An Accelerator Test of Semi-Empirical Cross-Sections

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We compare experimentally measured yields of isotopes of elements from $_{12}$Mg to $_{19}$K resulting from the fragmentation of ^{40}Ar with calculated yields based on semi-empirical cross-section formulae. The measurements, made at the LBL Bevalac using a beam of 287 MeV/amu ^{40}Ar incident on a CH_2 target, achieve excellent mass resolution ($\sigma_m \leq$ 0.2 amu) through the use of a Si(Li) detector telescope. The general agreement between calculation and experiment is good (rms difference $\simeq$ 24%), but some significant differences are reported.

1. Introduction. Cosmic ray composition studies rely heavily on semi-empirical estimates[1] of the cross sections for the nuclear fragmentation reactions which alter the composition during propagation through the interstellar medium. In many cases the errors in these cross section estimates result in significant uncertainties in cosmic ray source abundances or in propagation model parameters derived from observed abundances. To reduce these uncertainties, direct measurement of a wide range of nuclear fragmentation reactions would be desirable. In addition to measurements of key cross sections which strongly influence the interpretation of particular cosmic ray data, other cross section data are useful since they can be used as the basis for refining the semi-empirical formulae.

Accelerator calibrations of cosmic ray detectors provide a possible source of data for testing semi-empirical cross-section estimates. We have analyzed a set of data obtained during a calibration in which ^{40}Ar was fragmented in a CH_2 target, and have compared the observed isotope yields with those expected on the basis of the semi-empirical formulae. In this paper we report on a preliminary analysis of some of the systematic differences between the measured and calculated yields.

2. Experimental Setup and Data Analysis. The experimental data reported here were obtained at the Lawrence Berkeley Bevalac Laboratory accelerator in April, 1981 during the calibration of a set of detectors for a cosmic ray mass spectrometer. Figure 1 shows a schematic diagram of the experimental setup. A 287 MeV/amu ^{40}Ar beam exited the Bevalac vacuum and impinged on a 4.1 g/cm^2 CH_2 target. A variable thickness Cu absorber, located ~10m upstream from the target, was used to "tune" the energy of the beam so as to adjust the ^{40}Ar stopping point. The detector stack was located ~2m downstream of the target behind a thin multiwire proportional counter (MWPC) used to select for analysis those events within the central 20 cm^2 of the detector stack. The first four solid state detectors were

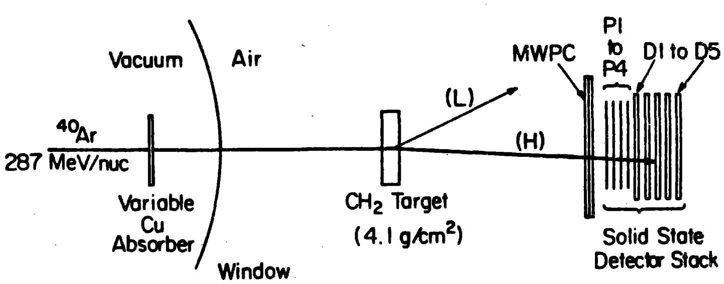
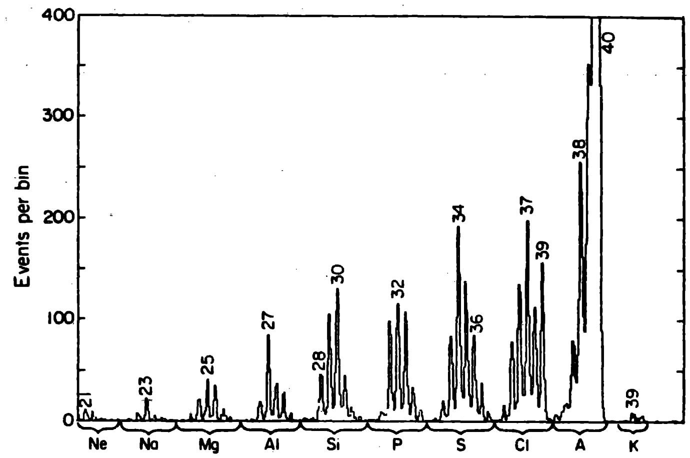


Fig. 1 : *Schematic diagram of the experimental setup (not to scale) showing an* ^{40}Ar *nucleus breaking up into heavy (H) and light (L) fragments.*

Fig. 2 : *Mass histogram of isotopes with $10 \leq Z \leq 19$ resulting from the breakup of ^{40}Ar. The mass (in amu) of selected isotopes is labeled. The observed mass resolution is ≤ 0.2 amu. The ^{40}Ar peak extends to >12,000 events. Note the ^{39}K and ^{40}K events tothe right of the ^{40}Ar.*



thin (<0.11 g/cm^2 total) and were not used in the present analysis. The CH_2 target constituted more than 80% of the grammage in front of the D1 detector.

Detectors D1 to D5 were large area Si(Li) devices, each 3 mm thick, except for D3, which was 5 mm thick. The outputs of detectors D1 to D4 were used to determine the charge (Z) and mass (M) of all heavy fragments stopping in D2 through D4. Figure 2 shows charge and mass distributions of Mg through K nuclei stopping in D3. Note that up to seven isotopes of each element can be identified. The present study is limited to data from a subset of the runs used to produce Figure 2, including data for which the non-interacting ^{40}Ar beam stopped in the first 2 mm of D2, so that nearly all of the fragments (those with $Z^2/A < (18)^2/40$) stopped in D2 to D4.

Because the experimental setup was designed primarily for detector calibration purposes, there are some limitations to its use for cross-section measurements. There was no absolute measure of the number of ^{40}Ar hitting the target. In addition, because of the target thickness, the energy at which the interactions occurred is not well defined. Finally, fragments emitted at large angles to the beam were not detected; the present analysis is limited to those within $\sim 1^{\circ}$ of the beam direction. On the other hand, with its excellent mass resolution, this data appears to be appropriate for measuring *relative* fragmentation yields, which for many purposes are adequate (see e.g., ref. 2). We have therefore adopted an analysis approach that takes advantage of this capability.

3. Calculations. The isotope yields expected on the basis of the Silberberg and Tsao (S&T) semi-empirical formulae[1] were calculated using a Monte Carlo approach. A large number (> 10^6) of ^{40}Ar nuclei simulated in this calculation were followed, taking into account ionization energy loss, as they traversed the stack of materials indicated in Figure 1. Distances traversed before undergoing a nuclear interaction were generated using the total cross-section formulae of Hagen[3]. The heaviest fragment nucleus produced in each such interaction was assumed to proceed forward with nearly the velocity of the fragmenting nucleus, while all lighter fragments were ignored. The relative probabilities of producing the various possible fragment were calculated from the Silberberg and Tsao cross section formulae[1], using their formulae[4] for scaling fragmentation on hydrogen to fragmentation on heavier nuclei where appropriate. Selected cross sections employed for the reactions $^{40}Ar + ^1H \rightarrow (Z,A) + X$ at 200 MeV/amu are listed in footnote 5. Two hundred MeV/amu is a typical interaction energy--the actual calculation took into account both energy loss and the energy dependence of the S&T cross sections.

The number of events of each product nuclide stopping in detectors D1 to D5, as determined by the calculation, was compared with the measured numbers of events stopping in D2 through D4. In addition, the Monte Carlo calculation provided a rough indication of the fraction of each nuclide which stopped outside the range we could measure, that is, in D1 or D5. In cases where these fractions were larger than the uncertainties in the observed yields, we treated the observations as lower limits.

4. Results and Discussion. The differences between observed and calculated yields should directly reflect inaccuracies in the S&T formulae. According to our calculations, most of the observed fragments are produced in a single interaction (the contributions from multiple interactions range from ~5% for Cl to ~25% for Mg), and ~92% of the interactions occur in the CH_2 target. Of the interactions in the CH_2, 46% involve collisions with H nuclei. Furthermore, cross sections for collisions with C are thought to scale from the cross sections on H (see, however, ref. 6). Thus our comparison of observed and calculated yields should provide a rather direct test of the accuracy of the S&T cross-sections for predicting relative yields for the inclusive reactions ${}^{40}\text{Ar}+{}^{1}\text{H}\rightarrow(Z,A)+X$ for fragments in the range $12\leq Z\leq 19$.

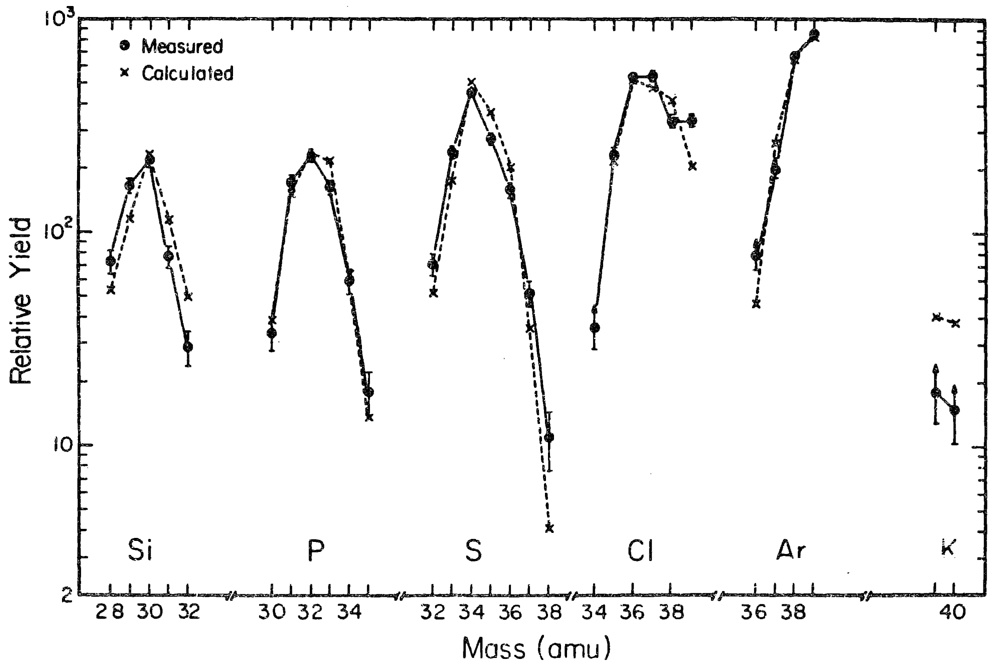


Fig. 3 : *A comparison of measured (●) and calculated (x) fragmentation yields, normalized to the same total yield of $14\leq Z\leq 18$ fragments. The experimental uncertainties are statistical only. Lower limits result when a significant fraction of the events stop outside the range of detectors D2 to D4.*

In Figure 3 we compare measured and calculated isotope yields. The calculated values have been normalized to have the observed total yield of fragments in the range $14\leq Z\leq 18$. Note that with this single normalization, the calculated and measured total *element* yields (from Si to Ar) each agree to $\leq 7\%$. However, for Al and Mg, the measured yields were considerably less than predicted with this same normalization. The origin of this difference is still under investigation.

The approximately Gaussian shape of the observed mass yield curves is expected on the basis of the semi-empirical formulae, and the observed widths of these distributions (standard deviations typically in the range 0.9 to 1.3 amu) are consistent with the predicted values. The *means* of the observed mass-yield curves, however, are systematically shifted to lower masses than expected from the calculations, as can be seen by inspection of Figure 3. For the elements $12\leq Z\leq 16$ these shifts lie in the range from 0.07 to 0.30 amu, with an average shift of 0.19 amu. The statistical significance of the individual shifts is 2 to 5 standard deviations. The observed mean mass of Cl fragments is greater than calculated by 0.08 amu, but the Cl production cross sections are calculated using peripheral reaction formulae, rather than the fragmentation formulae applicable for lighter elements. Furthermore, large discrepancies between measured and calculated yields are found for individual products of some peripheral reactions, such as ^{39}Cl, ^{38}Cl, and ^{38}S.

Figure 4 shows the distribution of ratios between the observed and calculated yields of individual nuclides with $14 \leq Z \leq 18$ for which at least 30 events were collected in the experiment. The distribution has an rms spread of 24%, comparable to the claimed accuracy of the S&T formulae[1].

Also notable are significant yields of the isotopes ^{39}K and ^{40}K (see Figures 2 and 3), which are produced by charge-exchange reactions. Our measurements provide lower limits for the yields of these isotopes (since some of the K fragments stop in D1 and are not counted in the present study) which are consistent with the S&T predictions for reactions of the type (p, xn)[7].

We find that significant information for refining the semi-empirical calculation of fragmentation cross sections can be obtained from data collected during the calibration of cosmic ray detector systems when such calibrations are performed under suitable conditions. Further analysis of the calibration which provided the data for the present study, and of other similar calibrations, should provide more detailed comparisons of semi-empirical cross-section predictions with experimental measurements.

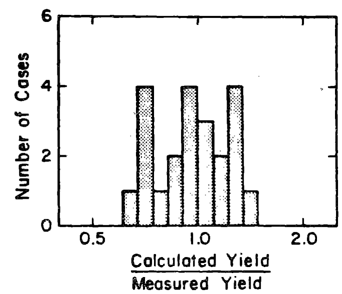


Fig. 4 : *Distribution of the ratio of calculated to measured yields for 22 nuclides, with the normalization discussed in the text. The rms is 24%.*

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[5]Selected cross sections (in millibarns) for ^{40}Ar+^{1}H→(Z,A)+X at 200 MeV/amu : ^{40}K - 3.8; ^{39}K - 3.9; ^{39}Ar - 54; ^{38}Ar - 52; ^{37}Ar - 19; ^{39}Cl - 11; ^{38}Cl - 34; ^{37}Cl - 37; ^{36}Cl - 46; ^{37}S - 1.5; ^{36}S - 16; ^{35}S - 29; ^{34}S - 37; ^{33}S - 8.7; ^{34}P - 3.5; ^{33}P - 14; ^{32}P - 13; ^{31}P - 6.3; ^{31}Si - 4.9; ^{30}Si - 9.8; ^{29}Si - 3.5; ^{29}Al - 2.1; ^{28}Al - 3.2; ^{27}Al - 2.3; and ^{25}Mg - 1.2.

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