\left[1+\tfrac{1}{2}\dot{\xi}_k\dot{\xi}_k+\tfrac{1}{2}\ddot{\xi}_k(\xi_k-x_k)-\tfrac{1}{2}(\mu r+1)\frac{(\xi_k-x_k)\dot{\xi}_k(\xi_s-x_s)\dot{\xi}_s}{r^2}\right].$$

With such formulas we can obtain in a pure "classical" way the interaction "potential" exact to the second order of time derivatives. For instance we can use Dirac's method[3] of obtaining equations of motion from the conservation laws $T_{\mu v,\,v}=0$ ($T_{\mu v}$ denotes the energy-impulse tensor of the pure mesonic field with appropriate point sources representing nucleons). It is convenient in deducing the interaction potential between two nucleons to set their masses equal and to choose the center-of-mass coordinate system. In this way, after apparent symmetrization, we get for the scalar meson interaction:

$$\vartheta(1,2)=-g^2\frac{e^{-\mu r(12)}}{r_{(12)}}\left[1-\frac{1}{2}\dot{\xi}_k^{(1)}\dot{\xi}_k^{(2)}\right.$$
$$+\frac{1}{2}\frac{\dot{\xi}_k^{(1)}(\xi_k^{(1)}-\xi_k^{(2)})\dot{\xi}_s^{(2)}(\xi_s^{(1)}-\xi_s^{(2)})}{r_{(12)}{}^2}(\mu r_{12}+1)$$
$$\left.+\frac{(\ddot{\xi}_k^{(1)}-\ddot{\xi}_k^{(2)})(\xi_k^{(1)}-\xi_k^{(2)})}{4}\right].$$

The transition to quantum theory can now be made by a simple rule: All time derivatives of the variables of the first nucleon should be replaced by quantum-mechanical commutators with the appropriate free nucleon Hamiltonian, e.g.,

$$\dot{\xi}_k^{(1)}\rightarrow i[\kappa_1{}^{(1)}\xi_k^{(1)}]=\alpha_k{}^{(1)},$$

and so on. This is also the case with time derivatives of other operators (for instance Dirac matrices). In the scalar interaction case it is easily seen that besides the normal static interaction we get three relativistic terms. Two of them are analogous to the Breit correction; the third term with $\dot{\xi}_k$ gives spin-orbit coupling.

It can be easily verified that the same correspondence treatment gives all the results mentioned above concerning other meson fields. For pseudoscalar mesons with pseudoscalar coupling, we obtain in the same manner the known noncentral static interaction, but without any inadmissible singularity. Thus it is obvious that it is not true that the static noncentral potential must be inherently connected with a $1/r^3$ singularity (compare also reference 4). This result is a consequence of the rules of multiplication of Dirac operators. If two "relativistic" (that is, mixing) matrices are multiplied, the result may be a nonrelativistic (nonmixing) matrix (e.g., $\rho_1\alpha_k=\sigma_k$). This shows that there exists an intimate connection between spin couplings and "Zitterbewegung."

A detailed report of this work will be published elsewhere.

I am very much obliged to Professor L. Infeld for suggesting this problem and for many helpful discussions.

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A Mechanism for Sputtering in the High Vacuum Based upon the Theory of Neutron Cooling*

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A PHILLIPS Ion Gauge Discharge[1] has been used as a source of ions to measure absolute sputtering ratios (number of atoms sputtered per incident ion) for silver metal bombarded by argon ions. The ions streamed from the plasma through a 0.115-in. drilled hole in the P.I.G. cathode through a $\frac{1}{4}$-in. aperture in an accelerating shield. The target was entirely surrounded by the shield, and biased positive to return secondary electrons and thereby ensure a correct measurement of the ion current (steady to within 5 percent). No shield was used for ion energy less than 500 v. The circuit is shown in Fig. 1.

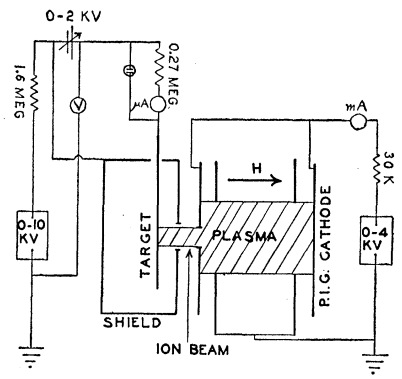

FIG. 1. Ion source and associated circuit.

A typical set of operating conditions would be the following: P.I.G.: $H=1000$ gauss; $P=1.2$ microns; $i=10$ ma; $v=1800$ v. Target current $=54$ μa; target voltage $=3500$ v.

It is to be noted that as the above pressure the mean free path is 4.2 cm, long enough to allow atoms to escape without back-scattering.

Absolute sputtering ratios are measured by simply bombarding the target for a measured time with a constant beam current. The weight loss of the target in micrograms gives the number of metallic atoms sputtered; thus the absolute sputtering ratio is

$$n = \text{No. of atoms sputtered/No. of ions incident.}$$

At 3480 volts: Positive ion current = 54 μa; weight loss, Ag target in $\mu g = 1458$ μg; time of bombardment = 3000 sec; $n = 7.9$ atoms/ions.

The result of a series of measurements at various ion energies are indicated in Fig. 2, as well as results of similar measurements by

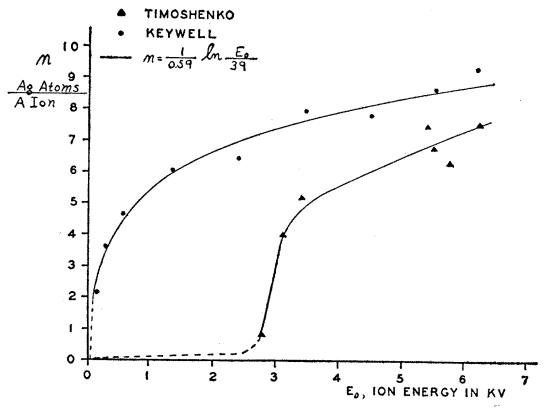

FIG. 2. Sputtering ratio *vs* incident ion energy for Ag—A.

Gregory Timoshenko.[2] The reason for the observed differences is not known.

A striking point of interest in the above data is the small number of atoms sputtered per incident ion compared to the number which is energetically possible. Neglecting heat conduction, a 4000-volt ion incident on silver has sufficient energy to sputter 975 atoms (4.1 ev/atom), yet the actual number sputtered is 8. This number, however, is just the order of the number of collisions required to "cool" a 4000-volt argon atom to an energy of approximately 40 ev, where we consider the silver lattice as a moderator and the argon atom to lose energy by a diffusion-collision process.[3] Neutron diffusion theory can be applied to this process.

According to standard theory, the initial energy of a neutron E_0 will be reduced to E_n after n collisions in a moderator of atomic weight M, where these are related by

$$E_n = E_0 e^{-n\xi}, \quad \xi = 1 - \frac{(M-1)^2}{2M} \ln\frac{M+1}{M-1}. \tag{1}$$

Similarly, if we consider an ion, at. wt A, to be cooled by collisions in the same moderator, it will make a relatively small number of collisions n and reach a characteristic energy below which it can cause no further disturbance in the metallic lattice. For argon ions incident on silver,

$$\xi = 1 - \frac{(M-A)^2}{2MA} \ln\frac{M+A}{M-A} = 0.59, \quad E_n = E_0 e^{-n\xi}. \tag{2}$$

The data observed can be fitted quite closely by least squares from 150–6200 v, as indicated in Fig. 2, by a relation of this form, where $E_n = 39$ v. The sputtering ratio formula for Ag is

$$n = (1/0.59) \ln(E_0/39) \text{ Ag atoms/A ion.}$$

Thus, in agreement with the observed inefficiency of ions in releasing secondary sputtered particles, the following theory of sputtering in the high vacuum is proposed: An energetic ion, upon striking the crystalline lattice, will be "cooled" by a diffusion-collision mechanism similar to neutron cooling. In the process it will make a small number of collisions with the atoms of the material being sputtered, these collisions being violent enough to cause the metal atoms to be dislodged from the lattice and be removed as sputtered material. After the incident ion has made sufficient collisions to cool it to some characteristic energy (the empirical value E_n), the sputtering process will stop. By use of formulas (1) and (2), the sputtering ratio formula is

$$n = (1/\xi) \ln(E_0/E_n).$$

There is a satisfactory agreement between theory and observation for Ag metal bombarded by A ions. The same analytic relation has been indicated for sputtering of Al, Pb, and Cu when these metals are used as cathode materials in the P.I.G. discharge run with argon gas. Further studies will be attempted with additional metals and gases.

I wish to thank Dr. John Backus for use of the 13-in. pole-face magnet and for many helpful suggestions.

* Assisted by the program of the ONR.

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Slow Neutron Resonances in In^{113} and In^{115}†

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THE resonance absorption of slow neutrons by indium was reported in 1936 by Amaldi and Fermi.[1] In recent years the indium cross section has been measured by groups at several laboratories[2–4] and resonances have been reported at 1.44, 3.8, and 9.0 ev. The very strong resonance at 1.44 ev has been assigned to In^{115} on the basis of activation experiments.[2,5] Definite isotopic assignment of the other two resonances could not be made, but they were commonly attributed to In^{113} to account for the cadmium ratio obtained by measuring the activation of In^{114} However, if such isotopic assignment were correct, it would appear that indium has fewer resonances than would be expected from simple

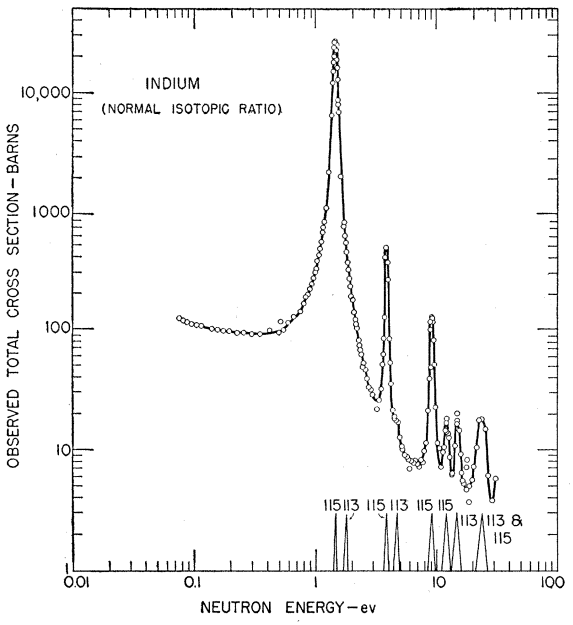

FIG. 1. Total cross section for normal indium.