Table II. Ratio of intensities parallel and antiparallel to the polarization vector. The standard error on each point is ± 4%.

Element / Angle	He^4	C	N	O	Ne	Al	Fe	Cu	Ni
50°			1.03	1.05	0.98				
60°						0.97			
70°		1.06					1.05	0.96	0.97
80°			0.93	1.00	0.97				
90°	1.04	0.98							
100°						1.04	0.97	1.03	0.98
110°		0.96	0.94	1.04	1.03				
130°	0.95								

[2]J. M. Blatt and V. F. Weisskopf, Theoretical Nuclear Physics (John Wiley and Sons, New York, 1952), p. 530; E. M. Henley and B. A. Jacobsohn, Phys. Rev. 108, 502 (1957); E. Fermi, Nuclear Physics (The University of Chicago Press, Chicago, 1950).

[3]J. H. Coon, Phys. Rev. 80, 488 (1950); Willard, Bair, and Kingston, Phys. Rev. 90, 865 (1953); W. Selove, Phys. Rev. 103, 136 (1956); J. E. Perry, Jr., and S. J. Bame, Jr., Phys. Rev. 99, 1368 (1955); E. G. Fuller, Phys. Rev. 96, 1306 (1954); J. B. Reynolds and K. G. Standing, Phys. Rev. 101, 158 (1956); Levine, Bender, and McGruer, Phys. Rev. 97, 1249 (1955); Bodansky, Eccles, Farwell, Rickey, and Robison, Bull. Am. Phys. Soc. Ser. II, 3, 327 (1958); Burcham, McCauley, Bredin, Gibson, Rotblat, and Prowse, Nuclear Phys. 5, 141 (1958).

[4]J. N. Bradbury and L. Stewart, Bull. Am. Phys. Soc. Ser. II, 3, 417 (1958).

[5]Brolley, Putnam, and Rosen, Phys. Rev. 107, 820 (1957).

[6]E. M. Henley and B. A. Jacobsohn, Phys. Rev. (to be published).

[7]J. S. Bell and F. Mandl, Proc. Phys. Soc. (London) 71, 272 (1958).

[8]Heer, Roberts, and Tinlot, Phys. Rev. 111, 645 (1958).

[9]L. Rosen and J. E. Brolley, Jr., Phys. Rev. 107, 1454 (1957); L. Rosen and J. E. Brolley, Jr., Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958 (United Nations, Geneva, 1958), Paper UN-668.

[10]L. Wolfenstein, Annual Review of Nuclear Science, (Annual Reviews, Inc., Palo Alto, 1956), Vol. 6, p. 43.

[11]Oxley, Cartwright, and Rouvina, Phys. Rev. 93, 806 (1954); Chamberlain, Segrè, Tripp, Wiegand, and Ypsilantis, Phys. Rev. 93, 1430 (1954).

[12]T. D. Lee and C. N. Yang, Phys. Rev. 104, 254 (1956).

[13]N. Tanner, Phys. Rev. 107, 1203 (1957); D. H. Wilkinson, Phys. Rev. 109, 1603 (1958).

TIME-REVERSAL INVARIANCE AND THE INVERSE REACTIONS $C^{12}+\alpha \rightleftharpoons N^{14}+d$*

D. Bodansky, S. F. Eccles,† G. W. Farwell, M. E. Rickey,‡ and P. C. Robison‖
Department of Physics,
University of Washington,
Seattle, Washington
(Received January 5, 1959)

It was pointed out by Henley and Jacobsohn[1] that although time-reversal invariance in strong interactions can be investigated by examining detailed balance in an appropriate nuclear reaction and its inverse, no very precise comparisons of this nature were then available.[2] Subsequently, relatively precise polarization and asymmetry measurements have indicated that for p-p scattering at energies near 200 Mev the magnitude of the time-reversal noninvariant term of the scattering matrix is not more than a few percent of the average magnitude of invariant terms.[3] The experiment described here approaches the problem through the study of detailed balance in nuclear reactions. It further differs from the p-p experiments in that it also involves n-p forces and is in a quite different energy region.

Following the suggestion of Henley and Jacobsohn, we have measured the angular distributions for the inverse (ground state) reactions $C^{12}(\alpha,d)N^{14}$ and $N^{14}(d,\alpha)C^{12}$. The measurements were carried out using 41.7-Mev alpha particles and 20.0-Mev deuterons from the external beam of the University of Washington cyclotron. (It was necessary to degrade the normal 21-Mev deuteron beam in a thin absorber in order to

match correctly the natural 41.7-Mev alpha energy.) The energies of the beams were determined from measurements of the range of particles in aluminum, using recent range-energy data.[4] Carbon and nitrogen targets were obtained by using thin foils of polystyrene and Cymel,[5] respectively.

The deuterons in the (α, d) measurement were detected in two NaI(Tl) or CsI(Tl) scintillation counters (used in a "$dE/dx-E$"-type arrangement), while the alpha particles in the (d, α) measurement were detected in a counter combination consisting of a xenon ionization chamber and a scintillation counter. The essentially monoenergetic particle group of interest was identified by demanding a coincidence between pulses of proper magnitudes from the two counters of a detector. This was accomplished by displaying pulses from both counters on twenty-channel analyzers and establishing coincidences between events in selected channels of the two analyzers.

The observed angular distributions, converted to the center-of-mass system, are shown in Fig. 1. As no attempt was made to establish absolute cross sections, the distributions are arbitrarily normalized to give the closest over-all agreement. The two angular distributions show striking qualitative agreement, and more than half the points for each reaction lie within one probable error (typically about 4%) of the common smooth curve.

However, as can be seen in Fig. 1 and in the analysis by angular intervals given in Table I, consistent differences between the two distributions appear in certain regions, notably near 90° and near 130°. A re-examination of experimental difficulties suggests that the differences near 90° may be due to an underestimate of background contributions to the (α, d) counting rates and that the difference near 130° may be due to mechanical errors in determining the (d, α) angles. (Contributions to the errors from other sources, such as incorrect beam energies and multiple scattering losses, are believed to be comparatively small.) These differences are not outside the estimated maximum possible error, and we conclude that they do not represent significant evidence for a departure from detailed balance.

In an attempt to obtain an over-all characterization of the degree of agreement between the

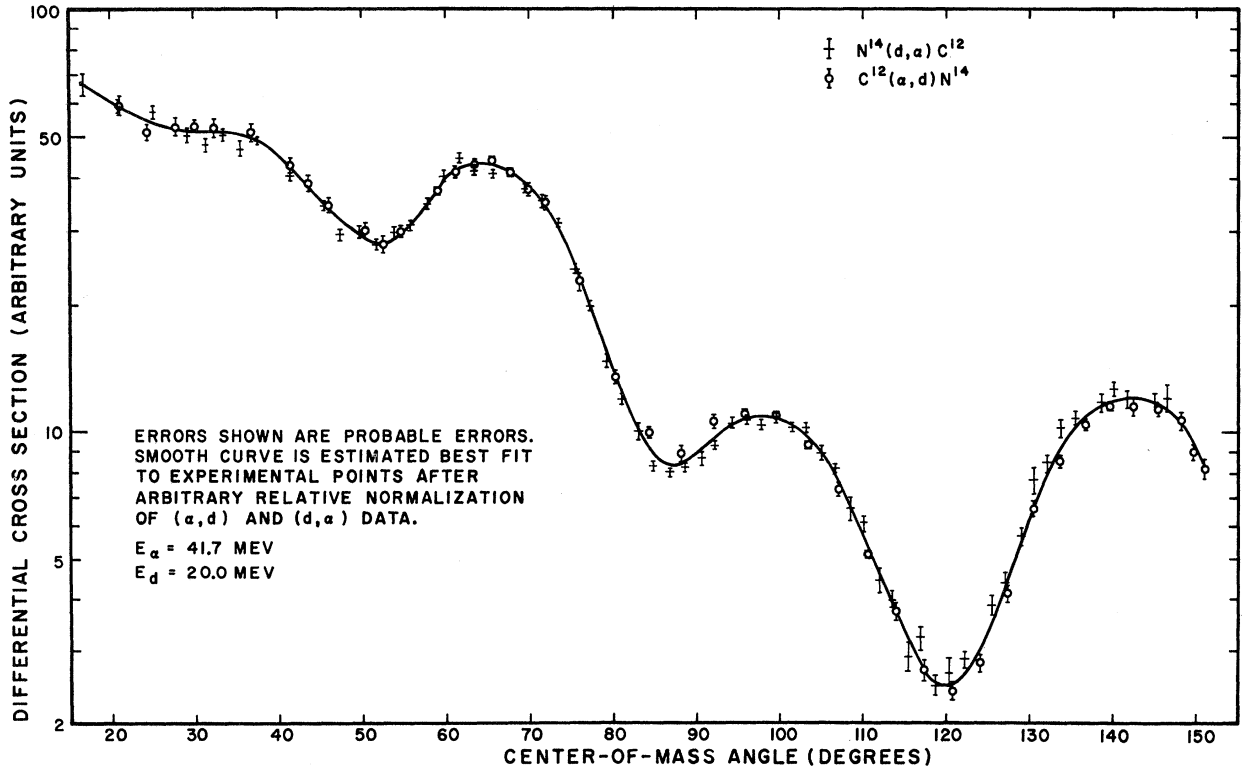

FIG. 1. Angular distributions (c.m.) for the inverse reactions $C^{12}+\alpha \rightleftharpoons N^{14}+d$ at matched energies. Probable errors on experimental points include statistical errors and estimated uncertainties in the subtraction of small background contributions to the measured counting rates.

Table I. Analysis of differences between distributions. For each 10° interval a deviation, d, from the smooth curve of Fig. 1 is found by (a) determining the fractional discrepancy between each experimental point and the smooth curve, (b) taking the algebraic sum of these discrepancies, and (c) dividing by the number of points in the interval. The difference, D, between the two angular distributions in any 10° interval is the algebraic difference between the deviations, d. In computing the average of the magnitude of D, noted at the bottom of the table, the smallest difference is omitted to compensate for the arbitrary relative normalization of the two distributions. For qualitative orientation, a typical probable error, ϵ, for individual points within each interval is also tabulated.

Angular interval (c.m. degrees)	$C^{12}(\alpha,d)N^{14}$ d (percent)	ϵ	$N^{14}(d,\alpha)C^{12}$ d (percent)	ϵ	Difference D (percent)
20-30	-1.2	5.0	+1.4	4.3	-2.6
30-40	+2.7	4.4	-3.6	3.4	+6.3
40-50	+1.6	4.0	-2.7	2.8	+4.3
50-60	+1.0	3.5	+1.0	2.7	0.0
60-70	-0.6	2.7	-1.8	2.2	+1.2
70-80	+1.1	4.3	+0.1	2.9	+1.0
80-90	+4.5	3.8	-2.9	2.8	+7.4
90-100	+4.7	3.1	-2.1	2.6	+6.8
100-110	-4.4	3.2	+1.3	3.6	-5.7
110-120	-1.4	4.2	+2.2	6.4	-3.6
120-130	-6.3	5.0	+5.5	6.6	-11.8
130-140	-4.3	2.9	+7.3	5.0	-11.6
140-150	-1.7	4.3	+3.6	4.6	-5.3
				Average difference: $\langle \lvert D \rvert \rangle_{Av}$	=5.6%

two distributions, we have calculated an average difference in the manner described in Table I. As seen from Table I, the calculated average difference between the measured angular distributions is less than 6% and would be smaller if the somewhat less accurate data beyond 110° were given reduced weight. Differences of this order can be understood in terms of experimental errors, and we believe that the present data, considered as a whole, are not inconsistent with the assumption of exact detailed balance. While experimental errors could tend to cancel an actual difference between the distributions over a limited angular region, such accidental reduction is unlikely over a wide region. Therefore (aside from a single unmeasured normalization factor) it is concluded that the differential cross sections for the reactions $N^{14}(d,\alpha)C^{12}$ and $C^{12}(\alpha, d)N^{14}$ from 20° to 150° (c.m.) probably differ on the average by less than 6%. This agreement is interesting in view of the wide, and somewhat irregular, fluctuations of the cross sections with angle.

A precise assessment of the upper limit placed by these results upon the fraction of the Hamiltonian which is noninvariant with respect to a time inversion must await analysis in terms of a specific model which can account satisfactorily for the observed angular distributions and which in addition can predict their sensitivity to possible violations of time reversal invariance. In the absence of such a theory, we apply the approximate criterion of Henley and Jacobsohn,[1] and conclude that the present results imply that this noninvariant fraction is probably less than 3%.

---

*Supported in part by the U. S. Atomic Energy Commission.

†Now at Instituut Voor Kernphysisch Onderzoek, Amsterdam 0, Holland.

‡Now at University of Colorado, Boulder, Colorado.

‖Now at Ramo-Wooldridge Corporation, Los Angeles, California.

[1]E. M. Henley and B. A. Jacobsohn, Phys. Rev. 108, 502 (1957); Phys. Rev. (to be published). We are indebted to Dr. Henley and Dr. Jacobsohn for many helpful discussions.

[2]Work reported recently includes Burcham, McCauley, Bredin, Gibson, Prowse and Rotblat, Nuclear Phys. 5, 141 (1958); Bodansky, Eccles, Farwell, Rickey, and Robison, Bull. Am. Phys. Soc. Ser. II, 3, 327 (1958); J. N. Bradbury and L. Stewart, Bull Am. Phys. Soc. Ser. II, 3, 417 (1958); L. Rosen (private communication to B. A. Jacobsohn). See reference 1 for

bibliography of earlier work.

[3]Hillman, Johansson, and Tibell, Phys. Rev. 110, 1218 (1958); and A. Abashian and E. M. Hafner, Phys. Rev. Lett. 1, 255 (1958).

[4]H. Bichsel (private communication).

[5]We are grateful to Dr. J. K. Magrane and Mr. H. R. Russell of the American Cyanamid Company for their assistance in providing us with foils of this nitrogen compound.

NEUTRON SPECTRA FROM $Be^9(He^3,n)C^{11}$ AND $Be^9(He^4,n)C^{12}$ USING PULSE SHAPE DISCRIMINATION IN AN ORGANIC SCINTILLATOR

A. E. Litherland, E. Almqvist, R. Batchelor,* and H. E. Gove
Chalk River Laboratories,
Chalk River, Ontario, Canada
(Received January 7, 1959)

It has been shown recently[1] that it is experimentally possible to use pulse shape discrimination to differentiate between neutron and gamma-ray induced pulses from some organic scintillators. This provides a powerful method for the study of fast-neutron spectra from nuclear reactions and also for the study of gamma-ray spectra, from a NaI(Tl) crystal, in coincidence with fast neutrons.

The purpose of this Letter is to report some measurements on the suitability for pulse shape discrimination of some commercially available organic scintillators and to report some preliminary observations of the high-energy neutron groups from the $Be^9(He^4,n)C^{12}$ and the $Be^9(He^3,n)C^{11}$ reactions.

The pulse shape discrimination method is based upon the fact that the ratio of the intensity of the long-period decay component (~200 mμsec) to that of the short-period component (~4mμsec) is different for recoil protons and electrons.[1] This difference was assessed for a number of scintillators by taking two pulses from the photomultiplier, a current pulse from the anode, and an integrated pulse from a lower dynode. After suitable amplification and stretching, a narrow band of current pulses was selected by a single-channel analyzer, the output of which opened a linear gate to allow the corresponding integrated pulses to be analyzed by a 100-channel pulse amplitude analyzer. If the pulses from the organic scintillator are caused by the neutrons and gamma-rays from a PuBe source two peaks will usually appear on the kicksorter, the higher being composed entirely of neutron pulses and the lower of gamma-ray pulses. A gamma-ray source produces a single peak. Table I lists the ratio, R, of the channel number of the neutron peak to the channel number of the gamma-ray peak (the corresponding electron energy is approximately 1 Mev), for a number of commercial organic scintillators.[2,3]

As part of a program to study neutron spectra and (n,γ) coincidences using a neutron detector which exhibits neutron gamma-ray discrimination, we have started a series of measurements with the liquid scintillator *NE*212.[2] The reactions $Be^9(He^3,n)C^{11}$ and $Be^9(He^4,n)C^{12}$ were chosen for study. The former reaction, which has not been studied previously, yields a number of neutron groups together with the associated gamma-rays, and gamma-rays from the reaction $Be^9(He^3,p\gamma)B^{11}$ are also emitted.[4] By using a mixture of He^3 and He^4 in the ion source of the Chalk River electrostatic accelerator the reactions could be studied by simply changing the deflecting-magnet field. The scintillator was placed at 0° and at a distance of 3 in. from a thin Be^9 target which was then bombarded by either 1.9-Mev He^3 or He^4 ions. The neutron output was monitored with a ZnS(Ag)-loaded plastic scintillator, *NE*404,[2] placed at 90° to the beam direction.

The separation of the neutron pulses and the gamma-ray pulses, from the *NE*212 scintillator, over a broad range of neutron energies, was effected by a circuit similar to that devised by Owen.[1] In this circuit the voltage between the last dynode and anode of a photomultiplier (Dumont 6363) was reduced to about 4 volts so that the current, leaving the last dynode during the "fast" part of the current pulse, was space-charge limited. The signal from the last dynode was consequently negative during the "fast" part

Table I. Neutron—gamma-ray discrimination properties of some organic scintillators. R is the ratio of the channel number of the neutron peak to that of the gamma-ray peak.

Scintillator	R
*NE*202	1.17
*NE*210	1.11
*NE*211	1.11
*NE*212	1.30
Stilbene	1.33