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Brief Reports

Brief Reports are short papers which report on completed research or are addenda to papers previously published in the **Physical Review**. *A Brief Report may be no longer than 3½ printed pages and must be accompanied by an abstract.*

Mass yield distribution for the interaction of silver with 300 GeV protons

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The results of radioactivation, mass spectrometric, and fragment detection experiments have been combined to give a complete mass yield distribution for the interaction of silver with 300 GeV protons. Spallation accounts for approximately 80% of the total reaction cross section and fragmentation for nearly 20%.

Predictions of the mass-yield distribution for the interaction of energetic particles with nuclei have been made recently on the basis of various approaches, such as statistical models and percolation theory.[1-4] To test such models, it is necessary to compare their predictions with complete mass-yield data. The determination of mass-yield curves has traditionally involved the assay of the yields of radionuclides produced in the interaction, supplemented to a limited extent by mass spectrometric determinations of the yields of stable isotopes. The interaction of silver with GeV energy protons has been studied in this manner and mass-yield curves have been reported at various energies in the 3–300 GeV range.[5-8] While the curves are rather well determined for mass numbers ranging from that of the target down to $A \approx 40$, the scarcity of suitable radionuclides at lower mass numbers as well as the paucity of mass spectrometric data[9] have led to large uncertainties in the mass-yield curve for $A < 40$.

We have recently determined the complete mass-yield distribution of fragments with $A = 6$–28 emitted in the interaction of krypton and xenon with 80–350 GeV protons with a multiple time of flight, ΔE-E spectrometer.[10,11] The yields in this mass region display a power-law dependence, $\text{Yield}(A_f) \propto A_f^{-2.6}$. These results, as well as those for the isotopic yield distribution,[12] have been interpreted in terms of a liquid-gas phase transition in the vicinity of the critical point.[11,12] Total isobaric yields for a silver target may be obtained readily by interpolation between the krypton and xenon data. We have assumed that the total isobaric yields scale with the total reaction cross section and thus vary as $A^{2/3}$. The results may be combined with the radioactivation and mass spectrometric data to obtain a complete mass-yield curve for the interaction of silver with high-energy protons.

The fragment data have been obtained at a laboratory angle of 34°. Integrated cross sections could be obtained from these data knowing that the angular distributions are isotropic in a system moving along the beam direction with a speed $v/c = 0.007$ and 0.002 for krypton and xenon, respectively.[13] Since the cross sections for fragment production were found to be independent of the proton energy between 80 and 350 GeV,[11] the results may be combined with the radioactivation data obtained at 300 GeV.[7,8]

Hudis *et al.*[9] have used mass spectrometric assays of rare gases to obtain total isobaric yields at $A = 21$, 38, and 83 for the interaction of silver with 29 GeV protons. Since the cross sections for the formation of fragmentation and spallation products from silver are virtually independent of bombarding energy between 29 and 300 GeV,[7,14] the mass spectrometric data may be used in the construction of the mass-yield curve. We have increased these cross sections by 3% in order to make them consistent with the value of the monitor cross section used in the radioactivation experiments.[7,8]

The total isobaric cross section at $A = 21$ obtained in the counter experiment,[11] 6.0 mb, is a factor of 2.6 lower than the mass spectrometric value of 15.5 mb. Comparison of individual fragment cross sections with those of specific radionuclides for which cross sections have been reported,[7,8] e.g., ^{22}Na, ^{24}Na, and ^{28}Mg, show a similar discrepancy. However, it is difficult to make an accurate comparison of the individual cross sections because the charge distribution in this mass region depends on the target neutron-to-proton ratio, N/Z.[15] Since silver has a lower N/Z than either krypton or xenon, it is difficult to properly scale the yields of individual products from krypton and xenon to silver. We have, therefore, normalized the fragment isobaric cross sections to the mass spectrometric value at $A = 21$.

The large discrepancy in the absolute values of the cross sections obtained in the counter experiment, and in the mass spectrometric and radioactivation experiments, presumably reflects systematic errors in the determination of the rate at which proton-target interactions occur. The

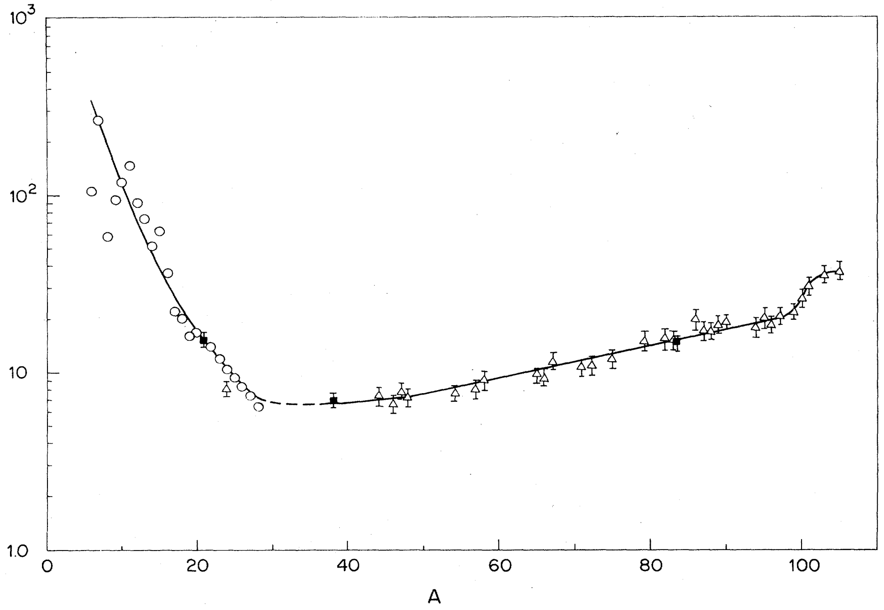

FIG. 1. Mass-yield curve for the interaction of silver with 300 GeV protons. Open circles represent fragment cross sections (Ref. 11); the curve through these points is the power-law fit. Open triangles represent radioactivation cross sections (Refs. 7 and 8); closed squares represent mass spectrometric cross sections (Ref. 9). The solid curve between $A = 38$ and 105 shows the trend in these data. The two curves have been joined by the dashed curve between $A = 28$ and 38.

counter experiment uses a completely different method for the measurement of this quantity than the mass spectrometric and radioactivation experiments. The cross sections determined by the latter two techniques are based on absolute measurements of monitor reaction cross sections such as $^{12}C(p,pn)^{11}C$ (Ref. 16), and $^{27}Al(p,3pn)^{24}Na$ (Ref. 17), and these cross sections are not completely consistent with each other. The counter experiment cross sections are based on the measured intensity of the circulating proton beam and on the number of target atoms per cm^2 in the gas jet, as determined by the measured number of protons from p-p elastic scattering with the hydrogen component of the gas jet.[11] These measurements are subject to sizeable systematic uncertainties.

The resulting mass-yield curve is displayed in Fig. 1. Radioactivation cross sections are shown for all mass numbers for which the measured yields account for at least $\frac{1}{3}$ of the total isobaric cross section. The unmeasured yields at these mass numbers were estimated with the aid of nuclear charge dispersion curves.[7,8] The mass spectrometric datum at $A = 83$ is in excellent agreement with the radioactivation results and that at $A = 38$ is consistent with the data in the $A = 44$–50 mass region. The spallation cross sections decrease exponentially with decreasing mass over most of the mass range, as shown by the portion of the solid curve between $A \approx 48$ and 98. At lower mass numbers, the mass-yield curve gradually levels off and then begins to increase sharply below $A \approx 28$, where fragmentation becomes the dominant mechanism. The solid curve through the fragment cross sections is the power-law fit.[10,11]

The integrated spallation cross section is approximately $1b$. The total reaction cross section for the interaction of silver with high-energy protons is approximately $1.2b$.[18] Since the fission cross section of silver amounts to at most a few mb,[19] the fragmentation cross section is approximately $0.2b$. The integrated cross section between $A = 6$ and 28 is $1.26b$, indicating that several fragments are emitted in each interaction. In actuality, the multiplicity must be even higher than suggested by these data because the power law extends down to $A = 1$ (Ref. 11). Such high multiplicities have been observed in relativistic collisions,[20] and are consistent with our model of fragmentation,[10–12] in which a central collision imparts enough excitation energy to the struck nucleus to permit the hot remnant to cool and expand to the vicinity of the critical point, and break up into fragments.

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