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Very-High Energy ($E \rightarrow E_{beam}$) Light Particle Production Near 0° in Heavy-Ion Collisions, $E/A \leq 40$ MeV/u.

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Studies of heavy-ion collisions at $E/A \sim 10$ MeV/u to 20 MeV/u with the production of nucleons and other particles at forward angles with velocities several times that of the projectile have been observed by many groups (TAM, ORNL, MSU, HMI). This is usually attributed to projectile fragmentation with Fermi motion of the light particle[1,2] which is often described by a source temperature T_s, accounting for the additional velocity component. However, experiments reported by Borcea *et al.*[3] and those done[4] at the Hahn-Meitner Institute (VIKSI) have suggested that high-energy alpha particles observed near $\theta = 0°$ in ^{20}Ne-induced collisions, $E/A \leq 20$ MeV/u, may arise from mechanisms such as cluster transfer reactions. Here we report observation of a similar phenomenon with a variety of projectiles ($Z \geq 8$), $E/A = 9$ to 40 MeV/u.

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The projectiles and bombarding energies studied are shown in Table I. Most of the data presented here were taken using a 50 mm diameter by 150 mm long BGO scintillator situated 0.5 m to 1 m behind a tantalum target which also served as a beam stop and permitted measurements at $\theta = 0°$. Additional detectors (NaI), were situated at angles $\theta \geq 0°$. The BGO detector could stop protons up to about 400 MeV and α particles up to 1.5 GeV. Particles were identified in the BGO using time-of-flight (TOF) while those in the NaI($T\ell$) were identified with a combination of pulse-shape discrimination (PSD) and TOF. In addition to thick-target measurements at $\theta = 0°$ we have also recently utilized a thin/thick target scheme with TOF used to separate the thin target spectra from the thick target spectra. This allows us to take spectra at $\theta = 0°$ with a well-defined beam energy (unlike the thick target stopped-beam data).

Some of the light particle spectra observed at $\theta = 0°$ are displayed in Figures 1 and 2. They typically peak at an energy near that corresponding to the projectile velocity (although the spectra shown are cut off by lower discriminators), then fall off as $\sim \exp - E_L/T_L$ (where E_L is the fragment's lab energy and T_L is a slope parameter) and finally turn over and reach some end-point energy, $E^0_{\max}$. This type of spectrum is typical of a 3-body phase-space with some threshold Q value determining $E^0_{\max}$, *i.e.* the kinematic energy limit at $\theta = 0°$. In the case of the ^{16}O projectiles (Fig. 1), the α spectra near $\theta = 0°$ extend out to

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the full beam energy while the proton spectra typically extend out to about half the beam energy. Deuterons, tritons and ^{3}He particles are less intense but also extend out to a significant fraction of the beam energy. As also observed in Ne-induced[3,4] reactions $E/A \doteq 10$ MeV/u, alpha particles are several times more copious than protons emitted near $\theta = 0°$. The high-energy portions of the light-particle spectra, especially for protons and alpha particles, are sharply peaked in angles near $\theta = 0°$, whereas the lower-energy particles along with the deuterons and tritons are emitted more isotropically[1-4], the latter being consistent with conventional compound-nuclear evaporation. In contrast, the ^{58}Ni data exhibit α-particle endpoints which are much less than the full beam energy. The slope parameters are also much lower. The data for ^{32}S and ^{40}Ar are intermediate *viz.* E_α (and E_p) approach a significant fraction of, but not the full beam energy (but still $v >> v_{\mathrm{beam}}$).

We have calculated spectra expected[1] assuming fragmentation (with Fermi motion) of a fast source moving with some fraction of the projectile velocity, v_p and having a source "temperature," T_s. The latter, while it will be called a "temperature," does not imply thermal equilibrium and hence necessarily correspondence to a nuclear temperature. It is known that most fragmentation data $\theta \geq 20°$ can be fit with a moving source model with a source velocity of about half the beam velocity ($v_s \approx 0.5v_p$). The latter is characteristic of a region of overlap between the projectile and target where nucleon-nucleon collisions dominate. However, the moving source model with $v_s \doteq 0.5v_p$ does not properly predict the observed angular distributions as $\theta \rightarrow 0°$ especially for the α-particles.

In order to fit the high-energy particle data as $\theta \rightarrow 0°$ (Fig. 3) one needs *both* $v_s \rightarrow v_p$ and an increase in T_s. The slope parameters, T_s, deduced from our high-energy particle spectra assuming $v_s = v_p$ are rather larger *viz.* T_s (protons) $\doteq 4$ to 11 MeV and T_s (alphas)$\doteq$ 7 to 17 MeV (Table I). The most notable exception is the ^{58}Ni data, which indicates T_s (protons) $\doteq$ 4 MeV and T_s (alphas) $\doteq$ 6 MeV. In thermal equilibrium the source "temperature" for emitted nucleons should be comparable to a typical nuclear fermi energy, T_F, of 3 to 8 MeV. Instead, we require source "temperatures" of 10 to 20 MeV to reproduce many of the alpha spectra. The moving-source temperatures needed to fit the data is shown in Fig. 4 and compared with other results, mostly for data where $v \approx v_p$ to $v_p/2$ and $\theta \geq 5°$. Although the trends are similar *i.e.* T_s increases with E/A_{beam}, the α-particle data at $\theta = 0°$ exhibits significantly higher T_s values.

As suggested by (Ne, α) experiments at lower energies[3] the high-energy portions of the alpha spectra and in particular the fact that $E^0_{\mathrm{max}} \doteq E_{\mathrm{projectile}}$ suggest that mechanisms other than fragmentation *e.g.* cluster transfer may be important and can produce very-high energy light particles. In this model one treats

(^{16}O, α), (^{20}Ne, α), (^{40}Ar, α) as a massive transfer reaction with $E^{\alpha}_{\rm max}$ given by the kinematic limit with $Q_\alpha \equiv Q(\mathrm{X}, \alpha) \approx 0$ to -50 MeV. We display these limits on some of the figures. There appears to be some correlation.

We plan to extend our measurements to $E/A > 40$ MeV using the new k = 800 Phase II cyclotron at MSU-NSCL. This work was supported in part by NSF (UM, MSU) and DoE (ANL).

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Table 1

System	$E^{b)}$	E/A	Protons		Alphas	
	(MeV)	MeV/u	T_L(MeV)$^{a)}$	T_s(MeV)$^{b)}$	T_L(MeV)$^{a)}$	T_s(MeV)$^{b)}$
^{32}S+^{181}Ta	305	9.5	6.4	4.4	12	7
	450	14	11	7.3	19	10
^{58}Ni+^{181}Ta	600	10.3	5.2	4.2	11	6
^{16}O+^{181}Ta	480	30	12	7.7	24	14
	640	40	15	9.5	28	17
^{40}Ar+^{181}Ta	800	20	8.4	5.5	12	7
	1200	30	16	10.4	25	15

a) ANL-ATLAS; b) MSU-NSCL ; c) $\frac{dN}{dE} \approx \sqrt{E_L}\, e^{-\frac{E_L}{T_L}}$; d) Moving source fit ($v_s = v_p$)

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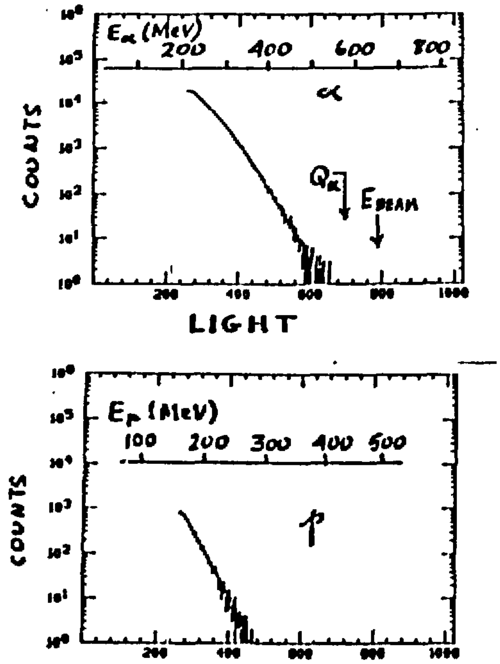

Fig. 1. Spectra of protons and α particles in BGO from $\mathrm{Ta}(^{16}\mathrm{O},x)$ at $\theta = 0°$, $E/A = 40\,\mathrm{MeV/u}$.

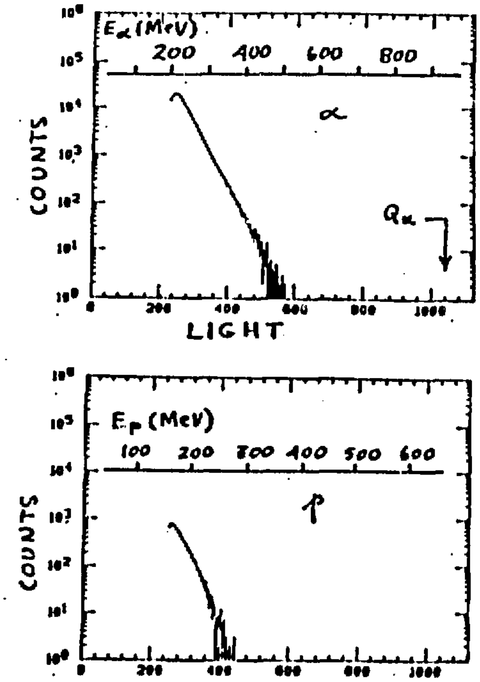

Fig. 2. Spectra of protons and α particles in BGO from $\mathrm{Ta}(^{40}\mathrm{Ar},x)$ at $\theta = 0°$, $E/A = 30\,\mathrm{MeV/u}$.

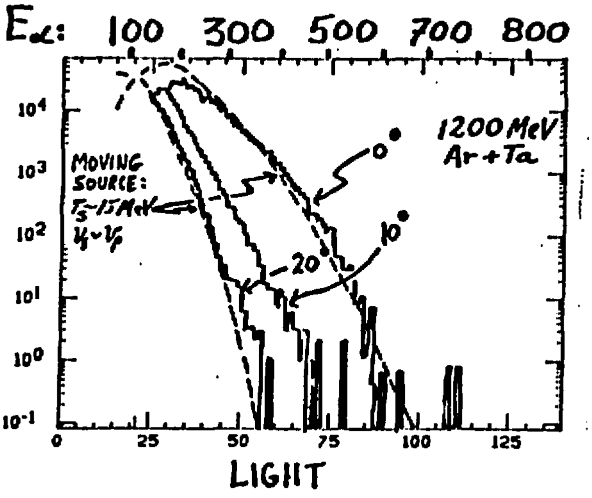

Fig. 3. Angular distribution of high energy α particles and moving-source fit ($v_s \approx v_p$).

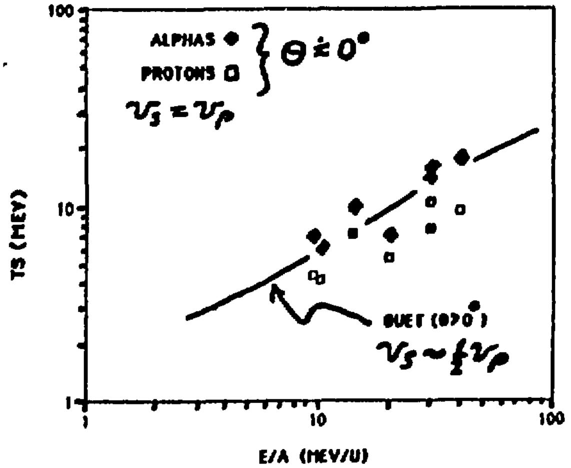

Fig. 4. Systematics of moving source slope parameter ("temperature").