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Using a two-dimensional pulse-height analyzer in conjunction with a coincidence technique, we have measured angular correlation functions for coincident fragment pairs, the fission excitation function, and the most probable kinetic energy release for binary fission in the bombardment of ^{238}U with ^{40}Ar from the Berkeley HILAC. Evidence is presented that compound nuclei of Z = 110 are produced in these reactions.

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A detailed account of the analysis and the experimental techniques used is given in refs. [1], [2], and [3]. We shall give a brief description and only discuss some of the few modifications we had to introduce.

The target consisted of 150 mg/cm^2 UF_4 supported by a 100 μg/cm^2 thick Ni foil. The coincident fission fragments were detected with two silicon-diode crystals. One of the detectors, D-1 was also used to count elastically scattered ^{40}Ar ions for the determination of the absolute fission cross section and to measure their energy spectrum.

Detector D-1 could only be moved in the horizontal plane containing the beam axis. The angle of this arm with respect to that axis is defined as ψ_1. The mount for the second detector was constructed so that it moved about the radius of a sphere. The position of this detector was adjusted by means of a horizontal radial arm. The angle of this arm with respect to the beam is defined as ψ. A vertical radial arm permitted the detector to be raised or lowered. The angle of this detector with respect to the horizontal plane is defined as ξ. The overall accuracy in ψ and ξ was about $\pm 0.2^\circ$. The angular resolution of the system was estimated from the widths of the angular correlation functions at two radial positions of the detectors.

The electronic system was slightly different from that used earlier in that we used a Victoreen 40 by 40 channel, two-dimensional, pulse-height analyzer triggered by the coincidence pulse from the cross-over point output signals from the amplifiers of the two detector systems. The pulse-height pairs, $E_1 - E_2$, for coincident fission fragments were easily separated from those for other events, such as $^{40}Ar-^{238}U$, charged particle-charged particle, and accidental $^{40}Ar-^{40}Ar$ coincidences. The correlation function $W(\xi,\psi_1\ \psi)$ with detector D-1 at a fixed position ψ_1, was determined by measuring the number of coincidences per number of incident beam particles as a function of the position (ξ,ψ) of the other detector.

Best angular separation between fragment pairs originating from nuclei with different linear momenta is obtained at maximum energy of ^{40}Ar (415 MeV) and ψ_1 at 90°. In fig. 1 the correlation functions $W(0,90,\psi)$ obtained in the fission of ^{238}U with ^{4}He, ^{12}C, ^{16}O, ^{20}Ne, and ^{40}Ar all of an energy of 10.4 MeV/nucleon. The curves for the lighter ions were taken from refs. [1] and [2]. The function with ^{4}He exhibits one narrow peak whereas those with the other ions in addition have a wider one.

As was shown in refs. [1] and [2] the narrow and wide peaks consist of fragments from nuclei produced in reactions characterized respectively, by complete fusion (CF) and incomplete fusion (ICF) of target and ion nuclei.

The mode of the total kinetic energy of the primary fragments at infinite separation in the c.m. system of the compound nucleus in a CF process is given by [2]:

$$E_C^P = m_I E_I (1+4 \tan^2 \bar{\psi}_{CF})/(m_I+m_t)$$

where m_I and m_t are the masses of the ion and target nuclei, respectively; E_I is the laboratory energy of the ion and $\bar{\psi}_{CF}$ is the angular position at which the CF peak has a maximum.

Within experimental errors we find E_C^P to be independent of E_I and given by 255±4 MeV. On the basis of the liquid drop model, Nix has estimated E_C^P to be 221 MeV for the nucleus $^{278}110$ [4]. This agreement between experimental and calculated values is remarkably good and hence constitutes kinematic evidence for compound nucleus formation in a CF reaction.

At 415 MeV ^{40}Ar the FWHM of the CF peak, when corrected for experimental angular resolution, is 10.0° in the horizontal plane and 8.8° in the direction of ξ. Using the formula developed in ref. [2] it can be shown that the latter spread is due to the effects of neutron emission only. This is in sharp contrast to the ICF peak where, in order to explain the widths, we have to infer that the fissioning nuclei have large spreads in linear momenta along and vertical to the beam axis.

Values for the total fission cross section, σ_f, as a function of E_I obtained in these experiments have already been published [5]. To these values were fitted those for the total interaction reaction σ_R as calculated using the parabolic approximation to the real part of the optical model potential. We shall not present the formulas used to estimate σ_R since they have been given in several papers [3,5]. In the fit we used the values -70 MeV, 1.26 fm, and 0.44 fm, respectively, for the parameters V_o, r_o, and d of the real part of the optical potential. These values are very nearly equal to those obtained in a similar analysis of σ_f for other ions incident on ^{238}U [3].

Values for the ratio σ_{CF}/σ_R, where σ_{CF} is the cross section for compound nucleus formation in a CF process, can be obtained from an integration of the peaks in the correlation functions. Assuming this ratio to be independent of E_I and equal to that measured at 10.4 MeV/nucleon the data for ^{12}C, ^{16}O, ^{20}Ne [2], and ^{40}Ar incident on ^{238}U fit to within 15% the empirical formula: $\sigma_{CF}/\sigma_R = (1 + 0.03\ A_I)^{-1}$, where A_I is the mass number of the ion. The values for σ_{CF} estimated from this formula and the formula for σ_R have been used successfully to fit experimental cross sections for nuclides produced in (I,xn) reactions [5]. (Here, x denotes the number of neutrons emitted from the compound nucleus.) Hence, there is no discrepancy between the results from these two sets of experiments.

It is interesting to note that ground state nuclides of element 110 probably never will be observed since fission is competing too severely with neutron emission in the decay of the compound nucleus. An empirical extrapolation suggests element 107 to be the heaviest element one might have a chance to identify with a reasonable degree of confidence with present day beam intensities and combinations of targets and ions [6]. The possible existence of new, closed proton and neutron shells beyond the known ones at $Z = 82$ and $N = 126$, such as $Z = 114$ and $N = 184$, changes drastically this gloomy picture since such shells will stabilize the nuclei against fission and thus presumably reduce the level widths for fission [6]. It appears from the conclusion drawn from the present experiments that the success of attempts to produce nuclei by (I,xn) reactions in the region of the next shells will depend on their strength. In addition, if the shells are at $Z = 114$ and $N = 184$ the availability of neutron-rich ions and targets will be important.

Figure Caption

Fig. 1. Angular correlation functions for coincident fragment-pairs for various ions of 10.4 MeV/nucleon incident on ^{238}U. Both detectors and the beam axis are in the same plane. One detector is at 90° to the beam axis and the coincidence rate is measured as a function of the position ψ of the other detector. The curves are normalized and have not been corrected for angular resolution.

FOOTNOTE AND REFERENCES

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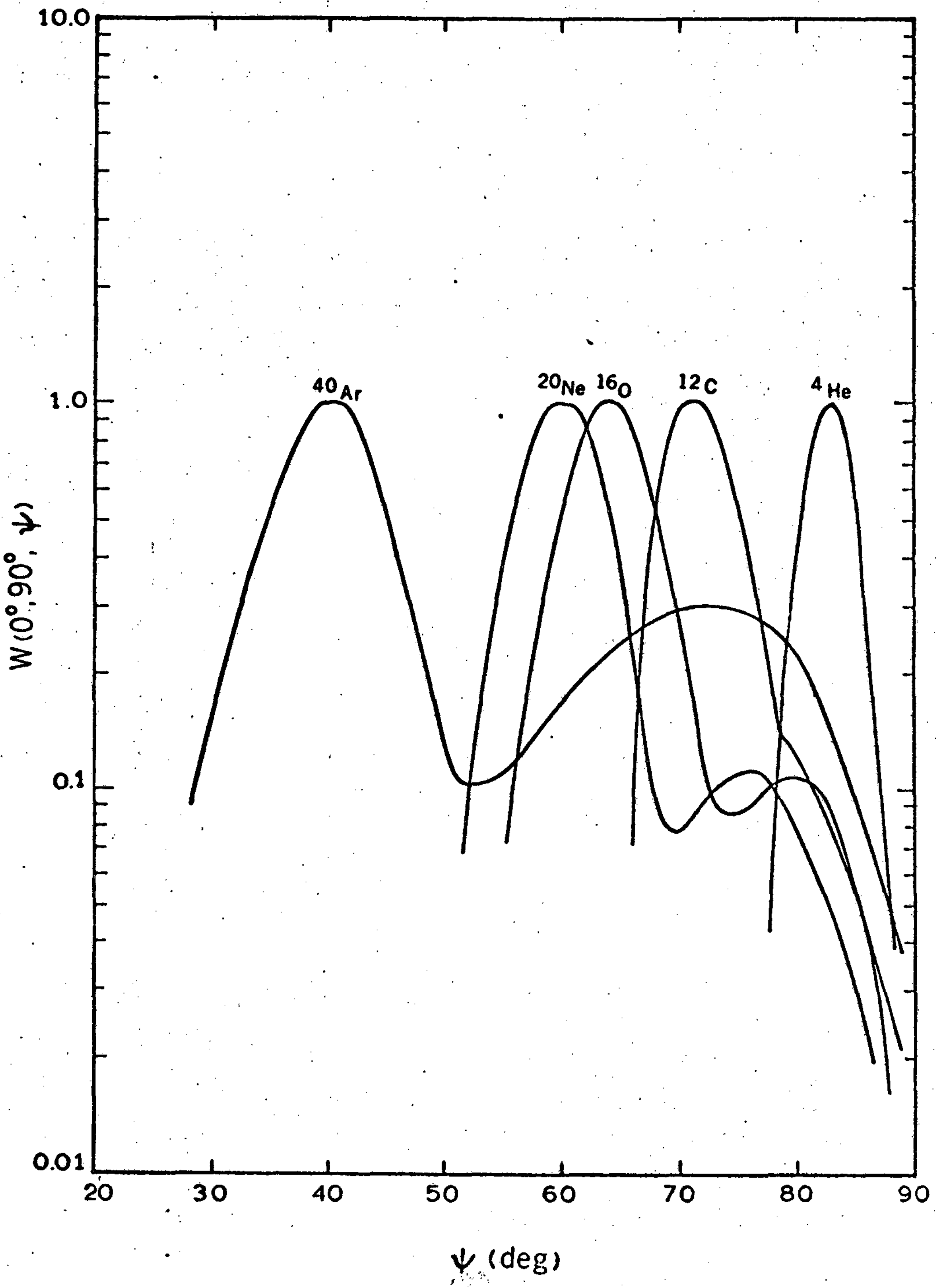

Fig. 1

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