ing p is a broadening of the bands which begins at $p \approx 10^{16}/\mathrm{cm}^3$. Assuming similar behavior for shallow donors, our results indicate that oxygen produces several discrete heat treatment centers which can be formed by the clustering of small numbers of oxygen atoms during heating near 450°C. The observed bands can be separated into four distinct groups, each with its own energy level scheme. These are not

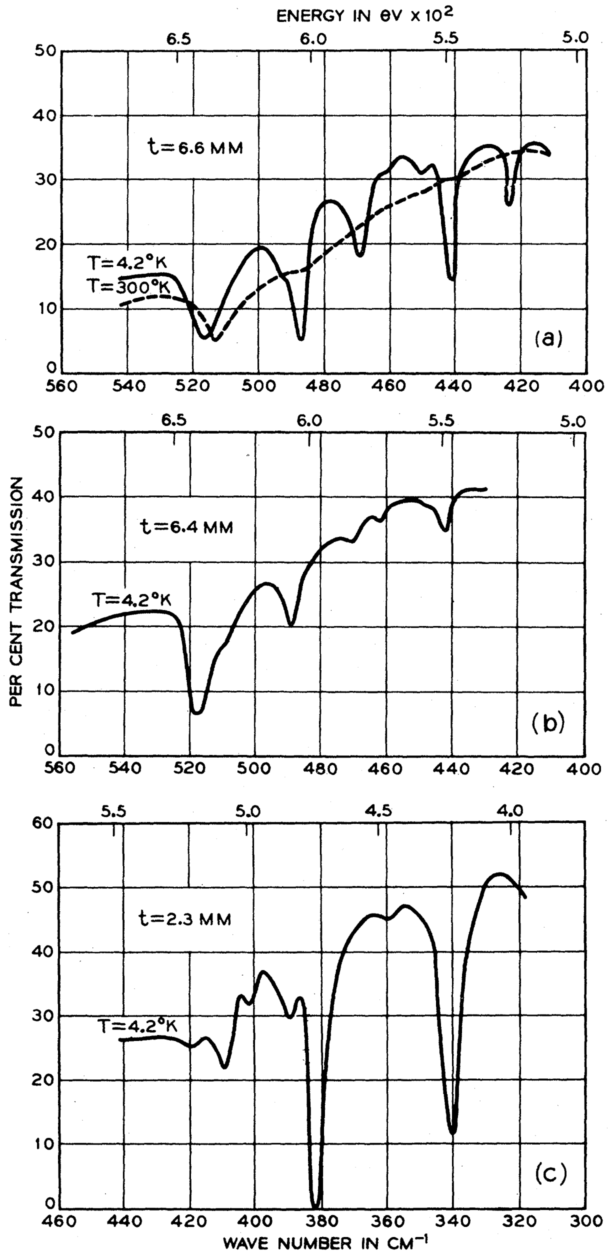

FIG. 1 Electronic spectra of (a) heat treatment centers, $n = 10^{15}/\mathrm{cm}^3$, (b) heat treatment centers, $n = 2.5 \times 10^{14}/\mathrm{cm}^3$, and (c) arsenic in silicon, $n = 2 \times 10^{15}/\mathrm{cm}^3$.

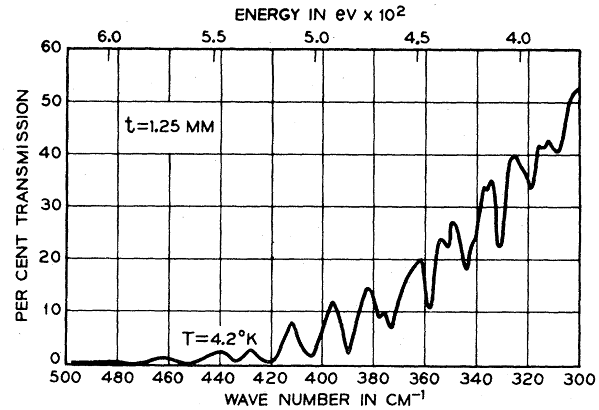

FIG. 2. Electronic spectrum of heat treatment centers in silicon for $n = 4 \times 10^{16}/\mathrm{cm}^3$.

identical but are more similar to each other than to the Kohn-Luttinger scheme. Each pattern has two strong lines with separations close to the calculated $(2p, m=\pm1)$-$(2p, m=0)$ spacing[8] which permit estimates of E_0 of 0.066, 0.056, 0.052, and 0.045 ev.

Although the nature of these centers has not been definitely established, further investigation of the energy level schemes and the kinetics of heat treatment are in progress

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EFFECTS OF ATOMIC ELECTRONS ON p-p AND n-p SCATTERING*

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Early estimates of the effect of screening have shown it to be small.[1] Recent improvements in experimental techniques and refinements in the theoretical interpretation, however, indicate the desirability of considering the problem more fully bringing in the dynamic effects as well. The main effects appear to be the Coulomb excitation of the molecular electrons which exists even if the parameter m/M approaches 0 and the acceleration effect which vanishes in the above limit and is caused by the acceleration of the target atom or molecule. Only the latter effect is present in the n-p case. If classical mechanics were applicable, these processes would not require a change in the interpretation of the data. The probable excitation energies of the electronic system are in fact so low as to affect the nucleon energy by negligible amounts. But conditions for the applicability of the classical theory are not satisfied in the 0-10 Mev range of the precision p-p experiments. Quantum mechanics distinguishes between collisions without excitation which give rise to coherent scattering and collisions with electron excitation which result in states incoherent with the incident wave. For purely Coulombian fields and large values of $\eta = e^2/\hbar v$ classical mechanics is a good approximation, and the absence of the dynamic effects is, in this limit, explicable as a compensation of the inelastic differential cross section $d\sigma_{\text{inel}}/d\Omega$ by $\delta(d\sigma_{\text{coh}}/d\Omega)$, the change in the coherent cross section caused by the change in the collision matrix resulting from the presence of σ_{inel}. With the relatively small η in the p-p case, this compensation cannot be expected to be accurate and the large S-wave anomaly cannot be treated classically. At high energies, the passage of the proton through the electron distribution can be pictured by classical mechanics with relatively more justification on account of the shortness of the proton wavelength and of the collision time.

For a pure Coulomb field the dipole effect of Coulomb excitation, calculated employing classical mechanics for the motion of the protons (SCT) in a collision of a proton with a hydrogen atom in its ground state is

$$3\eta^2 s^2 = (0.075/E_{\text{Mev}})\, s^2, \quad s = \sin\Theta, \quad \Theta = \theta/2. \quad (1)$$

Here θ is the scattering angle in the center-of-mass system. Effects of particle spins and of adiabaticity of collisions are neglected in the above formula. The latter effect is not quite negligible at the lowest energies (~300 kev) for which there are data but is not serious. The formula just quoted is not quite accurate even in the SCT, the smallness of the curved part of the proton trajectory in comparison with atomic dimensions having been made use of in the approximate derivation. This effect amounts to ~0.3% increase in scattering at $\Theta = 15°$ at 1830 kev and 0.07% at $\Theta = 45°$. In these numbers the s-wave anomaly is used through the employment of the experimental cross section but its effect on Coulomb excitation has been neglected. On the above basis the fractional change in σ has a maximum at about $\Theta = 15°$. These effects are comparable with those of vacuum polarization.[2] Their residue after a consideration of related changes in σ_{coh} should enter the determination of p-wave phase shifts from experiment. The formula quoted gives decreases of 1.1, 0.3, 0.05% in the s-wave phase shift K_0 at 860, 1200, 2105 kev, respectively. With neglect of the compensation effects, the true K_0 would be expected to vary somewhat more steeply with energy than under the neglect of the presence of σ_{inel}. Such a change would shorten the range of force derived from experiment. The f function would have to be corrected by 0.03, 0.01, 0.002(5) at the three energies, respectively. In the absence of other data these corrections would amount to roughly a 2% decrease of the range parameter. At lower energies the effects change sign. It would be incorrect to use these numbers for quantitative conclusions because they do not include the previously mentioned compensation effects.

Neglecting particle spins, the dipole Coulomb excitation to p-states involves the consideration of reaction channels with the following values of the total angular momentum J, the initial partial wave orbital angular momentum L_i and final orbital angular momentum L_f: $(0+, L_i = 0), (0+, L_f = 1)$; $(1-, L_i = 1), (1-, L_f = 0), (1-, L_f = 2)$; $(2+, L_i = 2), (2+, L_f = 1), (2+, L_f = 3)$; etc. The + or - after each J value denotes the parity. States with the same J and parity appear between two semicolons in the list and form a coupled system whose collision matrix U can be calculated by means of coupled equations on appropriate radial functions. The compensation effects are approximately additive and an idea of their importance can be obtained treating each atomic principal quantum number n separately. The effect of coupling on the atomic ground-state channels is to change the absolute value of the diagonal element of U from 1 to $\rho = (1-\rho'^2)^{1/2} \cong 1 - \rho'^2/2$ and also to change the argument of that element from $2iK$ to $2i(K+\delta K)$ where K is the real phase shift. If the ρ' and δK corresponding to the same L_i were equal, the change in the coherent part of σ would be

$$\delta(d\sigma_{\text{coh}}/d\Omega) \cong (2/k^2)\text{Re}\,\{A_0 \sum_L (2L+1)P_L\,(\cos\theta)e_{L0}(2i\delta K_L\ -\tfrac{1}{2}\,\rho_L{}'^2)(2i)^{-1}\exp\,(2iK_L)\}, \tag{2}$$

with

$$A_0 = -(\eta/2s^2)\exp\,(-i\,\eta\ln s^2) + \sum_L (2L+1)P_L(\cos\theta)e_{L0}[-1+\exp(2iK_L)]/(2i),$$

$$e_{L0} = \tan^{-1}(\eta/L) + \tan^{-1}[\eta/(L-1)] + \cdots + \tan^{-1}\eta.$$

For pure Coulomb scattering, neglecting proton identity,

$$d\sigma_{\text{coh}}/d\Omega \cong k^{-2}\{\eta^2/4s^4\ +(\eta/s^2)\ \sum_L (2L+1)e_{L0}P_L\,(\cos\theta)[(\rho_L{}'^2/4)\sin(\eta\ln s^2) - (\delta K_L)\cos(\eta\ln s^2)]\}. \tag{3}$$

The compensation effect is caused by the second term in braces in (3) or more generally by (2). For $J=0+$ there are only two coupled radial functions but three final substates corresponding to different atomic magnetic quantum numbers leading to spherical symmetry of σ_{inel}. The ratio of the inelastic to the coherent effects for $J=0$ is for the pure Coulomb case

$$(s^2/\eta)/[\tfrac{1}{4}\sin(\eta\ln s^2) - (\delta K/\rho'^2)\cos(\eta\ln s^2)]\,. \tag{4}$$

For 1830 kev and $\Theta = 15°$ a very crude estimate of this ratio is $\cong -0.6$. This number is not significant on account of the many omitted effects, except for showing that exact compensation is unlikely as is clear from the angle dependence of (4) and the effect of K_0 through (2).

Dipole excitations arising from the acceleration effect appear in the SCT as a consequence of terms in the Hamiltonian having the form

$$H'_{\text{acc}} = -e^2(\vec{R}(t)\cdot\vec{\rho}_a)/R_>{}^3\,, \tag{5}$$

where $R_>$ is the greater of the quantities $\vec{R}(t)$, $\vec{\rho}_a = \xi\vec{\rho}$, with $\xi = m/(m+M)$. Here $\vec{R}(t), \vec{\rho}$ are, respectively, vector displacements from target proton to incident proton and electron. At large distances H'_{acc} is much smaller than H'_{CE} but extends to smaller distances. For the larger θ the SCT employing the approximations previously mentioned gives the same result for the acceleration effect as for Coulomb excitation. The signs of the two additions to the Hamiltonian are the same at the larger R so that no cancellation of amplitudes is expected. If in (5) one replaces $R_>$ by $R(t)$, much larger values for the probability of excitation are obtained. Such a replacement corresponds to the most naive picture of the acceleration effect but is not correct since the usual type of perturbation calculation must be arranged so as to have separability of the unperturbed Hamiltonian. In the n-p case the acceleration effect is caused entirely by nuclear forces and the estimates made here are inapplicable.

The presence of the two effects makes the interpretation of low energy nucleon-nucleon scattering less certain. A calculation of effects in the hydrogen molecule is likely to be difficult. The main object of the present note is to point out the presence of the electron effects which apparently has to be considered more carefully than heretofore.

In addition one has to consider the recoil on the nuclei caused by the ejection of an electron. For small θ the rapid variation of cross section with angle increases this error. Estimates have not shown clearly that these effects and the related inclusion of the effect of small m in the reduced mass are important and improved estimates of the effect of electron-cloud screening in the ground state of hydrogen have yielded only negligible effects. The complications arising from the presence of the dynamic electron effects interfere with the employment of the low-energy region for the detection of p-wave anomalies. They increase the relative importance of measurements at higher energies.

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SEARCH FOR MASS-550 PARTICLES*

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Alikhanian et al.[1] have reported evidence for the existence of cosmic-ray particles with a mass about 550 times that of the electron, and with an abundance relative to μ mesons of 0.5%. The particles appeared to come from the atmosphere rather than from nuclear interactions in local material, implying a mean life in the microsecond range or greater.

We have searched for such particles (here denoted X particles) using the apparatus shown in Fig. 1. Slow cosmic-ray particles are selected

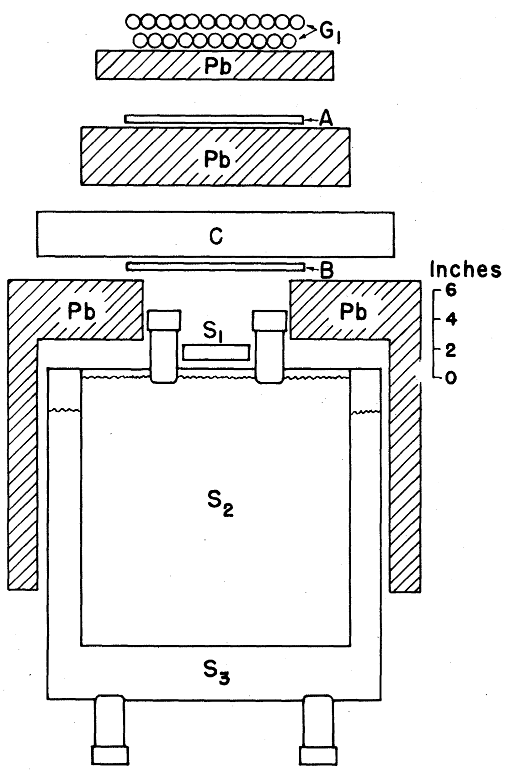

FIG. 1. Experimental disposition. G_1 is a tray of 12-inch Geiger counters. A, B, and S_1 are square plastic scintillators. C is a water-filled Čerenkov anticoincidence counter. S_2 and S_3 are cylindrical liquid scintillators.

by an incident telescope consisting of Geiger counter tray G, scintillators A, B, and S_1, and Čerenkov anticoincidence counter C. The particles stop in a thin-walled 64-kg liquid scintillator S_2 enclosed below by the anticoincidence jacket S_3. An oscilloscope is triggered by a coincidence $G\bar{C}S_1S_2\bar{S}_3$ (the bar denotes an anticoincidence) and the pulses from S_1, S_2, A, B, and S_3 are presented on a 20-μsec trace, using suitable artificial delays. Anticoincidence guard counters (not shown in Fig. 1) are used to eliminate edge effects in S_1.

Besides triggering the primary trace, a stopping particle initiates a gate 155 milliseconds in duration (50 milliseconds in the earlier runs) as well as a slow sawtooth which carries the vertical positioning control of the scope slowly upward. The gate activates a secondary coincidence circuit, which triggers another 20-μsec sweep on $S_2\bar{S}_3$ events occurring during the gate. Thus each stopping particle is investigated for evidence of decays over a six-decade range of mean lives, from 10^{-7} to 10^{-1} sec. Delays in the range 20 μsec to 1 msec have the secondary trace superimposed on the primary, but are easily recognized.

During the last half of the experiment, the slow gate also activated a pulse pair selector circuit, which triggered a secondary trace whenever there occurred a pair of pulses separated by less than 10 μsec. Thus any X-π-μ mode, or any X-μ mode with a μ energy greater than about 2.5 Mev, would have been detected with high efficiency.

The mass of each particle is calculated from the ionization loss in the thin scintillator S_1 and the total energy released in S_2. The resolution curve for such a mass measurement has a long tail on the high side caused by the Landau distribution of pulse heights in S_1. Excellent discrimination against π and μ mesons is nevertheless achieved with the aid of the Čerenkov anticoincidence counter, which limits the range of mesons accepted by the incident telescope. The mesons are excluded by accepting only those scope traces which show an S_2 pulse greater than 50 Mev and no delayed pulse in the microsecond range. From a study of the rate and time distribution of the μ mesons identified by a 2.2-μsec delayed pulse, it was determined that leakage due to μ^- mesons captured in carbon was 0.025%. Leakage due to unresolved $\mu^\pm$ decays was 0.1%; the added energy of the decay electron in this case may make the apparent mass of such an event appear as high as 450,