two $J^{\pi}=0^+$ states will give another measure of the usefulness of these product wave functions.

At 5259 keV in ^{208}Pb (see Fig. 2) there is a state, reported here for the first time, that has a (p,t) angular distribution identical to the $L=0$ transition to the nearby 4878-keV level. In the (t,p) reaction, a pair of unresolved levels are populated at 5259 keV. The angular distribution is consistent with a $0^+ + 3^-$ assignment and from this the 0^+ strength has been estimated (see Table I). Since it is difficult to construct 0^+ states in ^{208}Pb so low in excitation energy, this state should be a prime candidate for the $J=0$ "two-phonon octupole state." In both reactions, its strength is about $\simeq 10\,\%$ of that to the 4878-keV level. This suggests that the mixing of the $0_-0_+|0\rangle$ wave function with the double-octupole-phonon state is at least relatively small. A detailed calculation is necessary to predict the (t,p) and (p,t) cross sections to this latter state.

The results of this study indicate that the interaction between the pairing-removal phonons and the pairing-addition phonons of Bohr's theory[1] is small for ^{208}Pb (this is equivalent to stating there is little interaction between the particles and holes). This is brought out by the equivalence of the (t,p) and (p,t) cross sections to the pairing vibration state in ^{208}Pb and to the ground states of ^{210}Pb and ^{206}Pb, respectively. Additional evidence comes from the observation that the shift of the two-neutron separation energy is quite small for these two states. The weakness of this interaction is further suggested by the relatively small splitting of the nearly degenerate 2^+ levels at ≈ 5600 keV in ^{208}Pb.

We wish to acknowledge that a series of discussions with B. Mottelson and R. Broglia prompted the successful search for 2^+ strength above the $0_-0_+|0\rangle$ state in ^{208}Pb. Discussions with R. Sorensen are also gratefully acknowledged.

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[1] A. Bohr, in Proceedings of the International Symposium on Nuclear Structure, Dubna, 1968 (International Atomic Energy Agency, Vienna, Austria, 1968), p. 169.

[2] J. H. Bjerregaard, O. Hansen, and O. Nathan, Nucl. Phys. 89, 337 (1966); J. H. Bjerregaard, O. Hansen, O. Nathan, L. Vistisen, R. Chapman, and S. Hinds, Nucl. Phys. A113, 484 (1968).

[3] D. R. Bes and R. A. Broglia, Nucl. Phys. 80, 289 (1966).

[4] P. D. Barnes, E. R. Flynn, G. Igo, and D. D. Armstrong, Phys. Rev. (to be published), and Bull. Am. Phys. Soc. 13, 65 (1968).

[5] E. R. Flynn, G. Igo, R. Woods, and P. D. Barnes, Phys. Rev. Letters 19, 798 (1967).

OBSERVATION OF CHARGE-ASYMMETRY EFFECTS IN THE REACTION ^{2}H(α, ^{3}H)^{3}He AT 27.4 MeV c.m.*

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The differential cross section for the reaction ^{2}H(α, ^{3}H)^{3}He was measured from 31° to 149° c.m. with an 82-MeV α-beam. The measurements were made to test the Barshay-Temmer theorem which requires ^{3}H and ^{3}He yields to be independently symmetric about 90° c.m. We find a pronounced and angle-dependent deviation from 90° symmetry, as large as 10 % at some angles. Our results thus constitute the first clear-cut evidence for a violation of the above theorem.

Charge independence and charge symmetry of nuclear forces are two of the most fundamental and most fruitful concepts in nuclear physics. In recent years, however, attention has been focused on charge-dependent phenomena which indicate possible limitations to these conservation laws. Comparison of $^1S_0$ scattering lengths for the n-p and p-p systems implies a breaking of charge independence of about 5 %.[1] Comparison[2] of calculated Coulomb energy differences with measured mass differences of isotopic multiplets is also consistent with a deviation from charge independence of this amount. Evidence for deviations from charge symmetry is much weaker, if it exists at all. Okamoto[3] uses the difference in charge form factors[4] of ^{3}He and ^{3}H to obtain a Coulomb energy difference which is smaller than the binding-energy difference by about 0.2 MeV. He finds that this discrepancy holds for heavier nuclei[5] and is consistent with a (1-2)% deviation from charge symmetry. Pappademos[6] and Gupta and Mitra,[7] on the other hand, conclude that the Coulomb energies and masses of ^{3}He and ^{3}H are consistent with charge symmetry. Although a (1-2)% deviation from charge symmetry could not be ruled out from a comparison[1] of the Coulomb-corrected $^1S_0$ scattering length of two protons and the $^1S_0$ scattering length for two neutrons determined from the reaction[8] $^2\mathrm{H}(\pi^-, nn)\gamma$, more recent determinations[9-11] of the n-n scattering length appear to limit deviations from charge symmetry to considerably less than 1%. In addition, Schiff[12] prefers to ascribe the difference in form factors between ^{3}H and ^{3}He to an asymmetric S state thus maintaining charge symmetry, and Wilkinson and Hay's[13] analysis of Coulomb and binding energy differences for $1p$-shell nuclei shows consistency with complete charge symmetry.

The near-perfect charge independence of nuclear forces has led to the isospin formalism for the classification of nuclear states. Small deviations from charge independence then manifest themselves in so-called isospin impurities in nuclear states which are usually inferred from the observation of isospin-forbidden transitions in electromagnetic transitions,[14] β decay,[15] or nuclear reactions.[16,17] Barshay and Temmer[18] have suggested a geometric test to observe isospin impurities or charge-dependent effects. They consider the reaction

$$A + B \rightarrow C + C', \tag{1}$$

where C and C' are members of the same isospin multiplet and either A or B has isospin 0. If isospin is a valid concept, the angular distribution of each reaction product must be symmetric about 90° c.m. This geometric test of isospin conservation has been examined with the reaction[19,20] $^3\mathrm{He}(^3\mathrm{H}, \alpha)^2\mathrm{H}$ at c.m. energies less than 1 MeV and found to be consistent with symmetry about 90° c.m. A similar result was reported[21] for the reaction $^{10}\mathrm{B}(\alpha, {}^7\mathrm{Li})^7\mathrm{Be}$ and for the reaction[22] $^{12}\mathrm{C}(^{14}\mathrm{N}, {}^{13}\mathrm{C})^{13}\mathrm{N}$. We have measured the angular distribution of ^{3}He and ^{3}H from the reaction $^2\mathrm{H}(\alpha, {}^3\mathrm{H})^3\mathrm{He}$, with 82-MeV alpha particles, and report the first clear-cut deviation from 90° symmetry.

The alpha particle beam from the Oak Ridge isochronous cyclotron entered our target gas cell through a 2.5-mg/cm^2 Be foil, emerged through a 2.1-mg/cm^2 Havar foil and was stopped in a Faraday cup. The gas cell contained deuterium at 300 Torr at liquid-nitrogen temperature. Charged particles leaving the target were detected by a conventional ΔE-E telescope consisting of a 322-μ Si passing detector and a 2-cm-thick NaI stopping detector. A pair of defining slits between the gas volume and the telescope fixed the scattering-plane acceptance at 0.6° and the solid angle at $\sim 4\times10^{-5}$ sr. Linear pulses from the stopping detector and the ΔE detector were gated by a coincidence requirement and routed to the x and y inputs respectively, of a 200×100-channel analyzer.

The tritons from the reaction $^2\mathrm{H}(\alpha, {}^3\mathrm{H})^3\mathrm{He}$ observed at a lab angle θ_L were emitted at the center-of-mass angle $\theta_{\mathrm{c.m.}}$ in conjunction with a ^{3}He particle emitted at the c.m. angle $\pi-\theta_{\mathrm{c.m.}}$. Because of the equal masses of ^{3}He and ^{3}H, the ^{3}He particles observed at θ_L thus correspond to tritons emitted at $\pi-\theta_{\mathrm{c.m.}}$ and symmetry about 90° c.m. then requires equal laboratory yields of both ^{3}He and tritons for all θ_L. This test of the Barshay-Temmer theorem[18] thus does not require accurate measurements of absolute differential cross sections but only ratios of yields of ^{3}He and ^{3}H. The experimental advantages are evident: Difficulties connected with beam integration, absolute angle determination, target pressure measurement, and small changes in beam spot position are all eliminated. The only corrections that must be applied to the ratio $\sigma(^3\mathrm{He})/\sigma(^3\mathrm{H})$ are due to multiple scattering in various foils and to reactions in the stopping counter.

Our results for the ratio of ^{3}He and triton yields as a function of c.m. angle are shown in the lower part of Fig. 1 and separate absolute differential cross sections for each particle are shown in the upper part of Fig. 1. Because the tritons at forward angles have an energy of about 60 MeV, some of them will undergo nuclear reactions in the stopping counter and thus be lost from the triton peak. This effect[23] was always smaller than 2% and the correction for it introduces errors small compared with the errors due to statistics and due to uncertainties in back-

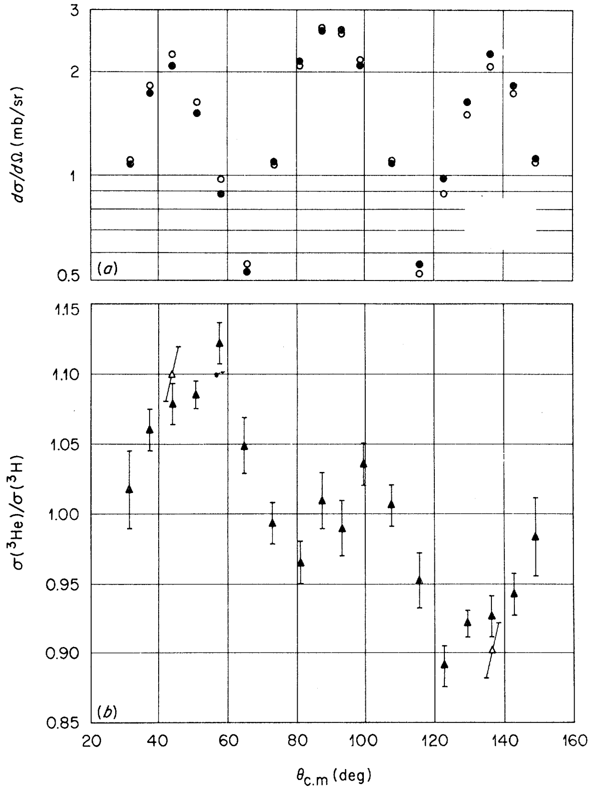

FIG. 1. Upper half: the measured differential cross sections for the process $^4He+{}^2H\rightarrow{}^3He+{}^3H$ using an 82-MeV α-beam. Open circles represent ^3He yields and the closed circles represent ^3H yields. Relative errors are smaller than the size of the data symbols and the absolute scale is uncertain to ±10 %. Lower half: the angular dependence of the ratio of ^3He to ^3H yields. The Barshay-Temmer theorem requires this ratio to be 1.0 at all angles.

ground subtraction. The errors in the ratio are represented by the error flags, while the absolute cross sections have relative errors smaller than the circles on the figure, but are subject to a systematic absolute error which we estimate to be about ±15 %, due to the normalization procedure. This normalization involved measuring the elastic scattering for 82-MeV alpha particles at 37° c.m. with a helium-filled gas cell, and comparing the results with the absolute differential cross-section measurements of Darriulat et al.[24]

Three important checks were made to establish the validity of these data. First, the data were reproducible in two separate runs with changed defining-slit geometries, and gas densities which differed from each other by a factor of 4. Second, the ratio $\sigma(^3He)/\sigma(^3H)$ at 90° c.m. must be unity irrespective of charge symmetry and our data near 90° are consistent with this requirement. A third check is that the ratio should invert if measured with a deuteron beam on a ^4He target at the proper c.m. conditions. We accelerated deuterons with the same cyclotron conditions as for the α beam and automatically obtained the proper c.m. energy requirements with the 41-MeV deuteron beam. We remeasured $\sigma(^3He)/\sigma(^3H)$ at the supplementary c.m. angles 42.7° and 137.3° with respect to the α direction. We found that the ratio did indeed invert and these points are plotted as open triangles in the lower part of Fig. 1. All these checks give us confidence that there were no systematic biases in our experiment, and that multiple-scattering effects were negligible, as we expected.

We thus find that in the reaction we studied there is a pronounced and angle-dependent deviation from 90° symmetry for ^3He or ^3H, which violates the theorem of Barshay and Temmer.[18] This could be due to three sources: (1) isospin impurities in the incident channel (most likely in the deuteron), (2) isospin impurities in the exit channel, or (3) impurities introduced in the intermediate state by the reaction mechanism. Isospin impurities in the ground states of light nuclei result from the presence of the Coulomb field and the impurity level is expected to be of the order of 1/137 or less.[6] The effect of such impurities should also be evident at lower energies. However, the accuracy of the low-energy measurements[19,20] does not allow one to draw any definite conclusions. Source 3, above, could contribute to the effect if the reaction proceeded through a broad intermediate resonance at ~27-MeV excitation in ^6Li which would mix T states. Such a resonance has been found[25] in ^6Be from a study of ^3He-^3He elastic scattering. A study[26] of d-α elastic scattering reveals no such resonance in ^6Li up to an excitation energy of 25.1 MeV. On the other hand, the shape and magnitude of the angular distribution look like those for a direct reaction with $l=0$ transfer most likely. Distorted-wave Born approximation calculations of a single-nucleon transfer are in progress to investigate the asymmetry that might be expected from the difference in charge form factors for ^3He and ^3H.

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[1] E. M. Henley, in *Isobaric Spin in Nuclear Physics*, edited by John D. Fox and Donald Robson (Academic, New York, 1966), p. 3.

[2] D. H. Wilkinson, in *Isobaric Spin in Nuclear Physics*, edited by John D. Fox and Donald Robson (Academic, New York, 1966), p. 30.

[3] K. Okamoto, Phys. Letters 11, 150 (1964).

[4] H. Collard, R. Hofstadter, A. Johansson, R. Parks, M. Ryneveld, A. Walker, M. R. Yearian, R. B. Day, and R. T. Wagner, Phys. Rev. Letters 11, 132 (1963).

[5] K. Okamoto, Phys. Letters 19, 676 (1965).

[6] J. N. Pappademos, Nucl. Phys. 42, 122 (1963).

[7] V. K. Gupta and A. N. Mitra, Phys. Letters 24B, 27 (1967).

[8] R. P. Haddock, R. M. Salter, M. Zeller, J. B. Czirir, and D. R. Nygren, Phys. Rev. Letters 14, 318 (1965).

[9] E. Baumgartner, H. E. Conzett, E. Shield, and R. J. Slobodrian, Phys. Rev. Letters 16, 105 (1966).

[10] H. Meiner, R. J. Slobodrian, H. E. Conzett, A. D. Barker, J. Ernst, and F. G. Resmini, Bull Am. Phys. Soc. 14, 512 (1969).

[11] E. E. Gross, E. V. Hungerford, J. J. Malanify, and R. Woods, Bull. Am. Phys. Soc. 14, 22 (1969), and to be published.

[12] L. I. Schiff, Phys. Rev. 133, B802 (1964).

[13] D. H. Wilkinson and W. D. Hay, Phys. Letters 21, 80 (1966).

[14] E. K. Warburton, in *Isobaric Spin in Nuclear Physics*, edited by John D. Fox and Donald Robson (Academic, New York, 1966), p. 90.

[15] S. D. Bloom, in *Isobaric Spin in Nuclear Physics*, edited by John D. Fox and Donald Robson (Academic, New York, 1966), p. 123.

[16] C. P. Browne, in *Isobaric Spin in Nuclear Physics*, edited by John D. Fox and Donald Robson (Academic, New York, 1966), p. 136.

[17] E. G. Adelberger, C. L. Cocke, C. N. Davids, and A. B. McDonald, Phys. Rev. Letters 22, 352 (1969).

[18] S. Barshay and G. M. Temmer, Phys. Rev. Letters 12, 728 (1964).

[19] C. D. Moak, Phys. Rev. 92, 383 (1953).

[20] B. Kuhn and B. Schlenk, Nucl. Phys. 48, 353 (1963).

[21] H. T. Fortune, A. Richter, and B. Zeidman, Phys. Letters 30B, 175 (1969).

[22] W. Von Oertzen, J. C. Jacmart, M. Liu, F. Pougheon, J. C. Roynette, and M. Riou, Phys. Letters 28B, 482 (1969).

[23] D. F. Measday, Nucl. Instr. Methods 34, 353 (1965).

[24] P. Darriulat, G. Igo, H. G. Pugh, and H. D. Holmgren, Phys. Rev. 137, B315 (1965).

[25] J. G. Jenkin, W. D. Harrison, and R. E. Brown, to be published.

[26] R. C. Hammond, J. R. Morales, and T. A. Cahill, Bull. Am. Phys. Soc. 14, 1212 (1969).

RADIO PULSES AND THE DETECTION OF LARGE AIR SHOWERS*

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Radio pulses can be used to measure the arrival directions of large cosmic-ray air showers. Since nearly all very large showers and nearly all large zenith-angle showers had detectable radio pulses, the method shows promise for the detection of such showers.

The study of radio pulses from air showers can be divided into two broad categories: the investigation of the mechanism of radio pulse production and the use of radio pulses as a tool for shower detection. We will address ourselves mainly to the second category: Can radio pulses be used to measure very large air showers? The question can be divided into four parts: (A) Can air-shower radio pulses be distinguished from background? (B) Does a sufficiently high proportion of showers have detectable radio pulses? (C) Can the arrival direction be found? (D) Can the core location and the size of each shower be found? We report here measurements that show affirmative answers to the first three questions.

Radio pulses have been observed in association with air showers at Mt. Chacaltaya, Bolivia (altitude 5200 m, geomagnetic latitude 4°S). The Bolivian Air-Shower Joint Experiment (BASJE) array now consists of five scintillation detectors on a circle of 150 m radius and of a cluster of detectors at the center of the circle. Five additional detectors are designed to determine shower arrival directions from particle arrival times. For our study of radio pulses associated with air showers, the BASJE array was triggered whenever there were more than 25 particles in any two of the outer circle detectors and in the center detector. The trigger rate was 3.6/h. For each shower the BASJE particle data allow us to determine arrival direction, core location, and size. Radio pulses were detected with seven log-periodic antennas. The antenna arms were placed in an EW plane, since previous experi-