predicted by any of the current theoretical calculations and since $N = 154$ is the highest neutron number that is currently accessible to experimental study, extrapolations of barrier parameters to obtain neutron-induced fission cross section estimates are probably very uncertain beyond $N = 154$. This effect could be particularly important for estimates of superheavy-element production cross sections.

This work was supported by the U. S. Energy Research and Development Administration.

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Breakup of α Particles in the Fields of Nuclei

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(Received 3 February 1978)

The spectra of protons, deuterons, tritons, and ^{3}He observed from the bombardment of 140-MeV α particles on a number of nuclei exhibit broad peaks. The behavior of these peaks suggests that they result from the breakup of the incident α particle. The breakup yield accounts for about 10% of the total reaction cross section. It appears that this process can be described in terms of a simple projectile-breakup model, similar to that originally proposed by Serber for deuteron breakup.

It has been known for some time that loosely bound projectiles such as the deuteron and ^{6}Li breakup in the field of a nucleus.[1-3] At an incident energy of 70 MeV, the proton yield resulting from deuteron breakup on ^{208}Pb accounts for approximately 30% of the total reaction cross section.[4] The deuteron breakup process was discussed in an early paper by Serber.[1] For an incident energy per nucleon much larger than the projectile separating energies, one would expect the breakup of more tightly bound particles to become important. In this Letter, we present evidence that the breakup cross sections for α particles in the field of the nucleus are relatively large at incident energies in the region of 140 MeV.

Complete charged-particle energy spectra have been recently measured over a wide angular range for 140-MeV α particles on various target nuclei.[5] Figure 1 shows the proton, deuteron, triton, and ^{3}He spectra at several laboratory angles for 140-MeV α particles on ^{209}Bi. Very broad, pronounced peaks are observed in all spectra. The locations of these peaks are approximately equal to $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, and $\frac{3}{4}$, respectively, of the incident α-particle energy. These peaks are at least 30 MeV wide. Similarly, the broad peaks which dominate the ^{3}He yields at forward angles for 140-MeV α particles on ^{58}Ni, ^{90}Zr, ^{120}Sn, and ^{232}Th are interpreted as due to the breakup of α

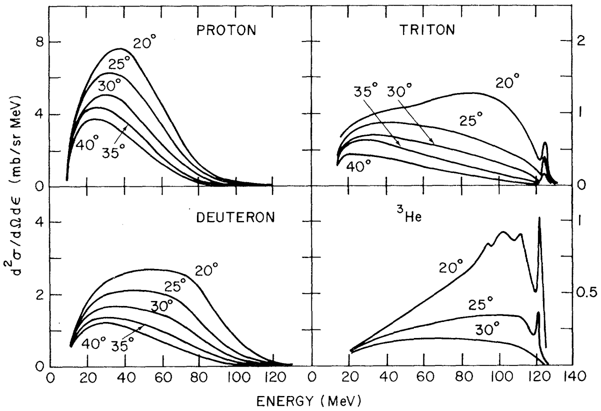

FIG. 1. The proton, deuteron, triton, and ^{3}He spectra at several laboratory angles for 140-MeV α particles on ^{209}Bi.

particles in the field of the nucleus.

We have carried out a calculation for α-particle breakup analogous to the Serber model for deuteron breakup.[1] We will consider only the ^{3}He channel. Similar treatments can be extended to the other breakup channels. For simplicity, we have also made the assumption that the nucleus is is transparent to the ^{3}He particles and have treated the ^{3}He particles as spectators in the breakup process. (In the case of deuteron breakup, it does not make much difference whether the nucleus is assumed to be transparent or opaque.[1])

The probability, $P(\vec{p})$, that the ^{3}He particle has a momentum $\vec{p}$ in an α particle is given by

$$P(\vec{p}) = |\psi(\vec{p})|^2, \tag{1}$$

where

$$\psi(\vec{p}) = \frac{1}{h^{3/2}} \int \psi_\alpha(r) \exp\left[\frac{i}{\hbar}\vec{p}\cdot\vec{r}\right] d^3r$$

is the Fourier transform of the relative wave function of the ^{3}He and neutron in an α particle. A wave function of the Eckart form is used[6]

$$\psi_\alpha(r) = C\left(\frac{\alpha}{2\pi}\right)^{1/2} \frac{e^{-\alpha r}}{r}(1-e^{-\beta r})^4, \tag{2}$$

where $\alpha = (2\mu\epsilon_\alpha)^{1/2}/\hbar$ with μ and ϵ_α being the reduced mass and the separation energy. The parameter β was determined by fitting the elastic-electron-scattering data. It also fits the momentum distribution found in the quasifree scattering reactions such as ^{4}He$(p, 2p)^3$H.[7] C is a normalization constant. The differential cross section for the observed particle can be written as

$$(d^2\sigma/d\Omega_x dE_x) \propto |\psi(\vec{p})|^2 m_x (2m_x E_x)^{1/2}, \tag{3}$$

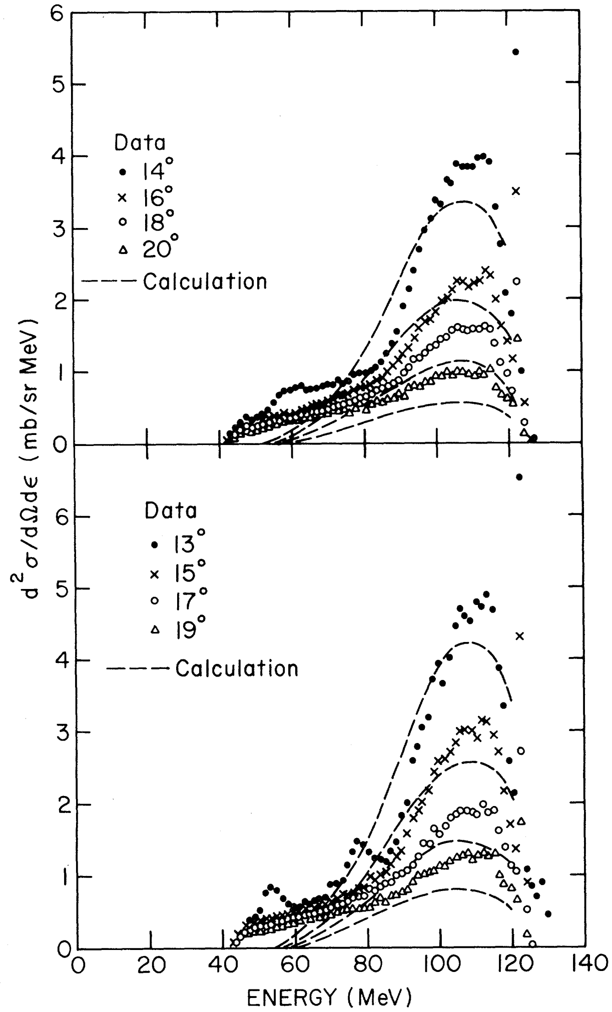

FIG. 2. The ^{3}He energy spectra for 140-MeV α particles on ^{209}Bi. The long dashed curves are the breakup-model calculations.

with $\vec{p} = \vec{p}_x - \vec{p}_0$, and

$$|\vec{p}|^2 = |\vec{p}_0|^2 + 2m_x E_x - 2|\vec{p}_0|(2m_x E_x)^{1/2}\cos\theta,$$

where $\vec{p}_0$, $\vec{p}_x$, m_x, and E_x are the momentum of the observed particle due to the c.m. motion of incident α particle, the final momentum, the mass, and the energy of the observed particle, respectively.

Figure 2 shows the breakup-model calculations compared with the experimental ^{3}He energy spectra at various angles for ^{209}Bi. Figure 3 shows a comparison of the calculated ^{3}He angular distribution (shifted by 6°, i.e., $\theta_L = \theta + 6°$, to roughly account for the Coulomb repulsion from the target) and the experimental data, normalized at $\theta_{\rm lab} = 13°$. Although our data points were limited to angles larger than 12°, the agreement is en-

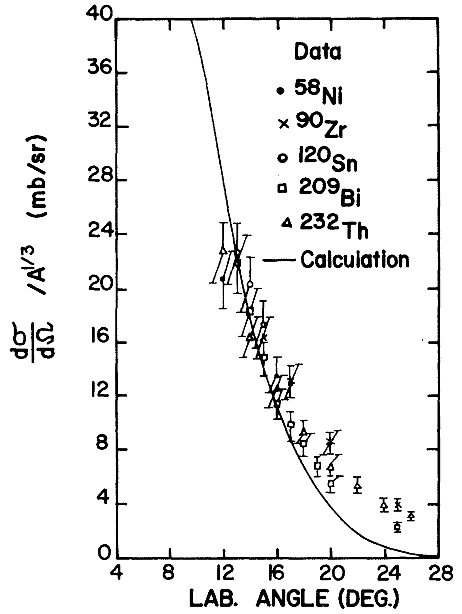

FIG. 3. The calculated ^{3}He angular distribution compared with the experimental data, divided by $A^{1/3}$. The calculation was normalized to the experimental data at $\theta_{\mathrm{lab}} = 13°$.

couraging. By integrating the calculation normalized to the experimental data for ^{209}Bi, the total breakup cross section for the ^{3}He channel is found to be about 2% of the total α-particle reaction cross section on ^{209}Bi at 140 MeV.

The breakup cross section for the triton channel is approximately the same as that for the ^{3}He channel. The total breakup cross sections for the proton and deuteron channels also appear to be comparable to those for the triton and ^{3}He channels. The neutron channel can be expected to be similar to the proton channel. If we assume that the unobserved component of the α particle undergoes a large-momentum-transfer interaction with the target it will have a small probability of emerging with the appropriate energy at a given angle to be identified with the α-particle breakup process. Under this assumption, the cross sections for all five channels should be summed to obtain the total breakup cross section. We estimate that the total breakup cross section for 140-MeV α's on ^{209}Bi could be as large as 10% of the total reaction cross section. It should be noted, however, that recent observations of heavy-ion-induced reactions which also exhibit peaks attributed to projectile breakup have been interpreted in terms of correlated fragments.[8] Complete correlation of α-particle breakup fragments would reduce our estimate of cross section by a factor of 2.

The magnitude of the breakup peak increases with the target mass. According to the breakup model, the cross section for α breaking up into ^{3}He-n is predicted to be proportional to $\frac{1}{2}\pi R_\alpha R$, where R_α is the mean α radius, $R_\alpha = \int r|\psi_\alpha(r)|^2 d^3r$, and $R = r_0 A^{1/3}$. The experimental α-particle breakup cross sections into ^{3}He-n channel for five target nuclei, divided by $A^{1/3}$, are shown in Fig. 3. It is apparent that the breakup cross section has an approximate $A^{1/3}$ dependence as predicted by breakup model.

The agreement between the simple calculations and the experimental energy spectra suggests that the broad peaks observed in the particle energy spectra are due to the breakup process. The locations, shapes, and intensities of these peaks are determined by the same momentum distribution of the observed particle in the projectile as determined in the reactions $^{4}\mathrm{He}(p,pn)$-$^{3}\mathrm{He}$ and $^{4}\mathrm{He}(p,2p)^{3}\mathrm{H}$.[6,7] In order to understand the absolute magnitude of the cross section and the detailed behavior of the peaks it will be necessary to carry out distorted-wave calculations. In this regard it is interesting to note that the breakup process can be described by a first-order diagram in which the upper vertex represents the usual breakup of the incident projectile into its components and the lower vertex the interaction of the neutron with the target. In the case of stripping reactions to discrete final states this vertex represents the appropriate overlap integral and in quasifree scattering, the n-A scattering cross section. In the case of the breakup reaction it would appear that this vertex represents essentially the total n-A cross section at the appropriate neutron energy, $\sim\frac{1}{4}(E_\alpha - 20)$ MeV.

The projectile breakup may be an important part of the total cross section for any complex projectile at sufficiently high energies. The behavior of broad peaks in the spectra resulting from such projectiles should be compared with the prediction of this simple process.

The authors wish to thank N. S. Chant, P. G. Roos, and N. S. Wall for many helpful discussions and to M. Collins for the help in data taking. This work was supported in part by the National Science Foundation.

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Coulomb-Nuclear Interference for High-Spin States Excited by ^{86}Kr, ^{40}Ar, and ^{16}O Projectiles

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(Received 9 November 1977)

We report the first experimental evidence for Coulomb-nuclear interference in the excitation of high-spin states by very heavy projectiles. The data are intepreted with use of a model described previously, and the feasibility of using this method to study the deformed nuclear surface is demonstrated.

Inelastic excitation in the Coulomb-nuclear interference (CNI) region has been studied extensively for ions such as helium,[1] carbon,[2] and oxygen.[3] However, little attention has been given to CNI in the scattering of very heavy projectiles from highly deformed nuclei. Previously[4] we introduced a new theoretical formalism describing such processes. We present here the first experimental data for such systems, and interpret the results with that formalism.

We have studied the systems ^{86}Kr + ^{232}Th, ^{40}Ar + ^{238}U, and ^{16}O + ^{162}Dy, with projectiles from the Berkeley SuperHILAC, and the Oak Ridge isochronous cyclotron. In all cases the de-excitation γ-ray cascade was detected in coincidence with backscattered particles, using standard Ge(Li) and annular silicon-detector arrangements. The annular geometry yielded average particle scattering angles of $\theta_{\mathrm{c.m.}} \sim 165°$.

Thick targets were used, and γ-ray spectra as a function of incident beam energy were generated by taking coincidence cuts in the heavy-ion spectrum, each corresponding to a different effective beam energy. The relation of incident beam energy (checked by time-of-flight measurements) to detected particle energy was determined using elastic kinematics and theoretical stopping powers. With these methods we obtained spectra