Influence of the emitter Coulomb field on two-proton correlation function

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Abstract

The experimental two-proton correlation functions measured in $^{36}Ar + ^{45}Sc$ at 80 MeV/nucleon have been compared with predictions of a new three-body quantum model which includes the Coulomb interaction of the particles with their emitter. For a realistic charge of the source, its Coulomb field strongly influences the shape of the correlation function leading to a significant reduction of the source radius deduced in the two-body approximation. The differences in the shape of the correlation function observed between the data and theoretical results highlight the limits of a static picture of the source and the importance of dynamical correlations.

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I. INTRODUCTION

Over the last decade, two-particle correlation functions have been extensively used to investigate the space-time structure of particle sources produced in heavy-ion collisions at intermediate energies. Indeed, the relative distance between the two particles, related to their emission points and their emission times, determines the amplitude of their correlations, due to final state interactions and quantum interference effects. The combination of these effects gives rise to a minimum at q=0 MeV/c and may lead in the case of two protons to a pseudo-resonance in the correlation function centered at the relative momentum q=20 MeV/c, which is strongly sensitive to the source dimensions. With the exception of long-lifetime source studies for which classical treatments have been developed [1–3], the theoretical description of the correlations has been reduced to a quantum two-body problem [4–7]. Since the phase space density of the emitted particles is generally small, the influence of the other produced particles on the pair correlations can be neglected. However, when the particles are emitted in the presence of a strong Coulomb field due to the emitter, the two-particle approximation may not be valid and thus, the source-particle interactions may have to be taken into account. The interactions with the third body are not by themselves a source of correlations but influence the shape of the correlation function. More precisely, a significant effect is expected for particles with different mass to charge ratio since they experience different accelerations in the Coulomb field of the emitting nucleus. Such an effect has been observed in p-d [8] correlation functions and has been proposed to explain the weakness of the correlations observed for the p-n system [9,10]. The supression of the p-n correlation functions is indeed partly due to the Coulomb repulsion of the protons by the emitting nucleus [11]. In the case of identical particles, such as the two-proton system, the distortion of the correlation function should be smaller [12,13] but could still remain significant at characteristic distances between the two particles of the order of few tens of Fermi, for which the condition of validity of the classical approach is not fulfilled [2].

In high-energy experiments, the effects of the interaction with the emitting source are usually treated as a correction term [14,15] acting as a simple momentum shift. In the intermediate-energy regime, the particle-source potential energies and the particle kinetic energies are comparable, the momentum shift being of the order of the particle momentum itself. Thus, this simple procedure is not justified and as all the final state interactions are developing simultaneously, a full three-body quantum model is needed. Such an approach has been worked out recently [16] allowing a theoretical description of particle correlations valid over a broad range of source lifetimes and particle energies. In this paper, we report the analysis, in the frame of this new model, of the experimental two-proton correlation functions measured in $^{36}Ar + ^{45}Sc$ at 80 MeV/nucleon for which a short lifetime is expected [17].

II. EXPERIMENT

Results from this experiment, performed at the National Superconducting Cyclotron Laboratory at Michigan State University, have been already published in ref. [17,18] where experimental details can be found. Central collisions ($b/b_{max} < 0.36$ in a geometrical picture) were selected by gating on the total transverse energy of the charged particles measured in the 4π Array. To maximize possible lifetime effects and exclude protons coming from the earliest stages of the reaction, the two-proton coincidences were selected by a low-momentum cut on their total momentum in the laboratory frame (P=400-600 MeV/c) [17].

From the two-proton coincidence yield $Y_c(p_1,p_2)$ and the proton singles yield $Y_s(p)$, the experimental correlation function (R(q)+1) is defined through the relation :

$$\sum Y_c(p_1,p_2) = C[R(q)+1]\sum Y_s(p_1)Y_s(p_2) \tag{1}$$

where q is the relative momentum and the normalization constant C was adjusted such that $< R(q) >= 0$ for q=60-100 MeV/c.

Selections on the relative orientation of the total momentum $\vec{P}$ and the relative momentum $\vec{q}$ of the proton pairs can reveal directional effects characterizing sources producing non-spherical phase-space distribution of the emitted particles. For emission from a long-lived source, antisymetrization effects are stronger for a transverse configuration ($\vec{q} \perp \vec{P}$, i.e. $\vec{q}$ perpendicular to the elongated dimension), producing an attenuated transverse correlation function as compared to the longitudinal correlation function ($\vec{q} \parallel \vec{P}$, i.e. $\vec{q}$ along the elongated dimension). An analysis which allows unambiguous and simultaneous determination of the radius and the lifetime of the source, requires a well-characterized source. For the present reaction [17], a clear difference was observed between longitudinal and transverse correlation functions defined by cuts on the angle $\psi = cos^{-1}(\vec{q}.\vec{P}/q.P) = 0° - 50°$ and $80° - 90°$ respectively, where P was the total momentum of the pair in the source rest frame. The tight selection of central collisions allowed a good estimate of the source velocity, v_{source}=0.18 c in the laboratory for a source at rest in the center-of-momentum system of the projectile and the target.

III. THE THREE-BODY QUANTUM MODEL

In the formalism of the model [16], the correlation function is defined as the ratio of the two-particle production cross-section to the one in which the final state interactions and the quantum statistic effects between the two particles are neglected :

$$R(p_1,p_2) = \frac{\sum_S \int dx_1 \int dx_2 W_S(x_1,p_1,x_2,p_2)|\psi^Z_{p_1,p_2}(x_1,x_2) + (-1)^S \psi^Z_{p_2,p_1}(x_1,x_2)|^2}{\sum_S \int dx_1 \int dx_2 W_S(x_1,p_1,x_2,p_2)(|\tilde{\psi}^Z_{p_1,p_2}(x_1,x_2)|^2 + |\tilde{\psi}^Z_{p_2,p_1}(x_1,x_2)|^2)} \qquad (2)$$

where $W_S(x_1,p_1,x_2,p_2)$ represents the particle emission probability. In eq. (2) the cross-sections are expressed in term of modulus squared of the wave functions averaged over the spin variable S and the space-time coordinates of the production points. The amplitude $\psi^Z_{p_2,p_1}(x_1,x_2)$ is the solution of the three-body problem involving two particles of charge z_1,z_2 and final 4-momentum p_1,p_2 emitted at the space-time points x_1,x_2 by a nucleus of effective charge Z. $\tilde{\psi}^Z_{p_2,p_1}(x_1,x_2)$ represents the solution to this problem for the two-particle correlations switched-off. In that case, it is reduced to two decoupled particle-nucleus interactions and the amplitude can be expressed as :

$$\tilde{\psi}^{Z}_{p_2,p_1}(x_1,x_2) = e^{iPX} e^{i\vec{k}^*.\vec{r}^*} \phi^{z_1 Z}_{\vec{p}_1}(\vec{r}_1) \phi^{z_2 Z}_{\vec{p}_2}(\vec{r}_2) \tag{3}$$

where $P = p_1 + p_2$, X is their c.m.s. 4-coordinates, $\vec{k}^*$ and $\vec{r}^*$ are the momentum and position of one particle in the two-particle rest frame. The amplitude $\phi^{z_i Z}_{\vec{p}_i}(\vec{r}_i)$ corresponds to the usual wave function describing the interaction of the particle i with the Coulomb center [16].

In the case of a strong Coulomb field, the adiabatic approximation may be applied allowing to analytically derive approximate solutions of the three-body problem. Assuming the relative motion of the two particles to be much slower than their motion with respect to the nucleus, it has been demonstrated in ref. [16] that the amplitude $\psi^{Z}_{p_2,p_1}(x_1,x_2)$ can be then written as the factorized expression :

$$\psi^{Z}_{p_2,p_1}(x_1,x_2) = e^{iPX} \psi^{Z}_{p_2,p_1}(x) \phi^{z_1 Z}_{\vec{p}_1}(\vec{r}_1) \phi^{z_2 Z}_{\vec{p}_2}(\vec{r}_2) \tag{4}$$

where $\psi^{Z}_{p_2,p_1}(x)$ is the Bethe-Salpeter amplitude of the two interacting particles (after separation of their c.m.s. motion) corresponding to a given potential. In the case of the two-proton system, this potential includes the long-range Coulomb interaction and the nuclear force limited to the S-wave short-range interaction.

Assuming that particles are produced independently and in spin states independent of the production points, the emission probability can be written as :

$$W_S(x_1, p_1, x_2, p_2) = \rho_S(p_1,p_2) w(x_1,p_1) w(x_2,p_2) \tag{5}$$

where $\rho_S(p_1,p_2)$ describes the population of the total spin-S states, $\rho_S(p_1,p_2) = (2S+1)/[(2s_1+1)(2s_2+1)]$ for unpolarized particles. Adopting the simple source used in the ref. [17], a radioactive decay law defined the emission time distribution characterized by the lifetime τ_0 and emission coordinates were chosen according to a pseudo-Gaussian of width r_0. The energy and angular distribution of the protons were generated by randomly sampling the experimental singles yield $Y_S(p)$. The adopted particle emission function can then be summarized as :

$$w(x_i, p_i) = e^{(-|\vec{r}_i|/r_0)^2} e^{(-t_i/\tau_0)} Y_S(p_i) \tag{6}$$

The two-proton correlation functions were calculated after transforming of the proton momentum into the source rest frame.

IV. COMPARISONS WITH THE EXPERIMENTAL DATA

A. Two-body calculations

The experimental data have been previously compared to theoretical correlation functions calculated in the Koonin-Pratt formalism [7]. From this analysis, a source radius of $r_0 = 4.7 \pm 0.3 fm$ and a lifetime of $\tau_0 = 25 \pm 15 fm/c$ have been extracted [17]. In order to assess a good level of confidence in the predictions of the new quantum model, we have first investigated the theoretical correlation functions obtained in the two-body approximation.

For a given set of parameters, within the range of source dimensions expected to reproduce the data, both formalisms predict the same shape and same height of the peak appearing at 20 MeV/c for the integrated two-proton correlation function as well as for longitudinal and transverse cuts. This result confirms the insensitivity of the two-proton correlation function to the shape of the nuclear potential for emission from a source with $r_{rms} > 2fm$ [6,19] as long as the potential parameters allow to reproduce the scattering length and the effective radius of the two-proton system [20]: in the Lednicky-Lyuboshitz model a square-well potential is used, while the Koonin-Pratt model employs a Reid soft-core potential.

A small discrepancy between the two model predictions is found in the behavior of the correlation function at large relative momenta. At q=80 MeV/c, the predictions of the Koonin-Pratt model are smaller by approximately 2 % than those of the Lednicky-Lyuboshitz model. As mentioned before, the experimental correlation functions are normalized arbitrarily at large relative momenta. We have therefore normalized both theoretical predictions according to the same prescription and the disagreement appears as a difference in the peak amplitude. The best agreement between the experimental data and the predictions of the new quantum model was searched in constraining simultaneously the transverse and the longitudinal correlation functions. A source lifetime of $\tau_0 = 25 fm/c$ and a radius of $r_0 = 4.5 fm$ were obtained which are within the error bars of the parameters deduced with the Koonin-Pratt model. Figure 1 summarizes these two-body calculations : the experimental data are represented by the open and solid circles and the predictions of new model and the Koonin-Pratt model are respectively shown by the solid and the dotted-dashed curves. For comparison, we also show recent predictions of the BUU transport model, based on the Koonin-Pratt formalism (dotted curves) [18].

B. Three-body calculations

The analytical formulation of the three-body calculations (the factorized expression of the wave function in eq.(4)) is based upon the adiabatic approximation. A careful derivation of this approximation using Green functions and within the frame of the perturbation theory has been done in ref. [16], and has led to the applicability condition :

$$\frac{R}{p_i|a_i|}\left(\frac{1}{|a|} + \frac{|f^S(k^*)|}{r^{*2}}\right) \ll 1 + \frac{|f^S(k^*)|}{r^*} \tag{7}$$

where p_i is the particle momentum, $|a|$ is the two-proton Bohr radius ($|a| = 58 fm$), $f^S(k^*)$ is the scattering length associated to the nuclear interaction ($f^0(0) = 7.8 fm$) and $|a_i| \approx 1/m_i z_i Z e^2 \approx 0.75 fm$ is the particle-nucleus Bohr radius for a source charge Z=39. The relative distance between the two protons is represented by r^* while R is the distance of their c.m.s with respect to the origin. With the low momentum cut in the laboratory, the average pair velocity in the source c.m.s. is $v = 0.18c$ which gives an average proton momentum of $p_i = 175 MeV/c$. For a lifetime of $\tau = 25 fm/c$, an average distance at the emission $\langle r_i \rangle = 5.5 fm$ and using the relations $R \approx \langle r_i \rangle/\sqrt{2}$, $r^* \approx (2\langle r_i \rangle^2 + v^2\tau^2)^{1/2}$, we conclude that the left side of eq.(7) is three times smaller than the right side. Although the applicability condition is not strongly fulfilled for these values typical of the data sample, taking into account the sufficient character of the condition, the adiabatic approximation is likely to be reasonable for the proton pairs considered here.

In order to generate proton pairs, we used the experimental distributions measured by the single protons, see eq.(6). This procedure avoids the use of an experimental filter and allows to take into account the angular dependence of the proton distributions and variations of the detection efficiencies of the hodoscope detectors, included in the experimental correlation function. However, the distributions of the single protons are already affected by the Coulomb boost produced by the emitter and cannot be employed as a direct input of the three-body quantum model. As a matter of fact, this approach treating explicitly the particle-nucleus Coulomb interactions, the effect of the source Coulomb field need first to be disentangled from the single-particle distributions. Consequently, for a given charge of the source assumed in the model and before generation of pairs, the ratio of the weights calculated without and with the Coulomb effect accounted for has been associated to each experimental single proton. More precisely, these weights have been averaged over the source dimensions to take into account their dependence on the position of emission.

By adopting the source parameters $r_0 = 4.5fm$ and $\tau_0 = 25fm/c$ deduced from the two-body calculations, we investigated the influence of the third body on the shape of the correlation functions. Figure 2 compares longitudinal and transverse correlation functions obtained for sources charges of Z=20 and Z=39 (the total charge of the system) to those evaluated in the two-body approximation. As expected, the Coulomb interaction with the source leads to an attenuation of the correlations between the two protons. It affects more strongly the longitudinal correlation function. In the transverse configuration the two protons have nearly the same energy and then experience a similar Coulomb boost. The lifetime effect appearing in the two-body calculations is thus strongly reduced and disappears completely for the highest source charge. Quantitatively, the peak at q=20 MeV/c in the longitudinal correlation function is suppressed by a factor of the order of 15% (9%) for an emitter of charge Z=39 (20).

Moreover, the third-body influence on the shape of the correlation function extents well beyond the peak at 20 MeV/c and remains noticeable at relative momenta as large as q=80 MeV/c. This effect modifies the balance between the attractive two-proton strong interaction and the repulsive Coulomb force (enhanced by the antisymetrization effects) which produce a flat correlation function at intermediate relative momentum (q=30-80 MeV/c) in the two-body approximation while a significant anti-correlation is predicted by the three-body calculations. One should note that all the theoretical correlation functions presented in the figure 2 have been normalized according to the criterion applied to the experimental data which thus explains the small offset above unity of the three-body calculations at very large relative momentum (q$\simeq$ 100 MeV/c).

Following the analysis done in the two-body approximation, we have compared the experimental correlation functions to three-body calculations performed over a broad range of source radii and lifetimes. According to a χ^2 statistical analysis of the shape of the correlation functions, the best agreement was found for the parameters $r_0 = 3.5fm$, $\tau_0 = 30fm/c$ and $r_0 = 3.0fm$, $\tau_0 = 30fm/c$ using Z=20 (figure 3) and Z=39 (figure 4), respectively. Figures 5 and 6 compare the corresponding angular integrated correlation functions (solid lines), the best fit in the two-body approximation (dotted-dashed lines) and the predictions of the microscopic transport model BUU (dotted lines) to the experimental data (solid points). Whereas an emitter charge of Z=39 is probably unrealistic (but nevertheless gives a limit on the maximum possible third-body effect), the results obtained with the charge Z=20 indicate the need of a significant reduction (1 fm) of the source radius to balance the suppression caused by the presence of the emitter Coulomb field. On the other hand, the lifetime value is not strongly affected, the lifetime effect observed in the data imposing to keep the same difference in amplitude, quite insensitive to the radius value, between the longitudinal and the transverse correlation functions.

However, the agreement is not extremely good since, as we mentioned earlier, the three-body calculations exhibit an anti-correlation in the intermediate region in relative momentum in contrast with the flat shape of the experimental correlation function. One should note that, on contrary to the work done in ref. [17] where only the peak region was considered, the statistical analysis of the two-proton correlation functions was performed over a large range in relative momentum (q=10-60 MeV). Although the conditions of validity of the three-body quantum model, weakly fulfilled for a part of the data, and the limited amount of pairs satisfying all the experimental cuts may explain to a certain extent this disagreement, the BUU results suggest that reaction dynamics play an important role [18]. Concerning the angular integrated correlation function, though the amplitude of the peak is slightly underestimated, the phase-space point distribution predicted by the microscopic model allows a good description of the correlation function at intermediate relative momenta (figure 5). The difference in the behavior of the theoretical correlation functions appears more pronounced when angular cuts are applied, especially in the transverse direction (figure 1). As a matter of fact, at relative momentum between 30 and 60 MeV/c, the BUU prediction remains above unity, in agreement with the data, whereas the correlation functions obtained in the two-body approximation with a Gaussian source present a noticeable negative correlation. Similar conclusions can be drawn from the analysis of experimental two-proton correlation functions measured in ^{14}N-induced reaction at 75 MeV/A [22].

This analysis reveals the limits, possibly emphasized by the influence of the emitter Coulomb field, of an oversimplified static picture of the source which assumes completely independent distributions of the production points, production times and momenta of the emitted protons. According to density distributions predicted by BUU transport calculations [23], over the range of central collisions selected by the total transverse energy cut, a strong impact-parameter dependence of the shape of the residual system (undergoing an expansion and rotation phase) is expected which thus questions the spherical image of the source commonly used [24]. In contrast to long-lived sources for which the relative distance between particles is mainly determined by the emission time difference, a significant contribution to the correlations should be expected from the spatial distribution of emission points for short-lived sources considered here. In this first attempt to take fully account of the interactions producing and affecting the two-proton correlations, only an effective charge of the emitter was considered. It is probable that, in the whole picture of an evolutionary source, the change of its charge along the time may play an significant role in the resulting intensity of the correlations.

V. CONCLUSIONS

The two-proton correlation functions measured in $^{36}Ar + ^{45}Sc$ at 80 MeV/nucleon have been analyzed in the frame of a new three-body quantum model which takes into account the Coulomb interactions of the particles with their emitter. In the two-body approximation, this approach gives similar results to the Koonin-Pratt formalism. For a realistic charge of the source, the influence of its Coulomb field on the shape of the correlation function appears to be important over a broad range in relative momentum and leads to a reduction of 1 fm (20 %) of the source radius previously deduced in the two-body approximation. However, a real good agreement with the experimental data, in term of shape of the correlation function can not be achieved. As suggested by the predictions of the microscopic transport theory BUU, this result seems to indicate the limits of a simple static picture of the source and the importance of the dynamical correlations in this particular set of data. Although the BUU model fails to reproduce experimental correlation functions at higher incident energies [18,26,27], its description of the dynamical evolution of the collisions may be used, in association with a three-body quantum model describing the particle correlations, as a guideline to investigate the particle source behavior, especially its geometrical characteristics, during a stage when a full equilibrium of the system is far from being reached and statistical model can not be applied.

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FIGURES

FIG. 1. Experimental longitudinal (solid circles) and transverse (open circles) two-proton correlation functions compared with predictions calculated in the two-body approximation : the new quantum model (solid lines), the Koonin-Pratt formalism (dotted-dashed curves) and the BUU transport model (dotted lines).

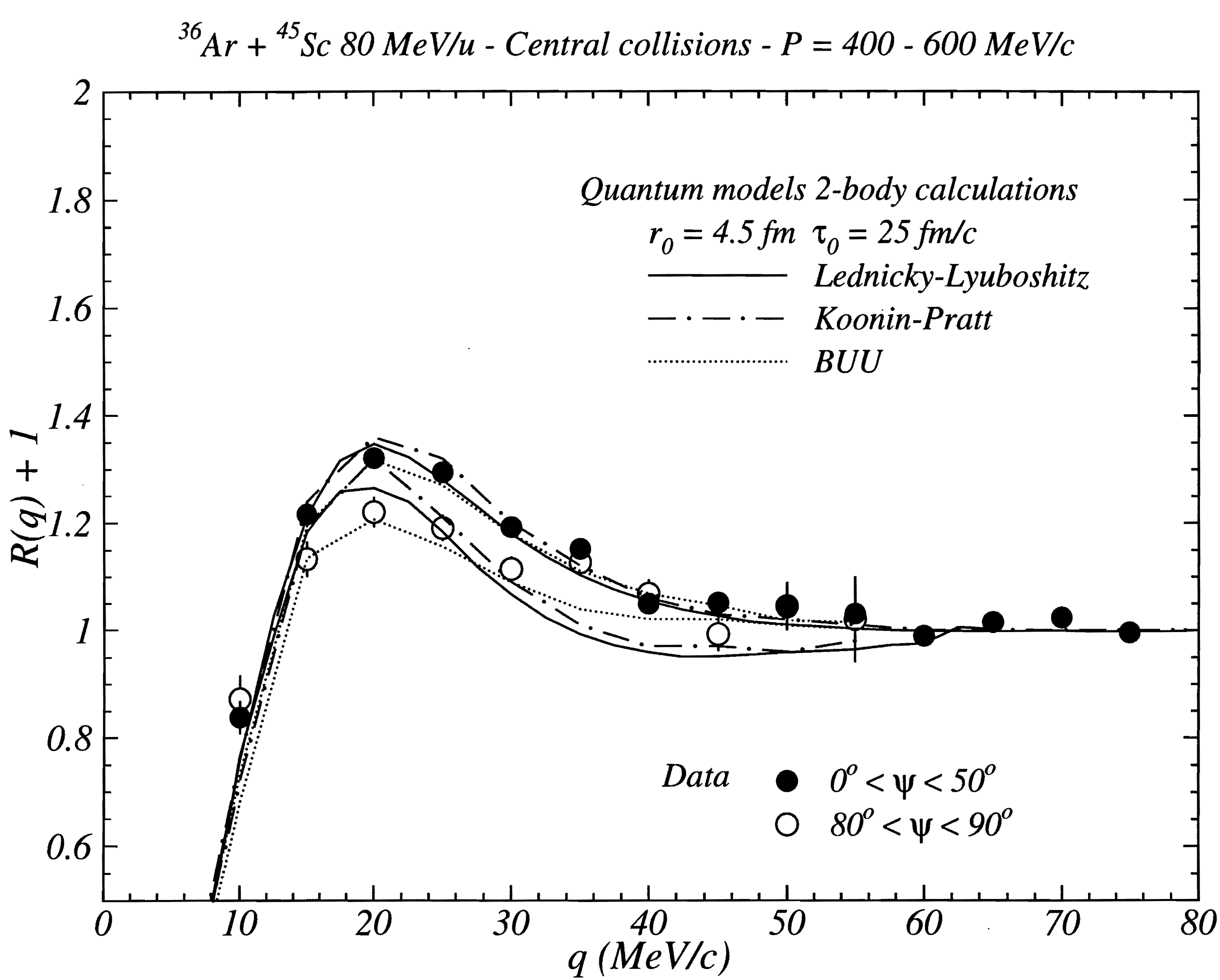
FIG. 2. Longitudinal (solid lines) and transverse (dotted-dashed lines) two-proton correlation functions predicted for the source parameters $r_0 = 4.5 fm$, $\tau_0 = 25 fm/c$ and different assumptions of the quantum model : two-body approximation, complete three-body calculations for source charges Z=20 and Z=39.

FIG. 3. Experimental longitudinal (solid circles) and transverse (open circles) two-proton correlation functions compared with predictions of the quantum model for a source with a radius $r_0 = 3.5 fm$, a lifetime $\tau_0 = 30 fm/c$ and a charge Z=20.

FIG. 4. Same as Fig.3 for a source with a radius $r_0 = 3.0 fm$, a lifetime $\tau_0 = 30 fm/c$ and a charge Z=39.

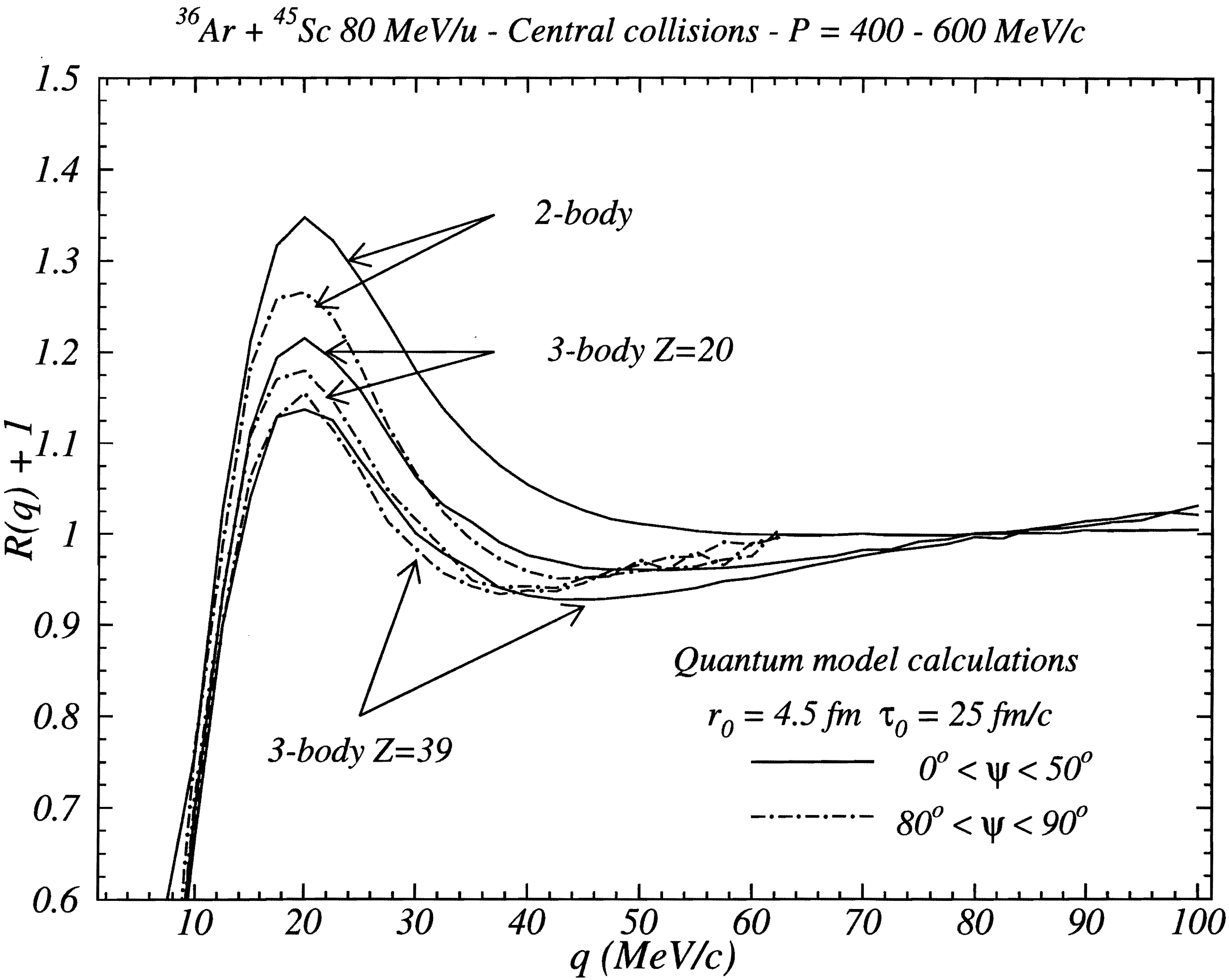
FIG. 5. Angular integrated two-proton correlation function (solid lines) predicted by the quantum model for the source parameters $r_0 = 3.5 fm$, $\tau_0 = 30 fm/c$ and Z=20 compared with the experimental data (solid circles), calculation in the two-body approximation giving the best agreement with the data (dotted-dashed curve) and the BUU transport model prediction (dotted line).

FIG. 6. Same as Fig.5 for three-body calculation obtained with a source of radius $r_0 = 3.0 fm$, lifetime $\tau_0 = 30 fm/c$ and charge Z=39.



$^{36}Ar + ^{45}Sc$ 80 MeV/u - Central collisions - P = 400 - 600 MeV/c
Quantum models 2-body calculations
$r_0 = 4.5$ fm $\tau_0 = 25$ fm/c
Lednicky-Lyuboshitz
Koonin-Pratt
BUU
Data
$0^o < \psi < 50^o$
$80^o < \psi < 90^o$
R(q) + 1
q (MeV/c)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0
10
20
30
40
50
60
70
80

Figure 1



36Ar + 45Sc 80 MeV/u - Central collisions - P = 400 - 600 MeV/c
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
R(q) + 1
10
20
30
40
50
60
70
80
90
100
q (MeV/c)
2-body
3-body Z=20
3-body Z=39
Quantum model calculations
r0 = 4.5 fm τ0 = 25 fm/c
0° < ψ < 50°
80° < ψ < 90°

Figure 2

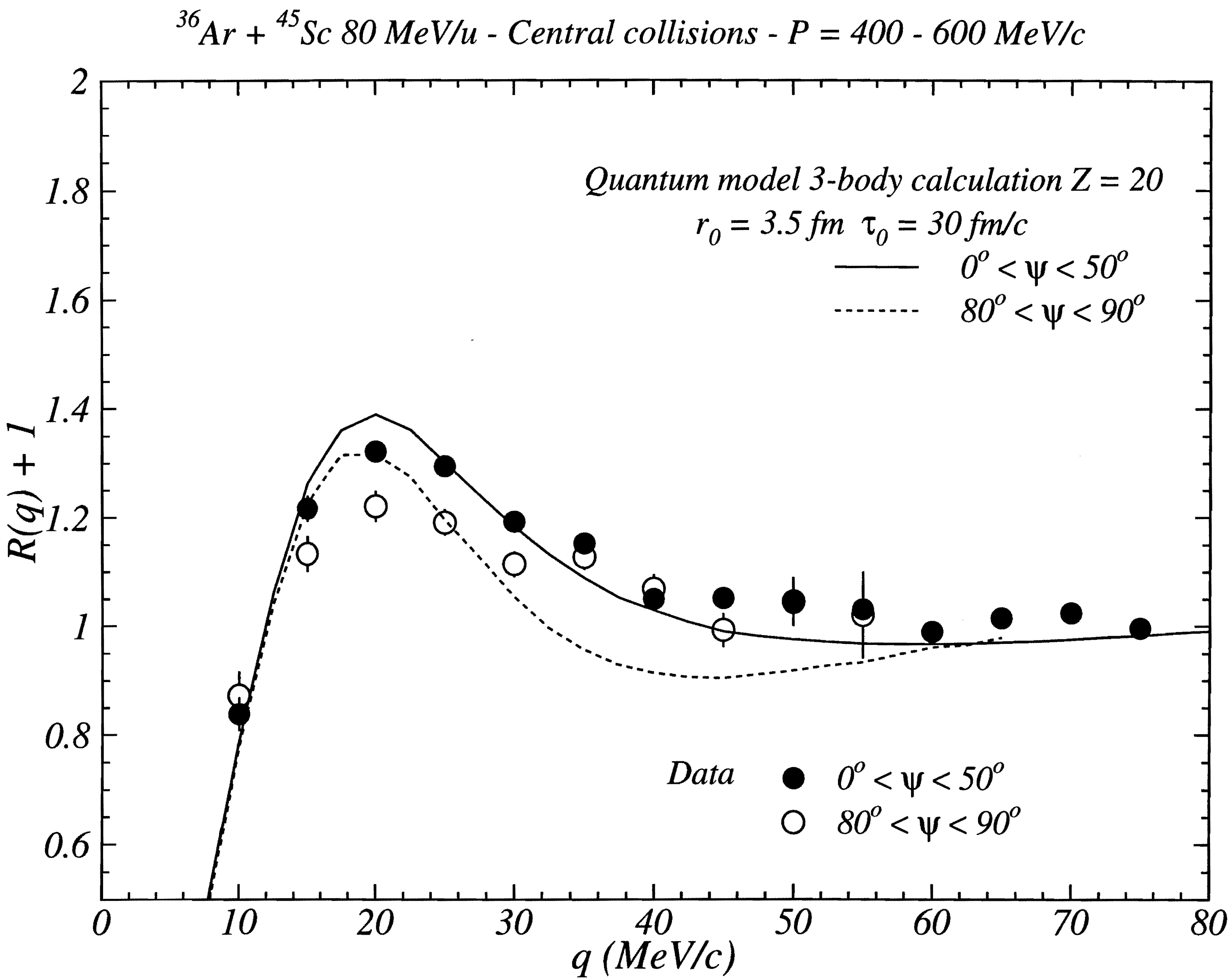
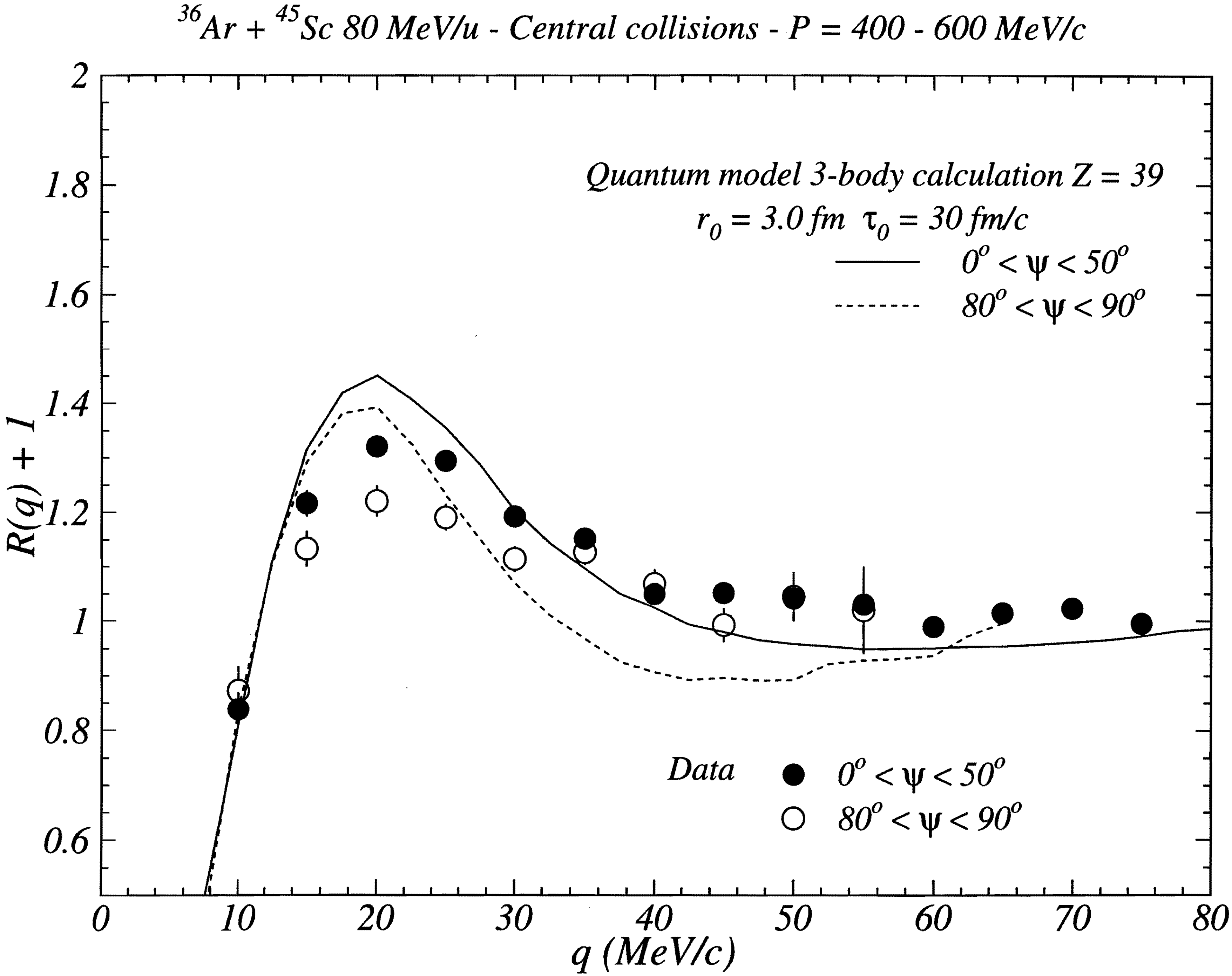
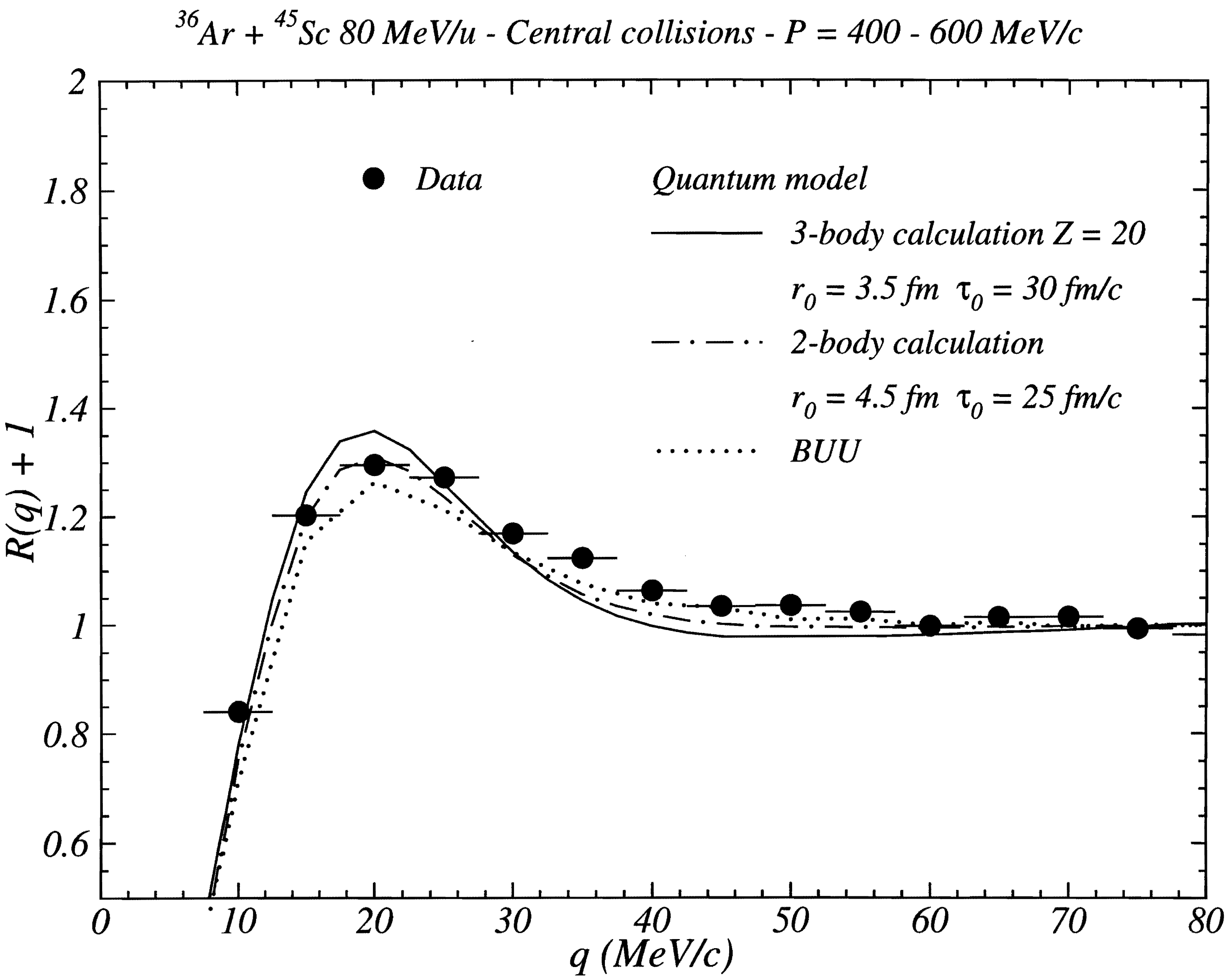

$^{36}Ar + ^{45}Sc$ 80 MeV/u - Central collisions - P = 400 - 600 MeV/c
Quantum model 3-body calculation Z = 20
$r_0 = 3.5$ fm $\tau_0 = 30$ fm/c
$0^o < \psi < 50^o$
$80^o < \psi < 90^o$
Data
$0^o < \psi < 50^o$
$80^o < \psi < 90^o$
R(q) + 1
q (MeV/c)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0
10
20
30
40
50
60
70
80

Figure 3



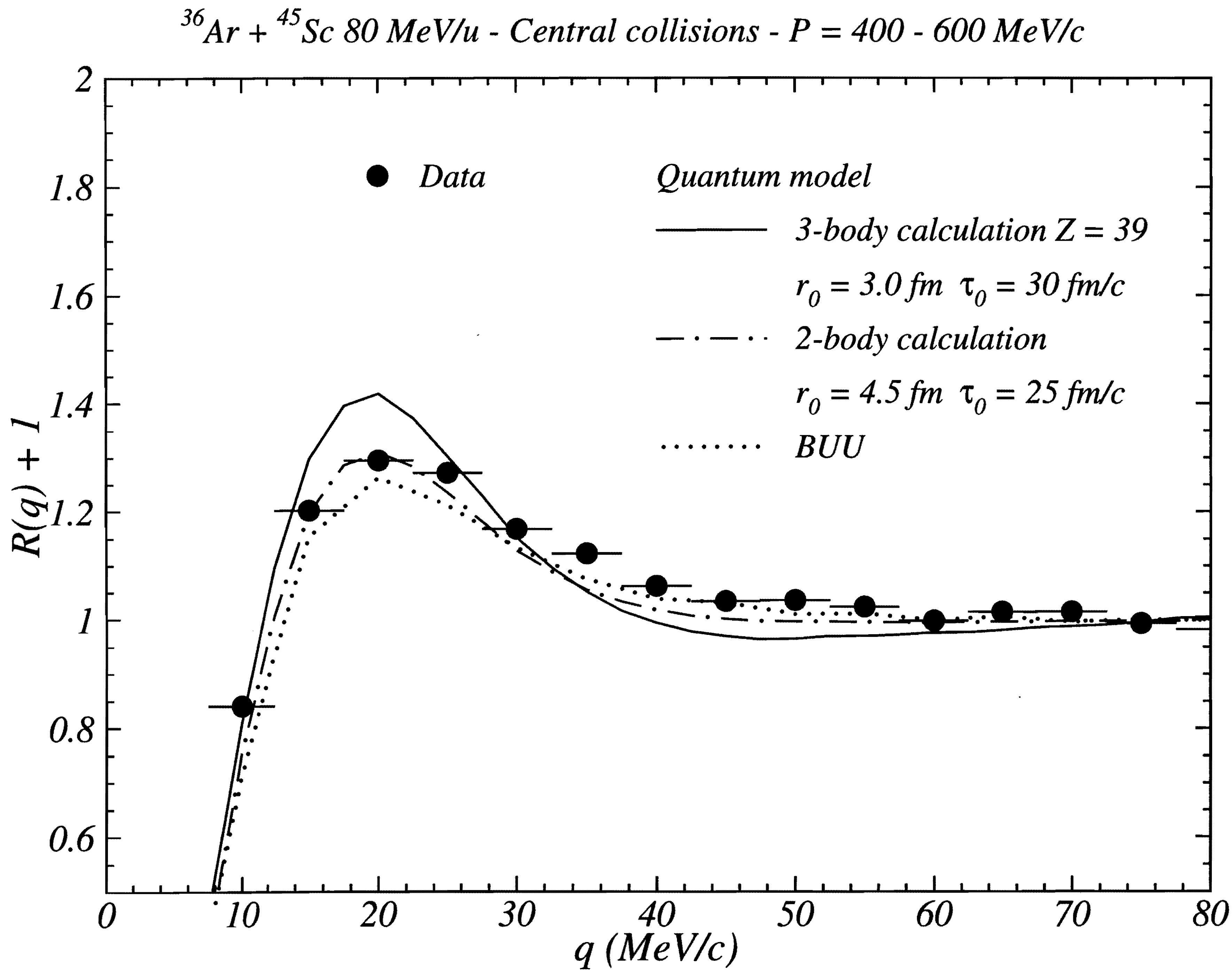
$^{36}Ar + ^{45}Sc$ 80 MeV/u - Central collisions - P = 400 - 600 MeV/c
Quantum model 3-body calculation Z = 39
$r_0 = 3.0\,fm$ $\tau_0 = 30\,fm/c$
$0^o < \psi < 50^o$
$80^o < \psi < 90^o$
Data
$0^o < \psi < 50^o$
$80^o < \psi < 90^o$
R(q) + 1
q (MeV/c)
0
10
20
30
40
50
60
70
80
0.6
0.8
1
1.2
1.4
1.6
1.8
2

Figure 4



$^{36}Ar + ^{45}Sc$ 80 MeV/u - Central collisions - P = 400 - 600 MeV/c
Data
Quantum model
3-body calculation Z = 20
$r_0 = 3.5$ fm $\tau_0 = 30$ fm/c
2-body calculation
$r_0 = 4.5$ fm $\tau_0 = 25$ fm/c
BUU
R(q) + 1
q (MeV/c)

Figure 5



$^{36}Ar + ^{45}Sc$ 80 MeV/u - Central collisions - P = 400 - 600 MeV/c
Data
Quantum model
3-body calculation Z = 39
$r_0 = 3.0$ fm $\tau_0 = 30$ fm/c
2-body calculation
$r_0 = 4.5$ fm $\tau_0 = 25$ fm/c
BUU
R(q) + 1
q (MeV/c)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0
10
20
30
40
50
60
70
80

Figure 6