1108 (1970).
[13]J. R. Comfort and B. C. Karp, to be published.
[14]R. C. Johnson and P. J. R. Soper, Phys. Rev. C 1, 976 (1970).
[15]H. Amakawa, A. Mori, and K. Yazaki, Phys. Lett. 76B, 157 (1978).
[16]J. P. Farrell, C. M. Vincent, and N. Austern, Ann. Phys. (N.Y.) 96, 333 (1976), and to be published.
[17]R. S. Mackintosh and A. M. Kobos, Phys. Lett. 62B, 127 (1976).
[18]P. W. Coulter and G. R. Satchler, Nucl. Phys. A293, 269 (1977).
[19]A. M. Lane, J. E. Lynn, E. Melkonian, and E. R. Rae, Phys. Rev. Lett. 2, 424 (1959).

Fragmentations of ^{40}Ar at 213 MeV/Nucleon

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Energy and isotope distributions were measured for peripheral reactions induced by ^{40}Ar at 213 MeV/nucleon. The data are consistent with the predictions of abrasion-ablation models. The influence of correlations in the nuclear ground state is discussed.

The study of ^{40}Ar-induced reactions at energies below 10 MeV/nucleon has led to important advances in our knowledge of deeply inelastic scattering.[1] At these energies the reaction is believed to proceed by a diffusion mechanism, leading to the emission of fragments from an equilibrated dinuclear system. At much higher energies, it is unlikely that a dinuclear system can ever be formed and there is evidence from studies with light projectiles like ^{16}O that a fast abrasion mechanism[2] becomes the dominant peripheral process. However, projectile excitation followed by equilibration and decay can also explain many features of the results with ^{16}O.[3-5] Since the characteristic features of heavy-ion reactions at lower energies are much better developed with projectiles like ^{40}Ar, it is likely that a better understanding of the high-energy processes will come from studies on such heavy systems. Here we present the first measurements of energy and isotope distributions in this new energy region with an ^{40}Ar beam at 213 MeV/nucleon.

The experiment used the ^{40}Ar beam of 10^8 particles/sec from the Bevalac to bombard a carbon target of thickness of 400 mg/cm^2. Projectile fragments were detected at several laboratory angles in the range 0–4° in a telescope consisting of nine 5-mm-thick silicon detectors, which could stop fragments heavier than nitrogen. The particle identification technique used the algorithm[6] $(E+\Delta E)^n - E^n \propto TM^{n-1}Z^2$, where T is the thickness of the ΔE detector, M and Z are the mass and charge of the particle, and n was set equal to 1.78. This expression was modified for the case of a multielement detector telescope[7] to give several identifications. For each event the weighted mean and χ^2-consistency function were determined. Events arising from reactions in detectors and statistical fluctuations in energy loss were rejected by making cuts on the tail of the χ^2 distribution. The resulting mass spectra had a resolution varying from 0.2 amu for oxygen to 0.5 amu for sulfur.

For isotopes close to the valley of stability, which were produced with high yields, the total cross section was obtained by integrating the angular distributions. For low-yield isotopes far from stability, the cross sections were obtained by adding the yields of all angles and assuming that the angular distributions for these isotopes were the same as for the more-abundant isotopes of that element. The cross sections were corrected for reaction losses in the detectors which varied from ~15% for sulfur to ~22% for oxygen. The absolute normalization is uncertain to within a factor of 2.

For projectile-fragmentation reactions at relativistic energies, the longitudinal momentum distributions of fragments in the projectile rest frame are well described by Gaussian distributions.[4] In the models of Ref. 3 the widths σ of these distributions are given by

$$\sigma^2 = \sigma_0^2 M_f (M_p - M_f)/(M_p - 1). \qquad (1)$$

Here M_f and M_p are the fragment and projectile masses and σ_0 is a constant. Transforming the Gaussian momentum distributions to laboratory energy distributions, we fitted the energy spectra of different fragments after correcting for broadening due to target thickness. One such fit is shown in Fig. 1(a). Figure 1(b) summarizes the values of σ_0 for those fragments where statistics allowed such an analysis. The line denotes the mean value of $\sigma_0 = 94 \pm 5$ MeV/c. If we assume that projectile disintegration is a fast process governed by the distribution of nucleon momenta before the collision, the parameter σ_0 may be related to the Fermi momentum of the projectile by the relation[3] $\sigma_0 = p_F/\sqrt{5}$. The mean value of σ_0 gives $p_F = 209 \pm 11$ MeV/c, compared to the value of 251 ± 5 MeV/c for ^{40}Ca measured in electron scattering.[8] Alternatively if we assume that the emitting system was in thermal equilibrium, the parameter σ_0 is related to the nuclear temperature[3] by $\sigma_0^2 = m_N T(M_p - 1)/M_p$, where m_N is the nucleon mass in MeV. Our results give $T = 9.6 \pm 1.1$ MeV, only slightly higher than results for ^{16}O-induced reactions at various energies.[4,9]

The experimental element and isotope distributions are shown in Figs. 2 and 3. Both fast-abrasion and thermal-equilibration models have also been used to describe isotope distributions.[2,5] In the model of decay of the excited projectile the cross section is proportional to $\sum \exp(Q_F/T)$, where the sum extends over all fragmentation channels, Q_F is the corresponding separation energy, and T is an effective temperature. In Fig. 3, the isotope distributions with $T = 9.6$ MeV are compared to the data for the elements

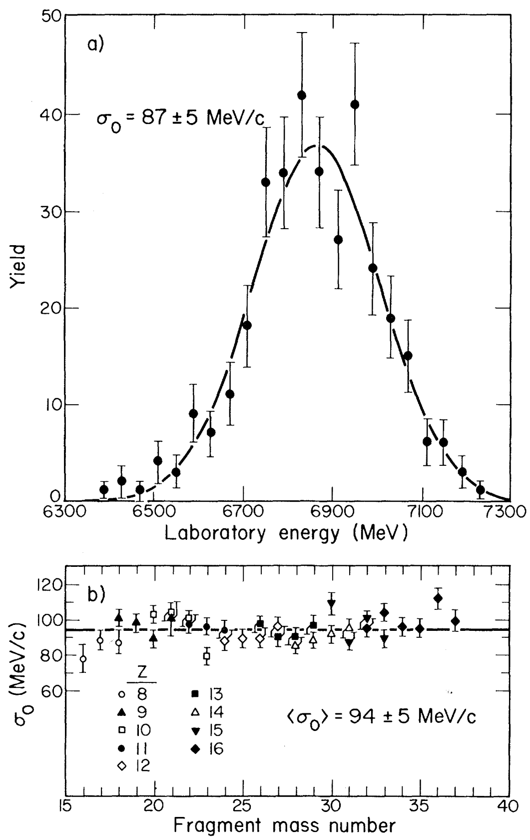

FIG. 1. (a) Measured energy spectrum of ^{34}S at 1.5° from fragmentation of 213-MeV/nucleon ^{40}Ar on a carbon target. The solid line corresponds to a fitted Gaussian momentum distribution. (b) Values of σ_0 for the fragments in the mass range 16 to 37. (For each fragment, the weighted mean of σ_0 obtained from the energy spectra at many angles is shown.)

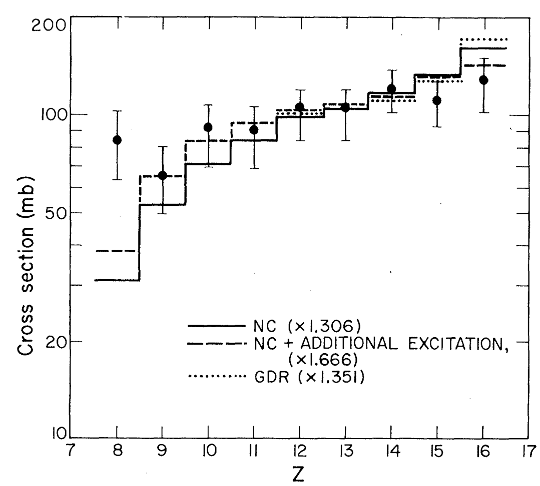

FIG. 2. Comparison of experimental element production cross sections for Ar + C with the predictions of the abrasion-ablation model (for a discussion see text). The model predictions are normalized to give the same total cross section as the experiment for elements from oxygen to sulfur. Where not separately shown the GDR (giant dipole resonance) curve merges with the NC (no correlation) curve.

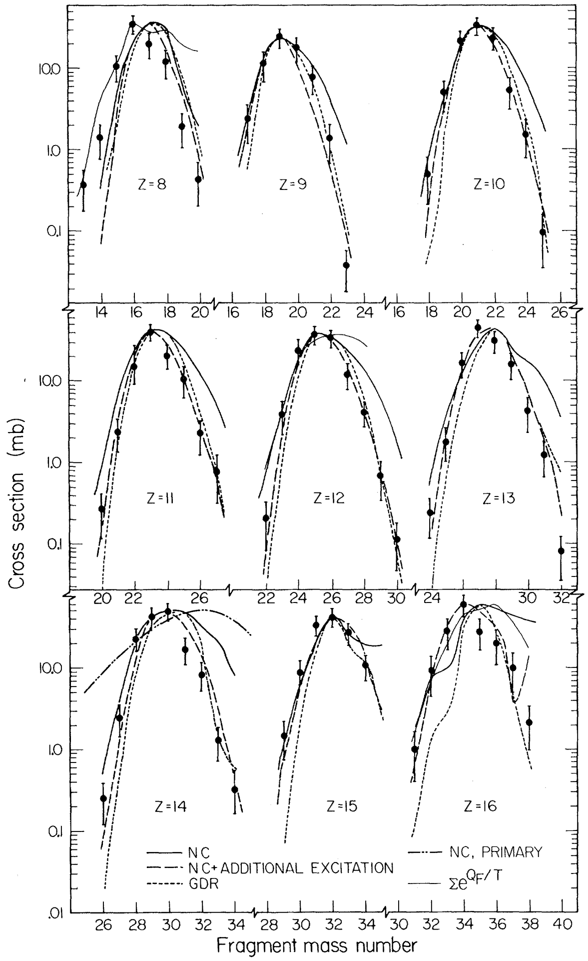

FIG. 3. Comparison of experimental isotope production cross sections for Ar + C with model predictions as described in text. The calculated curves have been normalized to reproduce the maximum experimental isotope cross section in each case. The normalization factors varied between 1 and 2.

with $Z = 8$, 12, and 16 (thin solid lines). The model does not predict the Gaussian isotope distributions observed experimentally. This failure is not remedied by different choices of the effective temperature.

The experimental element and isotope distributions can, however, be rather well described within the framework of abrasion-ablation models.[10,11] In these calculations, the primary-fragment mass distributions are determined from the geometry of the fireball model[12,13] and the primary isotope distributions depend on the extent of proton-neutron correlations in nuclei.[10,11] In fact, it has recently been suggested that in heavy-ion reactions at these energies the isotope distributions could be a sensitive probe of ground-state isospin correlations.[14] We investigated two assumptions: (a) no correlations[10] (NC), and (b) proton-neutron correlations arising from the zero-point vibration of the giant dipole resonance[11] (GDR). The de-excitation of the primary fragments by particle evaporation was calculated with the computer code OVERLAID ALICE,[15] assuming zero angular momentum throughout. The excitation energy of the primary fragments was taken to be equal to the difference in surface energies of the abraded projectile and a spherical nucleus of identical mass.[13] Typical values of this excitation energy for the primary fragments of mass 36 and 30 were 20 and 60 MeV, respectively. The final element and isotope distributions obtained from these calculations are shown in Figs. 2 and 3 by thick solid and dotted lines for assumptions (a) and (b). To demonstrate the importance of the ablation stage of the reaction, the dash-dotted line at $Z = 14$ shows the primary-fragment isotope distribution for the case of no correlation. Both calculations give a reasonable account of the element yields, but only assumption (b) is able to describe the relative isotope cross sections. However, it is important to realize that the predicted secondary distributions are sensitive to the excitation energy of the primary fragments, and they become narrower for higher excitation energies because of the decay towards the valley of stability. To investigate this effect, calculations were also done with an additional excitation energy by assuming a deposition of energy in the spectator nuclei by nucleons from the interaction region.[10] For primary fragments of mass 36, this added an average of about 80 MeV excitation energy. For assumption (a) the resulting isotope distributions are shown by the dashed lines in Figs. 2 and 3. (For the case of GDR correlations which produce narrower primary distributions, a similar increase in excitation energy results in a minor reduction of the widths of the isotope distributions and this is not shown in the figures.) It is clear from the figures that the experimental isotope distributions can also be explained by assuming no correlations if this extra excitation energy can be justified.

In conclusion, the simple model of the decay of an excited projectile as described in Ref. 5 cannot account for isotope distributions in our case, although this model was considered an acceptable alternative for ^{16}O-induced reactions. Since this model is based on drastic approximations, it will be important to investigate whether more sophisticated treatment of the decay of an excited projectile can explain the present data. The abrasion-ablation model however is able to give an excellent account of the present experimental data. Considering the importance of the ablation stage and the uncertainties of primary-fragment excitation energies, further investigations with projectiles of different A/Z ratios will be required to test the various models. Experiments of this type, measuring energy and isotope distribution at several energies, may eventually determine the importance of ground-state correlations in nuclei and the excitation energy deposited in the spectator nuclei during the reaction.

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[b]On leave from Max-Planck-Institut, Heidelberg, West Germany.

[1]See, e.g., W. U. Schröder and J. R. Huizenga, Annu. Rev. Nucl. Sci. 27, 465 (1977), and reference therein.

[2]J. Hüfner, K. Schäfer, and B. Schürmann, Phys. Rev. C 12, 1888 (1975); J. Hüfner, C. Sanders, and G. Wolschin, Phys. Lett. 73B, 289 (1978).

[3]A. S. Goldhaber, Phys. Lett. 53B, 306 (1974).

[4]D. E. Greiner, P. J. Lindstrom, H. H. Heckman, B. Cork, and F. S. Bieser, Phys. Rev. Lett. 35, 152 (1975).

[5]V. K. Lukyanov and A. I. Titov, Phys. Lett. 57B, 10 (1975).

[6]F. S. Goulding and B. G. Harvey, Annu. Rev. Nucl. Sci. 25, 167 (1975).

[7]D. E. Greiner, Nucl. Instrum. Methods 103, 291 (1972).

[8]E. J. Moniz, I. Sick, R. R. Whitney, J. R. Ficence, R. D. Kephart, and W. P. Trower, Phys. Rev. Lett. 26, 445 (1971).

[9]C. K. Gelbke, D. K. Scott, M. Bini, D. L. Hendrie, J. L. Laville, J. Mahoney, M. C. Mermaz, and C. Olmer, Phys. Lett. 70B, 415 (1977).

[10]L. F. Oliveira, R. Donangelo, and J. O. Rasmussen, Phys. Rev. C (to be published).

[11]D. J. Morrissey, W. R. Marsh, R. J. Otto, W. Loveland, and G. T. Seaborg, Phys. Rev. C 18, 1267 (1978).

[12]G. D. Westfall, J. Gosset, P. J. Johansen, A. M. Poskanzer, W. G. Meyer, H. H. Gutbrod, A. Sandoval, and R. Stock, Phys. Rev. Lett. 37, 1202 (1976).

[13]J. D. Bowman, W. J. Swiatecki, and C. F. Tsang, Lawrence Berkeley Laboratory Report No. 2908, 1973 (unpublished).

[14]J. P. Bondorf. G. Fai, and O. B. Nielsen, Phys. Rev. Lett. 41, 391 (1978).

[15]M. Blann, U. S. ERDA Report No. COO-3494-29, Rochester, N. Y., 1976 (unpublished).

Giant Dipole Resonance in ^{4}He with Noncentral Forces and Target-Recoil Corrections

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The ^{4}He giant dipole resonance is calculated with a continuum shell model which treats the center of mass correctly and includes possible noncentral components of the nucleon-nucleon interaction. The (γ,p) and (γ,n) cross sections and asymmetry coefficients agree well with the experiment. The b_2 asymmetry coefficient is shown to depend on the spin-orbit odd component of the effective nuclear force. The 1^- level positions and channel mixing are in best agreement with "solution II" of the R-matrix fit of Werntz and Meyerhof.

Because of its apparent simplicity as compared to other nuclei, the α particle should be the one system where investigation of the giant dipole resonance (GDR) is most complete. However, both experimental and theoretical ambiguities still remain.[1-5] Recent measurements[6] of the ^{3}H$(p,\gamma)^4$He asymmetry provide important new information which is necessary to further the