as discussed above. The polarized infrared room-temperature results are in general similar to those reported here. However, the infrared results above T_c are difficult to understand.

The values for the frequencies of $PbTiO_3$ are quite similar to those found for $BaTiO_3$[2-4] and related perovskites.[6] Also we have found no difference in E-mode frequencies propagating in the xy plane or in the z direction. In $BaTiO_3$ one mode is reported to show such a difference.[4]

Lastly, we should compare our observations with those of Shirane, Axe, Harada, and Remeika.[16] They measured by neutron diffraction the lowest mode above T_c and the lowest transverse E and A_1 modes at 22°C, and found these modes to be underdamped. At 22°C they obtain 97 and 148 cm^{-1} for the E(1TO) and A(1TO) modes at the zone center, which compares with 89 and 128 cm^{-1} reported here.

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[1a] F. Jona and G. Shirane, *Ferroelectric Crystals* (Pergamon, Oxford, England, 1962).

[1b] E. Fatuzzo and W. J. Merz, *Ferroelectricity* (Wiley, New York, 1967).

[1c] W. Kaenzig, in *Solid State Physics*, edited by H. Ehrenreich, F. Seitz, and D. Turnbull (Academic, New York, 1957), Vol. 4, pp. 1-197.

[2] L. Rimai, J. L. Parsons, J. T. Hickmott, and T. Nakamura, Phys. Rev. 168, 623 (1968).

[3] A. Pinczuk, E. Burstein, and S. Ushioda, Solid State Commun. 7, 139 (1969).

[4] M. Di Domenico, Jr., S. H. Wemple, S. P. S. Porto, and R. P. Bauman, Phys. Rev. 174, 522 (1968).

[5] C. H. Perry and N. E. Tornberg, in *Light Scattering Spectra of Solids*, edited by G. B. Wright (Springer, Berlin, 1969), p. 467, and Phys. Rev. 183, 595 (1969).

[6] For a discussion of some experimental linewidths in perovskites see P. A. Fleury and J. M. Worlock, Phys. Rev. 174, 613 (1968).

[7] M. L. Sholokhovich, Zh. Neorg. Khim. 3, 1214 (1958) [Russ. J. Inorg. Chem. 3, 207 (1958)].

[8] The notation $a(bc)d$ indicates that the laser beam enters the crystal in the crystallographic a direction, polarized in the b direction, and is scattered toward the monochromator polarized in the c direction, traveling in the d direction. See T. C. Damen, S. P. S. Porto, and B. Tell, Phys. Rev. 142, 570 (1966).

[9] K. Tani, J. Phys. Soc. Jap. 26, 93 (1969).

[10] E. Pytte, Phys. Rev. B 1, 924 (1970).

[11] S. Triebwasser, Phys. Rev. 101, 993 (1956).

[12] J. P. Remeika and A. M. Glass, Mater. Res. Bull. 5, 37 (1970).

[13] The damping coefficient also can be fitted to a form, in cm^{-1}, $\gamma = 65(T_u - T)^{-0.35}$. Actually, one can obtain $(T_u - T)^{-3/8}$ from Eq. (3) by replacing an arithmetic average of two quantities that are close in value by their geometric average.

[14] R. Loudon, Advan. Phys. 13, 423 (1964).

[15] C. A. Arguello, D. L. Rousseau, and S. P. S. Porto, Phys. Rev. 181, 1351 (1969).

[16] G. Shirane, J. D. Axe, J. Harada, and J. P. Remieka, to be published.

ANOMALOUS BETA-ALPHA ANISOTROPY IN THE DECAY OF ^{20}Na†

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An anisotropy has been observed in the β-α directional correlation for an allowed β^+ decay in ^{20}Na. The effect is much larger than expected from interference from the second-order "weak magnetism" alone. The possibility of an enhanced $E2$ interference is discussed.

The observation of anisotropies in β-α directional correlations for allowed transitions is one method for studying contributions from high-order matrix elements in β decay. The first positive correlation was reported by Nordberg, Morinigo, and Barnes[1] for the allowed β decay of ^{8}Li and ^{8}B. They found that the contribution from the "weak magnetism" due to the conserved vector current produced a small but measurable anisotropy in the β-α correlation. We report here a similar study for another β-delayed α emitter, ^{20}Na. An anisotropy has also been observed for this nuclide. The effect, however, is 7 times larger than was previously observed despite the fact that the β energy and logft are unfavorable for the appearance of momentum-dependent second-order effects in the allowed transition.[2]

This nuclide was produced in the reaction ^{20}Ne$(p,n)^{20}$Na using 22-MeV protons from the Texas A & M cyclotron. An "on-line" method was used for producing thin point sources of this short-lived nuclide.[3] The half-life was found to be 451 ± 2 msec which is significantly different from other values previously reported, but considerably more precise because of better counting statistics.[4,5] The α spectrum, which has been studied previously, contains 10 groups that can be associated with known 2^+ levels in ^{20}Ne between 7.4 and 12.9 MeV.[4,5] The directional correlation measurement was made for all the groups but the only statistically significant result was obtained for the most intense line at 2.148 MeV. This is from a 2^+ state in ^{20}Ne at 7.415 MeV. A kinematic shift in the α group, which was a function of the β-α angle, was observed due to the center-of-mass motion of the ^{20}Ne β^+ recoil. This was also seen in the ^{8}Li-^{8}B work reported earlier.[1] An interesting secondary kinematic effect also appeared relating to the nature of the β^+-ν correlation for Gamow-Teller (GT) and Fermi transitions. The correlation of the kinematic shift with angle was more pronounced for the 4.438-MeV α-group than with other groups. Spectra demonstrating the effect are shown in Fig. 1. From kinematic effects alone, the maximum shift should have been observed for the lower energy group if the β transitions were of the same type. However, the 4.438-MeV group actually showed the larger shift (20 ± 1 keV at 180°). Most of the difference in the peak widths in Fig. 1 is due to kinematic effects. The 4.438-MeV group is associated with the predominantly Fermi decay to the $T=1$ isobaric analog state at 10.270 MeV while the 2.148-MeV group is associated with a GT transition ($\Delta T = 1$). In Fermi transitions, the β^+-ν directional correlation favors the emission of the leptons in the same direction. As a result, the directional correlation of the β recoil with the β^+ is more positive than in GT transitions where the β^+ and ν tend to be oppositely directed.

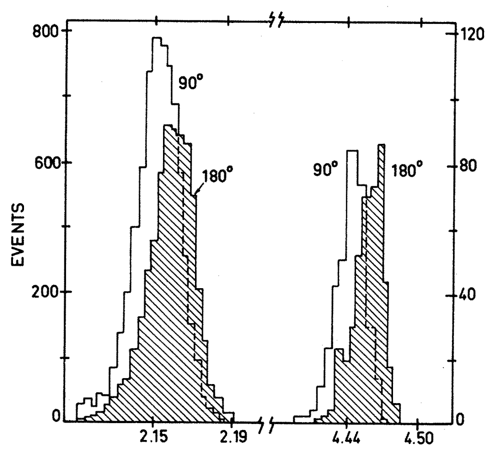

FIG. 1. Kinematically shifted alpha spectra in coincidence with β particles at different β-α angles for a GT transition (2.148 MeV) and a Fermi transition (4.438 MeV).

The results of the directional correlation measurement are shown in Fig. 2 for the 2.148-MeV α group in coincidence with the full β^+ spectrum associated with that transition. The points between 0° and 90° were taken from the same spectra as for the 90°-180° measurements by using the complementary 540-keV ^{16}O recoils which were also observed in the spectrum. The correlation in the laboratory fram can be expressed as follows:

$$W(\theta) = 1-(0.026 \pm 0.001)\cos\theta - (0.0251 \pm 0.0040)\langle W_\beta \rangle \cos^2\theta. \quad (1)$$

Only the data for the α group were used in the analysis. The average β energy $\langle W_\beta \rangle$ was taken to be 3.30 MeV.[5] The $\cos\theta$ term is related to the kinematic effect discussed previously and the coefficient of the $\cos^2\theta$ term ($a = -0.0251$) is the anisotropy coefficient which also appears in expressions for the β-ν directional correlation and shape corrections to β spectra for allowed de-

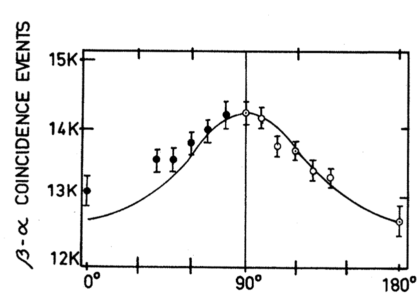

FIG. 2. β-α directional correlation for the 2.148-MeV α group. The open circles and closed circles are from the α group and the complementary ^{16}O recoil, respectively. The curve represents Eq. (1).

cays.[1,6]

The $B(M1)$ and $B(E2)$ values between the isobaric analog state in ^{20}Ne and the 7.415-MeV level have not been measured so it is not possible to obtain a quantitative theoretical value for a. We can obtain an estimate of the "weak magnetism" contribution to the interference effect using conserved vector current (CVC) theory by assuming that the $M1$ strength has the single-particle limit and using the experimental $\log ft$ for this transition (4.45) to evaluate the GT matrix element. Using the expression derived by Gell-Mann[7] for $|a|$, a value ~0.004 is obtained, approximately the same as had been calculated and measured for ^{8}Li and ^{8}B, but $\frac{1}{6}$ that observed for ^{20}Na. It is clear that other second-order matrix elements are contributing in this case. If they are associated with the axial-vector interaction only, then it is not possible to estimate their contribution using CVC theory.

An interesting possibility is the contribution from an enhanced second-order vector interaction which is the analog of the $E2$ matrix element.[8] For a nucleus like ^{20}Ne which is a "good rotational nucleus," several enhanced $E2$ transitions have been observed, even for cases where $\Delta T = 1$.[9] A more detailed expression for a incorporating the $E2$ matrix element has been derived by Weidenmüller.[10] This contribution was found to be negligible in the ^{8}Li-B^8 work. For ^{20}Na, the the ratio $B(E2)/B(M1)$ for the transition from the analog state to the 7.415-MeV level would have to be ~5 in order to account for the magnitude of the observed β-α anisotropy. The $M1$ and $E2$ strengths from the analog state to the 7.415-MeV state have not been measured so it is not possible to determine at this time which of the second-order matrix elements are responsible for this relatively large interference effect.

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[1]M. E. Nordberg, Jr., F. B. Morinigo, and C. A. Barnes, Phys. Rev. 125, 321 (1962).

[2]M. Morita, Phys. Rev. 113, 1584 (1959).

[3]R. D. Macfarlane, R. A. Gough, N. S. Oakey, and D. F. Torgerson, Nucl. Instrum. Methods 73, 285 (1969).

[4]R. D. Macfarlane and A. Siivola, Nucl. Phys. 59, 168 (1964).

[5]R. M. Polichar, J. E. Steigerwalt, J. W. Sunier, and J. R. Richardson, Phys. Rev. 163, 1084 (1967).

[6]C. S. Wu, Rev. Mod. Phys. 36, 618 (1964).

[7]M. Gell-Mann, Phys. Rev. 111, 362 (1958).

[8]J. Bernstein and R. R. Lewis, Phys. Rev. 112, 232 (1958).

[9]S. J. Skora, J. Hertel, and T. W. Retz-Schmidt, Nucl. Data, Sect. A 2, 347 (1966).

[10]H. A. Weidenmüller, Phys. Rev. Lett. 4, 299 (1960).

MECHANISM OF LITHIUM-INDUCED NUCLEAR REACTIONS*

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Peaks in the zero-degree yield curve of the reaction $C^{12}(Li^7,\alpha)N^{15}$ are interpreted as due to resonances in the $C^{12}t\alpha$ system.

Lithium-induced nuclear reactions have been interpreted as primarily direct in character at energies well below[1] and well above[2] the Coulomb barrier. However, they show strong signs of compound-nucleus formation near the Coulomb barrier.[3] The reaction mechanism is of interest in itself but there is an added spur to its understanding caused by the desire to use these reactions as tools in the study of nuclear structure. The $Li^7 + C^{12}$ reactions were studied with these interests in mind. The reactions show peaks at zero degrees with a spacing and width similar to that observed[4-7] in other lithium-induced reactions and lead to the suggestion that an extended structure of the lithium nucleus may be the source of these peaks.

Experimental measurements were made with thin (50 keV energy loss to 5-MeV Li^7 ions) self-supporting carbon targets and an E-ΔE detector telescope system. Targets were bombarded with Li^7 ions from the University of Iowa Van de Graaff accelerator. An angular acceptance of 1° was used in the detector system. Pulses were recorded in a ΔE vs E matrix in the memory of