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HIGH ENERGY PROTON EMISSION IN REACTIONS INDUCED BY 135 MEV 160 IONS

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HIGH ENERGY PROTON EMISSION IN REACTIONS INDUCED BY 315 MEV ^{16}O IONS

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Abstract:

Inclusive proton spectra have been measured for the reaction $^{197}Au(^{16}O,p)X$ at 315 MeV. The data, which are consistent with emission from a moving source, are compared with the fireball model and with models of preequilibrium emission.

In this letter we report the measurement of inclusive proton spectra from the reaction of 315 MeV ^{16}O ions on a ^{197}Au target. The motivation for this work was provided by the growth of interest in high energy proton emission accompanying heavy ion collisions. At low energies, ($E/A \leqslant 10$ MeV/nucleon) the emission of energetic light particles has been discussed in terms of break-up reactions,[1] cascade calculations,[2] preequilibrium models[3] and, more recently, hot spots[4] and jets.[5,6] At relativistic energies

(E/A $\geqslant$ 200 MeV/nucleon) the concept has emerged of a localized equilibrated source moving at a velocity midway between projectile and target residue, and quantitative descriptions of inclusive spectra have been possible in terms of the fireball[7] and firestreak[8] models. It is an important question to ask what happens to the concept of localization used in the fireball model as the bombarding energy is reduced. For example, it has been suggested[4] that this localization may persist in the form of hot spots on the nuclear surface. Nevertheless, it is clear that a transition must take place to mean field phenomena[9] and that the energy at which it occurs should be related to the relaxation time of nuclear matter. We find that at 20 MeV/nucleon, in the transition region between low and high energy processes,[10,11] the fireball model gives a surprisingly good account of the observed spectra. Simultaneously, however, a description appears possible in terms of conventional low energy concepts.

The $^{16}O^{6+}$ beam from the Lawrence Berkeley Laboratory 88-Inch Cyclotron was used to bombard a ^{197}Au target of 9.5 mg cm^{-2}. High energy protons were detected in a telescope consisting of 1 mm and 5 mm thick Si(Li) detectors, each of 5 cm diameter, and a 7.5 cm × 7.5 cm cylindrical NaI(Tl) detector. The detectors were mounted outside a sliding seal scattering chamber and viewed the target through a 0.002" Mylar window. A second telescope made up of a 200 μ Si surface barrier detector, a 5 mm Si(Li) detector and a veto detector, was mounted inside the scattering chamber and was used to measure low energy light particles. The detectors were calibrated up to 90 MeV proton energy with 45 MeV protons elastically scattered from ^{197}Au and polyethylene targets and also with protons produced in the $^{12}C(\alpha,p)^{15}N$ reaction at incident energies of 65, 90 and 110 MeV. The absolute cross sections are accurate to ± 30%.

In Figure 1 we show the proton spectra obtained from the gold target. The differential cross section decreases smoothly as a function of increasing angle and energy, as in previous observations at both high and low energies. In recent experimental studies, this type of spectrum has been analyzed by extracting the temperature as a function of angle in the centre of mass frame,[12] the variation with angle being taken as a signature of preequilibrium or hot spot phenomena. In a first analysis, we prefer to investigate whether the present data can be described by isotropic evaporation from a moving source with a single characteristic temperature, T. The justification for such an approach is illustrated in Fig. 2 where points of constant invariant cross section are plotted in the parallel and perpendicular velocity plane. It may be seen that the data are rather well described by circles centred about a velocity midway between target and projectile, as would be expected for evaporation from a system moving with this velocity. If we assume a simple exponential dependence of the cross section in the moving frame, then, transforming to the laboratory, we obtain

$$\sigma(\Theta_L, E_L) = \sqrt{E_L}\,\sigma_{inv}\; e^{-(E_L - 2a\sqrt{E_L}\,\cos\Theta_L + a^2)/T}$$

Here, Θ_L and E_L are the angle of observation and energy of the outgoing proton, σ_{inv} is the inverse cross section and a^2 is the energy of a proton with the velocity of the moving frame.

The best fit of this formula to the high energy region of the spectra ($E_L > 20$ MeV) is shown by the full lines in Fig. 1. These curves correspond to a source with a temperature of 8.1 MeV moving at a velocity of 0.10c in the laboratory. We note that these values are very much higher than would be expected for evaporation from the equilibrated compound nuclear system, for which the reaction kinematics and the Fermi gas model (with a = A/8) give 3.3 MeV and 0.016c. We note also that the fitted velocity is almost exactly one half that of the projectile (0.21c); it is, therefore, equally difficult to account for these data by evaporation from an excited projectile, although a large contribution is to be expected from this process at the most forward angles. This was confirmed in a recent study[13] of the $^{56}Fe(^{12}C,p)X$ reaction at 195 MeV, where the data were compared with cascade calculations at 10° and 30°.

Qualitatively, the experimental spectra are similar to those observed in relativistic heavy ion collisions which have been successfully described by the fireball model. We have made a simple fireball calculation using the techniques described in Refs. 7, 8, 14 to calculate the excitation energy and velocity of the fireball. The fireball temperature was calculated using the Fermi gas equation of state at normal nuclear density (r_o = 1.2 fm) and also at a 40% greater density (r_o = 1.07 fm). The values obtained for temperature (T), Fermi energy (ε_F) and chemical potential (μ) are presented in Table 1 and the predictions with r_o = 1.2 fm are shown by the dashed lines in Fig. 1. The agreement between experiment and theory is fair although the absolute cross section is underestimated by a factor of 2 at forward angles. The following points should be understood regarding this calculation: (i) It has been assumed that the simple geometrical formulae may be used at an energy where Coulomb effects are important and total fusion is still a significant process. (ii) If one is to believe in the separate identity of the fireball, then the simple assumption of emission of all unbound nucleons should be replaced by an evaporation calculation at such low excitation energies. (iii) No account has been taken of complex particle emission which, if included, would further reduce the predicted proton cross section. It is, however, important to realize that the agreement for these inclusive spectra is comparable to that obtained at much higher bombarding energies of 250 and 400 MeV/nucleon.

As an alternative, and perhaps more conventional approach, we have also investigated the extent to which these data may be described by preequilibrium models. We have used the hybrid formulation[3] of the exciton model[15] to calculate the angle integrated cross sections. In this model the initial exciton number is essentially a free parameter and in Fig. 3, we show the angle integrated cross sections assuming initial configurations of 16, 20, 24, 28 and 32 excitons. It may be seen that a value between 20 and 24 excitons describes the angle integrated spectrum well in both slope and absolute magnitude. This is very reasonable since it has been found that for light ion reactions the initial exciton number is usually only slightly greater than the number of nucleons in the projectile.[3] Also shown in the figure is the compound nuclear cross section predicted by the code overlaid ALICE,[16] which is able to give a good account of the low energy region.

Recently, preequilibrium models have been generalized[17] to predict angular distributions. Combining these methods with the 24 exciton hybrid calculation, one obtains the dotted curves in Fig. 1. The distributions are in reasonable agreement for angles greater than 30° but underestimate the 20° cross section by at least a factor of 2. This almost certainly arises from the neglect of projectile excitation at these angles and from the simplifications inherent in this calculation.

In conclusion, both the fireball model and the hybrid model can give a resonable description of the high energy proton spectra measured in this experiment. The great advantage of the hybrid model[3,15] is that it is a microscopic model in which the cross sections are calculated in closed form, in marked contrast to cascade calculations. However, it should be remembered that while this model allows for proton emission before the excitation energy is equilibrated over the whole system, leading to higher effective temperatures, there is no geometrical localization which is the basis of the hot spot and fireball models. The simultaneous success of the fireball calculation provides evidence that such localization may already be important at these energies. Finally, one may note that, as in the case of complex fragment emission,[10,11] a transition between the inclusive spectra observed at low and high energies appears to have set in at 20 MeV/nucleon. It is to be hoped that unified descriptions of heavy ion processes in this energy range may lead to the deduction of constants such as the thermal conductivity of nuclear matter as has been attempted for hadron-hadron collisions.[4]

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Footnotes and References

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Table I. Parameters of Fireball Calculation for the Reaction of 315 MeV ^{16}O on ^{197}Au.

# Participants	r_o fm	ε_F MeV	μ MeV	v/c	T MeV
51.5	1.2	33.52	33.05	0.06	7.6
	1.07	42.48	41.02	0.06	8.5

Figure Captions

Fig. 1 Cross sections for production of protons in the reaction $^{197}Au(^{16}O,p)X$, together with fitted and calculated spectra as described in the text.

Fig. 2 Points of constant invariant cross sections in the parallel and perpendicular velocity plane. The lines indicate contours of the constant cross section for isotopic evaporation from a source with half the projectile velocity.

Fig. 3 Angle integrated cross sections for the reaction $^{197}Au(^{16}O,p)X$ at 315 MeV together with predictions of the hybrid model as described in the text.

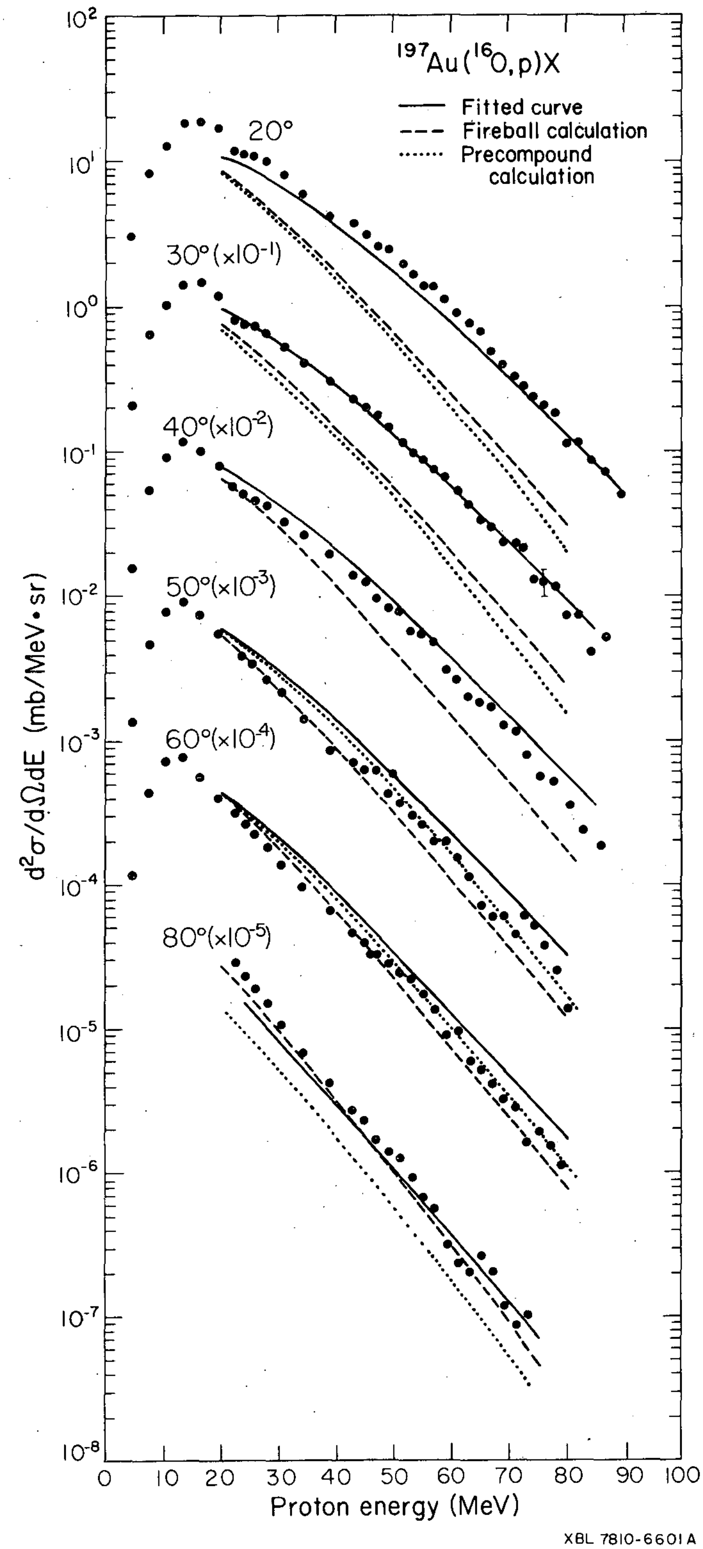
$^{197}Au(^{16}O,p)X$
Fitted curve
Fireball calculation
Precompound calculation
20°
30°(×10⁻¹)
40°(×10⁻²)
50°(×10⁻³)
60°(×10⁻⁴)
80°(×10⁻⁵)
$d^2\sigma/d\Omega dE$ (mb/MeV•sr)
Proton energy (MeV)
XBL 7810-6601A

Fig. 1

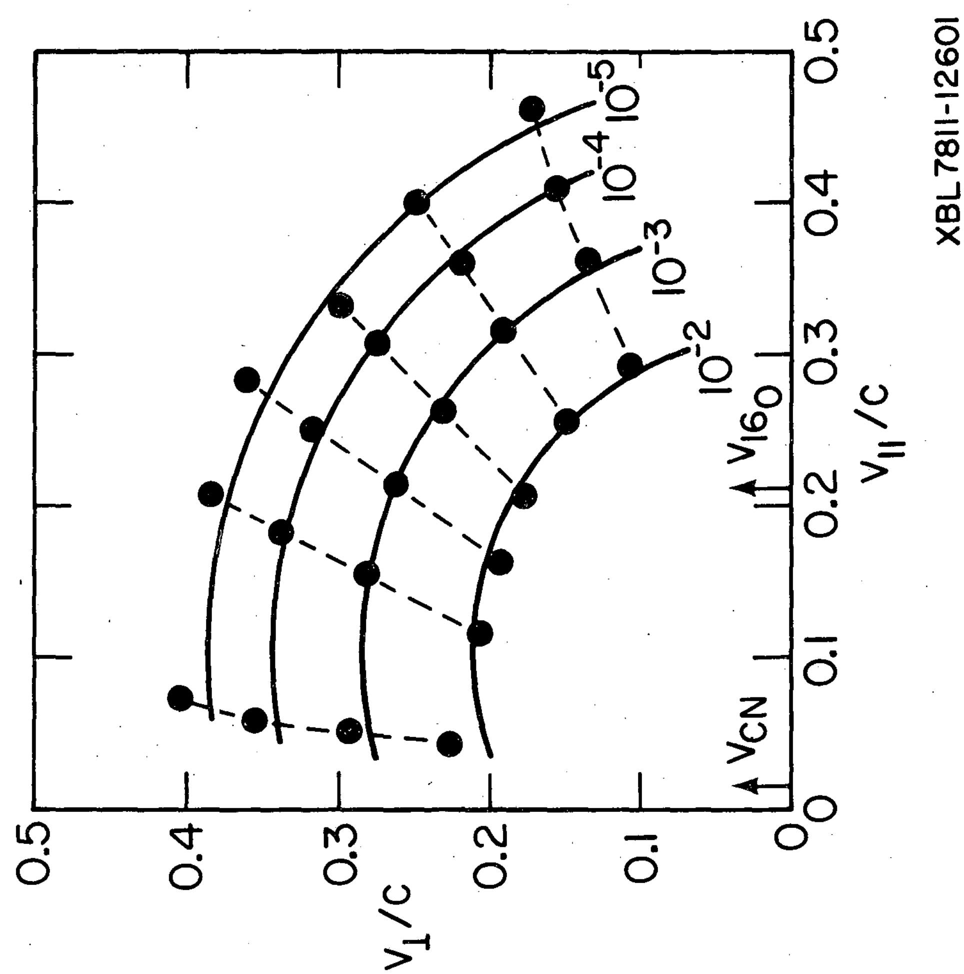
0.5
0.4
0.3
0.2
0.1
0
$V_\perp/c$
0.1
0.2
0.3
0.4
0.5
$V_{\parallel}/c$
V_{CN}
$V_{^{16}O}$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
XBL 7811-12601

Fig. 2

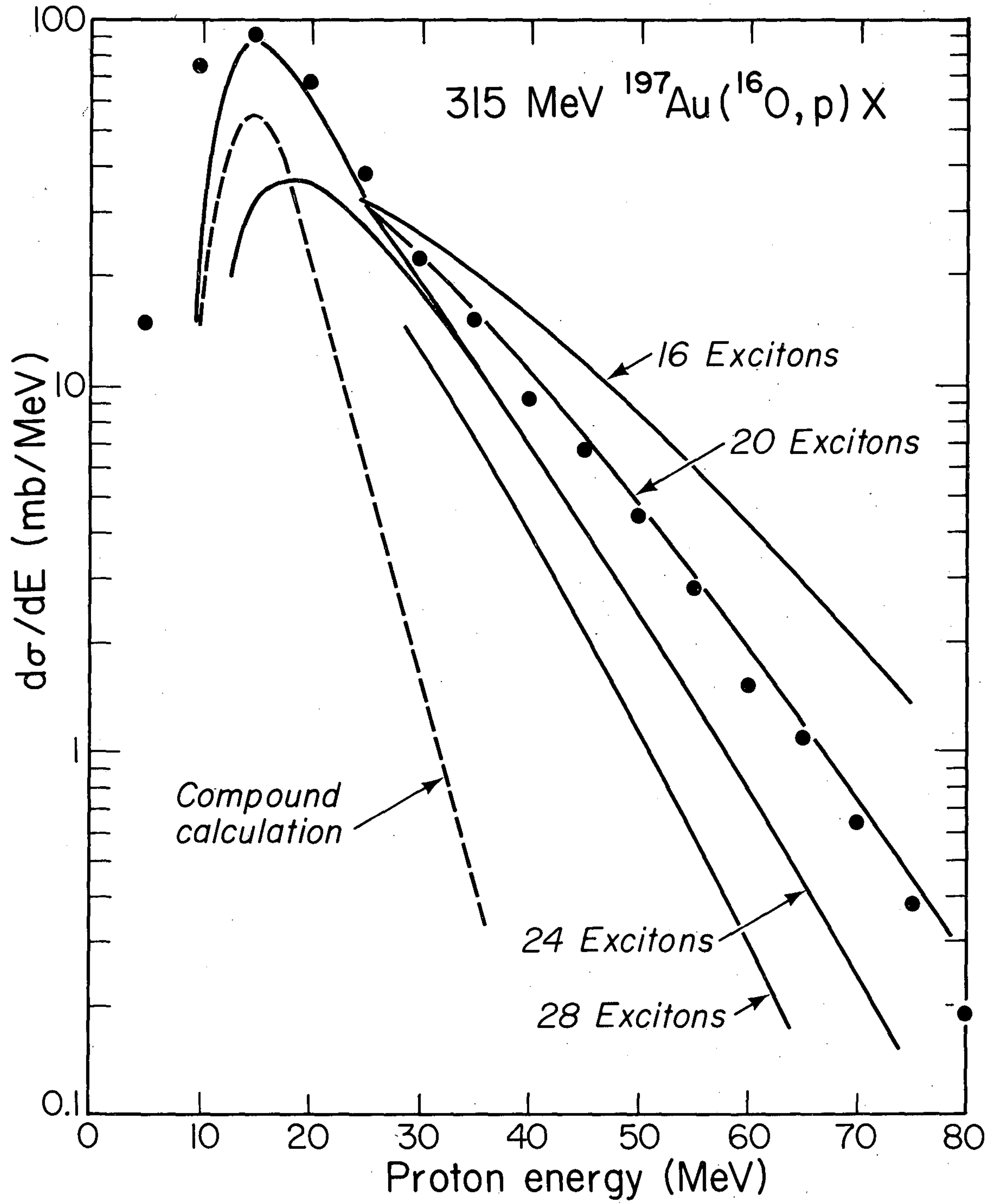
315 MeV ^{197}Au(^{16}O, p) X
dσ/dE (mb/MeV)
Proton energy (MeV)
16 Excitons
20 Excitons
24 Excitons
28 Excitons
Compound calculation
100
10
1
0.1
0
10
20
30
40
50
60
70
80
XBL 7810-6565

Fig 3

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