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S.P.Avdejev, V.A.Karnaukhov, G.Y.Korovin,
V.D.Kuznetsov, T.Nagy, L.A.Petrov

ON A SEARCH FOR SUPERDENSE NUCLEI OF Rb AND Cs AMONG THE PRODUCTS OF 8 GeV PROTON INTERACTIONS WITH Ta

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1. INTRODUCTION

Much attention has been given lately to the problem of probable existence of nuclear matter superdense state. The probability of nuclear states with increased density was first stated 35 years ago by Feenberg and Primakov who proceeded from qualitative considerations and analogies[1]. This work has brought to neither theoretical nor experimental consequences and during 25 years nuclear physics has been actually ignoring the problem of nuclear matter superdense state. Later the situation changed due to the growing interest in mesic degree of freedom in a nucleus. Migdal and his colleagues followed by a number of other authors have developed a theory of pion condensation (see reviews [2,3] with complete bibliography). In accordance with this theory, in case the density of nuclear matter exceeds some critical value n_c, there takes place a rearrangement of the system's ground state followed by the appearance of pion condensate. The energy gain at this phase transition can lead to a stationary or quasistationary state at a density n_s which is five-eightfold greater than the normal one. Theory is not able to calculate accurately the total energy of the superdense state which depends dramatically on the parameter of short-range nucleon-nucleon correlation g'. The experimentally obtained information on the value of this parameter is inaccurate and contradictory[4-6]. Nevertheless, one cannot exclude a possibility that a superdense state is bound stronger than an ordinary one. In this case, there should exist an independent world of condensed nuclei, stable and radioactive.

The properties of these unusual nuclei differ significantly from those, studied by physics until now, that is why the attempts to discover them experimentally seem to be of utmost importance.

Another model leading to the probable existence of superdense nuclei of a different type has been suggested by Lee and Wick[7]. They consider the phase transition of σ-field related to the hypothetic scalar σ-meson.

Now there are dozens of theoretical papers devoted to the problem of anomalous nuclei. Experimentalists are less active in this respect. The majority of their works are reviewed in ref.[8]. A search for superdense nuclei has been carried out in natural samples[9-11], among the products of high energy particle interaction with matter[12-15],among fission products[16-17]. These studies exclude with great assurance the natural existence of superdense nuclei with a binding energy exceeding 100 MeV per nucleon. The search for superdense nuclei with moderate binding energies is a more complicated problem and little has been done yet in solving it.

The most promising method of superdense nuclei synthesis are the reactions induced by heavy ions with the energy of several hundred MeV per nucleon. The dynamics of nuclei collisions, variations of nuclear matter density during interaction have been analysed in a number of papers within the frameworks of different cascade models[18-21] in hydrodynamic approximation[22,23]. It has been demonstrated that under these conditions one can obtain a density exceeding the critical n_c which, evidently, equals $(1.5\text{–}3)\, n_0$[24,25]. The situation is less favourable for obtaining compression if one uses relativistic nucleons as projectiles. But even in this case one cannot exclude the possibility of reaching the phase transition point by means of nondominant reaction channels or secondary processes.

The present work is a continuation of our previous research[26]. A beam of 8-9 GeV protons has been used for producing superdense nuclei. We have been basing on the assumption that the main mode of disintegration of a radioactive superdense nucleus is the beta-decay[8]. Migdal et al. have shown that the position of beta-stability line for superdense nuclei is shifted towards neutron deficiency from the β-stability valley of ordinary nuclei and can be evaluated by the following relation

$$\left(\frac{Z}{A}\right)_s = \frac{1}{2}\left[1 + \frac{a_q(n_s)}{4\alpha_\pi(n_s)} A^{2/3}\right]^{-1} \quad . \qquad (1)$$

Here $a_q(n_s)$ - the Coulomb energy parameter in the Weizsacker formula, and $\alpha_\pi(n_s)$ the parameter of symmetry energy taken at the condensed state density n_s. The second term in the brackets is equal to $2.6\cdot 10^3\, A^{2/3}$ at $n_s = 7n_0$. The β-decay energies of anomalous nuclei are growing and their half-lives are decreasing much faster than those of ordinary isotopes while moving away from the stability line. Nevertheless, as has been demonstrated in[8], one can expect to find relatively long-lived beta-active superdense nuclei. Basing on this we have used the off-line mass separation to single out superdense nuclei from products of nuclear reactions.

The investigation has been carried out for two elements Rb and Cs. Such a choice has been dictated by two reasons. First, according to[27] the existence of bound superdense nuclei is possible for $A > A_{min} = 20\text{–}70$. Second, these elements can be separated with a good degree of selectivity from other elements by using surface ionization.

The range of mass number for the search is defined on the basis of evaluation of beta-stability line position for superdense nuclei by formula (1). The anomaly can manifest itself by the appearance of relatively long-lived beta-activity, since "normal" isotopes in this region have small lifetimes. Another possible manifestation of anomaly are nonintegral values of the mass number. This is caused by the fact that binding energies of anomalous $(\epsilon_s A)$ and ordinary $(\epsilon_0 A)$ nuclei with a given number of nucleons can differ significantly. This will bring to mass difference $\Delta M = (\epsilon_0 - \epsilon_s)A$. For $A \approx 100$ the difference of binding energies per nucleon $|\epsilon_s - \epsilon_0| > 1$ MeV will result in a detectable shift of anomalous isotope peak in the mass spectrum.

2. EXPERIMENTAL PROCEDURE

The internal proton beam of the JINR synchrophasotron has been used. The energy of protons is (8-9) GeV. The target has been made of a tantalum foil (4 μm thick) rolled into a cylinder (diameter 3 mm). The weight of the target is (1.5-2.0) g. By means of a pneumatic probe the target has been inserted periodically into the zone of the beam. The total proton flux through the target in each experiment has been $(5\text{-}7)\cdot 10^{14}$. It has been determined by measuring the γ-activity of ^{24}Na, produced in the aluminium foil, fixed in front of the target. After (5-8) h irradiation the target was removed from the accelerator vacuum chamber and inserted into the ion source of the mass separator YASNAPP. In the focal plane there has been a special type collector. It was a metallic rod (900 mm long and of 12 mm ϕ) onto which magnetic tape was winded spirally with a step of 3 mm (or 1.5 mm). After activity collection the rod was removed from the separator chamber, the tape was unwinded and thus, the continuous distribution of activity turned to be devided into 3 mm (1.5 mm) segments spaced with respect to each other by 38 mm. This enables one to measure simultaneously and practically independently the activities of the neighbouring segments of the focal plane in a geometry which is close to 2π, with a space resolution of 3 (1.5 mm).

The distribution of beta-activity on the collector has been detected with 120 standard Geiger beta-counters SBT-11 with transversal dimension 28 mm. A special interface joined the counter assembly to the buffer memory in such a way that each counter had its own memory address. The periodically accumulated information was discharged into EC-1010 computer. This scanning system is described in detail in [28].

The scanning of the whole collector has been carried out in 3 steps during approximately 1.5 h. To calibrate the mass scale and identify the peaks in the mass spectra, the time dependence of beta-activity has been measured and the half-lives for each peak have been determined. At the first stage of these research an ion source with sirface ionization described in [29] has been used. The ionizer was made of tungsten. It has been heated to 2500°C by electron bombardment from two ring cathodes. Such a high temperature provided the necessary rate of activity diffusion from the target, which was made for these experiments as a bunch of tantalum wires (50 μm thick). With this source there has been observed a comparable yield of alkali, alkali-earth and rare-earth elements. More than that, in the ranges of mass numbers $32 \leq A \leq 44$ and $65 \leq A \leq 91$ there have been detected some peaks at nonintegral values of A, which have been assigned to multicharged ions of heavier isotopes. The reason for the appearance of multicharged ions is the electron beam induced ionization in the area of ionizer outlet.

In the present investigation the ion source has been modified to suppress multicharged ions and to obtain a high enough degree of selectivity of alkali elements separation. With this purpose a tungsten ionizer has been replaced by a tantalum one, which is heated by electron bombardment from one cathode, shifted to 28 mm from the outlet. Besides, the target has been also changed: the wire has been replaced by 4 μm thick foil. The use of such a target provided a high enough rate of alkali elements diffusion at weaker heating of the ionizer. The temperature was 2000°C in the target area and only 1400°C near the outlet.

This modification of the ion source ensured good selectivity of alkali element separation at high enough absolute efficiency. The Table shows a change in separation efficiency of elements next to the alkali elements when changing from high temperature ionization mode (η_1) to selectivity mode (η_2). The table gives the results of an experiment providing the best selectivity.

Note, that according to estimations the absolute efficiency of Cs separation in the present research has been (10-30)% which is by one order of magnitude higher than in the mode of high temperature ionization using a wire target.

Table

The ratio of separation efficiencies of different elements for two modes of the ion source

Mass numbers	A=66÷90			A=101÷137		
Elements	Ga	Sr	Y	In	Ba	La
η_2/η_1	10^{-3}	10^{-3}	10^{-2}	5.10^{-4}	7.10^{-4}	3.10^{-5}

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. The Range $100 \leq A \leq 138$

This range of mass numbers has been covered by the collector in the experimental searches for superdense Cs nuclei. In accordance with formula (1) it is expected that beta-stable superdense Cs has A= 117÷118. That is why special attention has been given to the investigation of the mass spectrum around this value of A.

Figure 1 shows the distribution of β-activity along the separator focal plane obtained in the high temperature mode of the ion source operation. Figure 2 is obtained by use of a modified ion source ensuring the alkali element selective separation. In the second case, when comparing it with the first one, the counting rate for cesium isotopes is approximately 10 times higher while rare earths are practically not observed. In this connection one regards as anomalous the behaviour of the peaks of mass numbers 116, 117, 120, 121, 122. Basing on the measurement of decay curves these peaks were assigned to the isotopes of antimony, tellurium, iodine and xenon. This identification was confirmed through measuring the X-ray spectra. The change from the mode of high temperature surface ionization to a softer mode did not give any considerable suppression of the peaks of Sb-Xe. The reason for this is still unclear. One can say definitely that such behabiour of the peaks of these elements, having ionization potential in the range of 8.6-12.1 eV, cannot be understood within the framework of surface ionization mechanism.

These mysterious peaks, unfortunately, fall into the mass number range which is most interesting for the search of superdense Cs. To get a clearer picture there has been carried out an experiment with double separation. With this purpose a 4 μm thick tantalum foil serving as a collector was inserted

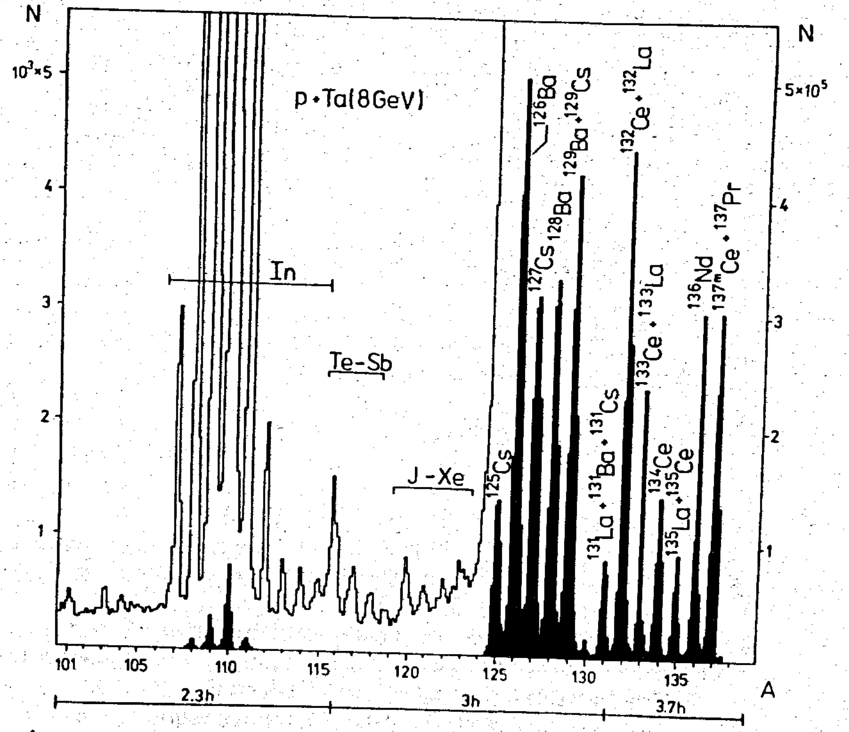

Fig.1. The distribution of beta-activity on the collector of mass separator for the products of tantalum target spallation induced by a 8 GeV protons ($100 \leq A \leq 138$). A high temperature ion source with surface ionization has been used. The right hand scale refers to the shaded spectrum. Below the ordinate axis the time of starting the measurement of different part of the spectrum counted from the end of irradiation is indicated.

into the focal plane of the mass separator. The two pieces corresponding to mass number ranges $113 \leq A \leq 124$ and $128 \leq A \leq 135$ were cut out of this foil. These two pieces of collector foil have been inserted into the ion source and the separation was repeated. We have specially excluded from the second separation the part of the collector foil, which carries most intensive Cs peaks ($^{125,127}Cs$), in order to suppress the tail from these peaks in the mass number range of interest. The spectrum obtained in this experiment is shown in fig.3. In the

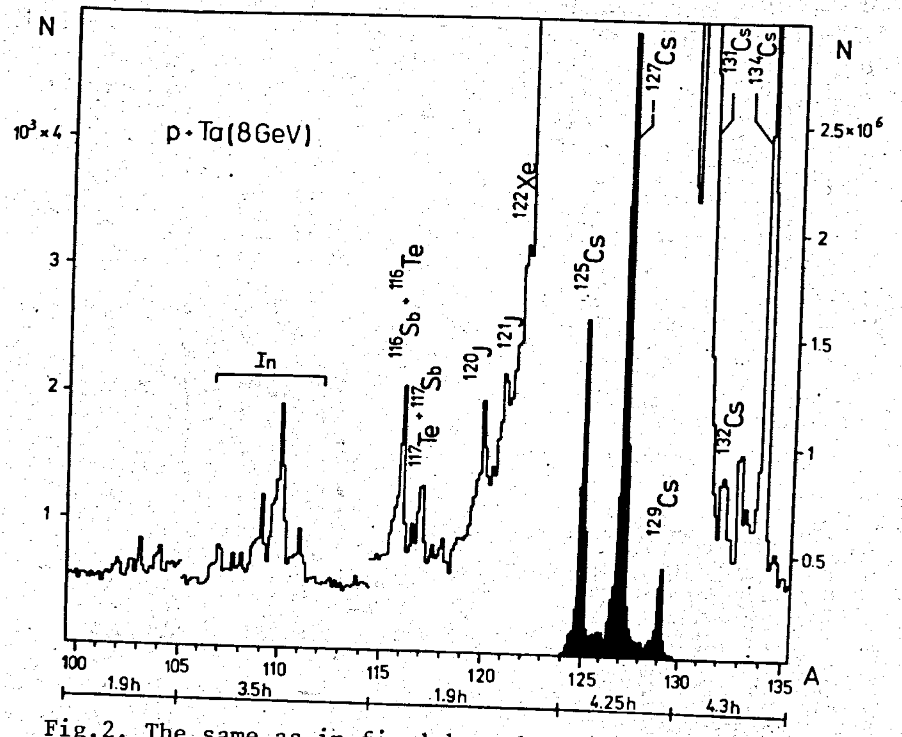

Fig.2. The same as in fig.1 but the mode of selective alkali element separation has been used.

range $100 \leq A \leq 124$ there are no peaks at all and the counting rate here is determined fully by the counter background. A dashed curve demonstrates the picture which could present the left-hand wing of intensive peaks $^{125,127}Cs$ if they are included into the second separation.

None of these experiments gave definite indications to the existence of anomalous Cs. We estimated the upper limit of superdense Cs yield Y in the assumption that it decays only through electron emission and that the contribution from the K-capture is insignificant. In this case the efficiency of decay registration is determined completely by the counters' geometry. The halflife was assumed to be equal to 5 h. We used ^{127}Cs as a reference isotope. Its yield was noted by Y_0. To define the value of Y_0 corresponding to the measured counting rate, the efficiency of ^{127}Cs registration was calculated on the basis of the known decay scheme of this nuclide. The registration efficiency is defined by the relative probability of positron decay and by the emission of conversion electrons.

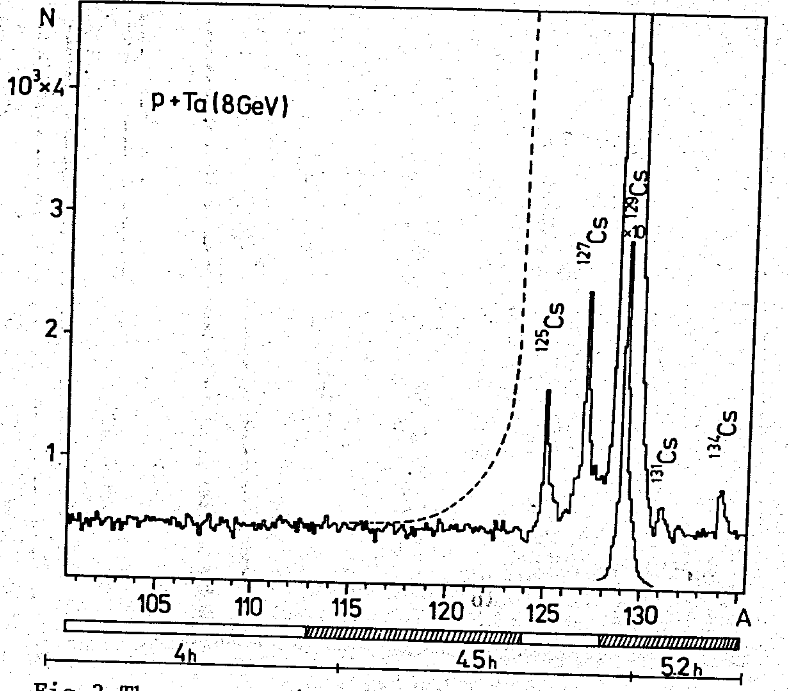

Fig.3. The same as in fig.1 but double mass separation has been used. Below the abscissa axis there are shaded areas indicating those parts of the spectrum for which double mass separation has been performed.

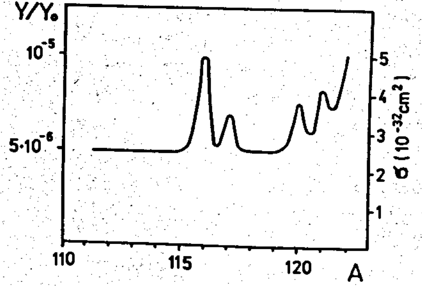

Fig.4. The upper limits for the relative yield (left-hand scale) and for the production cross section (right-hand scale) of superdense Cs (as a function of the mass number), assuming $T_{1/2} = 5$ h. Relative yield is taken with respect to the ^{127}Cs yield.

Basing on the experiments with single mass separation we have obtained the ratio Y/Y_0 in the function of the mass number demonstrated in Fig.4. In the range $112 \leq A < 122$ the upper limit of anomalous Cs yield in the units of ^{127}Cs yield varies from $5\cdot10^{-6}$ up to 10^{-5}. To transform these relative values into absolute cross sections one should know the cumulative cross section of ^{127}Cs production. For this, there are no direct experimental data and it has been evaluated by the Rudstam formula/30/, normalized for the experimental data on the independent yields of several isotopes of I, Cs, Ba, La /31/. The obtained upper limit for the cross section of anomalous Cs production is $5\cdot10^{-32}$ cm^2. The sensitivity reached in the experiment with double separation is lower due to decrease of total efficiency. The upper limit of superdense Cs yield is $5\cdot10^{-5}$ with respect to the yield of ^{127}Cs. But the estimate is valid for a wider range of mass numbers: $113 \leq A \leq 124$ and $131 \leq A \leq 133$.

3.2. Range $64 \leq A \leq 86$

This mass number range has been covered by the collector in the experimental searches for Rb superdense nuclei. In accordance with estimated by formula (1) it is expected that beta-stable superdense Rb has $A = 77 \div 78$. That is why the area of the mass spectrum near this value is of special interest.

Figure 5 shows the result of one measurement of beta-activity distribution on the mass separator collector in this range of A. The mode of selective alkali element separation was used. Besides, strong lines of the known Rb isotopes one can see distinctly in the spectrum only a weak peak of ^{68}Ga which is approximately 10^{-4} from the peak of ^{81}Rb. No anomalies have been found in the mass number interval $69 \leq A \leq 78$ at the level exceeding 10^{-5} with respect to the yield of ^{81}Rb. This evaluation has been carried out in the assumption that there is a 100% probability of anomalous nucleus beta decay and of 5 hour halflife. For other halflives in our experimental conditions one obtains higher values of the upper limit of anomalous nuclei yield. This can be seen in Fig.6 which presents the dependence of the evaluation of cross section upper limit for the production of superdense beta-active isotopes of Cs and Rb on the supposed halflife.

Up to now all experimental attempts to find superdense nuclei (including those described in this paper) have not brought positive results. But from our point of view this cannot be regarded as a basis for the statement that the theoretical supposition of the possibility that such nuclei do exist, is incorrect. New experimental approaches should be developed to give e final answer to this question.

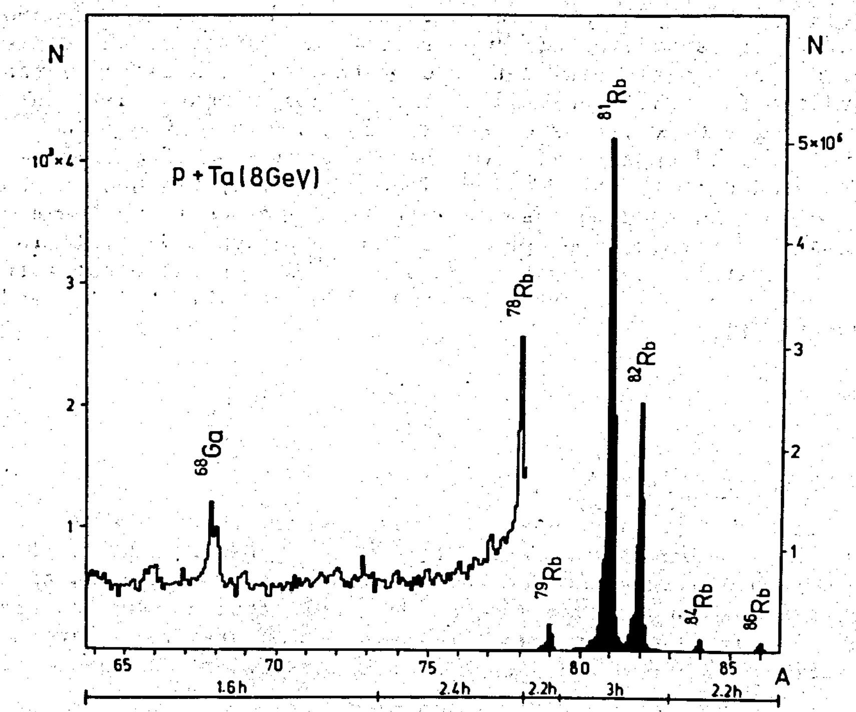

Fig.5. The distribution of beta-activity on the collector of the mass separator for the products of Ta-target spallation by 8 GeV protons, $64 \leq A \leq 86$. The mode of selective alkali element separation has been used. The right-hand scale refers to the shaded spectrum. The time of starting the measurements after the end of irradiation is shown below the abscissa axis.

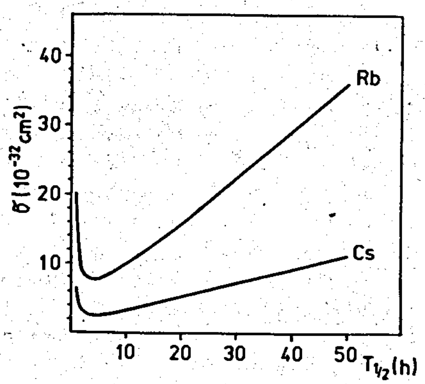

Fig.6. The evaluation of the upper limit of superdense Rb and Cs production cross section depending on the suggested halflife (the range of mass numbers is noted in the text).

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REFERENCES

1. Feenberg E., Primakoff H. Phys.Rev., 1946, 70, p.980.
2. Migdal A.B. Rev.Mod.Phys., 1978, 50, p.107.
3. a) Brown G.E., Weise W. Phys.Rep., 1976, 27C, p.1; b) Papers by Migdal A.B.; Sawyer R.F.; Baym G. and Cambell D.K.; Backman S.O.and Weise W. In: Mesons in Nuclei, vol.III, Rho M. and Wilkinson D.H. Eds.,North-Holland,1979.
4. Rho M. In: Proc. of 4th High Energy Heavy Ion Summer Study, Lawrence Berkeley Lab., LBL-7766, 1978, p.221.
5. Delorme J. et al. Phys.Lett., 1980, 91B, p.328.
6. Toki H., Weise W. Phys.Lett., 1980, 92B, p.265.
7. Lee T.D., Wick G.C. Phys.Rev., 1974, D9, p.891; Lee T.D. Rev.Mod.Phys., 1975, 47, p.267.
8. Karnaukhov V.A. Izvestiya AN SSSR, 1977, 41, p.1538.
9. Frankel S. et al. Phys.Rev., 1976, 13C, p.737.
10. Holt R.J. et al. Phys.Rev.Lett., 1976, 36, p.183.
11. Aleshin V.I. et al. Pisma v JETP, 1976, 24, p.114.
12. Kulikov A.V., Pontecorvo B.M. Phys.Lett., 1977, 66B, p.136.
13. Price P.B., Stevenson J. Phys.Rev.Lett., 1975, 34, p.409; Frankel K., Stevenson J. Phys.Rev., 1976, 14C, p.1455.
14. Gromov K.Ya. et al. Yadernaya Fiz., 1980, 31, p.289.
15. Bugorsky A.P. et al. Pisma v JETP, 1980, 32, p.487.
16. a) Borovoy A.A. et al. J.Phys.G: Nucl.Phys., 1980, 5, p.723; b) Aleshin V.I. et al. Yad.Fiz., 1979, 30, p.318.
17. a) Nikolenko V.G. et al. Pisma v JETP, 1978, 27, p.65; b) Samosvat G.S., Popov A.B. Yad.Fiz., 1979, 30, p.313; c) Popov A.B., Rudenko V.T., Samosvat G.S. Yad.Fiz., 1980, 32, p.342.
18. Bondorf J. et al. Zs.Phys., 1976, A276, p.385.
19. Baz A.I. et al. Preprint IAE-2660, Moscow, 1976.
20. Gudima K.K., Iwe H., Toneev V.D. J.of Phys.G: Nucl.Phys., 1979, 5, p.229.
21. Gudima K.K., Toneev V.D. Yad.Fiz., 1980, 31, p.1455.
22. a) Baumgardt H.G. et al. Zs.Phys., 1975, A273, p.359; b) Sobel M.I. et al. Nucl.Phys., 1975, A251, p.502.
23. a) Galitsky V.M. Usp.Fiz.Nauk., 1976, 120, p.138; Pisma v JETP, 1977, 25, p.175; b) Galitsky V.M., Mishustin I.N. Phys.Lett., 1978, 72B, p.285.
24. Ruck V. et al. Zs.Phys., 1976, A277, p.391.
25. Bunatian G.G. Yad.Fiz., 1979, 29, p.258.

26. Gromov K.Ya. et al. Yad.Fiz., 1980, 31, p.289.
27. Mishustin I.N., Karnyukhin A.V. Yad.Fiz., 1980, 32, p.945.
28. Karnaukhov V.A. et al. JINR, 13-12211, Dubna, 1979.
29. Beyer G.J. et al. Nucl.Instr. & Meth., 1971, 96, p.437.
30. Rudstam G. Zeit. für Naturforsch., 1966, 21a, p.1027.
31. Yu Y.W., Porile N.T. Phys.Rev., 1975, C12, p.938.

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