Letters to the Editor

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Masses of Light Nuclei from Nuclear Disintegration Energies

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(Received August 30, 1951)

IN the paper[1] with the above title, it is stated that now for the first time it is possible to calculate the masses of light nuclei in terms of O^{16} from nuclear reaction energies without using mass spectroscopic results.

In my book[2] in 1937, the masses of light nuclei were calculated from nuclear reaction energies without using mass spectroscopic data. Similar work[3] was done in 1936.

In *Modern Physics* the reaction energies of 17 reactions were used to calculate the energies of formation and the neutron and hydrogen masses. The other masses were obtained by the equation

$$ZH^1+(A-Z)n^1={}_zA^A+{}_zE^A,$$

where ${}_zE^A$ is the energy of formation of the atom out of protons and neutrons.

The neutron mass was found to be 1.00898 and the hydrogen mass to be 1.00815, which are very close to the new values[1] 1.008982 and 1.008142. The other masses differed slightly from the new values.

The reaction energies in 1937 were not known very exactly, and the recent paper[1] is a very thorough and important contribution.

[1] Li, Whaling, Fowler, and Lauritsen, Phys. Rev. **83**, 512 (1951).
[2] H. A. Wilson, *Modern Physics* (Blackie and Son, Glasgow, 1937), second edition, p. 262.
[3] H. A. Wilson, Proc. Roy. Soc. (London) **A154**, 560 (1936).

Application of Collective Treatment of Electron and Ion Vibrations to Theories of Conductivity and Superconductivity

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THE interaction between electrons and lattice vibrations suggested by Fröhlich[1] and Bardeen[2] as a cause of superconductivity can be treated very advantageously by means of a collective description, originally introduced in connection with the theory of plasma oscillations.[3] It will be shown in a paper to be published in the near future that, if the electrons and ions in a metal are approximated as clouds of charge, then the normal modes for the combined system correspond to two types of collective vibration: (1) the ordinary high frequency ($\sim 10^{15}$ cps) "plasma oscillations" of the electron gas, slightly modified by the small responses of the heavy ions; (2) the comparatively low frequency acoustical oscillations in which the ionic vibrations are almost entirely screened by the rapidly moving electrons. From the frequency of the acoustical vibrations one can calculate the speed of sound in terms of the ionic mass and the interionic spacing. We obtain agreement with the observed values within an error of 20 percent for alkali metals, and within a factor 2 for polyvalent metals.[4] These results are in harmony with the fact that the non-coulombic part of the interionic potential, which we have neglected in our treatment, is small for alkali metals, but appreciable for polyatomic metals.

It will be shown in another paper,[5] however, that a purely collective description of a dense aggregate of charged particles does not adequately treat all the significant properties of this aggregate. To the collectively describable part of the density (which takes the form of organized wave-like oscillations) must be added a randomly fluctuating part associated with the individual particles themselves. In a metal this individual-particles component of the charge density produces two significant effects: (1) each electron is surrounded by a cloud containing a deficiency of electrons (and therefore an excess of positive ions) which screens out most of its field within a distance of the order of 10^{-8} cm;[3,5] (2) each electron is followed by an acoustical disturbance resembling the wake behind a boat in the water. The angular width of this wake is of the order of $v_{\text{sound}}/v_{\text{electron}}$, which for the faster electrons is only about 3×10^{-3} radians in a typical metal. The wake carries away energy from the electron and thus gives rise to an electrical resistance. The latter can be expressed solely in terms of the ionic mass and the interionic spacing, and one obtains agreement with experimentally observed values at low temperatures within a factor of 2 for monovalent metals.

The description of electrical resistance in terms of a "wake" removes certain puzzling difficulties pointed out by Peierls.[6] By taking into account the conservation of the combined momentum of electrons and sound waves, he was led to the conclusion that the only sources of electrical resistance would be "Umklappprozesse" arising from the effects of lattice periodicities, and scattering of sound waves by each other arising from nonlinearities. This theory gives too small a value and a wrong temperature dependence for the resistivity at low temperatures. If one notes, however, that the sound energy is spatially distributed in the form of a wake, it becomes clear that the momentum in the sound waves is extremely unlikely to return to the electron from which it came, and that, as in the case of a boat in water, this momentum is carried far away to be scattered by obstacles, boundaries, etc., so that it is ultimately degraded into random thermal motion. For this reason, the more naive theory, which does not take into account the possibility that the sound momentum can return to the electron, leads to the right values for the resistivity of monovalent metals, while Peierls' theory, which incorrectly describes the possibility of return, does not lead to the correct values.

The acoustical wake of the electrons may also be important in the interaction of electrons. For example, if one electron follows in the wake of another, the energy of the pair is found to be reduced by about 10^{-4} ev. We wish to suggest here that this interaction may provide the basis of a possible model for superconductivity in terms of moving but flexible chains of electrons, each of which is held in the chain by the very narrow wake of the electron ahead of it. The individual electrons could be scattered only by being torn out of the chain. Thus one would obtain metastable chains of current flowing for practically indefinite periods. The entropy of the system would be lowered by the formation of such chains, so that they would be thermodynamically stable only at temperatures for which the binding energy of each electron in the chain is of the order of kT. Such an estimate leads to transition temperatures of the order of magnitude of those observed experimentally. Moreover, the dependence of the interelectronic interaction energy on the mass of the ion (through the sound velocity) has the right functional form to account for the isotope effect. The chief difference between the theory suggested by Fröhlich and Bardeen, and that suggested by us, is that they attribute the cause of superconductivity to the interaction of an electron with itself by way of the phonon field, whereas—in their terminology—

we may be said to attribute it to the interaction of neighboring electrons through the phonon field. This interaction is analogous to the (retarded) Möller interaction resulting from the virtual quanta of the electromagnetic field.

[1] H. Fröhlich, Phys. Rev. **79**, 845 (1950).
[2] J. Bardeen, Phys. Rev. **80**, 567 (1950).
[3] D. Bohm and D. Pines, Phys. Rev. **82**, 625 (1951).
[4] F. Seitz, *Modern Theory of Solids* (McGraw-Hill Book Company, Inc., New York, 1940).
[5] D. Pines and D. Bohm (to be published).
[6] R. E. Peierls, Ann. Physik **12**, 154 (1932).

Alpha-Alpha Scattering*

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(Received August 27, 1951)

THE differential scattering cross sections for 20.4±1.0-Mev alpha-particles by helium were determined at center-of-mass scattering angles of 60° and 90°. The experimental results are shown in Table I.

The scattered particles were detected by a proportional counter. The amplified pulses from the counter went to a pulse-height discriminator circuit which rejected pulses of amplitude appreciably smaller than those desired. The unscattered particles were collected in a faraday cage which was connected to a one-μf condenser. The voltage across the condenser was measured by a null method using a Compton electrometer as the null device.

There was an appreciable background counting rate resulting from the neutron flux accompanying the operation of the cyclotron. This background was reduced somewhat by shielding the counter with borax and paraffin. The background counting rate was determined before and after each set of scattering runs. Based on the internal consistency of the background data and the number of counts taken, a precision of ±10 percent was assigned to the background correction.

The scattering chamber was filled to a pressure of about 2.2 cm of Hg with helium of 99.5 percent purity furnished in standard cylinders by the Ohio Chemical Company. The pressure was determined by a U-tube manometer filled with Apiezon oil B. Impurity scattering is not believed to be important in this work because the alpha-alpha scattering cross section is at least as great as the alpha-air scattering cross section for the angles studied, hence the possible 0.5 percent impurity in the scattering gas could contribute a maximum error of 0.5 percent. Furthermore, the pulses produced by impurity-scattered particles were smaller than the genuine pulses, and experimental tests showed that impurity-caused pulses were counted with poor efficiency. Outgassing of the metal surfaces of the scattering chamber or leaks in the system would have caused the pressure of the scattering gas to increase during a period of data taking. No increases in pressure greater than one percent were noted.

No direct data on the cyclotron alpha-particle beam energy are available, so it has been estimated from measurements of the proton and deuteron beam energies. The probable errors quoted for the scattering cross section in Table I include the statistical probable error, the probable error in the background counts, and a collection of minor errors that are discussed in a paper on proton-alpha scattering[1] in which the same apparatus was used. A more detailed account of the apparatus and the procedure used in taking data are included there. The paper also describes the procedure by which proton-proton scattering was used to calibrate the apparatus, thus making a precise knowledge of certain geometrical factors and the capacitance of the condenser connected to the faraday cage unnecessary.

TABLE I. Results of the alpha-alpha scattering work for incident alpha-particles of 20.4±1.0 Mev. θ is the scattering angle in the center-of-mass system, n is the number of counts observed, R is the ratio of the number of genuine counts to the number of background counts, and σ is the differential scattering cross section in the center-of-mass system expressed in barns/sterad.

θ	n	R	σ
60°	900	19	0.086 (±5.5 percent)
90°	900	26	0.14 (±5.5 percent)

The results of the present work are directly comparable with those of Mather[2] who used the same cyclotron, but employed an entirely different apparatus which used photographic plates for the detection of the scattered particles. Mather gives the value 0.123±0.008 barn/sterad for the differential scattering cross section in the center-of-mass system at 60°. He gives no value for 90°, but his cross sections near 90° tend upward in qualitative agreement with the present work. The reasons for the large discrepancy between the present results and those obtained by Mather are not clear.[3] As explained in the account of proton-alpha work,[1] the present method yielded absolute proton-proton scattering cross sections within the estimated probable error, ±5 percent. The alpha-alpha work was made more difficult by the low alpha-particle beam current from the cyclotron (0.14×10^{-8} ampere into the scattering volume) which makes the procurement of data on alpha-alpha scattering require roughly 40 times as long as the procurement of an equivalent amount of data when accelerated protons are used. However, no reasons have been found for suspecting large errors resulting from this increased time required for obtaining the data.

* Assisted by the joint program of the ONR and AEC.
[1] C. H. Braden, Phys. Rev. **84**, 762 (1951).
[2] K. B. Mather, Phys. Rev. **82**, 126 (1951).
[3] Our attention has been called to unpublished work on alpha-alpha scattering at 30 Mev by E. Graves at the Massachusetts Institute of Technology. Graves' work indicates that the scattering cross section is quite energy-dependent. A possible explanation of the discrepancy between Mather's results and the present results may be that, because of changes in the cyclotron operating conditions, the present work was performed at an energy slightly different from that used by Mather.

Nuclear Binding Energies for Isotopes with Masses between 50 and 60

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(Received September 24, 1951)

RECENTLY we computed a list of nuclear binding energies and masses[1] for mass numbers <43, using recent reaction energy data[2] and the new mass spectrographical results of Ewald.[3] We tried to extend this list up to about $A=65$. In this mass region several reaction energy data are known, which appear to be reasonably reliable since similar measurements for lower mass numbers, often by the same authors, are in good agreement with one another and with Ewald's results. In the same region several stable isotopes have been measured mass spectrographically.[4–6] Among these measurements, which are not mutually consistent, we consider first those of Duckworth *et al.*[6] Their measurements of the Si- and S-isotopes are in reasonable agreement with the values computed from our aforementioned list (Table I).

It is of great interest to compare the differences in binding energies computed from Duckworth's results for the isotopes with masses $50<A<60$ (collected in Table II, column 3) with the values derived from reaction energy data (Table III). Table II, column 4, shows the binding energies derived from Duckworth's

TABLE I. Packing fraction differences (10^{-4} MU).

Doublet	Duckworth	Computed
$C_2H_4-Si^{28}$	19.45±0.06	19.42 ±0.01
C_2O-Si^{28}	6.45±0.03	6.43 ±0.01
CH_2-Si^{30}	24.53±0.03	24.46 ±0.01
O_2-S^{32}	5.50±0.03	5.54_4±0.00$_3$