Reaction Cross Sections for ^{16}O with Fe, Ni, Ge, and Zr†

A. W. Obst, * D. L. McShan, M. B. Greenfield, R. Holub, and R. H. Davis
Department of Physics, The Florida State University, Tallahassee, Florida 32306
(Received 26 April 1973)

Relative excitation functions for the total neutron production and total charged-particle (proton, α) production above 2 MeV from ^{16}O bombardment of natural targets of Fe, Ni, Ge, and Zr have been measured at $\theta_{lab}=90°$ and in the bombarding energy range from 30 to 60 MeV. For the most part, the onset of reaction product yields agrees well with the barrier heights as determined from ^{16}O elastic scattering. Absolute measurements for light charged-particle production were also made on Fe and Ni at $\theta_{lab}=60°$ and in the bombarding energy range from 37 to 60 MeV. Combined with an average number of emitted charged particles calculated from Weisskopf-Ewing evaporation theory and with the effects of angular momentum included, the results when compared to optical-model reaction cross sections suggest a moment of inertia of one half the rigid-body value.

I. INTRODUCTION

The prediction of barrier heights has been of considerable interest for some time in the study of heavy-ion collisions.[1-4] Measurements of ^{16}O elastic scattering on medium-mass nuclei[5] yield barrier heights that are 10–20% lower than the ordinary Coulomb barrier, defined here as $Z_1Z_2e^2/[1.35(A_1^{1/3}+A_2^{1/3})]$. Although straightforward, these estimates nevertheless depend on the optical-model parameters which describe the elastic scattering.

A directly comparable means of determining a barrier is to measure the onset of nuclear reactions. In any heavy-ion reaction, the most probable reaction products are neutrons, protons, and α particles. These were measured in the present study for ^{16}O projectiles incident on natural targets of Fe, Ni, Ge, and Zr over an energy region centered on the barrier. The barrier has been previously determined to be relatively insensitive to the isotope of a given element.[5] Absolute measurements of the charged particles are analyzed with evaporation theory. By using the total reaction cross sections from the optical-model analysis, moments of inertia are found (Sec. IV) which are one half the rigid-body value.

II. EXPERIMENTAL METHOD

The Florida State University super FN tandem Van de Graaff accelerator was used to produce a beam of 30–60-MeV ^{16}O ions of charge states five or six. Initially, relative excitation functions were measured using targets of natural Fe, Ni, Ge, and Zr evaporated onto 0.127-mm-thick gold disks and covered with a flash of gold. The neutron detector at 90° to one side of the incident beam consisted of a shielded long counter, containing a BF_3-filled proportional counter (45-cm-Hg BF_3, enriched to 90% in ^{10}B) while the charged-particle detector located at 90° on the other side of the incident beam consisted of a 2000-μm Si surface-barrier counter with a 0.025-mm gold foil in front to stop the elastically scattered ^{16}O ions. The above simple procedure is preferred in this case over the more conventional method of detecting the residual γ-ray activity corresponding to the formation of particular daughter products, since the purpose of the present experiment was to observe the onset of all reaction yields as a function of bombarding energy.

At each bombarding energy a background from a gold blank was measured and since both target and gold surfaces were the same (gold), any buildup of lighter contaminants might therefore be monitored. All of the yield above approximately 2 MeV was integrated, as indicated in the sample spectrum in Fig. 1. The energy spectrum here is somewhat distorted from a Maxwellian shape by

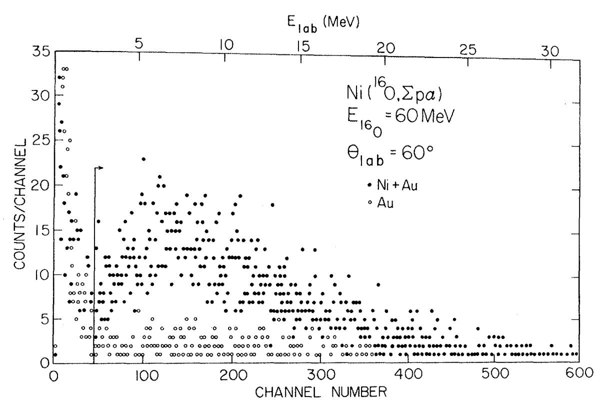

FIG. 1. Measured p-plus-α spectrum, indicating target and background yields.

the presence of the gold foil. The low-energy tail, visible in both neutron and charged-particle spectra, was excluded as this was attributed to noise. Further, it is present in both the target and blank spectra.

Since the efficiency of the neutron counter was not known, no attempt was made to obtain absolute neutron yields. In a separate experiment absolute charged-particle yields were measured by observing elastically scattered ^{16}O ions at 30° (Rutherford scattering) simultaneously with the p-plus-α yield at 60°. The targets for this experiment consisted of natural Fe, Ni, Ge, and Zr sandwiched by evaporation between thin evaporated layers of gold. The total thickness to the ^{16}O beam was estimated to be approximately 100 keV.

As before, a blank gold spectrum was measured at each energy. The relative uncertainties in the measurements range from ±2 to ±15% and are due to counting statistics and the reproducibility of the data. The uncertainty in the normalization of the absolute p-plus-α measurements is believed to be about ±20%. These uncertainties do not account for fluctuations in some of the data which are believed to be due to different amounts of lighter impurities on the targets and blanks as well as target nonuniformities in the relative measurements.

III. RESULTS

Relative excitation function measurements of the total neutron and total charged-particle production from ^{16}O bombardment of natural targets of Fe, Ni, Ge, and Zr are shown in Figs. 2–5. Laboratory yields and angles rather than center-of-mass data are shown for consistency and empirical emphasis.

In all cases except the p-plus-α yields from Zr a well-defined threshold can be seen and of these, all but the p-plus-α yield from Fe are in good agreement with estimates obtained from elastic scattering,[5] as shown by the arrows. Light impurities from buildup may be contaminating the p-plus-α yield curves for Zr and Fe. This plus

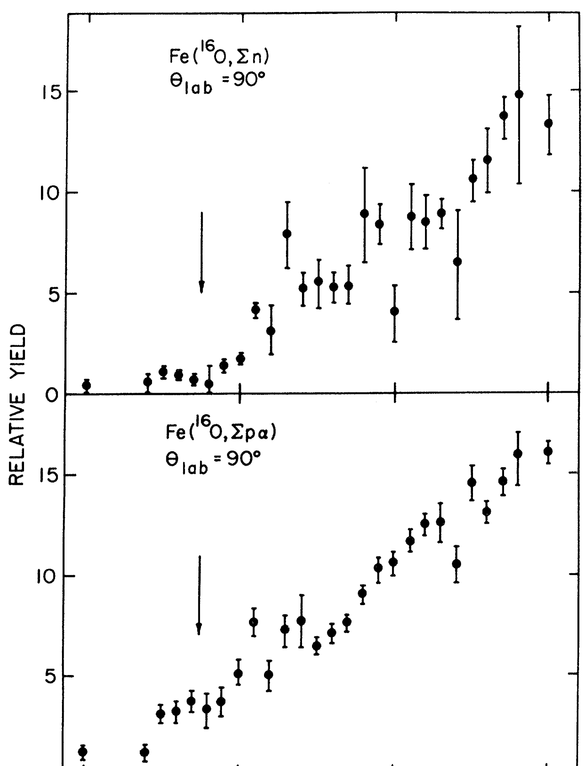

FIG. 2. Relative measurements of the total neutron and total p-plus-α yields from ^{16}O + Fe at 90° in the laboratory system. The arrows indicate the barrier height determined from elastic scattering (Ref. 5).

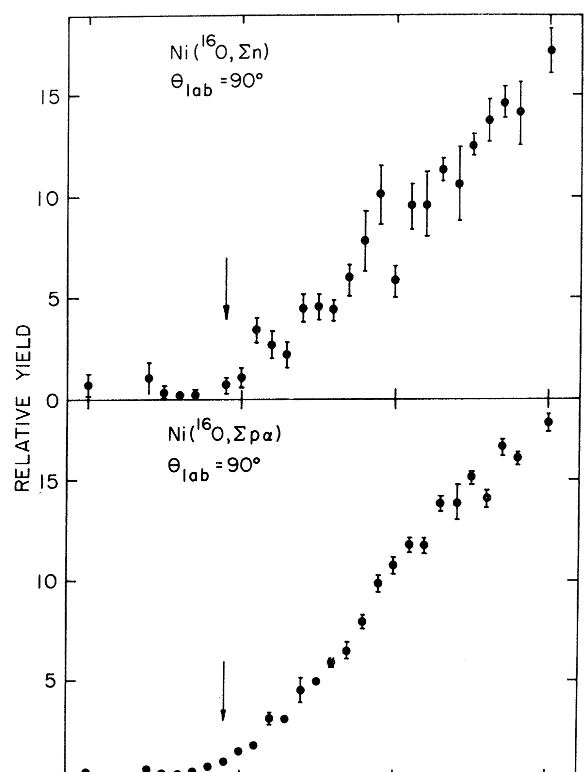

FIG. 3. Relative measurements of the total neutron and total p-plus-α yields from ^{16}O + Ni at 90° in the laboratory system. The arrows indicate the barrier height determined from elastic scattering (Ref. 5).

target nonuniformity is responsible for the fluctuation in the data, since the total neutron yield from ^{60}Ni has been measured to be smoothly varying with energy in two separate experiments.[6,7]

The present data shown in Fig. 6 consists of absolute p-plus-α yields for ^{16}O + Fe and ^{16}O + Ni at 60°, converted to the center of mass, divided by the number of particles emitted per compound nucleus formed, and then angle integrated. These plus an anisotropy correction are further discussed in Sec. IV. These data are seen to be consistent in shape with the relative data at 90°. Absolute p-plus-α yields for ^{16}O + Ge and ^{16}O + Zr are not shown since they were not thought to be reliable due to light-element contamination.

IV. DISCUSSION

The Jacobian for the center-of-mass transformation was calculated assuming the emission of the most prominent particle cluster as found from the evaporation cascade code discussed below. Since more particles are emitted per compound reaction with increasing bombarding energy, the downward correction of the compound-nucleus formation section also increases.

The number of charged particles emitted per compound nucleus formed was calculated using the evaporation cascade code written by Blann.[8] The code calculates the daughter populations following neutron-, proton-, and α-particle emission from Weisskopf-Ewing theory.[9] A standard optical-model program was used to calculate the formation[5,10] and inverse reaction[11] cross sections. Experimental binding energies[12] with pairing corrections[13] were used where known, and theoretical values were used otherwise.[12]

Competition from γ-ray decay is simulated by subtracting from the excitation energy of the compound nucleus an amount of energy taken up in rotation, i.e., the yrast energy. In effect particle decay, with dissipation of little angular momentum, is assumed to take place above the yrast energy. Near the yrast energy, the compound nucleus can decay only by γ emission which dissipates most of the angular momentum.[14] For a given spin, a

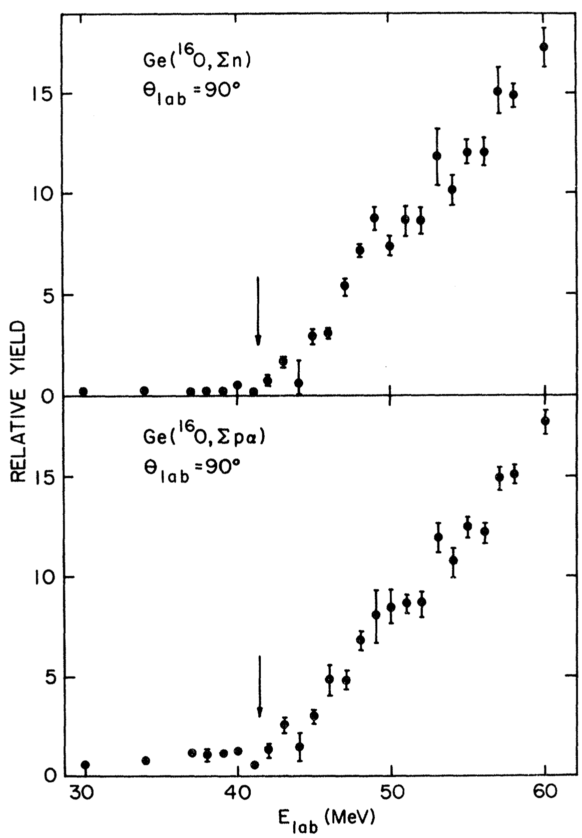

FIG. 4. Relative measurements of the total neutron and total p-plus-α yields from ^{16}O + Ge at 90° in the laboratoty system. The arrows indicate the barrier height determined from elastic scattering (Ref. 5).

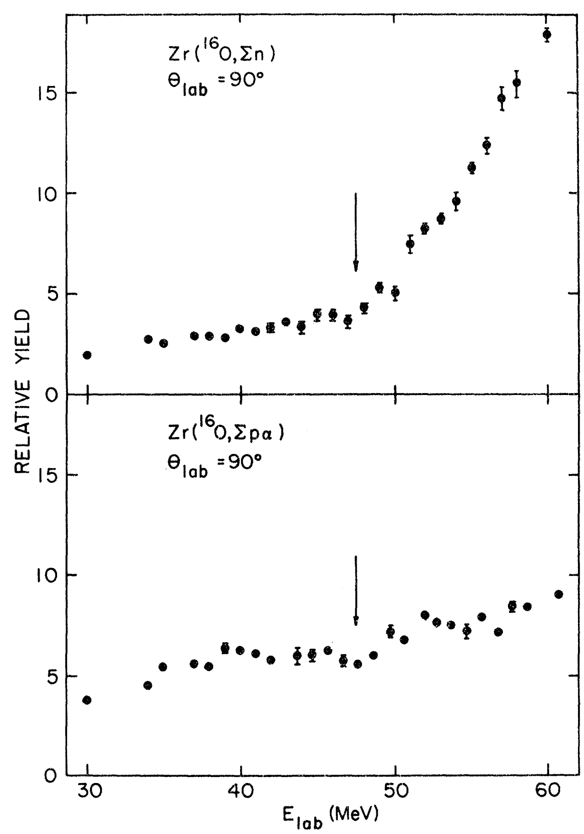

FIG. 5. Relative measurements of the total neutron and total p-plus-α yields from ^{16}O + Zr at 90° in the laboratory system. The arrows indicate the barrier height determined from elastic scattering (Ref. 5).

larger rotational energy corresponds to a smaller moment of inertia and the emission of fewer particles per compound-nucleus reaction.

The behavior of the p-plus-α particle emission number as a function of the moment of inertia, I, in terms of that for a rigid rotating sphere, is shown for $^{16}O + ^{58}Ni$ at 60 MeV in Fig. 7 and is typical of the isotopes of Fe and Ni. The emission number using a rotating liquid-drop moment of inertia with centrifugal stretching[15] is only slightly larger than that for a rigid rotating sphere. Below $I = 0.5 I_{rigid}$ the emission number stops decreasing since the neutron binding energies are somewhat larger than charged-particle binding energies, so that neutron emission becomes suppressed first, forcing flux back into charged-particle channels. As the moment of inertia is further decreased, approaching irrotational flow[16] for which $I/I_{rigid} \simeq \beta^2$, all particle channels close. The deformation parameter β here[12] is about 0.1.

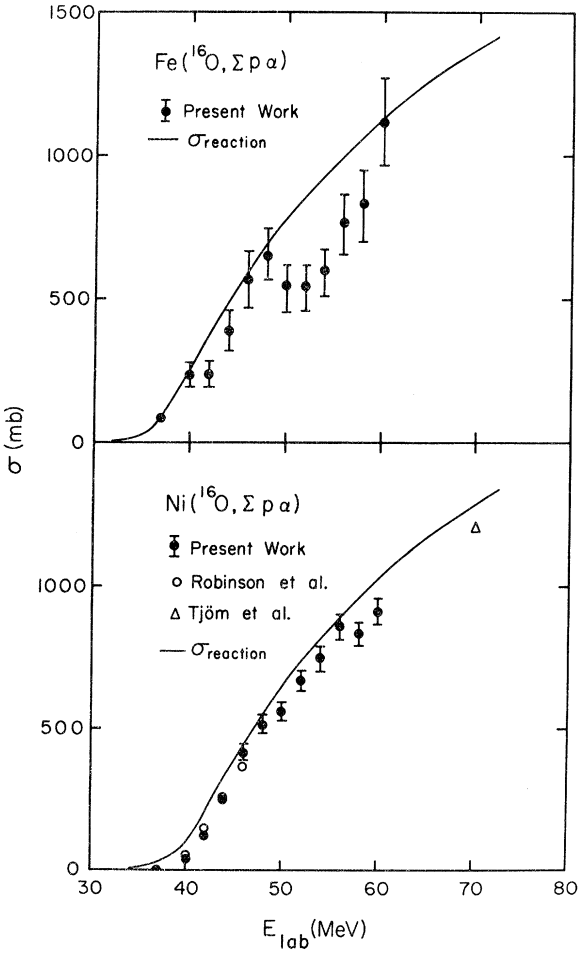

FIG. 6. Measured absolute cross sections for p-plus-α emission from $^{16}O + Fe$ (top) and $^{16}O + Ni$ (bottom) as a function of bombarding energy. A comparison with other data and with optical-model reaction cross sections is also shown.

The ratio of the Jacobian to the charged-particle emission number was averaged for each target by the isotopic abundance. Since the calculations indicate that one or more charged particles are emitted in over 99% of all compound events (the compound system is proton rich), the solid curves in Fig. 6 correspond to the total reaction cross section calculated from known ^{16}O elastic scattering parameters.[5,10] In order to compare the data with this angle-integrated reaction cross section, it is necessary to determine the anisotropy at 60°. Tjöm, Espe, and Skaali[17] have measured the total proton and total α-particle angular distributions for $^{16}O + ^{58}Ni$ at 70 MeV (natural abundance of ^{58}Ni is 68%) using a counter telescope. For their case, the 60° cross sections are reduced from $\int \sigma d\Omega / 4\pi$ by approximately 10%. Therefore, the data from the present work shown in Fig. 6 correspond to $(4\pi)\,[1.1\sigma\,(60°)]$. From the results of Becchetti *et al.*[18,19] the angle-integrated direct reaction cross section, most of which is inelastic, is less than 70 mb for 60-MeV $^{16}O + ^{58}Ni$. These channels, accounting for less than 7% of the reaction cross section, consist mainly of heavy-ion emission and therefore are not observed in the present work, due to the stopping foil. Compound elastic scattering here is believed to be negligible.[5] Also, the present energy range is below the threshold for fissionlike processes,[12,15] as determined in a separate experiment.[20]

In order to get agreement with predicted reaction cross sections in the present work, it was necessary to choose the smallest possible value of the

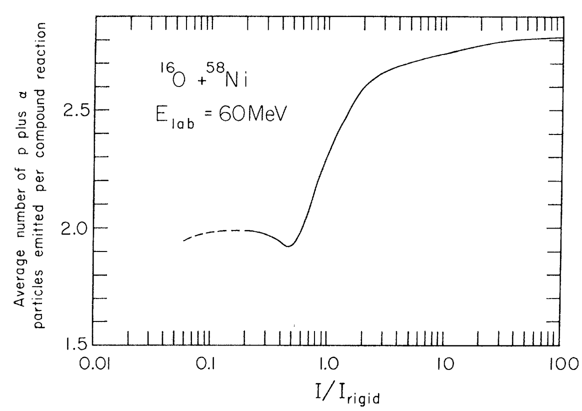

FIG. 7. Number of p-plus-α particles emitted per compound reaction for 60-MeV $^{16}O + ^{58}Ni$ as a function of I/I_{rigid}, where I is the moment of inertia of the compound system and I_{rigid} is the moment of inertia of a rigid rotating sphere.

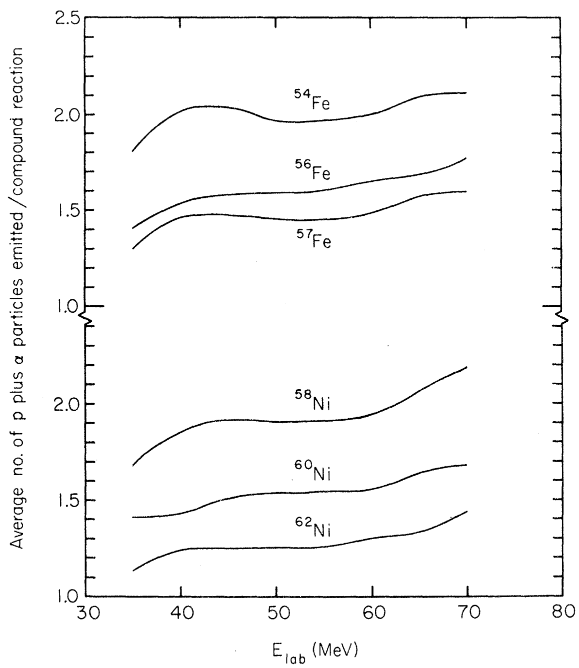

FIG. 8. Number of p-plus-α particles emitted per compound reaction for ^{16}O on the major Fe and Ni isotopes as a function of bombarding energy, using $I/I_{rigid} = 0.5$.

charged-particle emission number. This occurs at $I = 0.5I_{rigid}$. Below this value, the emission numbers become physically meaningless, as discussed above. Above this value, the measured cross sections fall below the reaction cross-section curves. The p-plus-α emission numbers per compound reaction for ^{16}O plus ^{54}Fe, ^{56}Fe, ^{57}Fe, ^{58}Ni, ^{60}Ni, and ^{62}Ni are shown in Fig. 8 as a function of bombarding energy, with $I = 0.5I_{rigid}$. Lack of complete agreement (Fig. 6) with the predicted reaction cross sections is probably due to omission of direct processes, as discussed above.

The reaction cross sections obtained in the present work are seen in Fig. 6 to be in good agreement with other available Ni data. In particular, Tjöm, Espe, and Skaali[17] obtain for the total proton and total α-particle cross sections at 70 MeV 2172 and 500 mb, respectively. From the evaporation cascade code, an average of 2.2 charged particles (see Fig. 8) are emitted at this energy. This leads to a reaction cross section of (2172 + 500)/2.2 or 1214 mb.

TABLE I. Comparison of Robinson's ^{16}O + Ni data at 46 MeV with Blann's cascade code. The first and second rows correspond to the emission of one or more neutrons and charged particles, respectively.

	^{58}Ni		^{60}Ni		^{61}Ni	
	Exp.	Th.	Exp.	Th.	Exp.	Th.
$\sigma(n)$ (mb)	110	19	220	241	269	365
$\sigma(p\alpha)$ (mb)	340	412	410	410	437	390

Robinson, Kim, and Ford[7] have measured the reaction products for $^{16}O + ^{58}Ni$ and $^{16}O + ^{60}Ni$ using γ-ray spectroscopy at $E_{^{16}O} = 38$ to 46 MeV. They obtain for the angle-integrated p-plus-α yields 52, 139, 248, and 388 mb at 40, 42, 44, and 46 MeV, respectively, when averaged isotopically. The agreement of the predicted neutron and charged-particle cross sections with Robinson's data[7,21] using $I = 0.5I_{rigid}$ is seen in Table I to be better for ^{60}Ni and ^{61}Ni than for ^{58}Ni. It is interesting that although a lower value of the moment of inertia cannot be conclusively discounted, Robinson's experimental value[22] for the emission number for 46-MeV $^{16}O + ^{58}Ni$ is 1.9, in agreement with the presently derived value only if $I = 0.5I_{rigid}$ (see Fig. 8).

In conclusion, the yrast energy may be fixed and γ-ray competition separately enhanced[23] in order to get a reduced number of emitted particles at a given bombarding energy, or, equivalently, the yrast energy, and hence the moment of inertia, are adjusted in order to get agreement with the data. The latter procedure, involving only one free parameter, yields a moment of inertia of one half the rigid-body value, in agreement with bound-state moments of inertia over a large range of masses.[24]

ACKNOWLEDGMENTS

The authors are indebted to M. Blann and F. Plasil for supplying their versions of the evaporation code and for many helpful discussions.

†Research supported in part by the National Science Foundation Grants Nos. NSF-GU-2612 and NSF-GP-25974.
*Present address: Department of Physics, University of Texas, Austin, Texas.
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