Electron-Induced Preequilibrium Alpha Emission

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(Received 9 May 1979)

This paper presents energy spectra of α particles emitted following the bombardment of ^{27}Al, ^{nat}Ni, ^{92}Mo, ^{94}Mo, and ^{197}Au with 120-MeV electrons, together with α-particle angular distributions from ^{197}Au and ^{nat}Ni for $E_\alpha = 30$ and 50 MeV. The data are compared with preequilibrium exciton-model and statistical-model calculations. It is concluded that few-step processes are dominant in the production of α particles with energies above 20 MeV.

There have been few studies of preequilibrium particle decay in photonuclear reactions compared to the extensive effort made to acquire and interpret data on preequilibrium effects arising from nucleon-induced reactions. There is some evidence that photon-induced preequilibrium complex-particle emission is observable in heavy nuclei,[1,2] and in a previous paper[3] we concluded that a preequilibrium component occurs in the (e,α) reaction for medium-weight nuclei. In this paper, we present measurements undertaken to determine the systematics of preequilibrium α emission from electron-induced reactions corresponding to excitations up to 120 MeV.

Targets of ^{27}Al, ^{nat}Ni, ^{68}Zn, ^{92}Mo, ^{94}Mo, and ^{197}Au were bombarded with 120-MeV electrons from the University of Glasgow electron linear accelerator. The α-particle detection system has been described previously.[3] The target thicknesses were determined by weighing, and were selected to give a maximum energy loss $\Delta E_\alpha < 0.05 E_\alpha$.

Spectra of α particles emitted at 30° in the laboratory frame are presented in Fig. 1. Previously we have shown the success of conventional statistical-model calculations in predicting the low-energy region ($E_\alpha \lesssim 12$ MeV) of the α-particle spectra from medium-weight nuclei[3] (see Fig. 2). In heavy nuclei the statistical component is considerably reduced since the Coulomb bar-

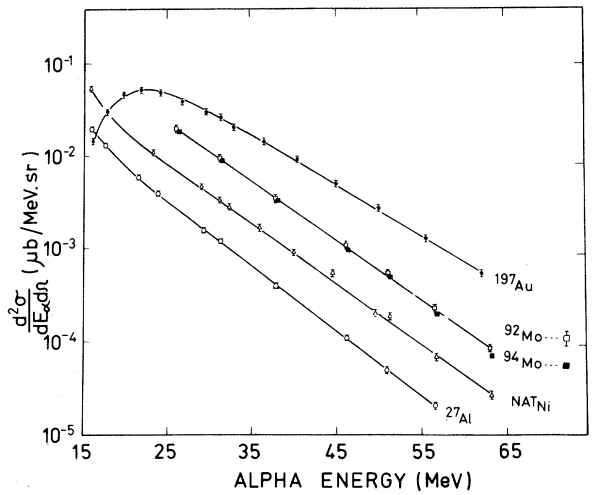

FIG. 1. α-particle energy spectra at $\theta_\alpha = 30°$, for $E_e = 120$ MeV. Errors shown are the sum of statistical and systematic contributions. The solid lines are a guide to the eye.

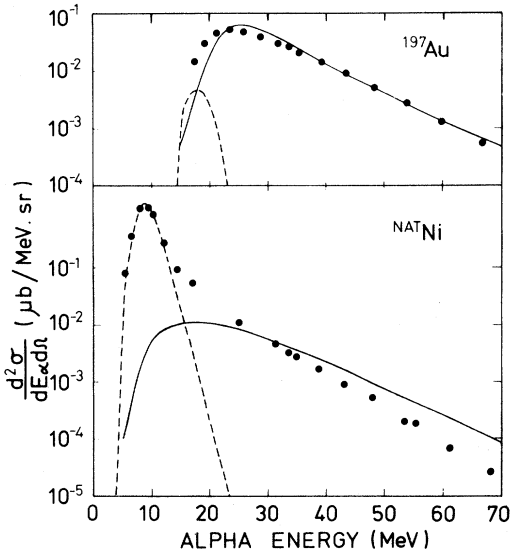

FIG. 2. α-particle energy spectra at $\theta_\alpha = 30°$, for $E_e = 120$ MeV. The solid circles are experimental points. The solid lines are the results of preequilibrium exciton-model calculations and the dashed lines are the results of statistical calculations neglecting photon absorption above $E_\gamma = 33$ MeV.

rier height exceeds the energy of α particles emitted following giant-resonance excitation. The expected position and magnitude of the ^{197}Au evaporation peak has been calculated here with use of the conventional Hauser-Feshbach approach described in Ref. 3. The neutron optical-model parameters were taken from Wilmore and Hodgson.[4] α-particle optical-model parameters were estimated from those for α scattering on gold and tungsten.[5] An optical potential $(V+iW)f(r_0,a)$ was employed, with $V=192$ MeV and $W=30$ MeV. The Saxon-Woods function $f(r_0,a)$ had a radius parameter $r_0=1.42$ fm and diffuseness parameter $a=0.55$ fm. The required values of $\sigma(\gamma,n)$ for ^{197}Au were taken from Veyssiere *et al.*[6] All other parameters employed are given in Ref. 3. The predicted evaporation component is shown in Fig. 2. The peak position is in agreement with the calculations of Meneghetti and Vitale.[1] It is evident that in heavy nuclei the α emission arises almost entirely from preequilibrium effects. This contrasts with medium-weight nuclei for which the Coulomb barrier is lower, and consequently a large evaporative component is observed, in close agreement with the statistical calculation.

The mass-number dependence of the evaporative (equilibrium) and preequilibrium contributions to the (e,α) cross section differ considerably. While the evaporative component peaks at about mass 60 and then falls off rapidly with increasing mass number, the preequilibrium component continues to increase steadily. The total (e,α) cross section integrated above $E_\alpha=25$ MeV is proportional to $A^{1.5}$ and this dependence becomes $A^{2.0}$ at $E_\alpha=50$ MeV. This mass dependence is in marked contrast with the $A^{1/3}$ dependence found for (p,α) cross sections,[7] and suggests a two-stage process. Such a process is likely to be initiated by a quasideuteron interaction,[8] for which the cross section is volume dependent and increases almost linearly with mass number. The second stage would then be an (N,α) reaction which if it were surface dependent ($\sim A^{2/3}$) or volume dependent ($\sim A$) would lead to a mass dependence between $A^{5/3}$ and A^2, as observed. A conclusion that the second stage of the process changes from a surface to a volume effect as the nucleon and α energies increase cannot yet be justified in view of the purely qualitative treatment here, neglecting absorption effects. Definite conclusions must await further calculations.

The apparent importance of a two-step, or at most few-step, mechanism in the emission of α particles above 25 MeV implies that the nuclear excitation is shared among relatively few nucleons at this stage of the reaction. An indication of the validity of this picture is obtained from the energy dependence of the spectra in Fig. 1. Since each of the spectra exhibits a smooth exponential decrease in cross section with increasing α energy an interpretation in terms of a nuclear temperature is suggested. The spectra were parametrized, therefore, by use of the expression $d^2\sigma/dE_\alpha d\Omega \propto \sigma_{\rm inv}(E_\alpha)\exp(-E_\alpha/T)$. The cross sections for α capture by the residual nuclei, $\sigma_{\rm inv}$, were calculated by Gadioli, Erba, and Hogan.[9] The resulting temperatures are given in Table I and exceed the values of 1.0–1.5 MeV for the equilibrium component of the (e,α) reaction[10] by about a factor of 4. The temperatures obtained from electrodisintegration experiments are only a mean value resulting from all excitations from threshold to the electron energy, and hence only general comparisons can be made with other reactions exhibiting preequilibrium effects. In the case of other preequilibrium spectra an elevated temperature has been associated[11] with a localized excitation, or "hot spot" within the nuclear volume. The concept of a "hot spot" has been applied to the analysis of preequilibrium α emission following deep-inelastic scattering of heavy ions.[12,13] This yielded temperatures of 3.5–4.0 MeV for α particles emitted in the forward direction following ~30-MeV excitation of the compound system. The higher temperatures observed in the present work reflect higher excitation energies, and possibly greater localization of the "hot spot."

A quantitative treatment of the process of sharing the initial excitation among an increasing number of nucleons is provided by the exciton model and calculations with this model have proved to be successful at predicting numerous

TABLE I. Temperatures corresponding to the preequilibrium component of the (e,α) reaction, derived from energy spectra at $\theta_\alpha=30°$ for $E_e=120$ MeV.

Target	Temperature[a] (MeV)
^{27}Al	5.3
^{nat}Ni	5.5
^{68}Zn	5.4
^{92}Mo	5.6
^{94}Mo	5.4
^{197}Au	6.1

[a]Error is ± 0.2 MeV.

preequilibrium reaction spectral shapes, e.g., Ref. 9 and Wu and Chang.[14] We have therefore compared typical spectra with results from the exciton model as applied to photonuclear reactions by Wu and Chang.[14] The only amendment to the technique employed in Ref. 14 was the substitution of a plane-wave, $E1$, virtual-photon spectrum in place of the bremsstrahlung spectrum. Coulomb distortion and finite-nuclear-size effects[15] on the photon spectra were neglected. These effects are expected to cause only small changes (<10%) to the calculated spectral shape, although the absolute magnitude may only be accurate to ~40% when they are neglected. Such correction factors are not important here since the preequilibrium calculations only yield relative cross sections. Uncertainties in the determination of the α-particle formation probabilities and the average two-body matrix elements used to calculate exciton-state decay rates do not allow the calculation of absolute cross sections. In Fig. 2 the calculated spectral shapes are compared with our data. The exciton-model calculations yield angle-integrated spectra, and these have been normalized to the data taken at $\theta_\alpha = 30°$. These spectra are in reasonable agreement with the data, particularly for ^{197}Au. The peak of the ^{197}Au(e,α) energy spectrum clearly arises from a preequilibrium component and not the equilibrium component as suggested by Murphy, Skopik, and Asai[16] who arbitrarily fit an evaporation-model shape to such data.

The spectral shapes obtained from exciton-model calculations are strongly dependent on the initial exciton number.[17] The initial exciton number used here was $n_0 = 4$, corresponding to the quasideuteron process in which a two-particle, two-hole state is formed. A lower initial exciton number would result in an increased high-energy component, and thus a flatter energy spectrum. It is evident that use of a lower initial exciton number would not improve the fits obtained here and in Ref. 14.

α angular distributions obtained for 30- and 50-MeV α particles from ^{nat}Ni and ^{197}Au are shown in Fig. 3. The form of the angular distributions for each α-particle energy exhibits no marked difference between the two nuclei considered. In both cases the asymmetry increases with increasing α energy. Although some calculations of preequilibrium nucleon angular distributions have been carried out,[18-20] we are unaware of any preequilibrium model which calculates complex-particle angular distributions, although

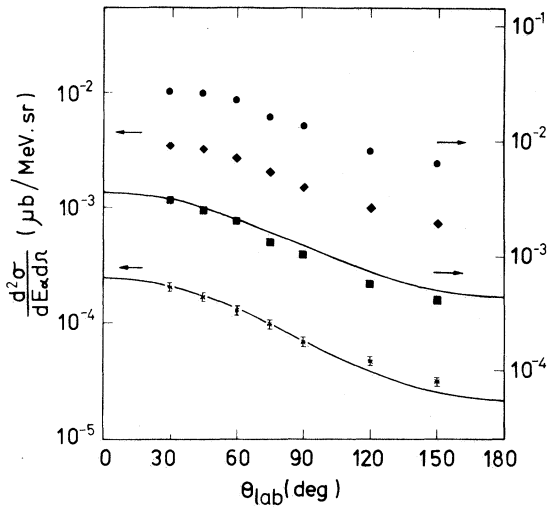

FIG. 3. α-particle angular distributions at $E_e = 120$ MeV for ^{197}Au (shown as circles for $E_\alpha = 30$ MeV and squares for $E_\alpha = 50$ MeV) and ^{nat}Ni (shown as diamonds for $E_\alpha = 30$ MeV and stars for $E_\alpha = 50$ MeV). The solid lines are the result of simple kinematic calculations described in the text. The sum of statistical and systematic errors is shown where it exceeds the size of the points.

work is in progress on this problem.[21,22] In the spirit of the exciton model we have been able to reproduce the distribution shown in Fig. 3, using crude kinematic considerations. α emission occurs when two neutrons and two protons with the proper momenta combine in an exciton state. Only the excited nucleons take part in the reaction, and the rest of the nucleus can be considered to act as a spectator. Hence the incoming photon momentum is shared by only a few nucleons at the preequilibrium stage, and a complex particle formed from these nucleons will have a large fraction of the incoming momentum transferred to it. Therefore the angular distribution obtained for particles of a fixed energy in the laboratory frame will arise from a range of particle energies in the center-of-mass frame of the excited nucleons. At forward angles the observed complex particles are at a lower energy in the center-of-mass frame than in the laboratory frame and conversely for backward angles. If the cross section falls rapidly with increasing particle energy, as is observed for the preequilibrium (e,α) reaction, then a forward-peaked angular distribution will be obtained for particles of a fixed energy in the laboratory frame (even if the emission is isotropic in the center-of-mass frame). To estimate the importance of this ef-

fect we have assumed that the average momentum transferred to the nucleus prior to the emission of a 50-MeV α particle is $k_\gamma = 70$ MeV/c. The number of nucleons, p, sharing the momentum at the time of α emission was varied to obtain the best fit to the angular distribution data. With use of the experimentally determined slopes for $\sigma(E_\alpha)$ the fits shown in Fig. 3 are obtained with $p = 6$. Similar fits can be obtained for $E_\alpha = 30$ MeV by varying k_γ and p in a qualitatively reasonable way. In view of the fair agreement observed, it seems plausible that the exciton model could describe the α-particle angular distributions.

In conclusion, we have observed a significant preequilibrium component in the (e, α) reaction which may be described by a two-step or few-step process in which only a few nucleons share the initial excitation energy prior to particle emission.

We are grateful to J. R. Wu and C. C. Chang for providing us with their exciton-model code PREQEC, and for carrying out calculations on our behalf. We wish to thank the U. K. Science Research Council for supporting this work.

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Magnetic Moments in Calcium Isotopes via a Surface-Interaction Experiment

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(Received 12 March 1979)

A rotation of the angular correlation of deexcitation γ rays from ^{40}Ca and ^{44}Ca was observed in a tilted foil geometry. The signs and magnitudes of the magnetic moments of the 2_1^+ level of ^{44}Ca and of the 3_1^- level of ^{40}Ca were determined to be $g = -0.28 \pm 0.11$ and $g = +0.52 \pm 0.18$, respectively. The experiment demonstrates that polarization of deeply bound electronic configurations can be appreciable and that this technique can be used as a quantitative measure of magnetic moments of picosecond nuclear levels.

The magnetic moments of the 2_1^+ levels of even Ca isotopes have not been measured hitherto, but it is evident that their values and signs can provide significant information regarding the shell-model structure of low-lying levels in this mass region. We report here the measurement of the magnetic moment of the 2_1^+ level of ^{44}Ca. The experiment utilizes the "tilted foil" hyperfine interaction, i.e., the interaction between the nuclear level and a polarized electronic ensemble associated with high-velocity ions emerging from a surface whose normal does not lie along the beam direction.[1,2] The polarization of electronic configurations manifested in the emittance of circularly polarized light has been extensively studied in the transmission (tilted-foil) geometry[3] and in the reflection (grazing-angle) geometry.[4] For deeply bound atomic levels such polarization can be observed via their hyperfine interaction with the nucleus. A rotation of the angular correlation

