

results<sup>2</sup> that in a majority of cases where an origin is present, the tracks appear to be coplanar with it, within the rather limited accuracy of measurement.

\* Assisted in part by the joint program of the ONR and AEC.

<sup>1</sup> G. D. Rochester and C. C. Butler, *Nature* **160**, 855 (1947).

<sup>2</sup> Seriff, Leighton, Hsiao, Cowan, and Anderson, *Phys. Rev.* **78**, 290 (1950).

<sup>3</sup> Armenteros, Barker, Butler, Cachon, and Chapman, *Nature* **167**, 501 (1951).

<sup>4</sup> Thompson, Cohn, and Flum, *Phys. Rev.* **83**, 175 (1951).

if a repulsion is really present, it should be so strongly spin-dependent.

The investigations related above were carried out on a suggestion by Professor O. Klein, to whom I wish to express my gratitude.

<sup>1</sup> Kelley, Leith, Segré, and Wiegand, *Phys. Rev.* **79**, 96 (1950).

<sup>2</sup> R. Jastrow, *Phys. Rev.* **79**, 389 (1950).

<sup>3</sup> R. Jastrow, *Phys. Rev.* **81**, 165 (1951).

## Erratum: The Angular Correlation Theorem and the Elimination of Interference Terms

[*Phys. Rev.* **83**, 189 (1951)]

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EQUATIONS (3) and (5) should read as follows:

$$(e_1 | \rho | e_2) = NS_1(i | H_1 | e_1)^*(i | H_1 | e_2), \quad (3)$$

$$S_1(i | H_1 | e_1)^*(i | H_1 | e_2) = 0 \quad (e_1 \neq e_2). \quad (5)$$

## Neutron-Proton Scattering with Repulsive Forces

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THE neutron-proton scattering at 90 and 260 Mev has been calculated using central forces and a square well with an impenetrable inner sphere. The radius of the sphere was varied between the limits 0 and  $1.2 \times 10^{-13}$  cm and the depth of the well between 38 and 140 Mev. The low energy scattering could be made to agree with experiment within wide ranges of the hard sphere radius and well depth. At 90 Mev the neutral total cross section varied between 0.20 and 0.28 barn, whereas the cross sections for the charged and symmetric theories could be brought in agreement with the experimental value of 0.079 barn. (These theories were considered in order to be able to compare results with earlier calculations.) The angular distribution was in poor agreement with experimental values, being much the same as those obtained for an ordinary well.

At 260 Mev the cross sections obtained were much too large, being about three times the experimental value of 0.038 barn. For the charged and symmetric theories the cross sections were generally larger than the corresponding values at 90 Mev. This increase of the cross sections with increasing energy was caused by too rapid an increase of the *P*- and particularly the *D*-phases. The effect is explained by the fact that the attractive outer region must be made much stronger for a model with a repulsive core than for an ordinary well, and the phase-decreasing effect of the repulsive core will be comparatively unimportant for the *P*- and *D*-phases. If the radius of the inner core is further increased, the depth of the outer region must be increased too in order to maintain low energy agreement, but the effect of the inner core will be more pronounced so that the *S*-phase will become negative. Negative *S*-phases will give angular distributions having maxima at 90° in contradiction with the U-shaped distribution expected from experiment.<sup>1</sup>

The conclusion from these considerations is that a strong repulsion can hardly be present in the neutron-proton interaction in triplet states of even parity.

The possibility of introducing repulsive forces into the proton-proton interaction has recently been investigated by Jastrow,<sup>2</sup> and later investigations have been extended also to the neutron-proton case.<sup>3</sup> Jastrow reports reasonable agreement with available experimental data, but the repulsion used is assumed to have negligible range in the triplet states. It seems strange to us that,

## The Magnetic Moment of S<sup>33</sup>

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EMPLOYING the nuclear induction spectrometer described earlier by Proctor,<sup>1</sup> signals of S<sup>33</sup> with a natural line width of about one gauss were detected in chemically pure CS<sub>2</sub>. The resonant frequency was compared with that of N<sup>14</sup> in a 3.2 normal solution of HNO<sub>3</sub> with the result

$$\nu(S^{33})/\nu(N^{14}) = 1.06174 \pm 0.00013. \quad (1)$$

Using the known magnetic moment<sup>2</sup> of N<sup>14</sup> and the fact that the spin of S<sup>33</sup> is  $\frac{3}{2}$ ,<sup>3</sup> the value of the magnetic moment was found to be

$$\mu(S^{33}) = +0.64292 \pm 0.00014. \quad (2)$$

The positive sign in Eq. (2) was verified by comparing the sign of the S<sup>33</sup> signal with that of N<sup>14</sup> and H<sup>2</sup>. In the case of H<sup>2</sup> a careful comparison of signal magnitudes was also carried out and within the experimental error gave a result consistent<sup>4</sup> with the spin and natural abundance (0.74 percent) of S<sup>33</sup>. The earlier determination of  $\mu(S^{33}) = 0.632 \pm 0.010$  nm by Eshbach, Hillger, and Jen<sup>5</sup> is in agreement with the more precise value of Eq. (2).

Signals of S<sup>33</sup> were not observed in other liquid sulfur compounds. This was probably due to the fact that the line widths, resulting from quadrupole<sup>6</sup> effects, were too broad.

We would like to express here our gratitude to Professor Felix Bloch for many helpful consultations during the course of this work.

\* Assisted by the joint program of the AEC and ONR.

<sup>1</sup> W. G. Proctor, *Phys. Rev.* **79**, 35 (1950).

<sup>2</sup> W. G. Proctor and F. C. Yu, *Phys. Rev.* **81**, 20 (1951).

<sup>3</sup> C. H. Townes and S. Geschwind, *Phys. Rev.* **74**, 626 (1948).

<sup>4</sup> F. Bloch, *Phys. Rev.* **70**, 460 (1946).

<sup>5</sup> Eshbach, Hillger, and Jen, *Phys. Rev.* **80**, 1106 (1950).

<sup>6</sup> C. H. Townes and B. P. Dailey, *J. Chem. Phys.* **17**, 782 (1949), report a quadrupole moment for S<sup>33</sup> of about  $-0.08 \times 10^{-24}$  cm<sup>2</sup>.

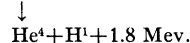
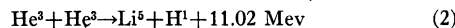
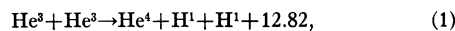
## The Reactions of He<sup>3</sup> + He<sup>3</sup>

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THE following reactions can be expected to compete when He<sup>3</sup> is captured by He<sup>3</sup>:



Three  $\mu$ a of He<sup>3+</sup> at 300 kev were obtained by accelerating a mixture of He<sup>3</sup> and He<sup>4</sup> in a Cockroft-Walton generator. The three  $\mu$ a of He<sup>3+</sup>, which constituted about two percent of the beam, were magnetically separated and directed against a clean 5-mil aluminum foil as shown in Fig. 1. Behind this foil was located a proton counter. After two hours of bombardment, the counting rate of the counter rose some fifteen times background.

Figure 2 shows the spectrum of protons observed by two different methods when two separate clean 5-mil aluminum foils were bombarded by the He<sup>3</sup>. In the first method the detector was

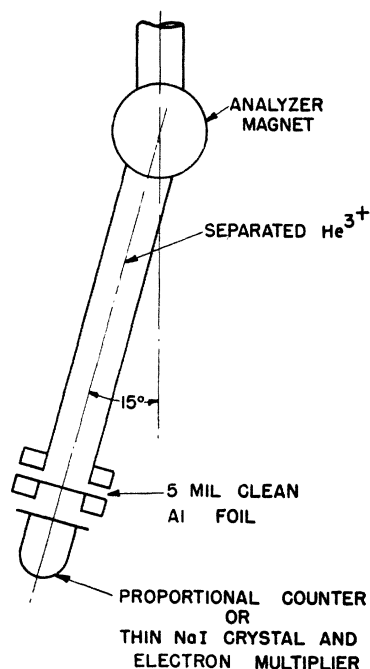


FIG. 1. Experimental set-up for observing the reactions of  $\text{He}^3 + \text{He}^3$ .

a proportional counter biased to detect only protons at the end of their range, and the counting rate was observed *vs* thickness of aluminum absorber. In Fig. 2, the result of a single experiment is given with the thickness of aluminum, including that of the 5-mil target, converted to its energy equivalent. There appears a large yield of 14.7-Mev protons from the reaction  $\text{He}^3 + \text{H}^2 \rightarrow \text{He}^4 + \text{H}^1 + 18.32$  Mev. This reaction always appears as a result of an accumulation on the target of deuterium which inevitably gets into the machine. The 14.7-Mev protons were used as an energy reference. In the second method a differential pulse-height selector was used to study the pulse-height spectrum produced by the protons in a thin NaI crystal. In this case, the 14.7-Mev protons from the impurity reaction  $\text{He}^3 + \text{H}^2$  served to calibrate the energy of the pulses. Figure 2 shows the spectrum obtained after converting the pulse height to energy, taking account of energy losses in the 5-mil window.

To aid in interpreting these very preliminary results, the statistical proton energy distribution for the three-body breakup

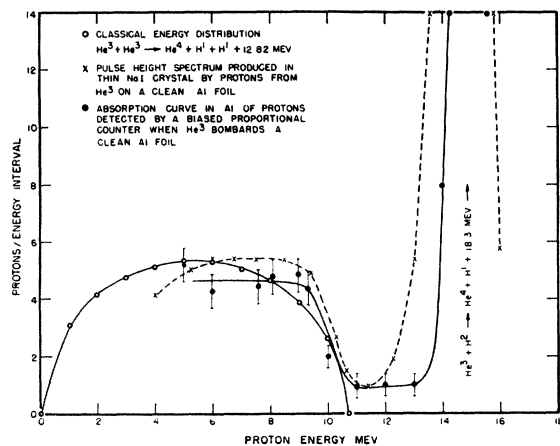


FIG. 2. Energy distribution of protons from bombarding  $\text{He}^3$  on clean aluminum.

(1) is given for comparison. The maximum observed proton energy agrees closely with that expected from the three-body breakup. The departure in shape of the calculated distribution from that observed cannot be accounted for by center-of-gravity motion, and suggests at least some of the competing reaction (2), namely, a breakup of  $\text{Be}^6$  into  $\text{Li}^5$  and a proton followed by the decay of  $\text{Li}^5$  to  $\text{He}^4$  and another proton. That the protons cannot originate from capture of  $\text{He}^3$  on aluminum itself seems virtually certain because of the build-up in the counting rate, and such protons would have a maximum energy of 11.7 Mev, which is clearly not the case observed here. Actually, a reaction on aluminum would be expected to show resolvable group structure rather than a continuum. In addition, the very high coulomb barrier would make such a reaction most unlikely.

It is concluded at present that the reaction being observed is that of  $\text{He}^3$  on  $\text{He}^3$  which has accumulated on the target. These data are preliminary and a further study of the reaction is under way.

The authors are indebted to Dr. M. E. Rose for discussion of the problem.

### A Numerical Variational Method\*

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RELAXATION methods in eigenvalue problems have been discussed by Southwell,<sup>1</sup> by Allen and others,<sup>2</sup> and by Fox.<sup>3</sup> The solution consists of two steps. First, the differential equation of the problem is replaced by a set of finite difference equations. Secondly, the solution so obtained is used in the Rayleigh-Ritz expression for the energy parameter. The energy parameter used in the difference equations must be equal to that found from the Ritz integral. For this reason a procedure which requires the consistency of these two values of the energy parameter is of interest and is described below.

At the suggestion of Professor G. Breit, the problem was set up on the basis of the variational principle for one and two independent variables. For one variable, the interval of the independent variable is subdivided by a set of equally spaced net points. The values at these points are used as variational parameters. Elsewhere the trial function is defined by a linear interpolation formula. The Rayleigh-Ritz energy integral then leads to a set of simultaneous linear equations in the variational parameters similar to those of Fox. The coefficients involve the energy and integrals of the potential energy. The equations may then be used in the same manner as the relaxation equations.

A similar procedure is used for two independent variables. The plane of the independent variables is divided by equidistant lines parallel to the axes of independent variables into square panels. The values of the function at the corner points of the panels are used as variational parameters and the function is defined elsewhere by an interpolation formula. The variational method again leads to a set of linear equations similar to the relaxation equations.

In both cases the equations contain fourth- and higher order differences similar to the difference correction obtained by Fox. The fourth-order differences in the variational equations are the negative of those obtained by Fox.

The method is well suited to the improvement of an approximate solution which is known precisely, but which only approximately satisfies the differential equation and boundary conditions. The procedure is analogous to that described previously and leads to similar difference equations which, however, include inhomogeneous terms depending on the approximate solution and on the differential equation. On the boundary the correction function is defined so that the sum of correction function and approximate solution satisfy the boundary conditions. Elsewhere it is defined in terms of net point values and an interpolation formula. The large number of variational parameters, one for each net point, make it