Energy Distributions of Product Particles from Nitrogen-Induced Nuclear Reactions on Beryllium

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(Received January 10, 1958)

The energy distributions of protons, deuterons, and alpha particles from N^{14} bombardment of Be^9 were measured with a particle-selective counter. The apparatus is described. The results show approximate agreement with the simple statistical assumptions of continuum theory both in regard to the shapes of the spectra and to the relative yields of protons, deuterons, tritons, and α particles. Reasonable agreement with the level-density formula $\omega(E)=\exp\{2[a(E-b)]^{\frac{1}{2}}\}$ is possible with $a=1.1$, $b=0$ for F^{19}; $a=1.4$, $b=0$ for Ne^{21}; and $a=2.6$, $b=4.9$ for Ne^{22}.

INTRODUCTION

NUMEROUS attempts have been made to deduce from the energy spectra of reaction products the level density in nuclei as a function of excitation energy. A graphical summary of some of the results is given by Igo and Wegner.[1] In each of the experiments most, if not all, of the excitation energy imparted to the compound nucleus comes from the kinetic energy of the bombarding particle, and it is not certain that the bombarding particle interacts with a large enough number of the target nucleons to produce a statistical sharing of the energy. Evidence has been found that the energy is not well shared in such reactions.[2–4]

The availability of energetic nitrogen ions at Oak Ridge National Laboratory has made possible experiments in which the sharing of energy is probably good. It is possible, in certain nitrogen-induced reactions, to form a compound nucleus at an excitation of 30–40 Mev with more than two-thirds of the excitation derived from nuclear binding energy, rather than incident kinetic energy. Moreover, even the incident kinetic energy is shared among many nucleons. Thus, if a uniformly excited compound nucleus ever exists, one might hope to find it in these reactions.

If the excitation energy is statistically distributed among the nucleons, the energy spectrum of the "boiled off" particle in a reaction should be given by[5]

$$N(\epsilon)d\epsilon=\text{const}\,\epsilon\sigma_c(\epsilon)\omega(E)d\epsilon,$$

where ϵ is the kinetic energy in the final system, $\sigma_c(\epsilon)$ is the cross section for the formation of a compound nucleus by bombardment of the residual nucleus with the particle at energy ϵ, and $\omega(E)$ is the density of levels in the residual nucleus at excitation energy E which corresponds to the emission of the product particle with kinetic energy ϵ, i.e., $E+\epsilon=Q+\epsilon_i$, where Q is the energy of the reaction and ϵ_i is the kinetic energy in the initial center-of-mass system. $\sigma_c(E)$ can be calculated under the assumption of the continuum theory.[6] Thus, it is possible to deduce $\omega(E)$ from the experimentally measured energy spectra of product particles.

Measurements of the energy spectra of protons, deuterons, tritons, and α particles from nitrogen-induced reactions have been undertaken with the Oak Ridge National Laboratory 63-Inch Cyclotron. It is the purpose of the present article to describe the apparatus and to present results obtained at zero degrees from the bombardment of beryllium.

APPARATUS

The particle-selective energy-measuring system is shown schematically in Figs. 1 and 2. The beam of 27-Mev nitrogen ions emerging from the cyclotron strikes a thin (0.23 mg/cm²) beryllium target. A nickel foil is placed beyond the target to stop the nitrogen ions. Since the Coulomb barrier of nitrogen on nickel is well above the bombarding energy, no nuclear reactions giving rise to charged particles are produced in the nickel.

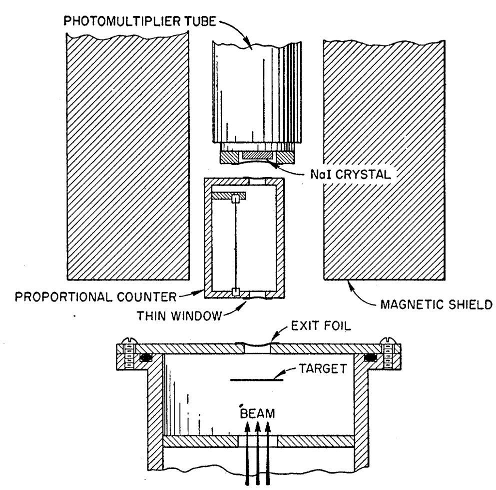

FIG. 1. Target and counter arrangement.

* Operated for the U. S. Atomic Energy Commission by Union Carbide Nuclear Company.
[1] G. Igo and H. E. Wegner, Phys. Rev. **102**, 1364 (1956).
[2] Austern, Butler, and McManus, Phys. Rev. **92**, 350 (1953).
[3] R. M. Eisberg and G. Igo, Phys. Rev. **93**, 1039 (1954).
[4] R. M. Eisberg, Phys. Rev. **94**, 739 (1954).
[5] See for example, J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), p. 367.
[6] M. M. Shapiro, Phys. Rev. **90**, 171 (1953).

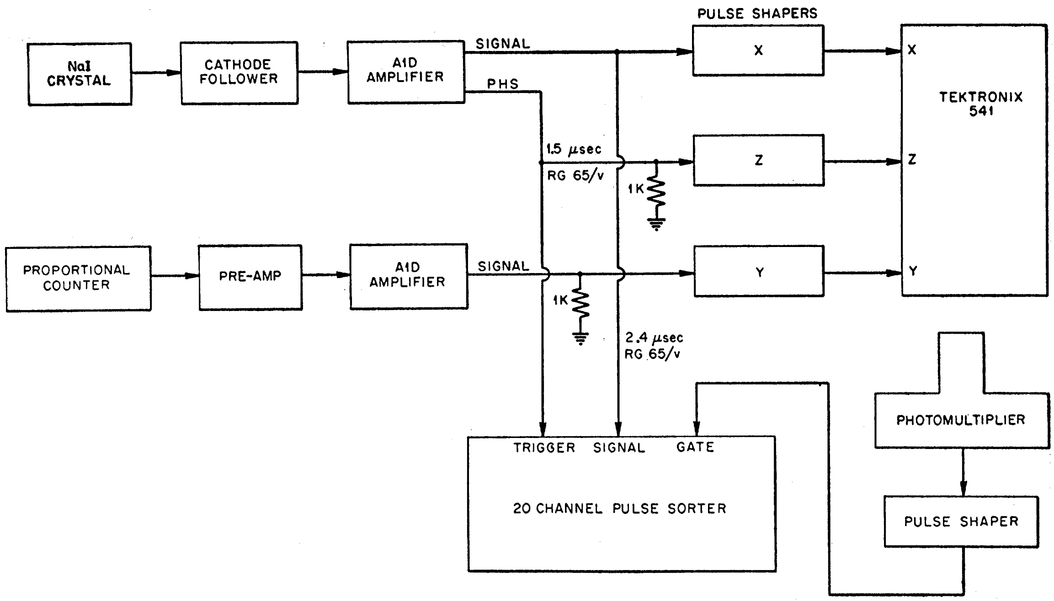

FIG. 2. Block diagram of circuits for dE/dx, E counter system.

The product particles from the reactions in the target leave the target chamber through the exit foil, traverse the proportional counter, and stop in the NaI crystal of the scintillation counter. The proportional counter pulse height gives a measure of the rate of energy loss (dE/dx) of the particle, while the scintillation counter pulse gives a measure of the energy (E) of the particle.

The dE/dx and E pulses are amplified, shaped to have flat tops, and fed, respectively, to the vertical and horizontal inputs of an oscilloscope. When both pulses are at their maximum heights, the cathode-ray beam is unblanked and a spot appears on the cathode-ray tube face. Figure 3 shows a time exposure of the cathode-ray tube face during which many particles traversed the counters. Bands are seen corresponding to protons, deuterons, tritons, and α particles. The bands occur because the product of E and dE/dx is approximately proportional to MZ^2, the mass times the charge of the particle, so that on a (dE/dx, E) graph, particles of different MZ^2 fall on different hyperbolas.

The band corresponding to the type of particle to be counted is cut out of one such picture taken at unit magnification, and the remaining picture is used as a mask over the cathode-ray tube. A multiplier phototube views the masked cathode-ray tube and the output of the phototube is used to gate a twenty-channel analyzer which records the pulse heights from the scintillation counter. The gate allows the analyzer to count only the type of particle desired.

Vertical position drift encountered in the Tektronix oscilloscope used in this experiment proved troublesome. This difficulty was overcome by using a model 541 oscilloscope with a modified plug-in preamplifier ac coupled to the main amplifier.

Difficulty was also encountered from overloading of the proportional counter amplifier by large pulses from low-energy α particles which stop in the proportional counter. The overloading tended to broaden the dE/dx distributions, making discrimination between protons, deutrons, and tritons uncertain. This effect was alleviated by inserting extra absorber before the proportional counter to remove the most intense part of the α spectrum.

The energy scales were determined by using resolved peaks from the reactions $d(N^{14},p)N^{15}$, $d(N^{14},\alpha)C^{12}$ and elastically scattered deutrons. Since only one calibration point for deuterons and none for tritons was available, the actual calibration curves were prepared by assuming that the crystal response for deuterons and tritons was

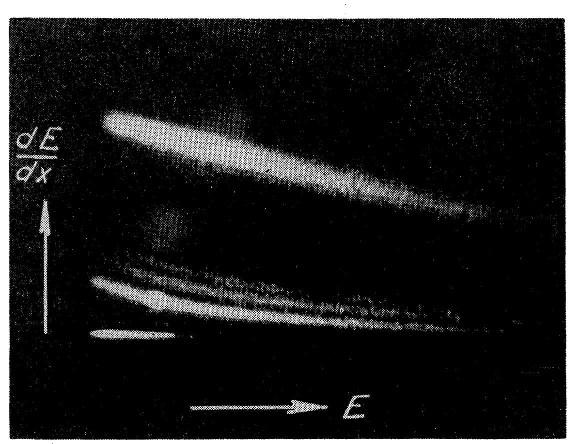

FIG. 3. Time exposure of the display on the cathode-ray tube. The uppermost band is due to alpha particles. The three closely spaced bands are due to tritons, deutrons, and protons, respectively, and the lowest band is due to gamma-ray background.

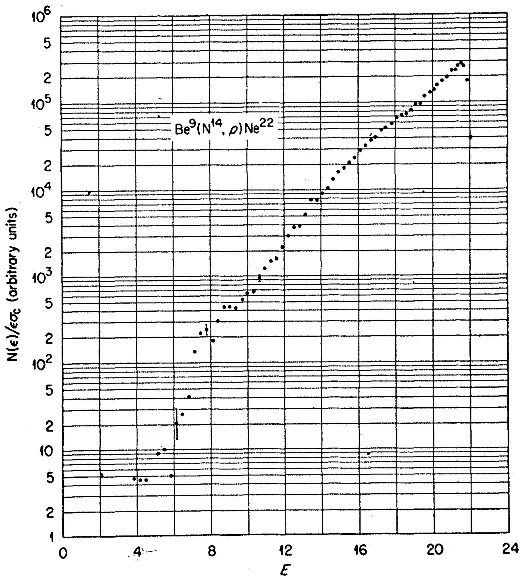

FIG. 4. Proton spectrum from $Be^9(N^{14},p)Ne^{22}$.

the same as for protons, and by using the range-energy relationship $R_d(E)=2R_p(E/2)$ and $R_t(E)=3R_p(E/3)$. The response to protons was found to be linear with respect to energy, but the pulse heights were about 24% larger than would be expected from extrapolation of the γ-ray peaks at 0.662 and 1.12 Mev from Cs^{137} and Zn^{65}. Since this result was unexpected, a comparison of γ to proton pulse heights for this crystal was made with protons from the Oak Ridge National Laboratory 86-inch cyclotron and the same effect was found. The proton response appears to be linear from about 6 to 22 Mev but about 24% larger than the γ response. The ratio of α to proton pulse heights in the NaI crystal was in agreement with the results of Eby and Jentschke.[7]

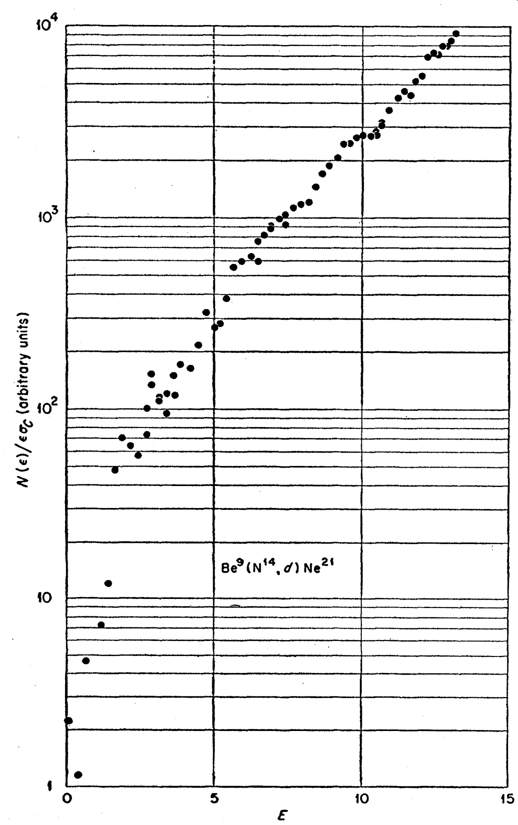

FIG. 5. Deuteron spectrum from $Be^9(N^{14},d)Ne^{21}$.

RESULTS AND DISCUSSION

Energy Spectra

Figures 4, 5, and 6 show the energy spectra of the product particles. The abscissa is the excitation energy of the residual nucleus and the ordinate is the counting rate in arbitrary units divided by $\epsilon\sigma_c$ and corrected for the variation with energy of the solid angle subtended by the counter and for the nonlinear energy scale brought about by the presence of absorber in front of the scintillation counter. In these figures the transformation is made with the assumption that the reactions are $Be^9(N^{14},p)Ne^{22}$, $Be^9(N^{14},d)Ne^{21}$, and $Be^9(N^{14},\alpha)F^{19}$. The mass values used were taken from Wapstra.[8] A table of solid angle transformations was found to be useful.[9] The values of σ_c were taken from Shapiro,[6] with r_0 taken to be 1.5×10^{-13} cm, and V_0 for tritons

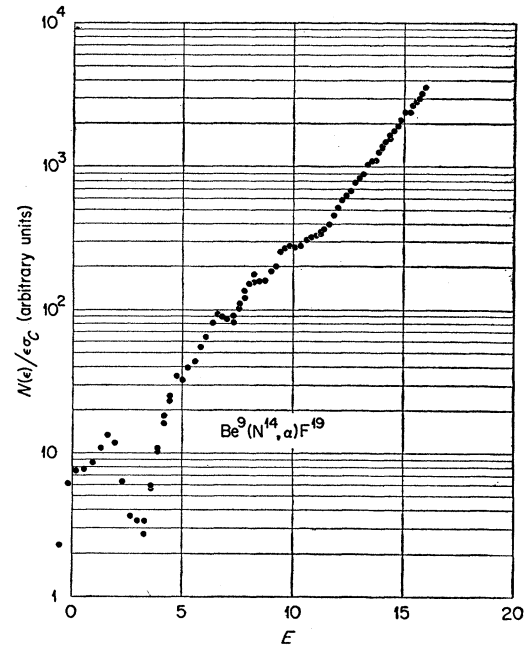

FIG. 6. Alpha-particle spectrum from $Be^9(N^{14},\alpha)F^{19}$.

[7] F. S. Eby and W. K. Jentschke, Phys. Rev. 96, 911 (1954).
[8] A. H. Wapstra, Physica 21, 367 (1955).
[9] J. B. Marion and A. S. Ginsbarg, "Tables for the Transformation of Angular Distribution Data from the Laboratory System to the Center of Mass System," Houston, Shell Development Company (unpublished).

taken to be 6.7 Mev. All data were taken at zero degrees with respect to the beam. Complete triton spectra are not reported because the separation between deuterons and tritons was not clean enough to provide reliable data.

The energy dependence of the density of nuclear energy levels is expected to be approximately of the form[10]

$$\omega(E) = C \exp[2(aE)^{\frac{1}{2}}],$$

where C is a slowly varying function of energy and a is a parameter to be determined. To compare Figs. 4, 5, and 6 with this formula, a family of curves of $2(aE)^{\frac{1}{2}}$ *vs* E was drawn with the same abscissa scale as in the figures, and a linear scale for the ordinate as shown in Fig. 7. These curves were compared to the figures by

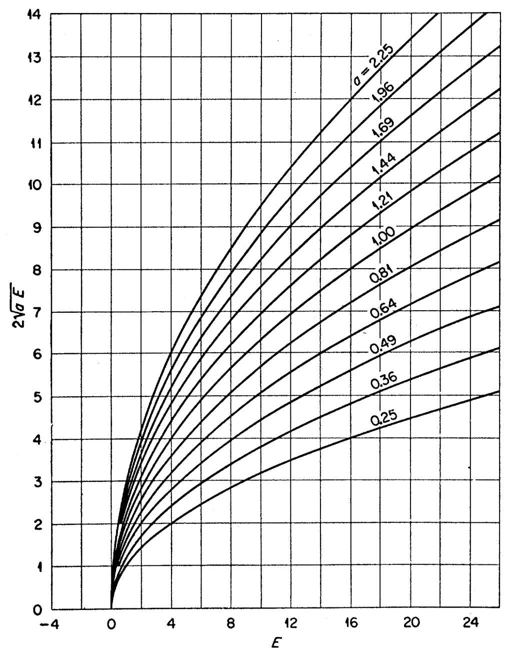

FIG. 7. Curves of $(aE)^{\frac{1}{2}}$ *vs* E for comparison of Figs. 4, 5, and 6 with the predictions of the Fermi gas level-density formula.

superposition. Sliding the ordinate is permissible because the normalization is arbitrary. Sliding the abscissa corresponds to making the reference level in the level-density formula different from the ground state as suggested by Hurwitz and Bethe.[11]

Inasmuch as the experimental data have structure and errors, it is not possible to choose a or the base level precisely. However, some limits on the values can be set. Figures 8–10 show the superposition of curves from Fig. 7 on curves traced from the data.

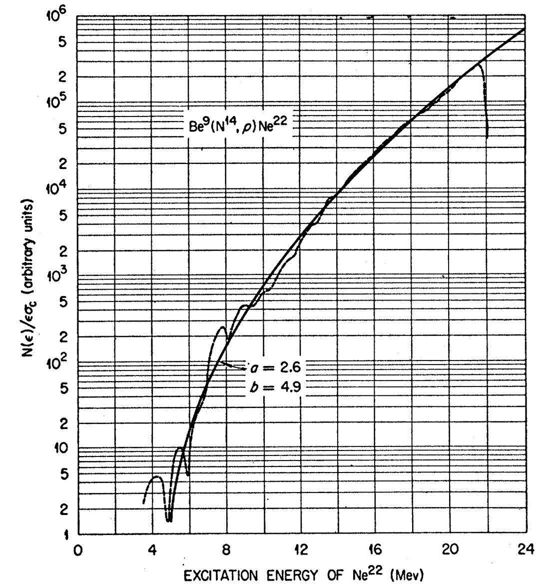

FIG. 8. A fit of the data from the reaction $Be^9(N^{14},p)Ne^{22}$ with the Fermi gas level-density formula. The ordinate scale is in arbitrary units.

The spectrum in Fig. 4 for the reaction $Be^9(N^{14},p)Ne^{22}$ cannot be fitted to the Fermi gas level-density formula if the ground state is chosen as the zero-energy level. One can, however, fit the Fermi gas formula by choosing the base level above the ground state. Figure 8 shows a possible fit with $\omega(E) = C \exp\{2[a(E-b)]^{\frac{1}{2}}\}$, with $a = 2.6$ Mev^{-1}, $b = 4.9$ Mev. Taking b different from zero is in fact reasonable for the nucleus Ne^{22}, since it is even-

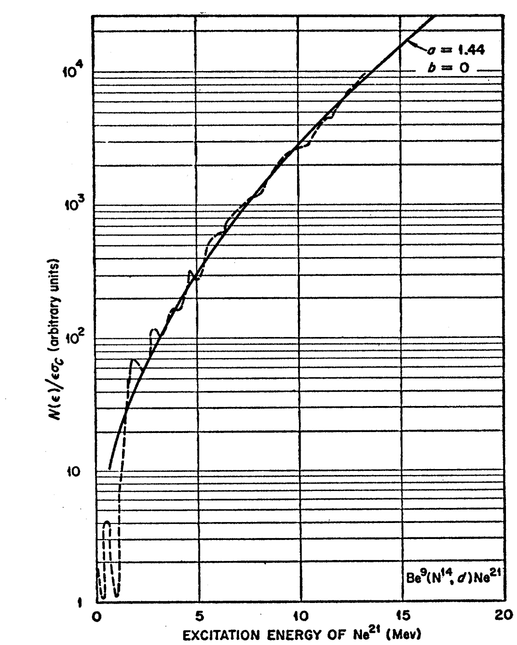

FIG. 9. A fit of the data from the reaction $Be^9(N^{14},d)Ne^{21}$ with the Fermi gas level-density formula. The ordinate scale is in arbitrary units.

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[10] J. M. Blatt and V. F. Weisskopf, reference 5, p. 371; J. M. B. Lang and K. S. Le Couteur, Proc. Phys. Soc. (London) **A67**, 585 (1954).

[11] H. Hurwitz, Jr., and H. A. Bethe, Phys. Rev. **81**, 898 (1951). See also I. G. Weinberg and J. M. Blatt, Am. J. Phys. **21**, 124 (1953).

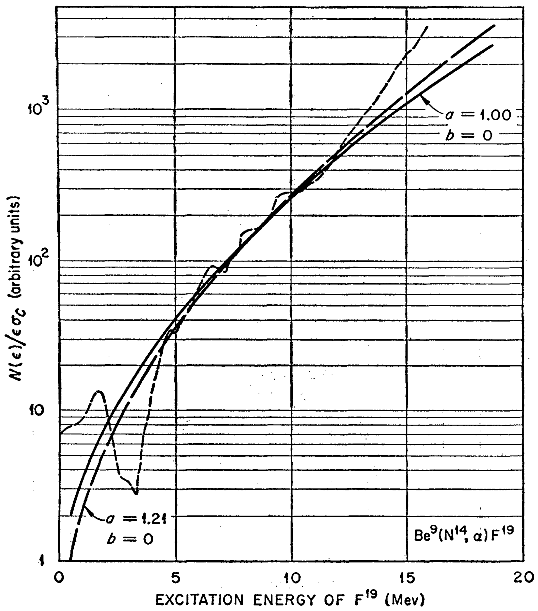

FIG. 10. A fit of the data from the reaction $Be^9(N^{14},\alpha)F^{19}$ with the Fermi gas level-density formula. The ordinate scale is in arbitrary units.

even and the pairing energy would be expected to depress the ground state. The empirical formula suggested by Newton[12] gives b between 3 and 4 Mev.

Table I shows a summary of the values for a and b obtained from the curve fitting of Figs. 8–10. The values should be taken as only approximate. Curves from Fig. 7 adjacent to the ones chosen give obviously poorer fits, so that a is good to approximately ± 0.2 Mev^{-1}. Even in the case of Ne^{22} where a and b were allowed to vary independently the same limits seem to apply to a, and b seems to be determined to about ± 0.5 Mev. The data for the reaction $Be^9(N^{14},t)Ne^{20}$ were obtained from dE/dx spectra as described in the next section.

It is evident that some of the experimental curves show too many low-energy particles to fit the Fermi level-density formula. It may be that all particles counted do not come from the assumed reaction. For example: In the α spectrum some contribution would be expected from α particles emitted after another particle, say a neutron from $Be^9(N^{14},n\alpha)F^{18}$. These α particles would constitute an error as far as this experiment is concerned. The extra particles would be expected to appear at low laboratory energies, and hence would seem to show an excess of energy levels at high excitation.

A calculation was carried out to compare the cross section for the emission of a neutron followed by an α particle to the cross section for the emission of an α particle first, regardless of what happens subsequently. The method used was to perform a double numerical integration over the theoretical energy spectra of the first and second particle. The level-density formula for all nuclei involved was taken to be $\omega(E)=C\exp[2(aE)^{\frac{1}{2}}]$, with $a=1$ Mev^{-1} and $a=2$ Mev^{-1} tried. The results were

$$\sigma(n\alpha)/\sigma(\alpha)=0.143 \quad \text{for } a=1,$$
$$\sigma(n\alpha)/\sigma(\alpha)=0.0037 \text{ for } a=2.$$

This indicates that if $a=1$, one should expect a 14% excess of α particles through the contribution of the $Be^9(N^{14},n\alpha)F^{18}$. The calculation is integrated over all energies and it is not clear how the shape of the energy distribution would be altered. It is expected, however, that the excess particles would appear at low laboratory energy (high excitation).

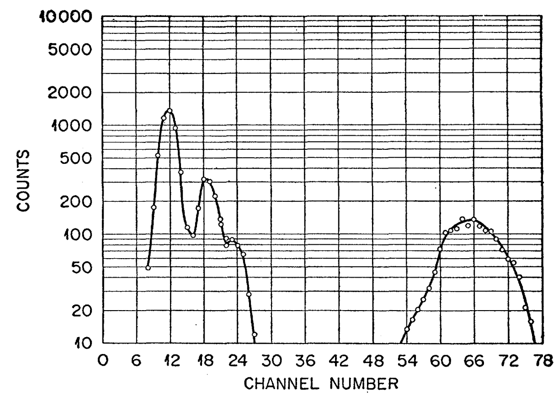

FIG. 11. A pulse height spectrum from the proportional counter.

The positions of the resolved peaks correspond approximately to levels listed in Ajzenberg and Lauritsen.[13] However, the uncertainty in the energy scale prevents a detailed comparison in this region. Since the low-lying levels correspond to high laboratory energies, a small drift in the gain of the counter causes a large shift in the apparent position of the level. The experimental uncertainty in the location of the ground-state group is about ± 0.5 Mev due to these drifts. No proton groups corresponding to the ground, first excited, or second excited states of Ne^{22} were observed. No explanation for this is offered.

Some error due to counting particles presumed to be masked out is present in the results, and the scatter of experimental points from different runs is probably due mostly to this effect.

TABLE I. Values of a and b obtained by fitting the spectra with the level-density formula $\omega(E)=C\exp\{2[a(E-b)]^{\frac{1}{2}}\}$.

Nucleons	a (Mev^{-1})	b (Mev)
F^{19}	1.1	0
Ne^{20}	2.6[a]	4.9[a]
Ne^{21}	1.4	0
Ne^{22}	2.6	4.9

[a] Not well determined; see text for note on errors.

[12] T. D. Newton, Can. J. Phys. **34**, 804 (1956).

[13] F. Ajzenberg, and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

Relative Numbers of p, d, t, and Alpha Particles

In the decay of the compound nucleus, from the assumption that all individual quantum states of the final system which conserve energy and angular momentum are equally probable, it follows that the probability of observing a particular mode of decay is proportional to the number of final states corresponding to the observed mode. Using this assumption, and including the barrier penetration probability of the product particle, one finds that

$$\log_e[N(\epsilon)/\epsilon\sigma_c m]-2[a(E-b)]^{\frac{1}{2}}-\log_e C=\text{constant},$$

where the constant is the same for all modes of decay of the same compoumd nucleus and m is the reduced mass of the final system. The barrier penetration prob-

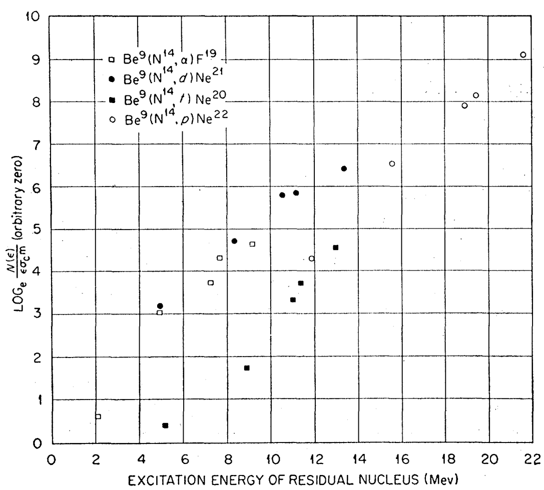

FIG. 12. $\text{Log}_e[N(\epsilon)/\epsilon\sigma_c m]$ *vs* E for the reactions $Be^9(N^{14},p)Ne^{22}$, $Be^9(N^{14},d)Ne^{21}$, $Be^9(N^{14},t)Ne^{20}$, and $Be^9(N^{14},\alpha)F^{19}$. The data are taken from proportional counter spectra like the one shown in Fig. 11.

ability is contained in σ_c. The level-density formula is assumed to be $\omega(E)=C\exp\{2[a(E-b)]^{\frac{1}{2}}\}$.

A set of numbers for comparing the different modes of decay was obtained by replacing the usual mask on the cathode-ray tube with a vertical slit and feeding the dE/dx pulses to the 20-channel analyzer, thus obtaining a dE/dx spectrum corresponding to a particular channel number for E. Such a spectrum is shown in Fig. 11.

Figure 12 shows the data obtained from these spectra as a plot of $\log_e[N(\epsilon)/\epsilon\sigma_c m]$ *vs* E. The points belonging to even-even residuals seem to fall more or less on one curve, while the other points tend to fall on another curve. In Fig. 13, $\log_e[N(\epsilon)/\epsilon\sigma_c m]-2[a(E-b)]^{\frac{1}{2}}$ is plotted against E. The ordinate here is simply the logarithm of the ratio of the experimentally determined density of states function to the expected function. For the proton, deuteron, and alpha reactions, a and b were chosen to fit the spectra as shown in Figs. 8, 9, and 10.

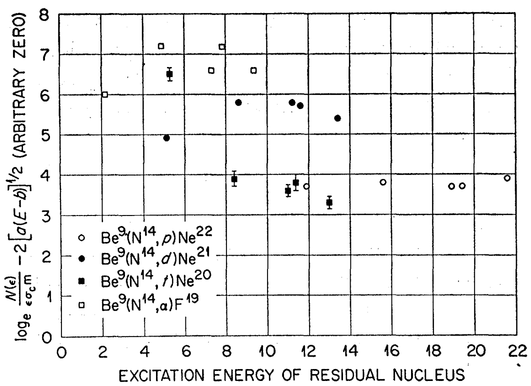

FIG. 13. $\text{Log}_e[N(\epsilon)/\epsilon\sigma_c m]-2[a(E-b)]^{\frac{1}{2}}$ *vs* E for the reactions $Be^9(N^{14},p)Ne^{22}$, $Be^9(N^{14},d)Ne^{21}$, $Be^9(N^{14},t)Ne^{20}$, and $Be^9(N^{14},\alpha)F^{19}$. The values of a and b are taken from the curve fitting shown in Figs. 8, 9, and 10; and a and b for Ne^{20} were taken to be the same as for Ne^{22} because of the similarity of triton and proton points in Fig. 12.

For the tritons a and b were chosen to be the same as for the protons because of the similarity between the triton and proton points in Fig. 12.

The high triton point at about 5.3 Mev probably indicates that the pulse height channel for the gate pulse happened to be on an energy level, which appears without averaging as a very large number of counts near the base level, where the density of states should be very low. Fluctuations in the other data at low excitations can be similarly explained.

No account has been taken in the figures of the $2s+1$ multiplicity of states due to the spins of the product particles. Figure 13, as it stands, suggests that an even-odd effect comes into the factor C in the level-density formula. The multiplicity factor, however, would bring the deuteron points closer to the proton and triton points and move the alpha points away from both. In any case, this experiment alone does not distinguish between the possibility that the statistical theory underestimates the alpha-particle emission probability by about an order of magnitude and the possibility that the level densities in the nuclei differ by about an order of magnitude through something like an even-odd effect.

A ratio as large as 10 of odd-even to even-even level densities does not contradict other experimental evidence,[14,15] but the situation is certainly not clear. It is interesting to note that Byerly and Stephens[16] found in the photodisintegration of copper a deuteron-to-proton ratio of about 10^3 times larger than the prediction of the statistical model, while the alpha-to-proton ratio is of the right order of magnitude, and energy distributions of all the particles are in rough agreement with the statistical model. The (γ,p) residuals for both copper isotopes are even-even with a magic number

[14] G. Brown and H. Muirhead, Phil. Mag. Ser. 8, 2, 473 (1957).
[15] Reference 5, p. 373.
[16] P. R. Byerly, Jr., and W. E. Stephens, Phys. Rev. **83**, 54 (1951).

of protons, and perhaps the parameters in the level-density formula need to be specially adjusted for this situation. It would seem that much more experimental evidence needs to be obtained to discover systematics which may exist.

CONCLUSION

The results of the present experiment suggest that the statistical theory of nuclear reactions describes adequately, at least, the shapes of the energy spectra of light particles from nitrogen-induced reactions at zero degrees. Angular distributions and experiments on heavier targets have yet to be explored. Heavy-ion reactions might provide a useful means of measuring statistical aspects of nuclear structure.

ACKNOWLEDGMENTS

The authors gratefully acknowledge their indebtedness to John G. Harris for constructing the proportional counters and mechanical apparatus, to Gertrude Foster for carrying out the cross-section calculations and for constructing graphs used in the analysis of the data, to A. Zucker for help and encouragement, and to R. S. Livingston for interest in and support of the experiment.

PHYSICAL REVIEW VOLUME 110, NUMBER 3 MAY 1, 1958

Elastic and Inelastic Scattering of 18-Mev Alpha Particles from Neon, Argon, and Xenon*

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The scattering of 18-Mev alpha particles from neon, argon, and xenon was studied with a multiplate reaction chamber. The scattered particles were defined within an rms angular width of 0.45° by a system of slit pairs, spaced every $2\frac{1}{2}°$ from 10° to 170°. The elastic scattering from neon and argon show the pronounced maxima and minima characteristic of diffraction scattering but are equidistant in ϕ, not $\sin(\phi/2)$. The ratio to Rutherford scattering varies as much as 25-fold between successive maxima and minima in the case of neon, the well-defined structure indicating a small mean free path for absorption of alpha particles in the nucleus. Nuclear interaction radii calculated by the formula $2kR\Delta[\sin(\phi/2)]=\pi$ were found to be 6.36×10^{-13} cm for neon and 6.95×10^{-13} cm for argon. Xenon, investigated chiefly for control purposes, showed no definite deviation from Rutherford scattering up to 50°. Groups corresponding to the excitation of the 1.63-, 4.25-, 4.97-, 5.81(5.63)-, and 7.2-Mev levels of Ne^{20} and the 1.46-Mev level of A^{40} were observed. No excited states were observed in xenon. Notably absent was excitation of the 6.74-Mev (0^+) level in Ne^{20}. As predicted by direct-interaction theories, the cross sections for inelastic scattering leading to the first excited (2^+) states of neon and argon could be approximated by the squares of spherical Bessel functions of the second order with interaction radii of 6.71×10^{-13} cm for neon and 6.60×10^{-13} cm for argon. These cross sections do not tend toward small values in the forward direction, which is interpreted as evidence for distortion of the incident and scattered waves. No fit was possible for any of the other excited states.

INTRODUCTION

THERE has been renewed interest in the scattering of alpha particles from nuclei following the establishment by Farwell and Wegner[1] of a pronounced variation with energy of the scattering cross section for heavy nuclei. They found that the ratio of the observed differential scattering cross section to the Rutherford cross section, $\sigma(E)/\sigma_R(E)$, was unity only for energies below certain values and decreased exponentially with higher energies. Further experiments on alpha-particle scattering from heavy nuclei were performed by Wall, Rees, and Ford,[2] Wegner, Eisberg, and Igo,[3] Ellis and Schecter,[4] and Gove,[5] all of whom measured the angular dependence of the cross sections. When the cross sections are plotted as functions of the apsidal distance of the classical path in a pure Coulomb field, the results are similar to those found by Farwell and Wegner: agreeing with the Rutherford cross section for the large apsidal distances, followed by an exponential fall-off toward the smaller.

Since these results were in striking contrast to the diffraction-like angular distributions found in the scattering of protons from various nuclei,[6] Bleuler and Tendam[7] and Eisberg, Igo, and Wegner[8] investigated the scattering of alpha particles from light nuclei. They found the expected diffraction patterns at bombarding energies of 19 Mev with aluminum and copper and of 40 Mev with aluminum, respectively. Subsequent to the start of the investigation reported here, more extensive measurements on light nuclei were published by Igo, Wegner, and Eisberg[9] at 40 Mev, by Gugelot

* Work supported in part by the U. S. Atomic Energy Commission. This article is based on a doctoral thesis submitted by L. Seidlitz to the Faculty of Purdue University. A short report was given in Bull. Am. Phys. Soc. Ser. II, 1, 29 (1956).
† Now at Palmer Physical Laboratory, Princeton University, Princeton, New Jersey.
[1] G. W. Farwell and H. E. Wegner, Phys. Rev. **95**, 1212 (1954).
[2] Wall, Rees, and Ford, Phys. Rev. **97**, 726 (1955).
[3] Wegner, Eisberg, and Igo, Phys. Rev. **99**, 825 (1955).
[4] R. E. Ellis and L. Schecter, Phys. Rev. **101**, 636 (1956).
[5] H. E. Gove, Phys. Rev. **99**, 1353 (1955).
[6] B. L. Cohen and R. V. Neidigh, Phys. Rev. **93**, 282 (1954).
[7] E. Bleuler and D. J. Tendam, Phys. Rev. **99**, 1605 (1955).
[8] Eisberg, Igo, and Wegner, Phys. Rev. **99**, 1606 (1955).
[9] Igo, Wegner, and Eisberg, Phys. Rev. **101**, 1508 (1956).

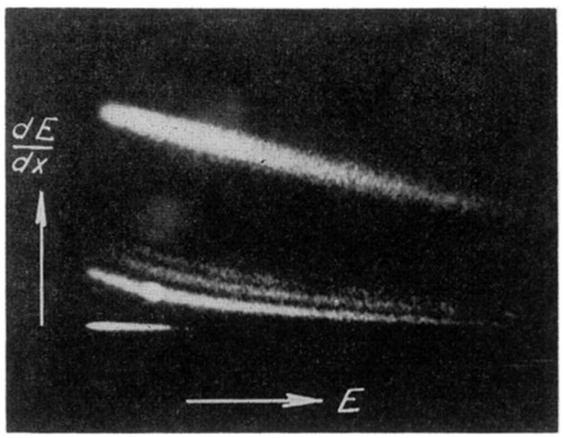

FIG. 3. Time exposure of the display on the cathode-ray tube. The uppermost band is due to alpha particles. The three closely spaced bands are due to tritons, deutrons, and protons, respectively, and the lowest band is due to gamma-ray background.