CONF-8806117--6

EXTENDED EMISSION SOURCES OBSERVED VIA TWO-PROTON CORRELATIONS*

T. C. Awes, R. L. Ferguson, F. E. Obenshain, F. Plasil, and G. R. Young
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

S. Pratt†
Department of Physics, University of Tennessee
Knoxville, Tennessee 37966-1200

CONF-8806117--6

DE88 012481

Z. Chen, C. K. Gelbke, W. G. Lynch, J. Pochodzalla,§ and H. M. Xu
National Superconducting Cyclotron Laboratory
Michigan State University, East Lansing, Michigan 48824-1321

Two-proton correlations were measured as a function of the total energy and relative momentum of the protons. The correlation is analyzed for different orientations of the relative momentum, which allows information on the size and lifetime of the emission source to be extracted. The most energetic particles are emitted from a short-lived source of compound nucleus dimensions while the lower energy protons appear to be emitted from a source considerably larger than the compound nucleus.

Two-particle correlations between light particles emitted in heavy-ion reactions may be used to extract information on the spatial extent and time development of the emission source. Such measurements have provided evidence for the formation and decay of localized regions of high excitation.[1-5] An interesting aspect of these measurements is the observation that the less energetic particles are emitted from sources of larger apparent dimensions. This has been interpreted as an indication that the lower energy particles are emitted at a later, more equilibrated stage of the reaction.[6,7] As originally pointed out by Koonin,[8] the dependence of the two-particle correlation on the direction of the relative momentum, with respect to the direction of emission,

MASTER

provide information on the source lifetime and shape. Although spatial and temporal effects are not strictly distinguishable, a long-lived spherical emission source will have a characteristically prolate appearance, elongated in the direction of emission.[7,8]

The experiment was performed at the Holifield Heavy Ion Research Facility in Oak Ridge. A natural Ag target of 9.9 mg/cm^2 areal density was bombarded by a ^{32}S beam of 22.3-MeV/nucleon incident energy. Protons were detected in a closely packed hexagonal array of 13 ΔE-E telescopes. Each telescope consisted of a 400-μm-thick Si detector and a 10-cm-thick NaI detector, and each subtended a solid angle of 0.67 msr with an angular separation of 4.1° between adjacent telescopes. The hodoscope was centered at a laboratory angle of 30°. The energy calibration is accurate to within 3%. An energy threshold of 12 MeV has been used in the off-line analysis of the proton data presented here. The correlation data have been corrected for random coincidences, which were always at a level of less than 10%.

The correlation function $R(\vec{K},\vec{q})$ is extracted from the ratio of the coincidence yield $Y_{12}(\vec{p}_1,\vec{p}_2)$ to the singles yields $Y_1(\vec{p}_1)$ and $Y_2(\vec{p}_2)$ of particles 1 and 2 according to:

$$\sum Y_{12}(\vec{p}_1,\vec{p}_2) = C_{12}\ [1 + R(\vec{K},\vec{q})] \sum Y_1(\vec{p}_1)\ Y_2(\vec{p}_2) \qquad (1)$$

where $\vec{p}_1$ and $\vec{p}_2$ are the momenta of the two protons and $\vec{K}$ and $\vec{q}$ are the total and relative momenta of the pair, respectively. The single overall normalization constant, C_{12}, was chosen such that after summing Eq. (1) over all $|\vec{K}|$ and directions, $\langle R(|\vec{q}|)\rangle = 0$ in the interval $52 < |\vec{q}| < 80$ MeV/c. For each gating condition, the sums on both sides of Eq. (1) were extended over all detector and proton energy combinations corresponding to the given bins of $\vec{q}$.

Examples of the measured directional dependence of the correlation functions are shown in Fig. 1 for the ^{32}S + Ag reaction for gates on the total kinetic energy of the emitted pair of E_{pp} = 60-70 and 90-100 MeV. For each energy gate the correlation is shown for relative momenta either parallel (θ_{rel} = 0° ± 30°, or 180° ± 30°) or transverse (θ_{rel} = 90° ± 30°) to the direction of the emitted proton pair. Within statistics, no difference was observed between transverse directions in and out of the reaction plane; therefore, all transverse directions have been summed together. The finite size of the detector hodoscope introduces cutoffs in the relative momentum, which are clearly seen in Fig. 1. For relative momenta in the longitudinal direction, the minimum angle between adjacent detectors introduces a cutoff at small q. Similarly, the maximum angle between detectors introduces a cutoff at large q for relative momenta transverse to the direction of emission. The location of these cutoffs has been verified by a Monte Carlo calculation which included the geometrical acceptance and energy and angular resolution of the hodoscope.

Also shown in Fig. 1 are theoretical results calculated for non-spherical gaussian-shaped sources of longitudinal and transverse "radii" R_L and R_T.

$$f_K(\vec{r}, t \rightarrow \infty) = f_o \exp - \frac{x^2 + y^2}{R_T^2} + \frac{z^2}{R_L^2} \qquad (2)$$

The relative wavefunctions were obtained by solving Schroedinger's equation with the Reid soft core potential for the l = 0,1 partial waves and with only the Coulomb potential for the higher waves. The theoretical correlation functions were averaged over the same directions as the experimental bins. Since the theoretical calculation does not include the dynamics necessary to predict the absolute probability of two-particle to one-particle events, the theoretical curves were multiplied by a different factor for each energy gate to match the experimental correlation function.

At high proton emission energies, both the longitudinal and transverse correlations are observed to exhibit strong enhancements of approximately equal strength (see Fig. 1a). The similarity of the correlation in the two directions indicates a spherical emission source. The calculation shown in Fig. 1a corresponds to the correlation expected from a spherical source of negligible lifetime and compound nucleus dimensions, $R_T = R_L = 4$ fm. [Note that equivalent sharp sphere radii are $\sqrt{5/2}$ larger than the radii used in Eq. (2).] More surprising is the result seen in Fig. 1b that, although the correlation is weaker for low proton emission energies, no obvious directional dependence is observed. The weak angle-integrated correlations observed for low-energy protons have previously been suggested to result from extended emission times, as from the later stages of an evaporation process. Calculated correlations are shown for an evaporative-type source with a transverse radius of 4 fm and a longitudinal dimension of 20 fm. Although the calculated longitudinal correlation is in reasonable agreement with the experimental result, the theoretical transverse correlation is Pauli suppressed, due to the short transverse dimension, in contrast to the observed result. It is seen that a better description of the low-energy proton result is obtained by the assumption of a spherical source of 6.5 fm radius.

The difference between the calculated longitudinal and transverse correlations can also be decreased by increasing the longitudinal dimension (or, equivalently, increasing the lifetime) while keeping the transverse size fixed. This is illustrated in Fig. 2 where the calculated correlation for both directions at $q = 25$ MeV/c (where the two correlations differ strongly) is shown as a function of the longitudinal size.

It is seen that the two correlations again become similar for very large longitudinal radii, that is, for long lifetimes, but that the correlation itself becomes very weak due to the increased volume, contrary to observation (see Fig. 1b).

The energy dependence of the proton emission source shape is shown in more detail in Fig. 3 for proton pair total kinetic energies ranging from 105 MeV down to 55 MeV. The source radii were extracted by fitting the measured longitudinal and transverse correlations to the theoretical correlations. As noted in the discussion of Fig. 1, although the high-energy protons appear to be emitted on a short timescale from a volume consistent with the combined system, the lower energy protons appear to be emitted from an extended spherical volume of up to twice the compound nucleus radius, rather than being emitted over an extended period of time from the compound nucleus. The trend expected for the case of evaporative compound nucleus emission is also indicated in Fig. 3. In this case the transverse radius would remain equal to the compound nucleus radius ($R_T = 4$ fm), while the longitudinal radius will appear to increase by the emission lifetime τ, $R_L = (R_T^2 + V_K^2\tau^2)$. It should be pointed out that the lowest proton energies considered here are still considerably above the Coulomb barrier, where a long evaporation timescale would clearly be expected. However, due to the experimental uncertainties and the weakness of the observed correlation at the lowest proton-pair kinetic energy of 55 MeV, the loose upper bound on the longitudinal radius allows that the emission source may in fact be elongated due to the emission timescale, although the large transverse radius does require a large spatial extent (see Fig. 3).

In conclusion, the observed directional dependence of the proton-proton correlations indicates that the lower energy protons are emitted from an extended source considerably larger than the compound nucleus rather than from the compound system over an extended period of time. At slightly lower bombarding energies, a similar diffuse emission source has also been inferred from the observation of low light-particle Coulomb energies, which could not be explained by deformation effects.[9] It is of interest that the temperatures expected to be attained for the present system are in the region of the nuclear liquid-gas phase transition, and hence an increased emission volume would be expected.

References

*This work was supported by the National Science Foundation under grant PHY-8608418 (University of Tennessee) and under grant PHY-8611210 (Michigan State University) and by the U.S. Department of Energy under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc. (ORNL).

†Present address: Department of Physics, Oregon State University, Corvallis, Oregon 97331.

§Present address: Institut fur Kernphysik, Johan-Wolfgang-Goethe Universitat, 6000 Frankfurt, Federal Republic of Germany.

1. W. G. Lynch et al., Phys. Rev. Lett. 51, 1850 (1983).

2. C. B. Chitwood et al., Phys. Lett. 172B, 27 (1986).

3. J. Pochodzalla et al., Phys. Lett. 174B, 36 (1986).

4. J. Pochodzalla et al., Phys. Rev. C 35, 1695 (1987).

5. Z. Chen et al., Nucl. Phys. A473, 564 (1987).

6. David H. Boal and Hubert DeGuise, Phys. Rev. Lett. 57, 2901 (1986).

7. Scott Pratt and M. B. Tsang, Phys. Rev. C 36, 2390 (1987).

8. Steven E. Koonin, Phys. Lett. 70B, 43 (1977).

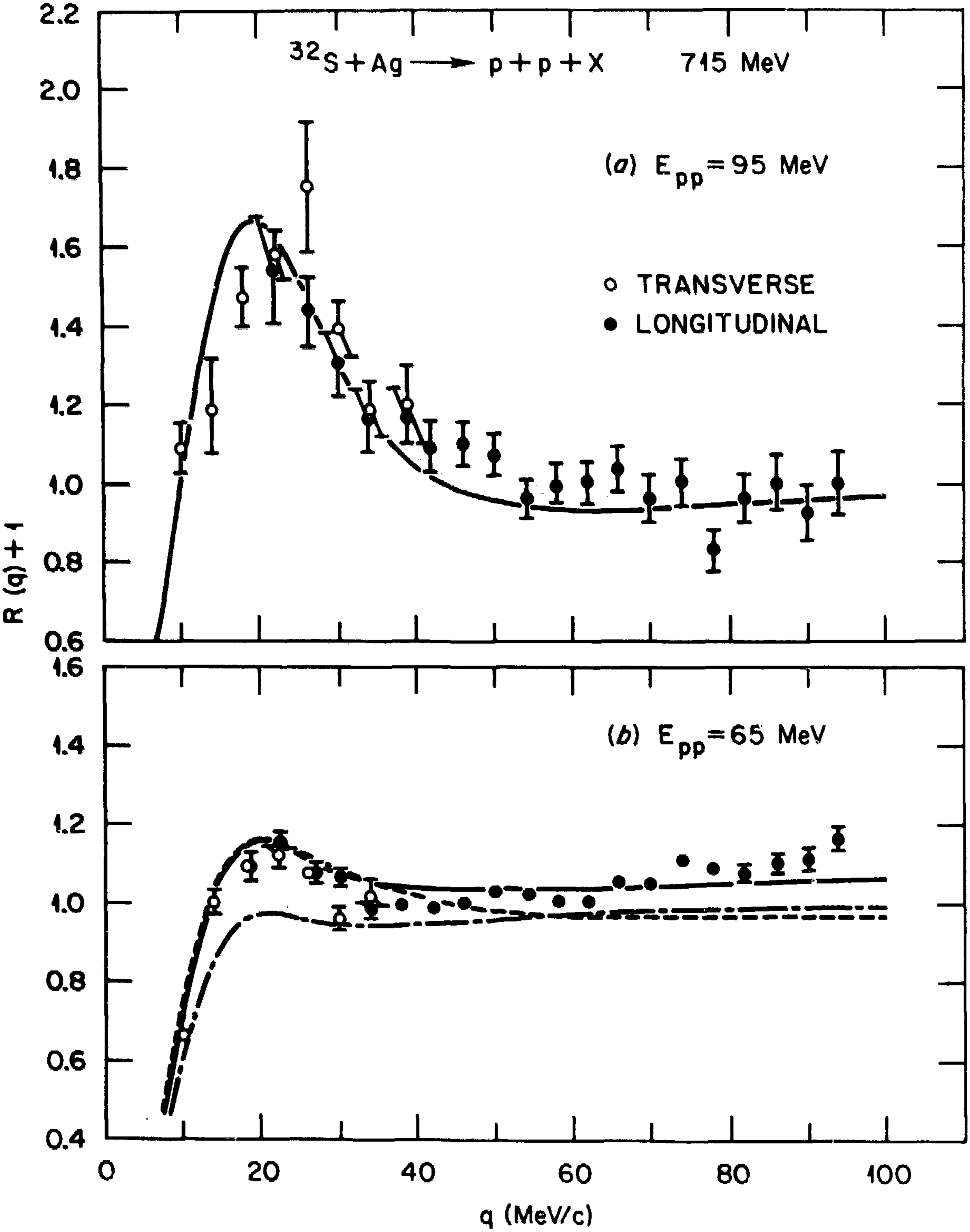
9. R. Lacey et al., Phys. Lett. 191B, 253 (1987).

Figure Captions

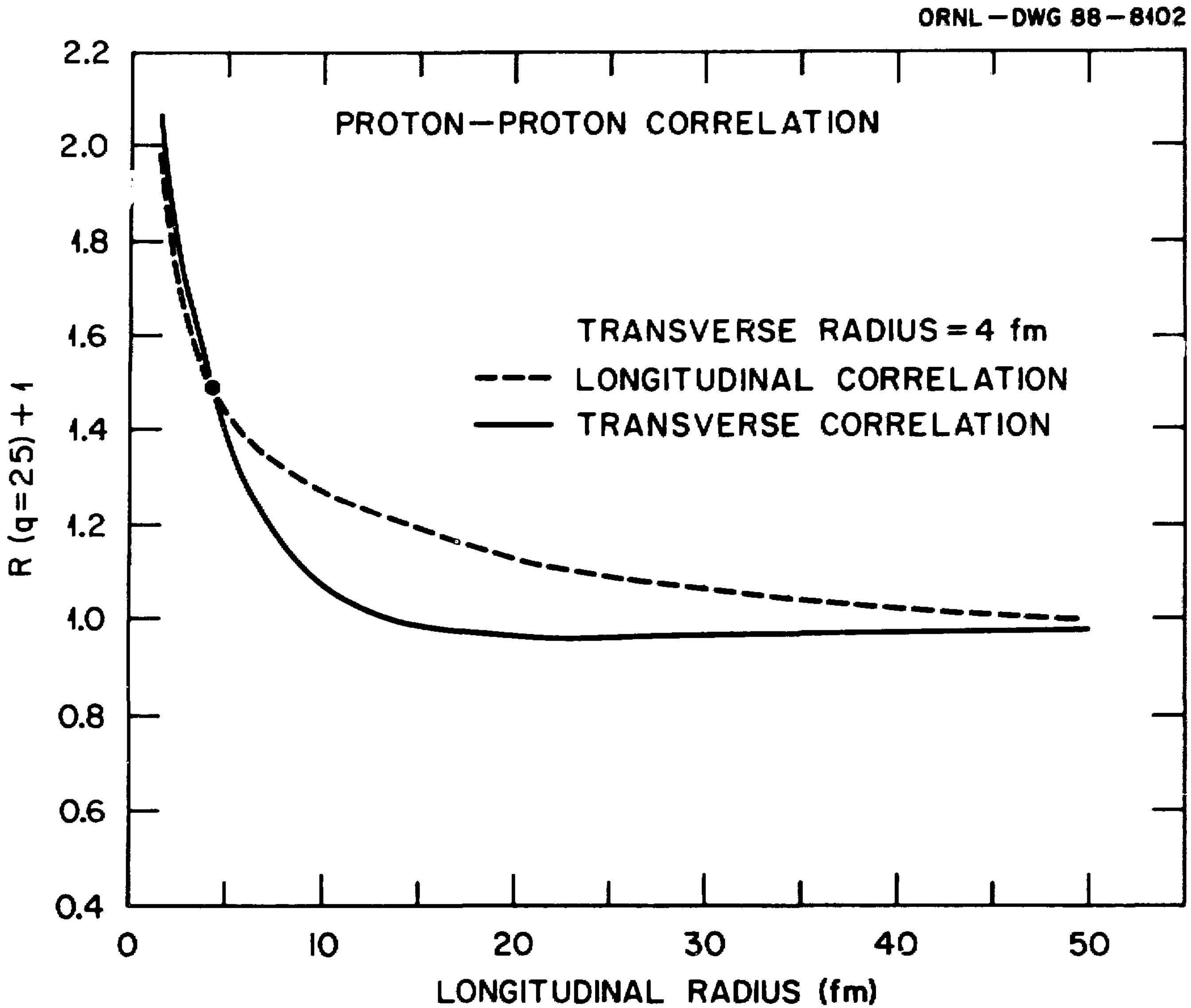
Fig. 1. Proton-proton correlations for the ^{32}S + Ag reaction at 715-MeV incident energy. The correlation is shown for relative momenta in the longitudinal (filled circles) and transverse (open circles) direction relative to the direction of the total momentum of the proton pair. The correlations are shown for total laboratory kinetic energy of the proton pair of (a) $90 < E_{pp} < 100$ MeV together with the calculated correlation for $R_T = R_L = 4$ fm and (b) $60 < E_{pp} < 70$ MeV together with calculations for $R_T = R_L = 6.5$ fm (solid line) and $R_T = 4$ fm, $R_L = 20$ fm (longitudinal correlation: dashed line; transverse correlation: dot-dashed line). Errors reflect statistical uncertainty only.

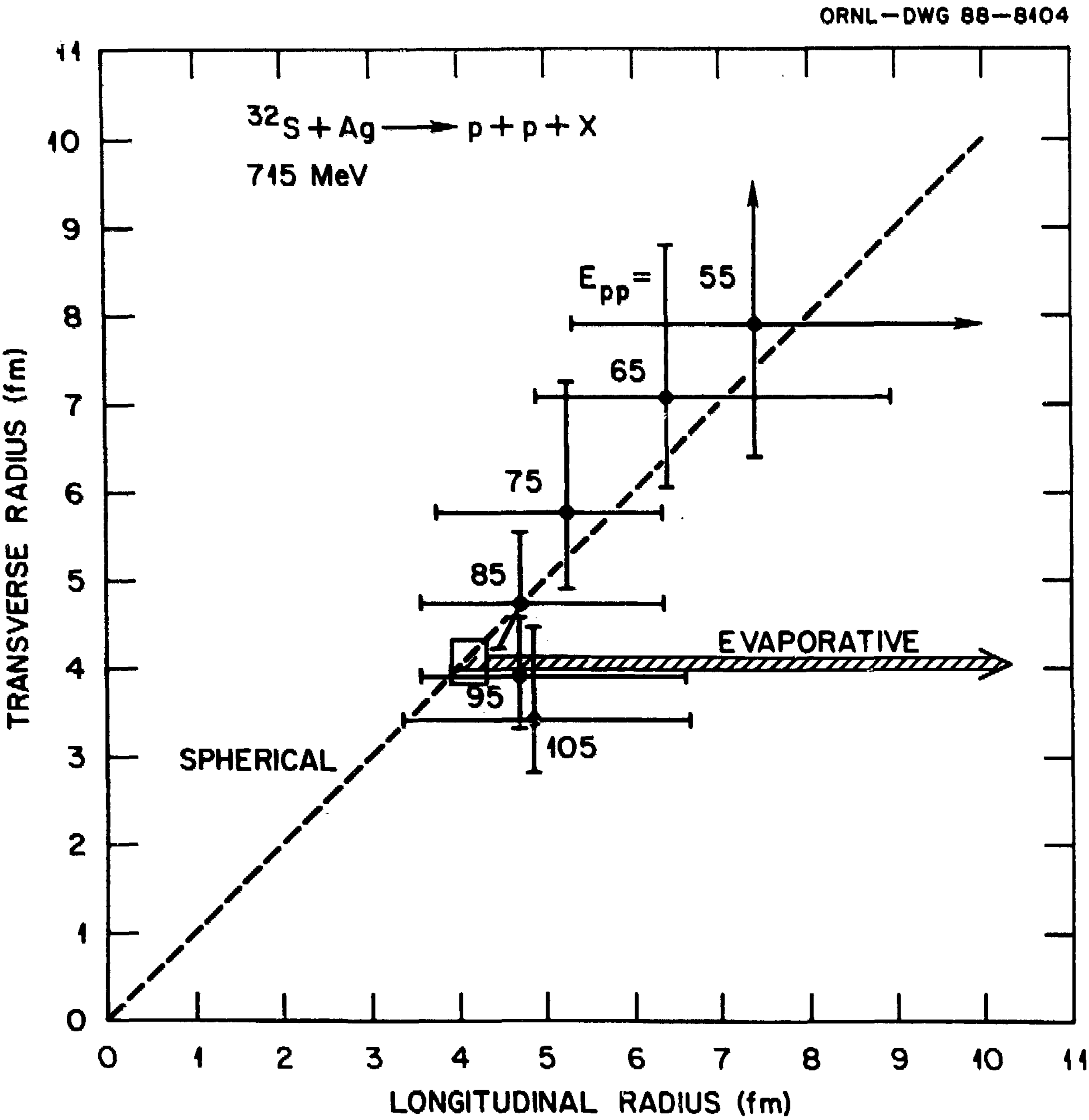
Fig. 2. Longitudinal radius dependence of the longitudinal and transverse proton-proton correlations at a relative momentum of 25 MeV/c for a source with a transverse radius of 4 fm.

Fig. 3. Longitudinal and transverse radii obtained by fitting the calculated correlations to the experimental longitudinal and transverse two-proton correlations for the ^{32}S + Ag reaction at 715 MeV. Results are shown for proton-pair kinetic energies ranging from 55 to 105 MeV. The error bars are conservative estimates obtained by independent variations which double the χ^2, which varied from 1.2 to 5.6. At 55 MeV the upper bounds on the radii are essentially open. Note: the equivalent sharp sphere radii are $\sqrt{5/2}$ larger than the indicated radii.



32S + Ag → p + p + X 715 MeV
(a) Epp = 95 MeV
○ TRANSVERSE
● LONGITUDINAL
(b) Epp = 65 MeV
R (q) + 1
q (MeV/c)
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0
20
40
60
80
100


ORNL—DWG 88—8102
PROTON—PROTON CORRELATION
TRANSVERSE RADIUS = 4 fm
LONGITUDINAL CORRELATION
TRANSVERSE CORRELATION
R (q=25) + 1
LONGITUDINAL RADIUS (fm)
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0
10
20
30
40
50



ORNL—DWG 88—8104
$^{32}S + Ag \rightarrow p + p + X$
715 MeV
E_{pp} =
55
65
75
85
95
105
EVAPORATIVE
SPHERICAL
TRANSVERSE RADIUS (fm)
LONGITUDINAL RADIUS (fm)
0
1
2
3
4
5
6
7
8
9
10
11