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FRAGMENTATION OF $^{40}$Ar AT 213 MeV/NUCLEON*

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Abstract:

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. 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 becomes the dominant peripheral process. However, projectile excitation followed by equilibration and decay can also explain many features of the results with $^{16}$O. 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 thorium and carbon targets of thickness 140 and 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 $\Delta E$ 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 multi-element detector telescope to give several identifications. For each event the weighted mean and $\chi^2$-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 $\chi^2$-distribution. The resulting mass spectra had a resolution varying from 0.2 amu for oxygen to 0.5 amu for sulphur.

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 sulphur to ~22% for oxygen. The absolute normalization is uncertain to within a factor of two.

For projectile fragmentation reactions at relativistic energies, the longitudinal momentum distributions of fragments in the projectile rest frame are well described by Gaussian distributions. In the models of Ref. 3 the widths $\sigma$ of these distributions are given by

$$\sigma^2 = \sigma_0^2 \frac{M_f (M_p - M_f)}{(M_p - 1)}.$$  \hspace{1cm} (1)

Here $M_f$ and $M_p$ are the fragment and projectile masses and $\sigma_0$ 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). Fig. 1(b) summarizes the values of $\sigma_0$ 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 $\sigma_0$ may be related to the Fermi momentum of the
projectile by the relation $\sigma_0 = p_F^{\sqrt{2}}$. The mean value of $\sigma_0$ gives
$p_F = 209 \pm 11 \text{ MeV/c}$, compared to the value of $251 \pm 5 \text{ MeV/c}$ for $^{40}\text{Ca}$
measured in electron scattering. Alternatively if we assume that the
emitting system was in thermal equilibrium, the parameter $\sigma_0$ is related
to the nuclear temperature $T$ by $\sigma_0^2 = m_N T (M_p - 1)/M_p$ where $m_N$
is the nucleon mass in MeV. Our results give $T = 9.6 \pm 1.1 \text{ MeV}$, only slightly higher
than results for $^{16}\text{O}$-induced reactions at various energies.

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. 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 $T = 9.6 \text{ MeV}$ are compared to the data
for the elements 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.
In these calculations, the primary fragment mass distributions are deter-
mined from the geometry of the fireball model and the primary
isotope distributions depend on the extent of proton-neutron correlations
in nuclei. 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. We investigated two assumptions: (a) no correlations (NC) and (b) proton-neutron correlations arising from the zero-point vibration (isospin $T = 0$ mode) of the giant dipole resonance (GDR). The de-excitation of the primary fragments by particle evaporation was calculated with the computer code OVERLAID ALICE. Taking the excitation energy of the primary fragments as the difference in surface energies of the abraded projectile and a spherical nucleus of identical mass the 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). 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 distributions are sensitive to the excitation energy of the primary fragments. 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. 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, a similar increase in excitation energy results in a minor reduction of the widths of the isotope distributions - not shown in the figures.) It is clear from the figures that the experimental isotope distributions can also be explained assuming no correlations if this extra excitation energy can be justified.
In conclusion, the model of the decay of an excited projectile cannot account for isotope distributions in our case, although this model was considered an acceptable alternative for \(^{16}\)O-induced reactions. The abrasion ablation model is able to give a good account of the present experimental data. Considering 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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Footnotes and References

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Figure Captions

Fig. 1  (a) Measured energy spectrum of $^{34}$S at 1.5° from fragmentation of 213 MeV/nucleon $^{40}$Ar on carbon target. The solid line corresponds to a fitted Gaussian momentum distribution.

(b) Values of $\sigma_0$ for the fragments in the mass range 16 to 37. (For each fragment, the weighted mean of $\sigma_0$ obtained from the energy spectra at many angles are 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 sulphur.

Fig. 3 Comparison of experimental isotope productions cross-sections for Ar+C with model predictions as described in the 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.
a) $^{34}\text{S}$ at 1.5°

$\sigma_0 = 87 \pm 5 \text{ MeV/c}$

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b) $^{40}\text{Ar}$, 213 MeV/A

$\langle \sigma_0 \rangle = 94 \pm 5 \text{ MeV/c}$
$^{40}$Ar, 213 MeV/A

Cross section (mb)

NC (×1.306)
NC + ADDITIONAL EXCITATION, (×1.666)
GDR (×1.351)

Z

XBL 7810-11521
$^{40}$Ar, 213 MeV/A

![Graph showing cross section vs. fragment mass number for different Z values.]

**Fig. 3**

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