Excitation Study of $F^{19}(n,\alpha)N^{16}$ with a BaF_2 Crystal*

DANIEL M. SMITH,† NORMAN A. BOSTROM,‡ AND EMMETT L. HUDSPETH
The University of Texas, Austin, Texas
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The scintillation properties of crystalline BaF_2 have been investigated. It was found that this substance yields a reasonably well-defined photopeak when exposed to gamma rays from Na^{22}. With DuMont K1306 and 6292 photomultipliers, the signals from BaF_2 are about $\frac{1}{5}$ to $\frac{1}{10}$ as strong as those from NaI(Tl). With a BaF_2 crystal as a target, the excitation function for the $F^{19}(n,\alpha)N^{16}$ reaction was observed in the region from an apparent threshold near 3.2 Mev up to $E_n=6$ Mev. Several new resonances were found in this region. The cross section generally increases with increasing neutron energy, rising from 85 mb at 4.48 Mev to 200 mb near 6 Mev. Absolute accuracy of cross-section measurements was $\pm 15\%$.

INTRODUCTION

THE excitation function for the reaction $F^{19}(n,\alpha)N^{16}$ has been previously reported from this laboratory[1] and in a more complete study made by Marion and Brugger.[2] In both cases, the neutrons were incident on CaF_2. In the first case,[1] the activity induced by neutron bombardment of a CaF_2 ring was measured by using a separate detector; in the second case,[2] a CaF_2 crystal served both as a target and as a detector of induced N^{16} activity. The absolute value for the cross section for the $F^{19}(n,\alpha)N^{16}$ reaction was measured[2] with an accuracy of $\pm 40\%$ and with a resolution which varied between 30 and 100 kev.

In the present work, we have made use of a BaF_2 crystal as a target for neutron bombardment and as a detector of the induced N^{16} activity. This detector shows a maximum at the photopeak position for gamma rays and hence it may find additional uses in the laboratory.

The purposes of the present study were: (1) to obtain specific information on the scintillation properties of BaF_2, both for the general value of such an investigation and for the purpose of using a BaF_2 crystal in the $F^{19}(n,\alpha)N^{16}$ excitation study; (2) to measure with increased accuracy the absolute value of the $F^{19}(n,\alpha)N^{16}$ cross section from threshold to about 6 Mev; and (3) to examine more closely the resonances which appeared in earlier work.

SCINTILLATION PROPERTIES OF BaF_2

The scintillation properties of a BaF_2 crystal were first reported[3] from this laboratory several years ago. In the present work, we have made additional specific comparisons of BaF_2 and NaI(Tl). For this purpose, a single crystal of presumably unactivated barium fluoride in the form of a right circular cylinder was obtained from the Harshaw Chemical Company. The crystal surfaces (except for the face to be joined to the photomultiplier) were roughened with emery paper to provide diffuse reflection. These surfaces were then thickly coated with MgO by exposing them to burning magnesium. A thin polystyrene ring was placed on the top of the crystal, and a polystyrene annulus was placed at the base of the crystal to insure positional stability. This assembly was then wrapped with Scotch electrical tape in such a way that the tape itself did not come in contact with any surface which was covered with MgO. Both *DC*-200 and Celvacene were used for optical coupling, but a creeping tendency of a crystal mounted with either substance made it necessary to renew the MgO and the crystal mounting periodically.

Inasmuch as the spectrum of fluorescence yield from barium fluoride was unknown, it was thought desirable to mount the crystal on a special photomultiplier, to allow for the possibility that its spectrum peaked in or near the ultraviolet. In the present case, a DuMont K1306 tube was used.

Pulse-height spectra were obtained from BaF_2 and from NaI(Tl), under irradiation with gamma rays from Na^{22}. The spectra were measured under identical conditions of tube voltage and amplifier gain, save for a change of linear amplifier gain of 8. The spectra measured in this way are shown in Fig. 1. The positions of the corresponding photopeaks give as the ratio of intrinsic pulse heights in NaI(Tl) and BaF_2 a value of about 10.3. This result may be compared with earlier[3] rough estimates which gave a ratio, with a DuMont 6292 tube, of about 5. From these observations, it appears that the ultraviolet portion of the BaF_2 spectrum is not appreciable, but no specific measurements were made. Marion and Brugger[2] report a pulse-height ratio of about 10 for NaI(Tl) and CaF_2 mounted on an EMI 6255 tube. BaF_2 possesses an advantage over CaF_2 of exhibiting a reasonably distinct photopeak which serves as the basis for energy calibrations.

EXPERIMENTAL PROCEDURE

The $F^{19}(n,\alpha)N^{16}$ reaction was produced in a BaF_2 crystal by bombarding it with *d-d* neutrons. Neutrons

* Assisted by the U. S. Atomic Energy Commission.
† Now at Oak Ridge National Laboratory, Oak Ridge, Tennessee.
‡ Now at Texas Nuclear Corporation, Austin, Texas.
[1] Bostrom, Hudspeth, and Morgan, Phys. Rev. **99**, 643(A) (1955).
[2] Jerry B. Marion and Robert M. Brugger, Phys. Rev. **100**, 69 (1955).
[3] Bostrom, Hudspeth, and Morgan, Phys. Rev. **100**, 973(A) (1955).

of energies up to about 6 Mev were thus obtained from The University of Texas Van de Graaff generator. The specific energy of the neutrons was calculated from the known energy of the incident deuterons; the deuteron energy was determined by a nuclear moment fluxmeter in the gap of the analyzing magnet of the accelerator. The fluxmeter was calibrated through observation of some of the well-known $F^{19}(p,\alpha\gamma)$ resonances and the $Li^7(p,n)$ threshold. Absolute values of our bombarding energy are precise to about 0.2% or less.

The deuterium gas target was contained at about 25-cm pressure in a cell of depth 2.23 cm; deuterons passed into the cell through a 0.025-mil nickel foil. Each nickel foil was individually weighed and the stopping power calculated.

The neutron activation of F^{19} in the BaF_2 crystal was measured by following the delayed activity of the residual N^{16}. Competing reactions include $F^{19}(n,p)O^{19}$ (for neutrons of energy greater than about 4.5 Mev), which produces 29-second beta-radiation; $C^{12}(d,n)N^{13}$, a contaminant reaction arising from carbon deposits in the target cell, which yields 10-minute N^{13} annihilation radiation; and $Si^{28}(n,p)Al^{28}$, which takes place in the glass of the phototube and gives 2.3-minute Al^{28} beta-radiation. Preliminary bombardments with the baseline of the detecting equipment set at about 2.8 Mev established that the background of delayed activity above that energy accounted for a negligible fraction of the counts recorded during the first several N^{16} half-lives. Accordingly, the relative data for an excitation curve were taken at that baseline setting by counting the delayed activity over a thirty-second interval. The target was made a part of a "leaky integrator" circuit,[4] with the *RC* value equal to the mean life of N^{16}. Observations at a given bombarding energy were made alternately with deuterium gas in the cell, then with the gas pumped out. The integrator network, which included a 3-μf capacitor, was in each case charged to 1.3 volts (as read with an electrometer) and counting was begun at 1.0 volt. Each run was repeated five times.

The absolute cross section was measured at several energies and under several different sets of conditions by biasing the detector very near zero and making an analysis of the decay curve of the observed activity. For this purpose, a Sanborn recorder was connected to the output of the scaler, the resultant tape was divided into a series of ten-second intervals, and the total number of counts in successive intervals determined. The "gas out" data exhibited little or no evidence of short-lived activity; a smooth curve was accordingly drawn through the neighborhood of the "gas in" points and a background value, chosen by inspection, was subtracted from it. The number of N^{16} atoms at the beginning of the counting was then determined, and the absolute cross section for the $F^{19}(n,\alpha)N^{16}$ reaction was calculated from these data. To check the validity of this procedure, bombardments were also carried out with settings of the bias control at successively smaller values approaching zero. The resulting yields were plotted against the bias setting, and a smooth curve drawn through these points showed a horizontal plateau at approach to zero bias. The zero-bias ordinate of this curve was taken to be the correct total yield.

[4] S. C. Snowdon, Phys. Rev. 78, 299 (1950).

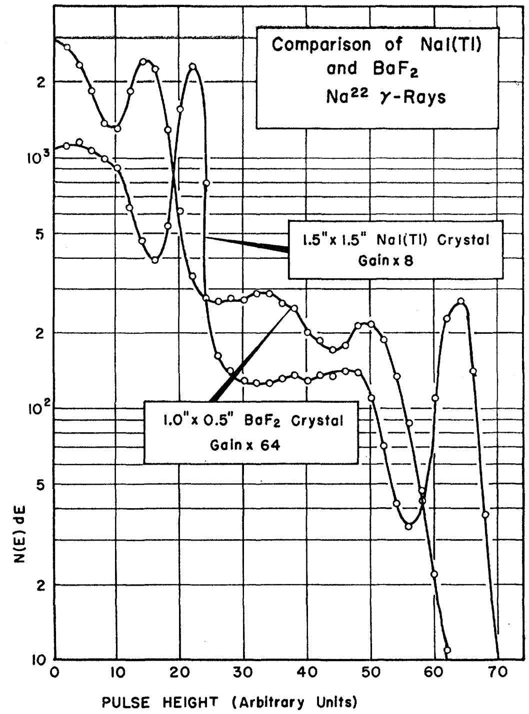

FIG. 1. Comparison of pulse-height spectra obtained with a NaI(Tl) crystal and with a BaF_2 crystal mounted on a DuMont K1306 phototube. Note difference in gain settings.

The net counts ("gas in"-"gas out") were corrected for gas pressure variations and for the change in the *d-d* cross section with bombarding energy. The latter was accomplished by dividing the pressure-corrected count at each energy by the 5° *d-d* cross section at that energy as obtained from graphical data. The 5° data were chosen, since this is approximately the mean effective angle subtended by the BaF_2 crystal. The effective solid angle subtended by the crystal was obtained by graphical analysis.

RESULTS

The final excitation function for the $F^{19}(n,\alpha)N^{16}$ reaction is shown in Fig. 2. The relative curve was normalized to an average of three absolute measurements, performed at 4.48 Mev and indicated in the figure by triangular symbols. Two of these determinations were made with the cylindrical barium fluoride crystal at target-crystal distances of 3.0 inches and 5.0 inches. The third was made with an irregularly shaped barium fluoride crystal at a distance of about five inches. The resulting value for the cross section at

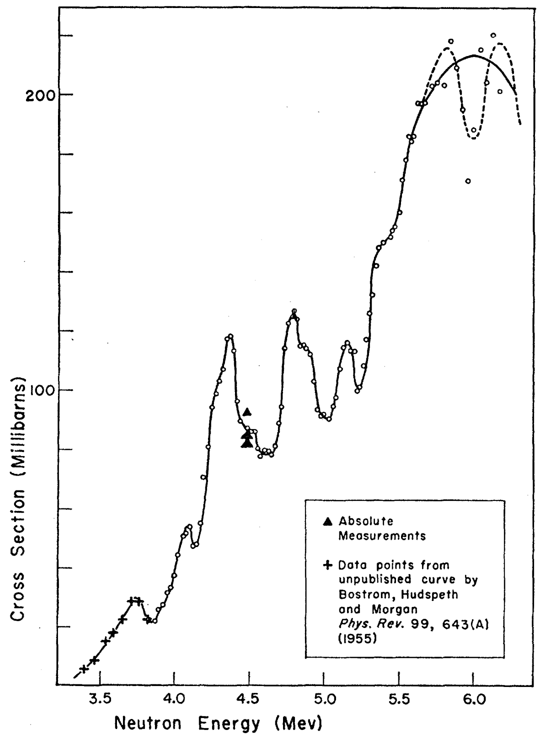

FIG. 2. Excitation function for $F^{19}(n,\alpha)N^{16}$. Absolute measurements were taken with different BaF_2 crystals and with various geometries.

TABLE I. Resonances observed in the reaction $F^{19}(n,\alpha)N^{16}$.

Present work	Reference 2
	3.4[a]
	3.61±0.05
3.75±0.05	3.69±0.05
	3.77±0.05
4.08±0.05	4.11±0.05
4.36±0.05	4.42±0.05
4.52[a]	
4.79±0.05[b]	4.86±0.05
5.15±0.05	
5.40[a]	
5.9[a]	5.9 ±0.1

[a] Resonance not resolved.
[b] Evidence for neighboring resonance about 0.2 Mev beyond this energy.

4.48 Mev is probably reliable to within about 10%, in consideration of the uncertainty of about 5% in the *d-d* cross section and the possible errors incurred in the evaluation of the effective crystal solid angle. Slight drifts in the baseline settings and in the electrometer, together with statistical errors, limit the over-all reliability of the normalized curve to about 15%.

The agreement of the present work with that of Marion and Brugger[2] is quite good, insofar as the relative shape of the curve is concerned. Marion and Brugger, using *p-t* neutrons, reported the resolution of the peak near 3.7 Mev into three distinct peaks, but their resolution at higher energies was inadequate to observe some of the resonances reported here. For the sake of completeness, we included in Fig. 2 the earlier work of this laboratory near 3.7 Mev, although the work of Marion and Brugger exhibits higher resolution.

The data above 5.7 Mev were taken near the limit of stable operation of the electrostatic generator at that time. The shape of the curve in this region is therefore less dependable, and only the general trend has been indicated by the solid line. The dotted curve shows a reasonable interpretation of the data; the relative data of Bostrom also showed indications of two maxima in this region.

A summary of our data and those of Marion and Brugger is shown in Table I. Our resonance energies are consistently lower but are within the estimated errors of measurement. The apparent threshold in each case lies near $E_n=3.2$ Mev; the threshold calculated from mass values is approximately 1.5 Mev. The yield just beyond the calculated threshold is strongly suppressed by the low penetration function for alpha emission. On this basis it is to be expected that the experimentally observed threshold would be near 3 Mev or more and that the rise in yield beyond this value would show the general trend which is observed.