# SOME REMARKS ON THE DISINTEGRATION OF HIGHLY EXCITED Ag AND Br NUCLEI OBSERVED IN PHOTOGRAPHIC EMULSION IN VIEW OF THE QUARK MODEL

By T. Jacobsen, F. O. Breivik and S. O. Sørensen

Institute of Physics, University of Oslo*

*(Received November 6, 1979)*

The angular distribution of the tracks of the particles emitted from highly excited Ag and Br nuclei after the cascade are consistent with isotropy, in disfavour of the hypothesis of fission preceding some subsequent disintegration by isotropic single particle emission. If it is assumed that the highly excited nucleus behaves as a gas of quarks which are confined within the Ag(Br) nucleus, the confinement may possibly cause delays between the subsequent emissions of particles in favour of thermodynamical equilibrium. Some comments are given on the mass of a quark in the nucleus and on the energy distribution of the particles emitted from these excited nuclei.

## Introduction

As is well known, the evaporation model [1–5] is believed to represent the most important mechanism for emission of particles from highly excited Ag and Br nuclei observed in photographic emulsion exposed to high energy beams [6–9], the very fast cascade or shower particles excluded. However, whereas the excitation energy must be high enough to justify the assumption of continuous energy levels of the excited nucleus, this model should not be used for excitations above or too near the binding energy of the nucleus, i.e. about 600 MeV [4] because the nuclear temperature $T$ must be low enough to justify the assumption of thermodynamical equilibrium between the successive emissions. The two main features of this model which most easily may be checked are the energy spectrum of the emitted particles, and the ratio of doubly and singly charged particles. However, the model does not provide or use some explicit "existence" factor for the probability to have a doubly charged particle in the nucleus. The ratio is calculated based on the principle of detailed balance and the assumption of equal cross sections for emission and absorption of some particle [4]. In fact, if such small "existence factors" were introduced as weight factors for the probability of emission of some type of particle, the fits of the evaporation model would be completely destroyed [4]. This model is based on the assumption

* Address: Institute of Physics, University of Oslo, P.O.Box 1048, Blindern, Oslo 3, Norway.

of isotropical emission of particles in the Ag(Br) reference system, in good agreement with the experimental results [10–13].

Because of the high excitation energy and correspondingly high $T$ for such nuclei, it has been discussed if some other mechanisms could play an important role in the disintegration [8, 9]. It has been investigated with a negative result whether fission initiated by violent nuclear surface oscillations which lowers the potential barrier could account for the emission of heavy fragments, i.e. Li, Be, B nuclei etc. [14]. The concept of fragmentation which implies local heating of the nucleus has also been discussed [15].

In this note we present the result of a very simple angular distribution test of isotropical emission of particles from some especially large stars of Ag and Br disintegrations in photographic emulsion. We find that the angular distributions are consistent with isotropy, disfavouring the hypothesis of fission preceding the disintegration of the intermediate nuclei. We discuss some simple features of simultaneous emission of several particles from the excited nuclei in terms of phase space distributions.

As an alternative to the intranuclear cascade model [16] of the excitation mechanism of the Ag(Br) nuclei, the excitation may be thought of in terms of quark-quark scattering. If the quarks are confined within the excited nucleus, it may behave as a "bag of quark gas". Due to the confinement, emission of some particle may be delayed long enough to establish thermodynamical equilibrium between the successive emissions. The mass of a quark in a nucleus is briefly discussed.

## *Experimental material and method*

Our experimental results have been obtained by measurements by means of microscopes using standard technique on 113 Ag and Br stars in Ilford G5 emulsion exposed to a 4.5 GeV/$c$ $\pi^-$ beam at the Berkeley Bevatron. We have calculated the angles between the tracks based on measurements of the coordinates of the star origo and one point of each track so far from the origo that the error of a measurement is negligible.

The distribution of the number $N_h$ of the tracks of the particles emitted from these stars is shown in Fig. 1, where $N_h$ is the sum of the tracks with ionization at least 1.4 times minimum, i.e. the minimum ionizing cascade or shower tracks excluded. The average $N_h$ is about 23 corresponding to an average excitation energy of about 1000 MeV, which is above the 600–800 MeV corresponding to 14–19 tracks acceptable for the evaporation model [4, 5].

## *The angular distribution of the emitted particles*

We now propose a very simple angular distribution test of anisotropical emission of particles emitted from the highly excited Ag and Br nuclei. The test is based on the following argument. We assume that a highly excited Ag(Br) nucleus fissionates to two intermediate nuclei which subsequently disintegrate by evaporation. A simple calculation shows that the velocity of the intermediate nuclei may surpass the velocity of some of the particles emitted from these nuclei. Therefore, some tendency to clustering of the tracks could

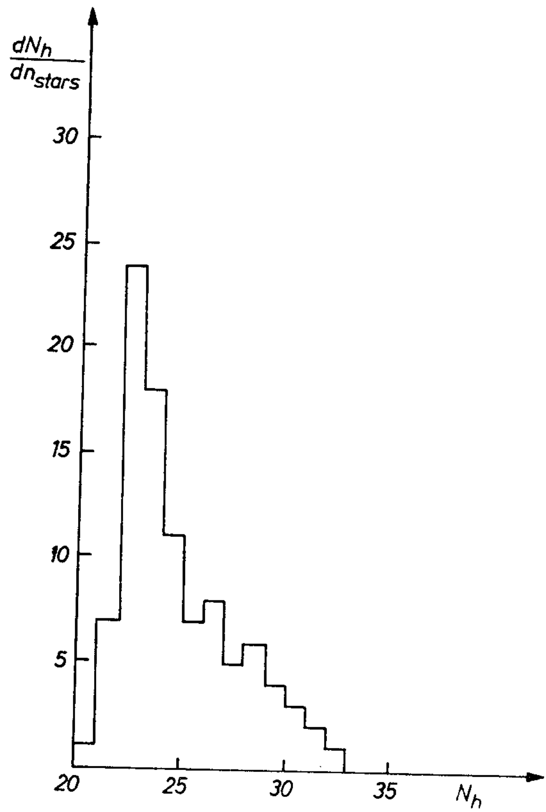


Fig. 1. The distribution of the number of tracks $N_h$ of the particles emitted from the highly excited Ag and Br nuclei in the photographic emulsion, the beam track and the minimum ionizing cascade or shower tracks excluded

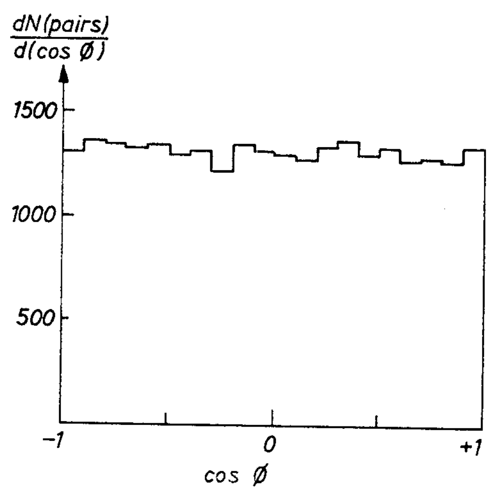


Fig. 2. The distribution of the angles $\phi$ between all pairs of tracks of Ag or Br stars in photographic emulsion in terms of cos $\phi$, all minimum ionizing tracks excluded

be expected. We therefore measured the angles between all the combinations of pairs of tracks, the cascade tracks and the beam track excluded.

The distribution of the angles $\phi$ for all the stars in our sample is shown in Fig. 2 in terms of $\cos\phi$. Apart from the tiltering of this distribution, no enhancements are seen near $\cos\phi = -1$ or $+1$, as expected from the hypothesis of two-bunch clustering, or anywhere else. (This test may be useful for jet-search.)

The tiltering of the distribution of $\cos\phi$ reflects the velocity of the excited Ag(Br) nucleus in the emulsion which gives the emitted particles some velocity component in the forward or beam direction. This is seen by the distribution of $\cos\theta$, where $\theta$ is the angle between any $N_h$-track and the beam track, shown in Fig. 3. The forward/backward ratio

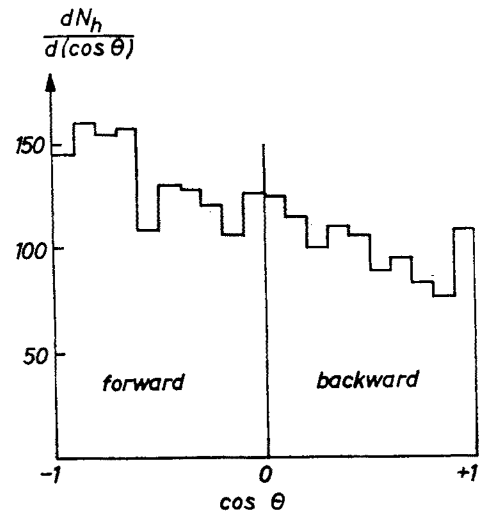


Fig. 3. The distribution of the angles $\theta$ between a track from a Ag or Br star in the photographic emulsion and the direction of the incident $\pi^-$ for all tracks in the star, the shower or cascade tracks excluded, in terms of $\cos\theta$

of this distribution corresponds to a velocity of about $0.015c$ of the excited Ag(Br) nucleus due to the momentum transfer from the incident $\pi^-$. Since the excited Ag(Br) nucleus shows no measurable track in the emulsion, and a track of some few $10^{-6}$ m would have been seen, the disintegration must have been finished within less than about $10^{-12}$s.

## *Simultaneous emission and phase space distribution*

The mechanism of nuclear evaporation is thought to be dominating for excitation energies below the total binding energy. When the excitation energy exceeds this limit, thermodynamical equilibrium can not be assumed, and, as a consequence, interference between several emissions may be expected. In that case the disintegration may possibly be described partly as a many body phase space final state, in agreement with the observed isotropy. In addition to the $\overline{N}_h = 23$ charged particles, about $N_h/3 \approx 8$ neutral particles will be emitted, i.e. totally about 31 particles, of which some are

$\alpha$'s or heavier particles. A detailed study of the "explosion" model would require an appropriate computer program. However, since this model on the average would give less energy to the heavier particles, in disagreement with the experimental results [6], this model can not describe the dominant emission mechanism from these highly excited Ag(Br) nuclei. Therefore, single particle emission seems to be favoured in spite of the fact that several nucleons in the highly excited Ag(Br) nuclei simultaneously must have excitation energies above the binding energy. Thus, it seems as if some mechanism may prevent simultaneous emission of several particles from the highly excited Ag(Br) nuclei.

### *The excitation mechanism*

The excitation mechanism of the Ag(Br) nuclei has been extensively studied in terms of intranuclear cascades [16] which can deposite so much energy in the nuclei as observed. This energy is partly due to kinetic energy given to the nucleons bound within the Ag(Br) nucleus, and partly due to production and absorption of mesons in the Ag(Br) nucleus. For very high excitations, the meson-absorption is probably the main mechanism since very energetic nucleons would have a high probability to escape from the nucleus with most of the kinetic energy. For the stars in our sample, absorption of the incident $\pi^-$ seems unlikely since it would lead to a velocity of the excited Ag(Br) nucleus of about $0.05c$, while the measured value is less than $0.02c$.

The excitation mechanism may possibly alternatively be thought of in terms of quark--quark or antiquark-quark scattering [20]. If the quarks are confined in the nucleus, a quark of the target nucleon may only escape from the target nucleus if the quark is "dressed" by an antiquark to a colourless meson, or if it "picks up" two more quarks to make a colourless baryon, unless the target nucleon is scattered out of the target nucleus. While the "dressing" is a very fast process, the "pick-up" may be slow enough to allow for thermodynamical equilibrium in a gas of quarks confined within the volume of the nucleus. Hence, the nuclear temperature $T$ based on the nucleon-model of the excited nucleus may possibly not be very critical. We therefore tentatively assume that in a very highly excited Ag or Br nucleus the quarks are confined within the volume of the nucleus and not within the individual nucleons, as a "quark gas in a bag".

### *Particle formation in a quark gas*

No single quark may be emitted from the excited nucleus because of confinement, but some quarks may by chance form a colour-singlet nucleon which may be emitted. We define a probability per unit of time $P$ for three quarks to be in nearby phase space points with the effective mass of a nucleon. For a large nucleus, the probability per unit of time for six quarks to be in nearby phase space points with the effective mass of the deuteron could then be of the order $P^2$, and the probability per unit of time to form a $n$-nucleon cluster could be of the order $P^n$. We assume that the life-time of such a quark-system is of the order of the time needed to reach the surface of the nucleus. Since we must require

$$0 < P < 1, \tag{1}$$

there seems to be some possibility to obtain sufficiently long delays between the formations of the nucleon-clusters to permit thermodynamical equilibrium in the excited nucleus, namely for

$$0 < P \ll 1. \tag{2}$$

For the same reason the formation probability of complex clusters decreases with increasing nucleon-number $n$ of the cluster, in good qualitative agreement with the well known low probability for emission of heavy fragments.

On the other hand, if

$$0 \ll P < 1, \tag{3}$$

the quarks would recombine very rapidly, corresponding to very few free quarks in the nucleus, and the nucleus must then be near its ground state. Formally, there is a high probability for the formation of heavy fragments, but, on the other hand, there must be little energy for emission of such fragments.

In this picture, $0 < P \ll 1$ is used to describe the excited Ag(Br) nucleus as a state of quark gas. However, if this assumed quark gas should "explode" with simultaneous emission of several particles, $0 \ll P < 1$ would be required in order to form these particles. Since these two requirements are simultaneously mutually exclusive, "explosion" with phase space distribution of energy and momentum is unlikely according to the quark model of the excited nuclei.

### *Some remarks on the energy of the particles emitted from a quark gas*

We assume that a highly excited Ag(Br) nucleus behaves as a gas of quarks which are quasi-free but confined within the volume of the nucleus, and that the gas due to the high excitation energy tentatively may be described by the Maxwell–Boltzmann distribution for the kinetic energy $E_q$ of the quarks

$$dn/dE_q = \text{const} \cdot E_q^{1/2} \exp(-E_q/T) \tag{4}$$

where the most probable $E_q \approx T/2$.

If for simplicity it is assumed that three quarks may make a nucleon N if they join in nearby phase space points with nearly equal energies, the kinetic energy of the formed nucleon is

$$E_N \approx 3E_q. \tag{5}$$

The probability for three quarks to have about the same energy is equal to the probability to find a nucleon with the sum of these energies, i.e.

$$dn/dE_N \sim (dn/dE_q)^3 \approx \text{const} \cdot (E_q^{1/2} \exp(-E_q/T))^3,$$

$$dn/dE_N \approx \text{const} \cdot E_N^{3/2} \exp(-E_N/T), \tag{6}$$

and for $3n$ quarks to have about the same energy equal to the energy of a $n$-nucleon cluster is

$$dn/dE_{nN} \sim (dn/dE_q)^{3n} \approx \text{const} \cdot (E_q^{1/2} \exp(-E_q/T))^{3n},$$

$$dn/dE_{nN} \approx \text{const} \cdot E_{nN}^{3n/2} \exp(-E_{nN}/T). \tag{7}$$

The most probable kinetic energies are $E_{N,\,mp} \approx 3T/2$ and $E_{nN,\,mp} \approx 3nT/2$, respectively.

According to these crude estimates, the most probable kinetic energy of the particles emitted from a "gas of confined quarks" should be expected to increase for increasing $n$, in qualitative agreement with the experimental results [6, 7, 8, 17]. However, several effects which have been neglected ought to be taken into account in a more detailed discussion of the distribution of energy of the emitted particles, notably the momentum-distribution of the quarks in a nucleon, the effects of the potential barrier, the binding energy of a particle to the excited Ag(Br) nucleus as a "gas of confined quarks", and also the "cooling" of the nucleus after some particle emissions.

On the other hand, even if these effects have been neglected, the formulas above reproduce fairly well the main characteristics of the observed energy distributions of protons, $\alpha$-particles and $^8$Li, [6, 7, 8, 17], if $T$ is about 2–3 MeV. Thus, there are some indications that these observed energy distributions are reflections of the thermal energy of the confined quarks in the excited Ag and Br nuclei. The low value of $T$ as compared to the high value of about $T \approx 10$ MeV needed by the evaporation model used on the nucleon model of the excited nuclei, is due to the larger number of quarks in the nuclei.

*Nucleon dissociation to quasifree quarks in the nucleus and the mass of the quark in the nucleus*

Due to the confinement property of the quarks in a free nucleon, no single quark may escape from the nucleon. However, in a nucleus, the nucleons may in principle exchange quarks [19]. If the nucleus is excited, the excitation energy per nucleon may possibly exceed the binding energy of the quarks in a nucleon, and the nucleus could possibly behave as a "bag of quasifree but confined quarks". For $m_q \leqslant m_N/3$, where $m_q$ and $m_N$ are the masses of a quark [18, 19] and a nucleon in a nucleus, respectively, the nucleon in the nucleus could be expected to dissociate to quarks confined within the nucleus. However, the nuclei are well described by means of nucleons. For $m_q > m_N/3$, some nucleons may dissociate to quarks if some energy is absorbed by the nucleus. If the excited Ag or Br nucleus behaves as a "bag of confined quarks" when the excitation energy per nucleon is $\varepsilon$(MeV), ($h = c = 1$), $m_N + \varepsilon > 3m_q$ i.e. $m_N/3 < m_q < (m_N + \varepsilon)/3$. Thus, if an excited Ag or Br nucleus behaves as a "bag of confined quarks" for $\varepsilon \approx 10$ MeV, the mass of the quark in the nucleus would be a little more than one third of the mass of a nucleon in the nucleus.

## *Conclusion*

The angular distributions of the non-minimum ionizing tracks of some large-$N_h$ stars of Ag and Br disintegrations in photographic emulsion which excitation energy exceeds the binding energy are consistent with isotropy, in disfavour of the hypothesis of fission preceding some subsequent disintegration by isotropic single particle emission. "Explosion" of the nuclei with simultaneous emission of several particles, i.e. strong interference between several emissions, seems unlikely since it would give less kinetic energy to the heavier particles than to the lighter ones, in disagreement with the observations.

As an alternative to the nuclear cascade model of the excitation mechanism of the Ag(Br) nuclei, it may be thought of in terms of quark-quark scattering. If the excited nucleus behaves as a quark gas confined in a bag defined as the volume of the nucleus, the "formation probability" is seen to decrease with increasing nucleon-number $n$, in qualitative agreement with the experimentally observed frequency of different types of particles. The confinement requirement may cause delays between the subsequent particle emissions, needed to assure single particle emissions.

By tentatively using Maxwell-Boltzmann distribution of energy of the particles emitted, reasonable results are obtained, but more detailed studies are needed to make qualitative comparison with the experimental results. If the "quark gas model" of the excited nuclei shall work, the mass of a quark in the nucleus ought to be a little heavier than one third of the mass of a nucleon. Even if this model seems to give a comprehensive picture of the excitation and disintegration of the highly excited Ag(Br) nuclei, more qualitative tests are needed.

## REFERENCES

[1] J. Frenkel, *Sov. Phys.* **9**, 533 (1936).
[2] V. Weisskopf, *Phys. Rev.* **52**, 295 (1937).
[3] E. Bagge, *Ann. Phys.* **39**, 535 (1941).
[4] K. J. LeCouteur, *Proc. Phys. Soc.* **A63**, 259 (1950).
[5] Hagedorn and Macke, in W. Heisenberg, *Kosmische Strahlung*, Springer Verlag, 210, 1953.
[6] C. F. Powell, P. H. Fowler, D. H. Perkins, *The Study of Elementary Particle Physics by the Photographic Method*, Pergamon Press, London 1959.
[7] *Progress in Cosmic Ray Physics*, North Holland Comp., Amsterdam 1952.
[8] W. H. Barkas, *Nuclear Research Emulsions II*, Acad. Press, New York 1973.
[9] J. Miller, J. Hudis, *Ann. Rev. Nucl. Sci.* **9**, 159 (1959).
[10] J. B. Harding, *Phil. Mag.* **40**, 530 (1949); *Phil. Mag.* **42**, 63 (1951); J. B. Harding, D. H. Perkins, *Nature* **164**, 285 (1949); J. B. Harding, S. Lattimore, D. H. Perkins, *Proc. Roy. Soc.* **A196**, 325 (1949).
[11] G. Bernardini, G. Cortini, A. Manfredini, *Phys. Rev.* **79**, 952 (1959); G. Bernardini, E. T. Booth, L. Lederman, J. H. Tinlot, *Phys. Rev.* **80**, 924 (1950).
[12] J. Crussard, Bombay Conference on Fundamental Particles 1950.
[13] F. O. Breivik, T. Jacobsen, S. O. Sørensen, *Phys. Rev.* **130**, 1119 (1963).
[14] S. Katcoff, *Phys. Rev.* **86**, 41 (1952).
[15] R. Wolfgang, E. W. Baker, A.A. Caretto, J. B. Cumming, G. Friedlander, J. Hudis, *Phys. Rev.* **103**, 394 (1956).
[16] N. Metropolis, R. Bivins, M. Storm, J. M. Miller, G. Friedlander, A. Turkevich, *Phys. Rev.* **110**, 204 (1958).
[17] O. Skjeggestad, Thesis dr. phil., University of Oslo 1959.
[18] H. Fritsch, Ref. TH. 2699–CERN.
[19] M. B. Kislinger, *Phys. Lett.* **79B**, 474 (1958).
[20] S. Fredrikson, Ref. TH. 2720–CERN.