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[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

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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

of the current pulse but became positive during the "slow" part to an extent depending upon the relative intensity of the slow component to the fast component. The output of a pulse-height discriminator, set on the amplified positive pulse from the last dynode, was then used to open a gate for a linear pulse obtained from an earlier dynode. The output of the linear gate was displayed on a 100-channel pulse amplitude analyzer. Owen has used this circuit to display the neutron and gamma-ray pulse spectrum from a PuBe source.[1]

Figure 1 shows the pulse spectra obtained from the $Be^9 + He^3$ reaction for three values of the discriminator bias on the pulses from the last dynode. As expected, the effect of increasing the bias was first to eliminate the gamma-ray pulses at approximately bias 700 and then to cut off greater portions of the low-energy proton recoil spectrum. The bias 800 curve represents only the proton recoil distribution above 3 Mev proton energy. Experiments with PuBe neutrons and the 2.61-Mev gamma-rays from a radiothorium source (the latter give pulses corresponding to neutron energies of up to approximately 5 Mev) showed that >99% of the gamma-rays were eliminated from the PuBe neutron spectrum. In Fig. 2 the spectra are plotted on a logarithmic scale to show the effect of discrimination more clearly. Also shown is a calibration recoil proton pulse spectrum from the $Be^9(He^4,n)C^{12}$ reaction taken under the same conditions (bias 800) as the spectrum from $Be^9(He^3,n)C^{11}$. The steps in the $Be^9(He^3,n)C^{11}$ spectrum at approximately 9.5, 7.6, and 5.0 Mev correspond to neutron groups feeding the ground, first excited, and unresolved second and third excited states, respectively.[5] The step at 5.0 Mev is broader than expected from a single neutron group.

It is intended to pursue these and related measurements further, using larger tanks of liquid scintillator[6] and other methods of separating the neutron and gamma-ray pulses.

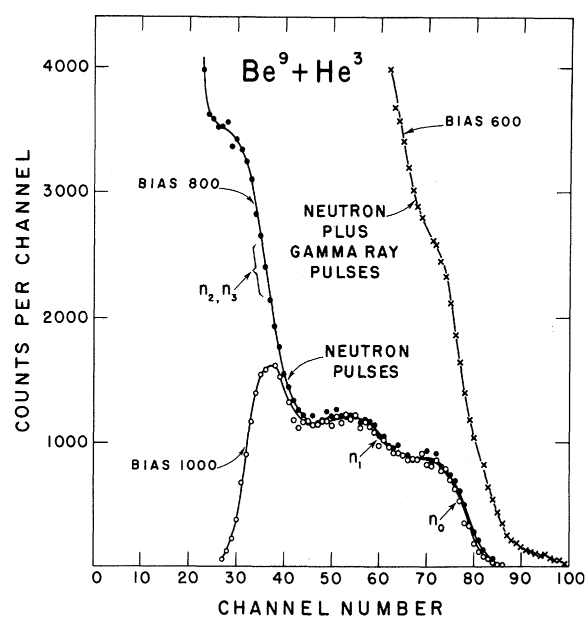

FIG. 1. Pulse-height spectra, obtained with a liquid scintillator, from the $Be^9 + He^3$ reaction, showing the effect of pulse shape discrimination. The steps n_0, n_1, n_2, and n_3 correspond to neutron groups feeding the ground, first excited, and unresolved second and third excited states respectively in C^{11}.

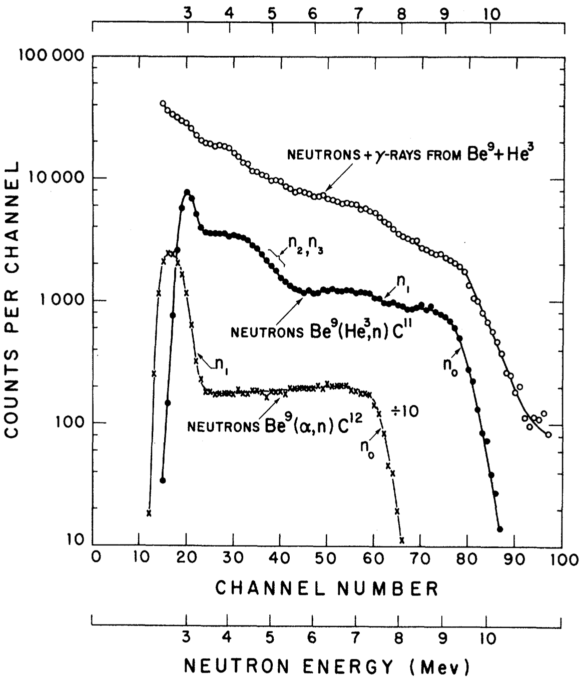

FIG. 2. Pulse-height spectra from the $Be^9(\alpha,n)C^{12}$ and $Be^9(He^3,n)C^{11}$ reactions.

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[1]R. B. Owen, Nucleonics 16, No. 6, 54 (1958); IRE Trans. on Nuclear Sci. NS-5, 198 (1958); and a paper to be published in Onde Electrique. The authors are indebted to R. B. Owen for the communication of his results prior to publication. It appears that the pulse-shape discrimination method was first suggested by F. D. Brooks, Progress in Nuclear Physics (Butterworths-Springer, London, 1956), Vol. 5, p. 284. An

experimental study of the effect together with a theoretical discussion has been published by G. P. Wright, Proc. Phys. Soc. (London) B69, 358 (1956).

[2]The encapsulated liquid scintillators, $1\frac{1}{2}$-in. diam by $1\frac{1}{2}$ in. long and the fast-neutron detector *NE*404, were obtained from Nuclear Enterprises, Winnipeg, Manitoba, Canada.

[3]The authors wish to acknowledge the cooperation of Professor L. Katz during early work on some of these scintillators and during unpublished work on a variety of inorganic scintillators.

[4]Ferguson, Gove, Kuehner, Litherland, Almqvist, and Bromley, Phys. Rev. Lett. 1, 414 (1958).

[5]V. Johnson, Phys. Rev. 86, 302 (1952).

[6]Preliminary observations, of pulse-height spectra from a 3-in. diam by 3-in. long *NE*212 liquid scintillator, indicate that the shape of the high-energy portion of the spectrum of pulses from monoenergetic neutrons (7-10 Mev) is less favorable for the analysis of complicated neutron spectrum than the spectrum from a smaller scintillator. See J. E. Hardy, Rev. Sci. Instr. 29, 705 (1958).

p-p *S*-WAVE PHASE SHIFTS FROM A BOUNDARY CONDITION POTENTIAL*

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Nucleon-nucleon scattering experiments have led to a potential model for the two-nucleon interaction that conventionally features a very hard repulsive core followed by some type of meson-theoretic attractive well.[1,2] While the hard repulsive core is needed to explain very high-energy nucleon-nucleon scattering, Moszkowski and Scott have pointed out recently[3] that the possibility exists of explaining lower energy (say below 200 Mev) nucleon-nucleon scattering by means of a potential featuring a somewhat softer core. The motivation for their remark is that an infinite repulsive core leads to difficulties when the many-body problem is expressed in terms of two-nucleon scattering amplitudes. If a modified potential exists that can give agreement with nucleon-nucleon scattering over the energy range of importance—with the core region chosen so as to eliminate the divergences that result from conventional perturbation expansions—then this model would be a convenient starting point for many-body calculations.[4]

(In the discussion of the present Letter, we restrict ourselves to the singlet-*S* nucleon-nucleon scattering state. *S*-state scattering is more sensitive to details of the core region than are scatterings from the higher angular momentum states. Hence if satisfactory results are obtained for the *S*-state, then it is reasonable to expect that a modified core can also be made to give agreement for *P* and higher waves. Also, by treating only the *S*-state, we side-step the complexities associated with tensor and/or spin-orbit terms that are necessary for a complete nuclear potential model, but which do not essentially relate to a modification of the central core potential.)

Moszkowski and Scott[3] chose a core potential that can be represented by assigning to the wave function at the core radius c the boundary condition

$$\left(\frac{1}{u}\frac{du}{dr}\right)_{r=c} = \frac{1}{c}. \qquad (1)$$

This boundary condition has the property that at zero energy the two-nucleon wave function goes over into the free-particle wave function for separations $r>c$. Mathematically, the core consists of an infinitely-repulsive region followed by a region that is infinitely attractive and of infinitesimal width, chosen so that the effects of the attractive and repulsive parts cancel out at zero energy. This is a convenient potential to use from the standpoint of Brueckner theory applications.[4]

The question remains as to whether a two-nucleon potential featuring the boundary condition given by Eq. (1) can yield the same results as a hard core potential.[1,2] Moszkowski and Scott[3] showed that for the simple case of a core followed by a square well, the two models could be made to agree to within 1/2 degree for the singlet-*S* phase shift over the laboratory energy range 0-250 Mev. This was an analytic result. Calculations for the more realistic case of a core followed by a Yukawa well require a computing machine. Such calculations were carried out on the Livermore UNIVAC, using conventional iteration techniques. If we define the potential as

$$V = -V_0\ e^{-\mu r}/\mu r, \quad r>c \qquad (2)$$

and use the boundary condition from Eq. (1), then we obtain the results shown in Table I, which are there compared with the model of Gammel and Thaler[1] and with the model of Signell and Marshak.[2] Four sets of parameters for the Moszkowski-Scott potential are shown. The first two