Michigan State University

National Superconducting Cyclotron Laboratory

PROTON EVAPORATION TIMESCALES FROM LONGITUDINAL AND TRANSVERSE TWO-PROTON CORRELATION FUNCTIONS

M.A. LISA, W.G. GONG, C.K. GELBKE, N. CARLIN,
R.T. de SOUZA, Y.D. KIM, W.G. LYNCH, T. MURAKAMI,
G. POGGI, M.B. TSANG, H.M. XU, K. KWIATKOWSKI,
V.E. VIOLA, Jr. and S.J. YENNELLO

MSUCL-901

AUGUST 1993

MSUCL-901
August, 1993

Proton Evaporation Timescales from Longitudinal and Transverse Two-Proton Correlation Functions

M.A. Lisa, W.G. Gong[1], C.K. Gelbke, N. Carlin[2],
R.T. de Souza[3], Y .D. Kim[4], W.G. Lynch, T. Murakami[5],
G. Poggi[6], M.B. Tsang, H.M. Xu[7]

National Superconducting Cyclotron Laborato y
and Department of Physics and Astronomy
Michigan State University, East Lansing, MI 48824, USA

K. Kwiatkowski, V.E. Viola, Jr., and S.J. Yennello[8]

Department of Chemist y
and Indiana University Cyclotron Facility
Indiana University, Bloomington, *IN* 47405, *USA*

Abstract

Differences between longitudinal and transverse two-proton correlation functions for the inverse kinematics reaction ^{129}Xe + ^{27}Al at E/A=31 MeV indicate emission from a long-lived compound nuclear system. Increased time scales for the emission of less energetic protons reveal the signatures of emission from a cooling system.

PACS number: 25.70.Pq

---

1 Present address: Lawrence Berkeley Laboratory, Berkeley, CA 94720, USA.
2 Present address: Instituto de Fisica, Universidade de São Paulo, C.P. 20516, CEP 01498, São Paulo, Brazil.
3 Present address: IUCF and Department of Chemistry, Indiana University, Bloomington, IN 47405, USA.
4 Present address: Physics Department, KEK, 1-1 Oho, Tsukuba, Ibaraki 305, Japan.
5 Present address: Department of Physics, Kyoto University, Kyoto 606 Japan.
6 Present address: Dipartimento di Fisica dell'Università and INFN, Largo Enrico Fermi 2, 50125 Firenze, Italy.
7 Present address: Cyclotron Institute, Texas A&M University, College Station, TX 77843, USA.
8 Present address: Department of Chemistry, Texas A&M University, College Station, TX 77843. USA.

Two-proton correlation functions probe the space-time structure of the proton-emitting source through the spatial dependence of final-state interactions and quantum interference effects [1-30]. For protons of a given velocity **v**, the strength of the final-state interaction mainly depends on the magnitude of the spatial separation between emitted protons, while directional information is carried by the quantum mechanical antisymmetrization which leads to a suppression of the correlation function at small relative momenta **q**. Emission from long-lived sources produces elongated phase space distributions [3-5] which should lead to detectable differences between longitudinal and transverse correlation functions with **q** oriented parallel and perpendicular to **v**, respectively.

Past experimental searches for this predicted lifetime effect [7-12] have either led to negative or statistically insignificant results, and it was suggested [12] that insufficient characterization of the source velocity may obscure the effect. Indeed, the only clear observation [6] of significant differences between longitudinal and transverse correlation functions was achieved for the emission of low-energy protons in central Ar + Sc collisions, in an experiment which utilized a 4π-detector for full event characterization. In light of these considerations, we have re-analyzed the high-statistics proton coincidence data [9,10] for the inverse kinematics reaction ^{129}Xe + ^{27}Al at E/A = 31 MeV. For this reaction, ambiguities of the emitting source velocities are relatively small; they range from $\beta = 0.209$ (for complete fusion reactions) to $\beta = 0.251$ (for emission from excited projectile fragments) [10]. We observe clear differences between longitudinal and transverse correlation functions when the appropriate angular cuts are made in the compound nucleus rest frame. These difference become largely washed out when the angular cuts are made in the laboratory rest frame as was done in ref. [10].

The experiment was performed at the National Superconducting Cyclotron Laboratory at Michigan State University. An ^{27}Al target of areal density 5.6 mg/cm^2 was irradiated by a ^{129}Xe beam at E/A = 31 MeV from the K1200 cyclotron. Light particles were detected by two arrays of ΔE-E telescopes consisting of 300-400 μm-thick silicon detectors backed by 10-cm-long CsI(Tl) or NaI(Tl) detectors. An array of 37 Si-CsI(Tl) telescopes was centered at polar and azimuthal lab angles of $\theta = 25°$ and $\phi = 0°$. Each telescope covered a solid angle of $\Delta\Omega = 0.37$ msr with a nearest-neighbor spacing of $\Delta\theta = 2.6°$. Centered at $\theta = 25°$ and $\phi = 90°$ was an array of 13 Si-NaI(Tl) telescopes, each covering $\Delta\Omega = 0.5$ msr of solid angle with a nearest-neighbor spacing of $\Delta\theta = 4.4°$. Proton energy resolution was on the order of 1%. More experimental details can be found in ref. [10].

The experimental two-proton correlation function is defined according to

$$1 + R(\mathbf{q}) = C \cdot \frac{N_{coinc}(\mathbf{q})}{N_{back}(\mathbf{q})}, \tag{1}$$

where $N_{coinc}(\mathbf{q})$ represents the yield of coincident proton pairs with relative momentum $\mathbf{q}$. In order to eliminate small differences in the shapes of the single- and two-proton inclusive energy spectra, the background yield, $N_{back}(\mathbf{q})$, is constructed using the event-mixing technique [31]. (Differences in the single- and two-proton inclusive energy spectra could, for example arise from different relative contributions from decays of projectile and fusion residues.) Two-proton correlation functions were constructed with cuts on the relative angle between the total momentum of the pair and the momentum of relative motion, $\psi = \cos^{-1}(|\mathbf{P}\cdot\mathbf{q}|/|\mathbf{P}|\cdot|\mathbf{q}|)$. The normalization constant C is adjusted such that R(q) vanishes for large q; it was determined independently of the angle ψ.

Proton emission from a long-lived source will lead to a phase space distribution elongated in the direction of total momentum [3-5]. For such distributions, the suppression of the correlation function at low q from quantum interference effects is less important for proton pairs whose relative momentum is oriented along the direction of the total momentum, and cuts on ψ will reveal finite lifetime effects in the correlation function. However, the relative orientation of **P** and **q** is a function of rest frame (since **P** depends on the rest frame, but **q**-- at least in the nonrelativistic limit-- does not). In order to see the effects of finite lifetime, therefore, it is important that the angle ψ is constructed in the frame of the emitting source [6,12]. This is illustrated in Fig. 1. The individual panels of the figure show longitudinal ($\psi = 0° - 50°$, filled symbols) and transverse ($\psi = 80° - 90°$, open symbols) two-proton correlation functions selected by the cut on the total laboratory momentum $P \geq 480$ MeV/c. For the top, center and bottom panels, the angle ψ was defined in the laboratory system ($\beta = 0$), the center-of-momentum frame of projectile and target (i.e. the rest frame of the compound nucleus, $\beta = 0.209$), and a rest frame moving with twice the velocity of the center-of-momentum system ($\beta = 0.417$). Consistent with the results of refs. [9,10], no significant differences between longitudinal and transverse correlation functions are observed when ψ is defined in the laboratory rest frame. When the angle ψ is defined in the rest frame of the compound nucleus, however, significant differences between longitudinal and transverse correlation functions emerge. They disappear again when ψ is defined in a rest frame moving with twice the speed of the compound nucleus.

The identification of lifetime effects from differences between longitudinal and transverse correlation functions can be difficult, if not impossible, for data containing a broad distribution of source velocities. Fortunately, for the present reaction, the range of source velocities is relatively narrow [10], thus allowing the study of lifetime effects without further event characterization. In the following, we will use a simple parametrization of the source function to illustrate the sensitivity to the present data to the average spatial dimension and lifetime of the emitting system.

The Koonin-Pratt formalism [1-3,5] allows the construction of the two-proton correlation function from the single-particle emission function g(**r**,t,**p**), which is a function of the space-time emission coordinates **r** and t, as well as the momentum **p** [3,5,10] of the emitted particles. In our schematic calculations, we parametrize the source in terms of surface emission from a sphere of sharp radius R and with an exponential lifetime τ [32]. Energy and angular distributions of the emitted protons were obtained by sampling the experimental yield Y(**p**). In the rest frame of the source, the source function was parametrized as

$$g(\mathbf{r},t,\mathbf{p}) \sim \delta(|\mathbf{r}|-R)\cdot\theta(\mathbf{r}\cdot\mathbf{p})\cdot\frac{\mathbf{r}\cdot\mathbf{p}}{|\mathbf{r}|\cdot|\mathbf{p}|}\cdot Y(\mathbf{p})\cdot\exp(-t/\tau)\ , \tag{2}$$

where $\theta(x)$ is the unit step function which vanishes for $x<0$, and $\delta(x)$ is the delta function which vanishes for $x\neq 0$. The source was assumed to be at rest in the center-of-momentum system, and the emitted particles were then boosted into the laboratory rest frame ($\beta = 0.2086$). Longitudinal and transverse correlation functions for a given R and τ were constructed according to the Koonin-Pratt formalism [5].

For a given parameter set R and τ, the agreement between measured and calculated correlation functions was quantified by the value of χ^2/ν (chi-squared per degree of freedom) evaluated in the region q=10-40 MeV/c, where the measured difference between longitudinal and transverse correlation functions is most pronounced and where distortions due to detector resolution are small [10]. Contour plots of χ^2/ν as a function of the parameters R and τ are shown in Fig. 2 for the two cuts on the total momentum of the emitted proton pairs, $P\geq 480$ MeV/c and $P\geq 580$ MeV/c. The best agreement between measured and calculated correlation functions is obtained for source radii of R = 3 - 4 fm; the extracted emission times are τ = 1700± 200 fm/c and 1200± 200 fm/c for the momentum cuts P ≥ 480 MeV/c and P ≥ 580 MeV/c, respectively. Calculated longitudinal and transverse correlation functions giving the best fit to the data are shown as solid and dashed curves in Fig. 3.

The extracted source radius is smaller than that of the compound nucleus. The reason for such a small source radius is not fully understood. It may reflect an artifact of the present schematic source parametrization which assumes emission according to Lambert's law and neglects anisotropies of emission resulting from angular momentum effects. It is interesting, however, that the extracted average emission time scale decreases slightly as the total momentum threshold is increased. Such a dependence is expected [5] for emission from a cooling compound nucleus.

In conclusion, we have presented angle-cut two-proton correlation functions for protons evaporated at forward angles in an inverse kinematics reaction. When the relative angle ψ is constructed in the center-of-momentum frame of the projectile-target system, clear differences between longitudinal and transverse correlation functions are observed. These differences are consistent with proton emission from a long-lived moving compound nucleus. Shorter lifetimes are extracted when the total momentum threshold for the coincident proton pairs is raised, a trend which is consistent with emission from a cooling system. The existence of a clear and direct measure of the sizes and lifetimes of compound nuclei offers a new probe of the physics of compound nuclear decays.

This work was supported by the National Science Foundation under Grant No. PHY-9214992.

References

1. S.E. Koonin, Phys. Lett. **B70**, 43 (1977).
2. W. Bauer et al., Annu. Rev. Nucl. Part. Sci. **42**, 77 (1992).
3. S. Pratt and M.B. Tsang, Phys. Rev. **C36**, 2390 (1987).
4. G.F. Bertsch, Nucl. Phys. **A498**, 173c (1989).
5. W.G. Gong et al. Phys. Rev. **C43**, 781 (1991).
6. M.A. Lisa et al., submitted to Phys. Rev. Lett.
7. T.C. Awes et al., Phys. Rev. Lett. **61**, 2665 (1988).
8. D. Ardouin et al., Nucl. Phys. **A495**, 57c (1989).
9. W.G. Gong et al., Phys. Lett. **B246**, 21 (1990).
10. W.G. Gong et al., Phys. Rev. **C43**, 1804 (1991).
11. D. Goujdami et al., Z. Phys. **A339**, 293 (1991).
12. D. Rebreyend et al., Phys. Rev. **C46**, 2387 (1992).
13. F. Zarbaksh et al., Phys. Rev. Lett. **46**,1268 (1981).
14. W.G. Lynch et al., Phys. Rev. Lett. **51**, 1850 (1983).
15. W.G. Lynch et al., Phys. Rev. Lett. **52**, 2302 (1984).
16. H. A. Gustafsson et al., Phys. Rev. Lett. **53**, 544 (1984).
17. C.B. Chitwood et al., Phys. Rev. Lett. **54**, 302 (1985).
18. J. Pochodzalla et al., Phys. Lett. **B174**, 36 (1986).
19. A. Kyanowski et al., Phys. Lett. **B181**, 43 (1986).
20. J. Pochodzalla et al., Phys. Rev. **C35**, 1695 (1987).
21. Z. Chen et al., Phys. Rev. **C36**, 2297 (1987).
22. Z. Chen et al., Phys. Lett. **B186**, 280 (1987).
23. Z. Chen et al., Nucl. Phys. **A473**, 564 (1987).
24. P. Depieux et al., Phys. Lett. **B200**, 17 (1988).
25. D. Fox et al., Phys. Rev. **C38**, 146 (1988).
26. P.A. DeYoung et al., Phys. Rev. **C39**, 128 (1989).
27. P.A. DeYoung et al., Phys. Rev. **C41**, R1885 (1990).
28. D.H. Boal et al., Rev. Mod. Phys. **62**, 553 (1990).
29. W.G. Gong et al., Phys. Rev. Lett. **65**, 2114 (1990).
30. B. Erazmus et al. Phys. Rev. **C44**, 2663 (1991).
31. M.A. Lisa et al., Phys. Rev. **C44**, 2865 (1991).

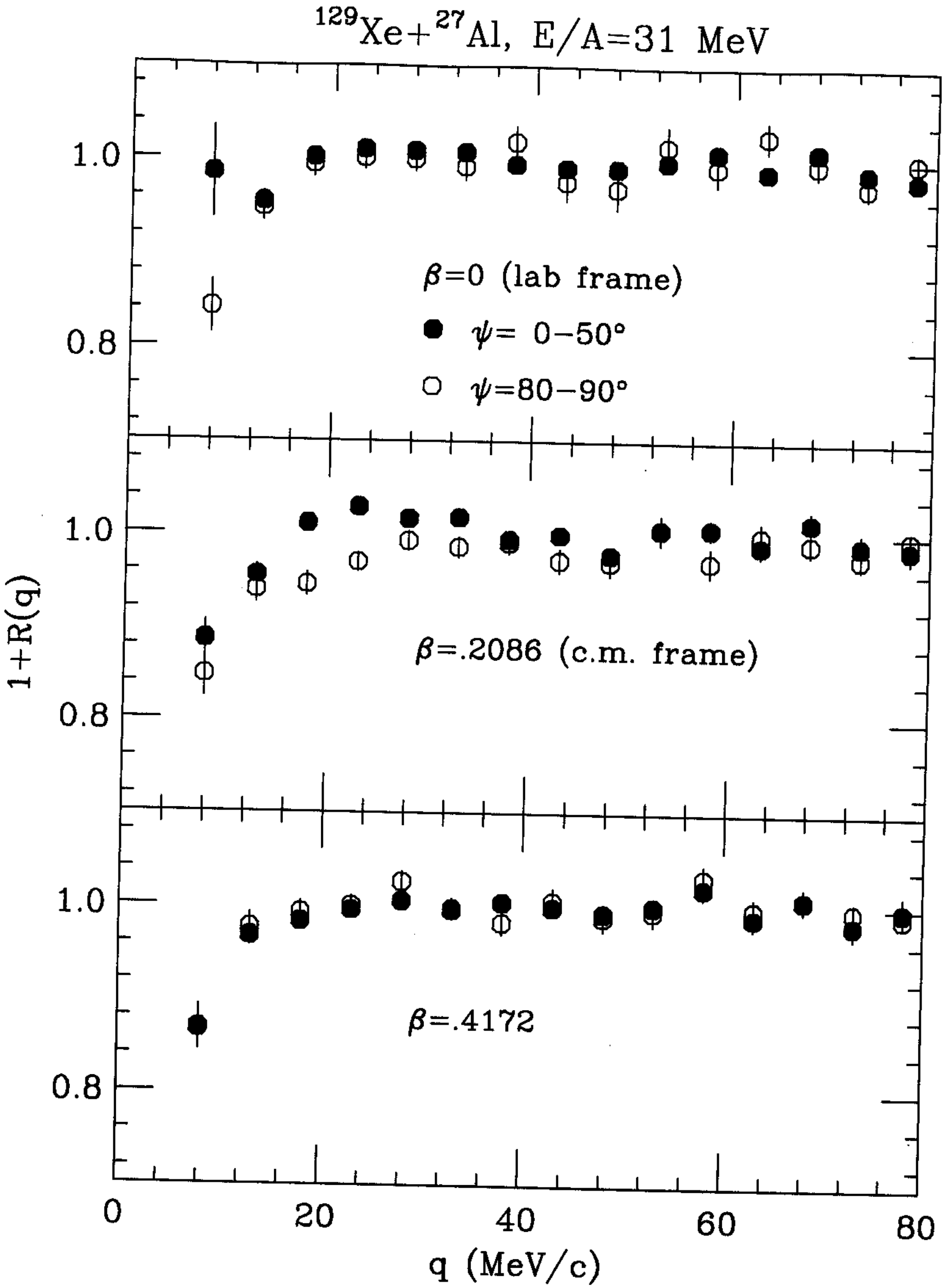
32. Y. Kim et al., Phys. Rev. **C45**, 338 (1992)

Figure Captions:

Fig. 1: Longitudinal (filled circles) and transverse (open circles) two-proton correlation functions for the reaction $^{129}Xe + ^{27}Al$ at E/A=31 MeV. Angular cuts in the upper panel were constructed in the laboratory frame of reference, and in rest frames moving in the lab with $\beta = 0.2086$ (center panel) and $\beta=.4172$ (bottom panel). The cut on the total momentum of the proton pair was $P \geq 480$ MeV/c.

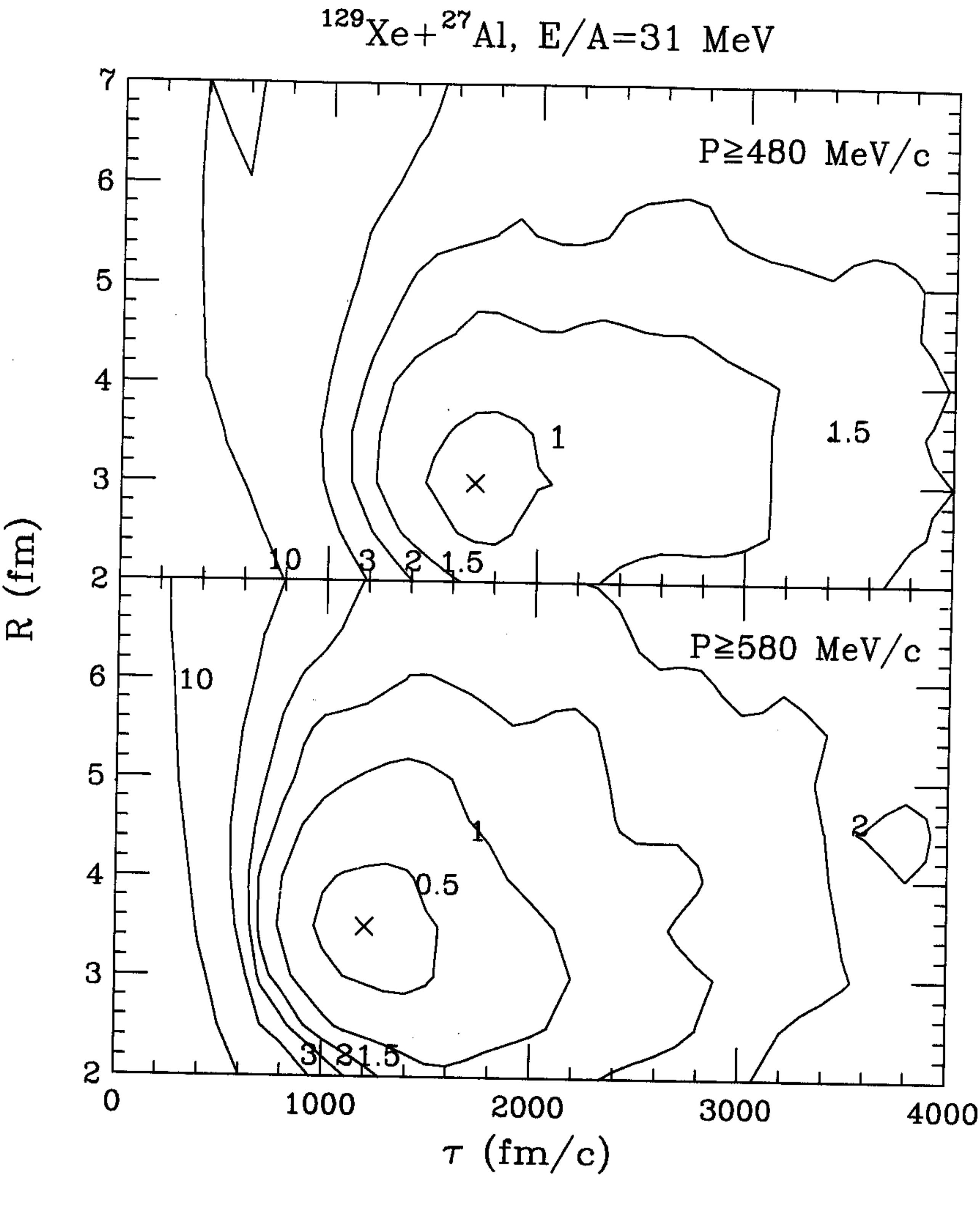
Fig. 2: Contour plots of χ^2/ν (chi-squared per degree of freedom) evaluated by comparing measured longitudinal and transverse correlation functions (over the range of 10 MeV/c $\leq q \leq$ 40 MeV/c to those predicted for emission from a schematic source with radius and lifetime parameters R and τ. The upper and lower panels compare correlation functions constructed from pairs with $P \geq 480$ MeV/c and $P \geq 580$ MeV/c, respectively. X's mark parameter sets used for calculated correlation functions shown in Fig. 3.

Fig. 3: Longitudinal (filled circles) and transverse (open circles) two-proton correlation functions for the reaction $^{129}Xe + ^{27}Al$ at E/A=31 MeV, evaluated in the center-of-momentum frame of the projectile and target. Top and bottom panels show data for cuts on the total momentum of the proton pair of $P \geq 480$ MeV/c and $P \geq 580$ MeV/c, respectively. Solid and dashed curves show calculations of longitudinal and transverse correlation functions using the source parametrization of Eq. (2) with the parameters given in the figure.



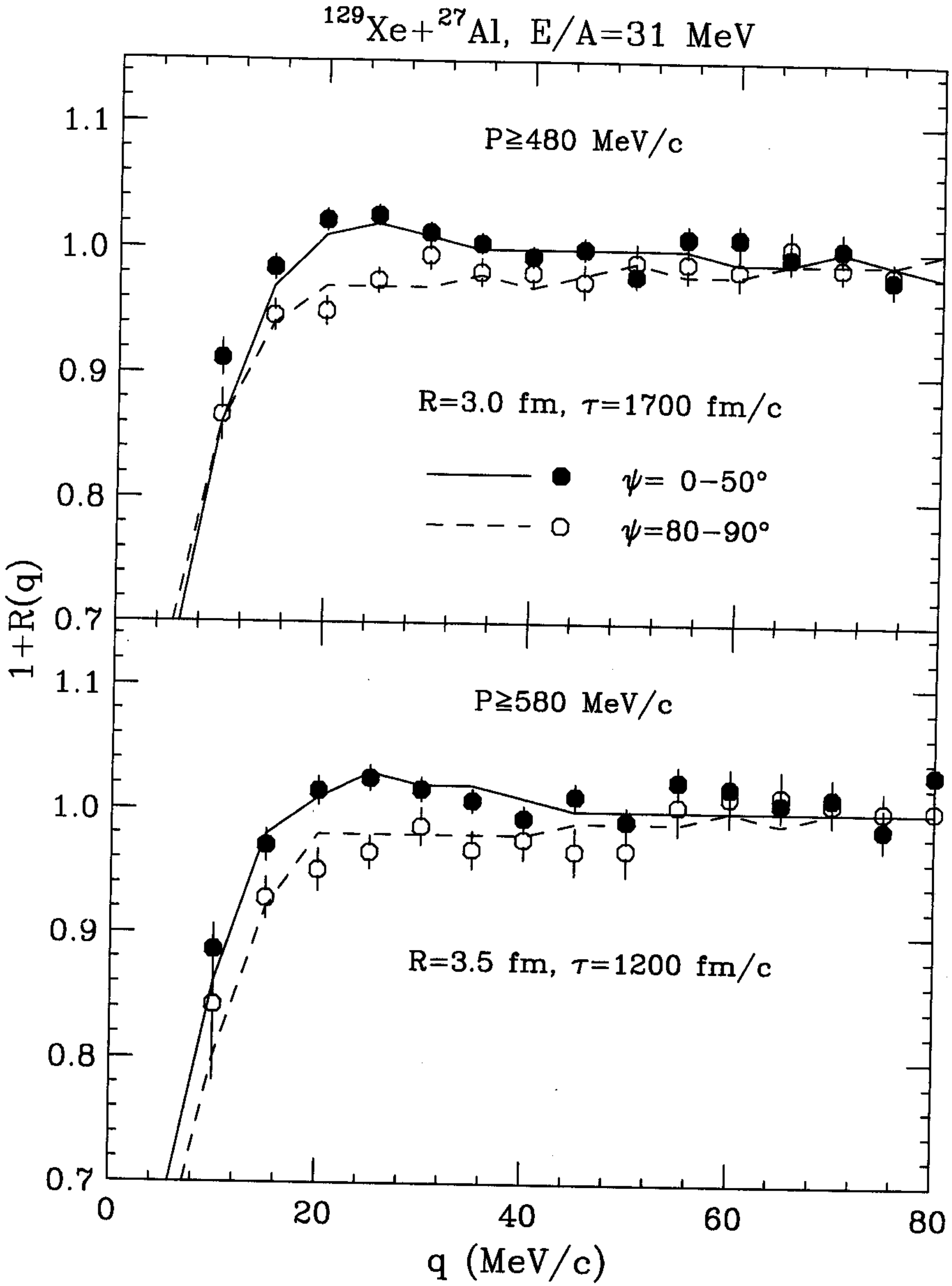
^{129}Xe+^{27}Al, E/A=31 MeV
1.0
0.8
β=0 (lab frame)
ψ= 0–50°
ψ=80–90°
1.0
0.8
β=.2086 (c.m. frame)
1+R(q)
1.0
0.8
β=.4172
0
20
40
60
80
q (MeV/c)

fig1



^{129}Xe+^{27}Al, E/A=31 MeV
P≧480 MeV/c
P≧580 MeV/c
R (fm)
τ (fm/c)
0
1000
2000
3000
4000
2
3
4
5
6
7
10
3
2
1.5
1
0.5

fig 2



^{129}Xe+^{27}Al, E/A=31 MeV
P≧480 MeV/c
R=3.0 fm, τ=1700 fm/c
ψ= 0–50°
ψ=80–90°
P≧580 MeV/c
R=3.5 fm, τ=1200 fm/c
1+R(q)
q (MeV/c)
1.1
1.0
0.9
0.8
0.7
0
20
40
60
80

fig 3