HIGH-RESOLUTION FAST-NEUTRON SPECTROSCOPY OF THE REACTION $^9Be(p,n)^9B$ AT 20 MeV*

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High-resolution fast-neutron spectra (to about 1%) have been obtained by means of the proton-radiator method, detecting the proton recoils with solid-state detector telescopes and particle identifier circuits. Our spectra confirm a broad peak at 1.4 MeV and resolve another at 3.2-MeV excitation.

The reaction $^9Be(p,n)^9B$ was studied at 14.1-MeV laboratory energy by Saji[1] with a proton-recoil–neutron spectrometer capable of achieving 3% resolution, but operating typically at 5% resolution. We have measured neutron spectra produced in this reaction by 20-MeV protons. Figure 1 shows a schematic drawing of our neutron spectrometer. Basically it consists of a suitable collimation system, a radiator of protons (recoils from a thin film of polyethylene), and a solid-state-detector telescope consisting of two detectors ($\Delta E, E$). The electronics includes low-noise preamplifiers, amplifiers, particle-identifier circuits[2] and multichannel analyzers.

In the recent past the direct application of solid-state detectors to neutron spectroscopy has been studied and discussed.[3,4] The (n,α) reactions in silicon are so numerous that such direct use is at present impractical for spectroscopic purposes.[4] Birk, Goldring, and Hillman[3] considered the spectroscopy of 6-MeV neutrons detecting proton recoils from a proton radiator using a single silicon detector. Such a method becomes rapidly impractical at higher neutron energies because it would be very hard (if not impossible) to separate the recoil protons from the peaks due to the (n,α) reactions in silicon. Thus, at higher energies the proton recoil detection with silicon detectors depends vitally on the coincidence requirement between the ΔE and E detectors.[1,5] A further refinement is achieved by means of a particle identification system.[2] A resolving power $E/\Delta E = 90$ is reached easily with our spectrometer. A detailed description of the latter and possible improvements will be published elsewhere.[6]

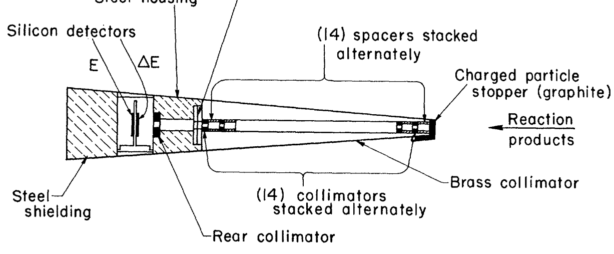

FIG. 1. Schematic of the collimator, radiator, and detector telescope assembly of the neutron spectrometer.

Considerable effort has been vested recently in establishing the existence of a state in ^9B, analog to the 1.70-MeV state in ^9Be. A state at about 1.4 MeV in ^9B was first reported by Marion et al.[7] and was also weakly seen at some angles by Saji[1] in his $^9Be(p,n)^9B$ experiment. More recent work on ^9B was carried out through reactions where an outgoing charged particle was detected, like $^{12}C(p,\alpha)^9B$,[8,9] $^{10}B(^3He,\alpha)^9B$,[10] and $^{10}B(d,t)^9B$.[11,12] Symons and Treacy[8] observed a broad peak in the α-particle spectrum of the reaction $^{12}C(p,\alpha)^9B$ at a channel energy of approximately 1.4 MeV. They calculated a fit to the observed peak using the procedure and notation of Barker and Treacy[13] with a channel radius of 4.35 fm and an energy of 1.7 MeV. Bauer, Anderson, and Wong[9] reached states of ^9B through the reactions $^{12}C(p,\alpha)$, $^9Be(p,n)$, and $^6Li(\alpha,n)$, using α particles between 12.7 and 18.3 MeV and protons at 6.3 and 7.4 MeV. They concluded that there was no state of ^9B at 1.7 MeV and argued against the possibility of its existence on the basis that the ^9Be "state" was probably ascribed to the neutron emission threshold, but that the "analog" could not be attributed to a proton threshold inasmuch that ^9B is proton unstable. However, it should be noted that a broad peak with barycenter at about 1.4 MeV is prominently visible in the spectra of Bauer, Anderson, and Wong[9] from $^{12}C(p,\alpha)^9B$ at 12.7 MeV, as well as the other reactions they studied, in excellent agreement with the results of Symons and Treacy.[8]

Our experiment was performed at 20-MeV laboratory energy, using protons from the Berkeley 88-in. variable-energy cyclotron. To re-

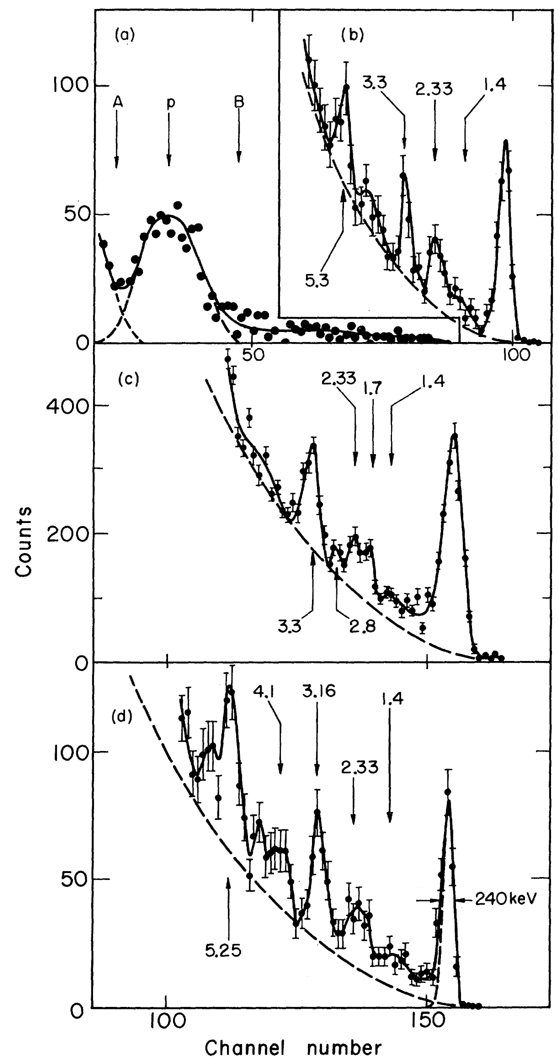

FIG. 2. Sample spectra obtained in the present experiment. The n-p cross section has not been unfolded as it does not alter the spectroscopic content appreciably. Solid lines have been drawn to help the eye. The energy labels on the peaks are actual determinations from conversions of pulse height to energy. The discrepancy between the thick and thin target determinations is still compatible with the quoted errors. (a) Particle identifier spectrum. Discriminators were normally located at A and B to select the proton recoils. However, a display of the energy spectrum of pulses above B did not show any structure. (b) Spectrum at 9° lab, using a ^{9}Be target of 18.8 mg cm^{-2} with ΔE-E coincidence requirement and no particle identification. The radiator thickness was approximately 0.08 mm. (c) Spectrum at 12° lab, same target as in (b) with coincidence requirement and particle identification. At this angle we find evidence for the 2.8-MeV state and indications of a peak at 1.7 MeV. (d) Spectrum at 17° lab, obtained with a 4.70-mg cm^{-2} ^{9}Be target and detection conditions as in (c). The structure of the spectrum near 2.33 MeV is consistent with the 12° spectrum of (c) although the statistics are poorer. The resolution of our neutron spectrometer, unfolding the target thickness effect, was 200 keV near 18 MeV, i.e., 1.1%.

duce background the beam was accelerated as 40-MeV H_2^+. The typical current was 1 μA on the target. Our ^{9}Be(p,n)^{9}B spectra agree in general with the results of Saji,[1] except that we have a significantly higher resolving power. Figure 2 contains some sample spectra, showing evidence for a peak at about 1.4 MeV in the neutron spectra. In addition the state assigned an energy of 3.07 MeV by Saji[1] and not well resolved from the 2.3-MeV state is seen completely resolved in our spectra, and we assign to it an energy of 3.16 ± 0.07 MeV. It is worth noting that the ^{9}Be(p,n)^{9}B time-of-flight spectra of Bauer, Anderson, and Wong[9] at 7.4 MeV and 15° laboratory angle show a peak at about 3.1 MeV, and the same is true for the ^{6}Li(α,n) spectra at 14.4 MeV at several laboratory angles.

Some comments are in order concerning the 1.4-MeV peak in the spectra leading to the ^{9}B nucleus. It is certainly true that such a peak may not be related to a proton threshold effect as mentioned above. Instead, it seems reasonable to relate it to the threshold of the channel ^{5}Li$+\alpha$, located at 1.685 MeV[14] in the ^{9}B system. The relation between thresholds and states has been discussed repeatedly by Baz,[15] Inglis,[16] and others. The conclusions are not clear cut, but indicate that it is more probable to observe states near thresholds than elsewhere. It is beyond the scope of this note to investigate this point in detail. With reference to our peak at 3.16 MeV it is worth noting that it appears consistently in the spectra reaching ^{9}B through the emission of a neutron, i.e., $X(x,n)^9$B, but is absent in charged-particle spectra. It seems reasonable that the state at 2.8 MeV observed in the latter is different from the state at about 3.2 MeV observed in neutron spectra, and in fact Fig. 2(b) seems to support this point.

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ENERGY DEPENDENCE IN THE $K_{e3}{}^0$ DECAY FORM FACTOR*

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In a very low momentum $K_L{}^0$ beam, a sample of $K_L{}^0 \rightarrow \pi^\pm e^\mp \nu$ decays has been identified in the 25-in. hydrogen bubble chamber by means of bubble density. Based on 531 events, the energy-dependence parameter for the $K_{e3}{}^0$ vector form factor was determined by $\lambda = +0.01 \pm 0.015$, which is consistent with no energy dependence.

A portion of the data from a low-momentum $K_L{}^0$ experiment has been carefully analyzed to identify the common decay modes and to determine the energy dependence of the form factor of the $K_{e3}{}^0$ decays.[1] Although this form factor is predicted by the $|\Delta I| = \frac{1}{2}$ rule to be the same as for $K_{e3}{}^+$ decays, some of the more recent experimental results have cast doubt on the validity of the rule. While the energy dependence for the $K_{e3}{}^+$ decay form factor is rather well known, that of the $K_{e3}{}^0$ is generally characterized by much larger experimental uncertainties, and with one exception, the $K_{e3}{}^0$ experimental results appear to indicate a larger energy dependence than seems to occur in $K_{e3}{}^+$ decay.[2] The present experiment yields, with relatively high precision, the result that the $K_{e3}{}^0$ form factor is consistent with no energy dependence, and is in good agreement with the result from $K_{e3}{}^+$ decays.

In this experiment, the decays were observed in the Lawrence Radiation Laboratory's 25-in. hydrogen bubble chamber exposed to a $K_L{}^0$ beam having a broad momentum spectrum extending from approximately 100 to 500 MeV/c and peaking at about 280 MeV/c. The K^0 particles were produced by K^+ charge exchange on a dense target located 22 in. from the center of the chamber; in this way we obtained a reasonably high rate of $K_L{}^0$ decays associated with only a few background tracks in each picture. Other details on the experimental technique, as well as a preliminary analysis of $K_L{}^0p$ interactions have been reported previously.[3]

Although the $K_L{}^0$ momentum is not well known, the direction is well determined from the known position of the small target and the observed decay point. If the identity of the decay secondaries is known, the decay may then be completely reconstructed except for the twofold quadratic ambiguity.

The correct decay mode could be identified by means of bubble density in a large fraction of the cases, since the $K_L{}^0$ momentum, and therefore the secondary momenta, were quite low. The average electron momentum from $K_{e3}{}^0$ decays was about 140 MeV/c. The tracks were identified by comparison of the observed bubble density with that predicted for π, μ, and e from the measured momentum, using the appropriate conical projection of the track on each view. These dicisions were made by phys-