LBL-17678 c.2
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

RECEIVED
LAWRENCE
BERKELEY LABORATORY

JUN 11 1984

LIBRARY AND
DOCUMENTS SECTION

Submitted for publication

FREEZEOUT DENSITY IN RELATIVISTIC NUCLEAR COLLISIONS MEASURED BY PROTON-PROTON CORRELATIONS

H.A. Gustafsson, H.H. Gutbrod, B. Kolb,
H. Löhner, B. Ludewigt, A.M. Poskanzer, T. Renner,
H. Riedesel, H.G. Ritter, A. Warwick, F. Weik,
and H. Wieman

April 1984

TWO-WEEK LOAN COPY
This is a Library Circulating Copy
which may be borrowed for two weeks.
For a personal retention copy, call
Tech. Info. Division, Ext. 6782.

LBL-17678 c.2

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

LBL-17678

Freezeout Density in Relativistic Nuclear Collisions Measured by Proton-Proton Correlations

H. A. Gustafsson, H. H. Gutbrod, B. Kolb, H. Löhner,[a)]
B. Ludewigt,[b)] A. M. Poskanzer, T. Renner, H. Riedesel,[c)]
H. G. Ritter, A. Warwick,[d)] F. Weik[e)] and H. Wieman

Gesselschaft fur Schwerionenforschung
D-6100
Darmstadt, West Germany

and

Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

This work was supported in part by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

a)Present address: Institut für Kernphysik, D-4400 Munster, West Germany

b)Institut für Kernphysik, Universität Marburg, D-3550 Marburg, West Germany

c)Present address: Springer Verlag, Berlin, West Germany

d)Present Address: Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720

e)Present address: Toledo Company, Koln, West Germany

LBL-17678

Freezeout Density in Relativistic Nuclear Collisions Measured by Proton-Proton Correlations

H. A. Gustafsson, H. H. Gutbrod, B. Kolb, H. Löhner,[a)]
B. Ludewigt,[b)] A. M. Poskanzer, T. Renner, H. Riedesel,[c)]
H. G. Ritter, A. Warwick,[d)] F. Weik[e)] and H. Wieman

Gesselschaft fur Schwerionenforschung
D-6100
Darmstadt, West Germany

and

Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Abstract

Proton-proton correlations were measured with the Plastic Ball for two systems, Ca + Ca and Nb + Nb, at 400 MeV/nucleon as a function of proton multiplicity. The source size radii extracted from these measurements were found to have a cube root dependence on the proton multiplicity of the event. The deduced freezeout density, the density at which collisions between fragments cease, was found to be about 25 percent of normal nuclear matter density.

PACS Number: 25.70 Np

a)Present address: Institut für Kernphysik, D-4400 Munster, West Germany

b)Institut für Kernphysik, Universität Marburg, D-3550 Marburg, West Germany

c)Present address: Springer Verlag, Berlin, West Germany

d)Present Address: Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720

e)Present address: Toledo Company, Koln, West Germany

Relativistic nuclear collisions produce a zone of hot matter that radiates protons, pions and composite particles. The effective source size of this participant region has been investigated by a number of groups using either proton pair correlations [1,2] or pion pair correlations [2-4] at small relative momenta. Proton-proton correlations came into use for source size measurements following the correlation predictions of Koonin [5] which, in addition to the second order interference effect due to quantum statistics, also include nuclear and Coulomb induced final state interactions between the two outgoing protons. The use of this method in nucleus nucleus collisions is still relatively novel and an effort is being made to explore its potential. One application is the extraction of freezeout densities, a quantity which is of interest both for an understanding of the reactions and for its bearing on models of fragment production near a critical phase change [6].

We report here source radii as a function of proton multiplicity for two different reactions; Ca on Ca and Nb on Nb, both at 400 MeV/nucleon. The proton-proton correlations were measured at the Bevalac with the Plastic Ball, a 4π detector with several features that are of significant value in this application. One obvious advantage is the large solid angle and rapid data collection ability. This is an important factor in these measurements where obtaining sufficient pair statistics is often a problem, particularly when selections are made on event type. Another important feature is the ability to more completely define the event type by detecting most of the charged particles in each event. The main difficulty, that the resolution is limited by the finite angular size of the detector modules, has been overcome by smearing the theoretical calculation, thus permitting a direct comparison with the measurement.

A detailed description of the Plastic Ball detector system appears elsewhere [7], but briefly it is a spherical array of 815 scintillator $\Delta E,E$ detector modules which cover the full solid angle region surrounding the target from 9 degrees to 160 degrees. The density of modules is greater, with a center to center separation of 3.5 deg., in the forward region between 9 and 30 degrees. For a typical proton energy of 50 MeV this corresponds to a Δp, $|p_1 - p_2|/2$, of 10 MeV/c. The rest of the ball is more coarsely segmented with a center to center separation of 7 degrees. The protons used in the correlation analysis were limited to those stopped in the E detector, giving complete energy and particle type information. The energy range of these protons is ~ 40 MeV to 200 MeV. In addition to the Plastic Ball itself there is an array of plastic scintillators called the Plastic Wall located down stream from the target which covers the region from 0 degrees to 9 degrees. The wall is used to complete the measurement of proton multiplicity and to define a trigger for event recording.

In measuring the proton multiplicity, N_p, we attempt to account for all participant protons including those bound in light composites (d,t, ^{3}He, and ^{4}He). These bound protons add approximately 40 percent to the proton multiplicity. The proton energy threshold in the laboratory frame was adjusted to approximately 15 MeV, slightly above the detector threshold to avoid instrumental uncertainties and limit the contributions from target spectators. The energy threshold for charge two ions is roughly 2 or 3 times higher. The projectile spectators are largely eliminated by excluding a region in $p_\perp$-rapidity space that was identified using low multiplicity, peripheral reaction events. Thus, N_p is actually the baryon charge multiplicity in the participant region, but we will abbreviate it simply to proton multiplicity.

Radii have been extracted by comparing measured correlation functions to theoretical predictions which depend on the source size radius. In practice, the correlation function is obtained from the data as a function of Δp (either one of the proton momenta transformed into the center of mass of the pair) by summing all p-p pairs, event by event, in bins ($N_{true}(\Delta p)$) according to Δp, and dividing by p-p pairs from different events ($N_{mixed}(\Delta p)$) to give

$$F(\Delta p) = \text{norml.} \times N_{true}(\Delta p)/N_{mixed}(\Delta p) \quad .$$

In forming the mixed pair sums each proton was paired with each proton in the preceding five events so that the statistical error in the ratio due to the mixed event pairs could be neglected compared to the true pair statistics. Mixed event pairs with both protons in the same detector module are rejected to be consistent with the ball's requirement of two different modules for true pairs. The measured correlation function is normalized to 1 in the region Δp = 70-100 MeV/c.

The theoretical correlation functions which we compare with our measurements were calculated by Koonin [5]. In the form used here the correlation function, $F(\Delta p)$, equals $1 + R(\Delta p)$ where $R(\Delta p)$ is the correlation function of ref. 5. The degree of correlation between the two protons is strongest when they are close in space, time and momentum. In the general form of Koonin's calculation the proton source density is treated as isotropic with a gaussian distribution in space and time, and the proton momenta are assumed to be independent of position. The gaussian spacial density, $\rho(r)=\exp(-r/r_g)^2$, may be thought of as representing the proton positions at the point of their last scattering. For our analysis we assume that the

time parameter is zero, i.e. all the protons are emitted at the same time. Consequently, our extracted radii are expected to be somewhat larger than the true spacial extent of the source [8]. This simplified form of the correlation function (shown in fig. 1) illustrates the effects of the final state interactions between the two protons. At $\Delta p=0$ the correlation function is zero due to the Coulomb repulsion. The peak in the correlation function at $\Delta p= 20$ MeV/c is generated by the attractive nuclear force. The amplitude of this enhanced correlation is strongly dependent on the source size parameter r_g and increases as the source gets smaller. The peak, in this case for identical fermions, is suppressed by roughly a factor of two due to Pauli exclusion. This suppression corresponds to the enhancement observed for identical bosons, the normal second order interferometry effect in pion-pion correlation measurements. The problem for this work is to compare experimental and theoretical correlation functions for the purpose of extracting the source radius r_g.

The difficulty in this comparison is caused by the smearing of the measured correlation function by the finite angular resolution of the detector modules. This causes an error in Δp which differs for each pair, being dependent on the individual proton momenta. The nature of the distortion in the measured correlation function is therefore affected by the proton momentum distributions, functions that can change depending on cuts being made on the data. The problem has been solved by including the finite angle distortion in the theoretical correlation using a Monte Carlo procedure. Our procedure uses the same mixed event pairs that are used in the experimental determination of the correlation function and therefore automatically includes the correct proton momentum distributions. An example of a distorted correlation function

is shown in fig. 1 along with the original undistorted function. The effect of the distortion is to move strength from low Δp to higher Δp. The added contribution at Δp around 50 MeV/c is less apparent since the effect is diluted by the larger number of counts in both numerator and denominator as Δp increases. The distorted spectrum can now be directly compared with our measured correlation function. It should be pointed out that the Plastic Ball has a reduced efficiency for detecting pairs in the low Δp region since these pairs will tend to both go into the same detector. The efficiency has been determined from the relative number of mixed event proton pairs occurring in the same module. The efficiency decreases from 70%, in the region of the correlation peak at $\Delta p =$ 20 MeV/c, to 0 as Δp goes to 0. This loss in efficiency does not affect the ratio, but the resulting drop in statistics prevents careful comparison of data and theory at low Δp below the peak in the correlation function. However, the correlation function is well determined at Δp = 20 MeV and above and thus gives a good measure of the radius. In fig. 2 we show an example of a measured correlation function along with the distorted theoretical correlation function. The distorted theoretical function in this case is a linear interpolation between the two bracketing predictions for r_g = 4 and 5 fm. This interpolated curve and corresponding radius of r_g = 4.7 fm was obtained by a least squares fit to the measured correlation function. Measured correlations as well as the distorted theoretical functions are calculated separately for each proton multiplicity bin.

The extracted radii are shown as a function of proton multiplicity in fig. 3. The error bars represent statistical errors only. For both the Ca + Ca and Nb + Nb system the radius increases with multiplicity. These results agree with multiplicity averaged $\pi - \pi$ measurements of others on a similar mass

system (Ar+KCl) at higher bombarding energy. The streamer chamber results of Beavis et al [3] at E/A = 1.5 GeV are the same as ours at N_p equal to 30. The $\pi - \pi$ measurements of Zajc et al [4] with a beam energy of E/A = 1.8 GeV are about 20% lower than our value. The proton-proton measurements with E/A = 1.8 Gev of Zarbakhsh et al [1], on the other hand, are roughly 1/2 our values. They separate their results into two multiplicity bins and contrary to our measurements they see smaller radii at larger multiplicity.

Our radii in fig. 3 are shown with a fit using the function $r_g = r_o(N_p A/Z)^{1/3}/\sqrt{5/2}$ where N_p is the participant baryon charge multiplicity and A/Z has been included to reflect the presence of neutrons. The extracted radii are the radius parameters for a gaussian source distribution, so by including $\sqrt{5/2}$ in the above function r_o becomes the radius parameter of an rms equivalent sharp sphere [9]. The value of r_o extracted from the fits is 1.9 fm for the two systems studied. Comparing this directly with r_o = 1.2 fm, the sharp sphere r_o for normal nuclei yields a participant region freezeout density about 25 percent of normal nuclear density. This density is somewhat lower than the commonly accepted freezeout density values of 0.3 to 0.5 times normal nuclear density [10].

We acknowledge the strong support of Professor R. Bock and helpful discussions with W. A. Zajc, G. Bertsch, S. E. Koonin, W. G. Lynch, F. Zarbakhsh, J. Randrup and M. Gyulassy.

This work was supported in part by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

References

1. F. Zarbakhsh, A. L. Sagle, F. Brochard, T. A. Mulera, V. Perez-Mendez, R. Talaga, I. Tanihata, J. B. Carroll, K. S. Ganezer, G. Igo, J. Oostens, D. Woodard, and R. Sutter, Phys. Rev. Lett. 46, 1268 (1981).

2. N. Akhababian, J. Bartke, V. G. Grishin, M. Kowalski, JINR, E1-83-670 Dubna (1982).

3. D. Beavis, S. Y. Fung, W. Gorn, A. Huie, D. Keane, J. J. Lu, R. T. Poe, B. C. Shen, and G. Van Dalen, Phys. Rev. 27C, 910 (1983).

4. W. A. Zajc, J. A. Bistirlich, R. R. Bossingham, H. R. Bowman, C. W. Clawson, K. M. Crowe, K. A. Frankel, J. G. Ingersoll, J. M. Kurck, C. J. Martoff, D. L. Murphy, J. O. Rasmussen, J. P. Sullivan, E. Yoo, O. Hashimoto, M. Koike, W. J. McDonald, J. P. Miller and P. Truol, (LBL No. 16930).

5. S. E. Koonin, Phys. Lett. 70B, 43 (1977).

6. M. W. Curtin, H. Toki and D. K. Scott, Phys. Lett. 123B, 289 (1983).

7. A. Baden, H. H. Gutbrod, H. Löhner, M. R. Maier, A. M. Poskanzer, T. Renner, H. Riedesel, H. G. Ritter, H. Spieler, A. Warwick, F. Weik and H. Wieman, Nucl. Instr. and Meth. 203, 189 (1982).

8. Using a source time parameter of 5 fm/c we estimate this error to be at most 6%.

9. The density for a non-spherical distribution would be somewhat higher because the measurement is sensitive primarily to the rms radius. For a ratio of major to minor axis of 1.5 the density would be only 12% higher.

10. A. S. Hirsch, A. Bujak, J. E. Finn, L. J. Gutay, R. W. Minich, N. T. Porile, R. P. Scharenberg, and B. C. Stringfellow, Phys. Rev. 29C, 508 (1984).

Figure Captions

1. The solid curve shows the p-p correlation function calculated by Koonin for a source of radius $r_g = 3$ fm and a source life time of $\tau = 0$. The dashed curve is the same correlation after applying the Plastic Ball distortion resulting from finite angular granularity.

2. The measured proton-proton correlation function for Ca + Ca with a proton multiplicity from 25 to 32. The solid curve is a least squares fit interpolation between distorted theoretical correlation functions for radii of 4 and 5 fm.

3. Extracted gaussian source radii as a function of proton multiplicity (N_p) for the two systems Ca + Ca and Nb + Nb at 400 MeV/nucleon. The curves are fits to the results with the function, $r_g = r_o(N_p A/Z)^{1/3}/\sqrt{5/2}$.

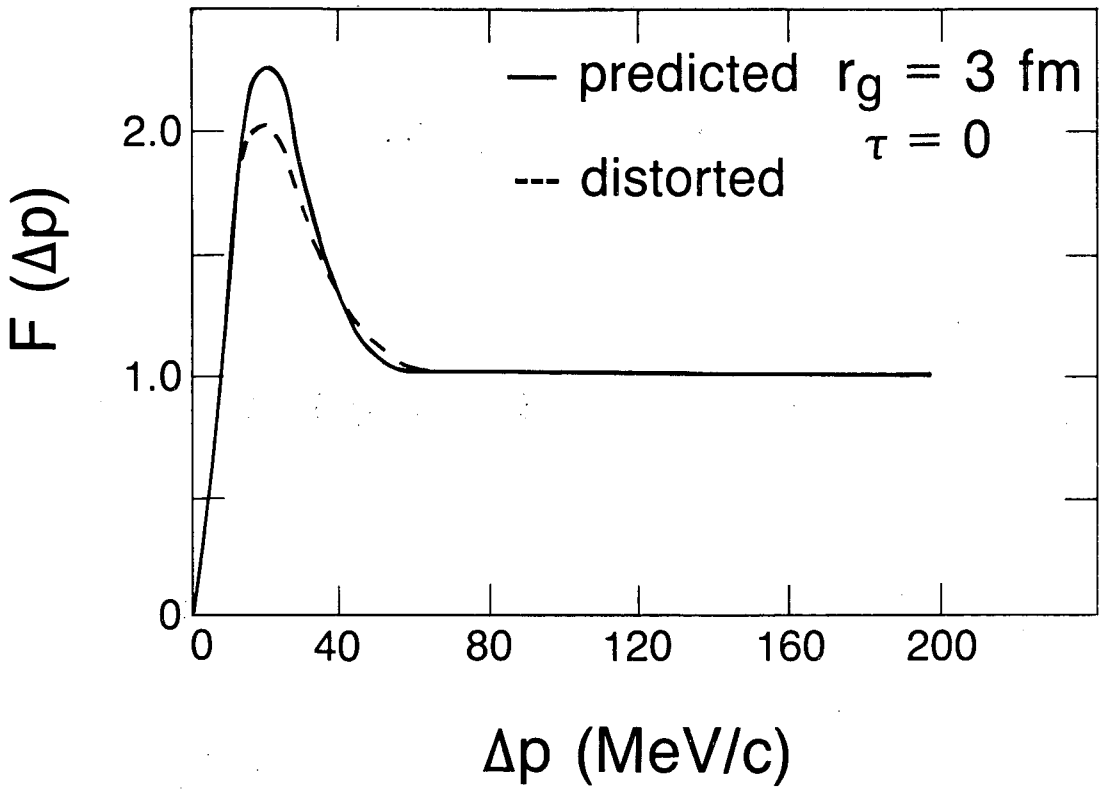

Fig. 1

XBL 844-10411

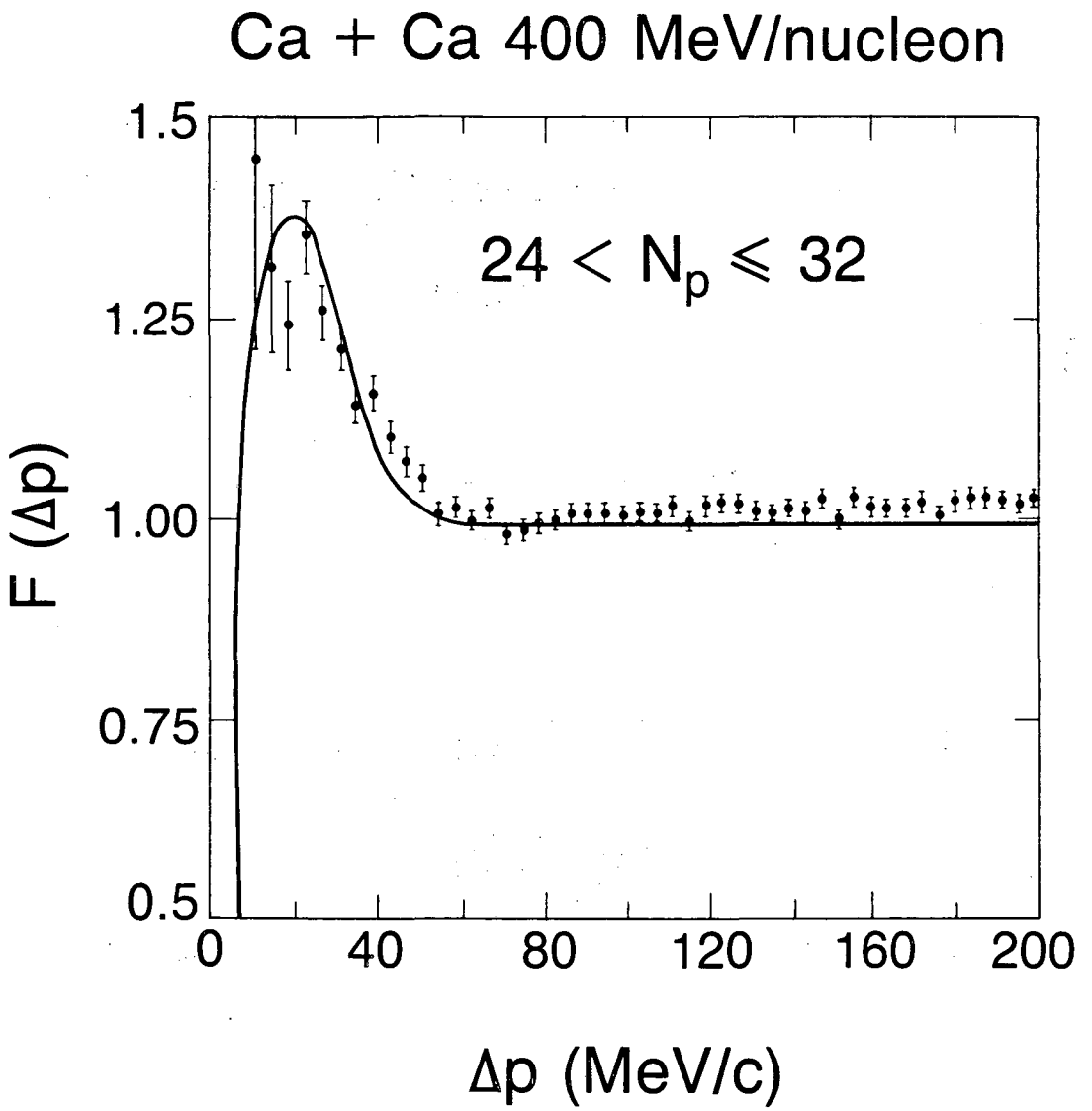

Fig. 2

XBL 844-10360

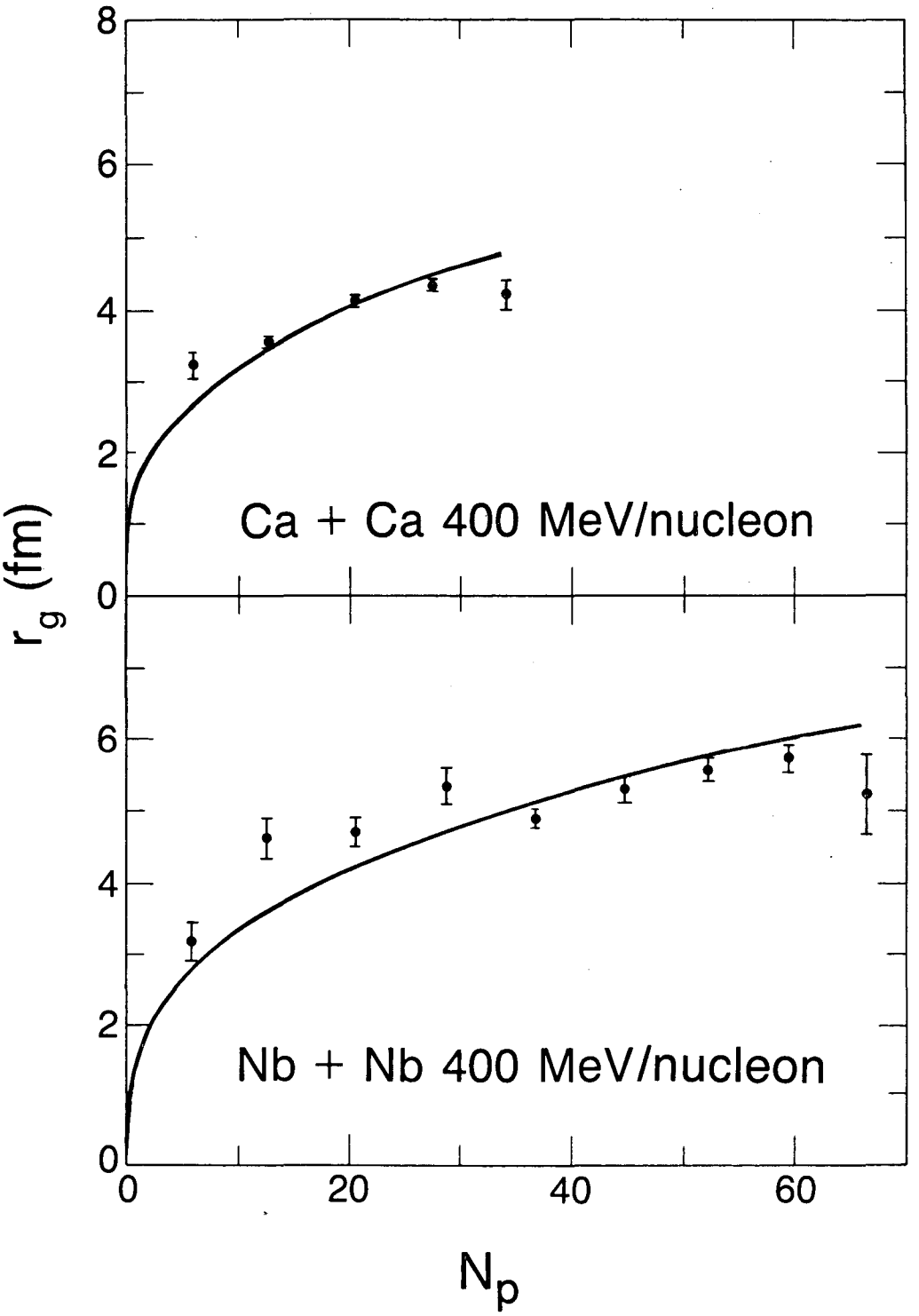

Fig. 3

XBL 842-10058

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720