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ELEMENTARY PARTICLES AND FIELDS
Experiment

Peripheral Fragmentation of ^{8}B Nuclei in Nuclear Emulsion at an Energy of 1.2 GeV per Nucleon

R. Stanoeva[1),2)], V. Bradnova[1)], S. Vokál[1),3)], P. I. Zarubin[1)*], I. G. Zarubina[1)], N. A. Kachalova[1)], A. D. Kovalenko[1)], A. I. Malakhov[1)], G. I. Orlova[4)], N. G. Peresadko[4)], P. A. Rukoyatkin[1)], V. V. Rusakova[1)], E. Stan[5)], M. Haiduc[5)], S. P. Kharlamov[4)], I. Tsakov[2)], and T. V. Schedrina[1)]

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Abstract—The results obtained by studying the charge topology of fragments produced in the peripheral dissociation of relativistic ^{8}B nuclei in emulsion are presented. Fifty-five events of the peripheral dissociation of a ^{8}B nucleus in events where there is no production of target-nucleus fragments and mesons ("white" stars) were selected. A leading contribution of the $^8\mathrm{B} \to {}^7\mathrm{B} + p$ mode, which has the lowest energy threshold, was revealed on the basis of these events. Information about the branching ratios for dissociation modes characterized by a higher multiplicity was obtained. The dissociation of the ^{7}Be core in ^{8}B bears resemblance to the dissociation of a free ^{7}Be nucleus. The transverse-momentum distributions of fragments originating from the $^8\mathrm{B} \to {}^7\mathrm{Be} + p$ dissociation mode were obtained. For these distributions, a small mean value of $\langle P_T \rangle = 52 \pm 5$ MeV/c in the c.m. frame suggests a low binding energy of the outer proton in the ^{8}B nucleus. An indication of a strong azimuthal correlation of the fragments ^{7}Be and p was found.

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INTRODUCTION

A low energy of proton separation from ^{8}B is a feature peculiar to this nucleus. This is indicative of the possible existence in ^{8}B of a proton halo separated in space from the core in the form of a ^{7}B nucleus. In $^8\mathrm{B} \to {}^7\mathrm{Be}$ relativistic-fragmentation reactions, so weak a binding leads to a rather narrow momentum distribution of ^{7}B nuclei [1, 2]. In just the same way as in the case of exotic nuclei, the possible increase in the radius of the ^{8}B nucleus because of the proton halo could lead to a relative enhancement of its interaction cross section. However, available experimental data show no enhancement of this type. In view of this circumstance, it is highly desirable to study in more detail the ^{8}B nucleus, especially characteristic features of its cluster structure. By way of example, a proton halo may arise from the deuteron cluster formed by an unpaired neutron and the outer proton. This possibility is suggested by the spin values of 3/2 and 2 for the ^{7}Be and ^{8}B nuclei, respectively.

The nature of a proton halo can be clarified on the basis of a more comprehensive analysis of relativistic ^{8}B fragmentation in peripheral interactions. This type of interactions is initiated in electromagnetic or diffractive processes or in collisions of nucleons in the case of a small overlap of colliding nuclei. A fragmenting projectile may receive an excitation in the vicinity of the energy threshold for dissociation to clusters. Nuclear-fragment systems whose total charge is equal to the charge of the parent nucleus are produced in the kinematical region of relativistic-nucleus fragmentation. By determining the relative production rates for various configurations of fragments, one can assess the significance of different cluster excitation modes. The $^7\mathrm{Be} + {}^1\mathrm{H}$, $2\mathrm{He} + \mathrm{H}$, $^6\mathrm{Li} + 2{}^1\mathrm{H}$, $\mathrm{He} + 3\mathrm{H}$, and 5H charge modes can be observed in ^{8}B breakup.

The opening angle of the relativistic-fragmentation cone is determined by the Fermi momenta of nucleon

[1)]Joint Institute for Nuclear Research, Dubna, Moscow oblast, 141980 Russia.
[2)]Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Blvd. Tsarigradsko chausse 72, BG-1784 Sofia, Bulgaria.
[3)]P.J. Šafárik University, Košice, Slovak Republic.
[4)]Lebedev Institute of Physics, Russian Academy of Sciences, Leninskii pr. 53, Moscow 117924 Russia.
[5)]Institute of Space Sciences, P.O.Box MG-23, 76-900, Bucharest-Maguerele, Romania.
[*]E-mail: zarubin@lhe.jinr.ru

clusters in a nucleus. Their magnitudes normalized to mass numbers are concentrated around the normalized momentum of the primary nucleus, the spread being a few percent. In selecting events that involve projectile dissociation into a narrow fragmentation cone, it turns out that either there are no nonrelativistic target-nucleus fragments ("white stars" in [3]), or their number is insignificant. Target fragments can readily be separated from relativistic-projectile fragments, since their fraction in the relativistic-fragmentation cone is insignificant and since they have nonrelativistic momenta.

In the fragmentation of a relativistic nucleus, the total ionization generated by fragments and the ionization per track can decrease to Z and Z^2, respectively, where Z is the projectile charge number. In order to reconstruct events, one needs the entire body of kinematical information about particles in the relativistic-fragmentation cone; for example, this makes it possible to evaluate the invariant mass of the system. In doing this, the accuracy depends crucially on the angular resolution of tracks. In order to ensure the best spatial resolution, it is necessary to detect relativistic fragments with the highest spatial resolution.

The nuclear-photoemulsion method, which forms the basis of the BECQUEREL project at the nuclotron at the Joint Institute for Nuclear Research (JINR, Dubna) [4], meets the above requirements. This project was developed with the aim of performing systematic searches for peripheral-fragmentation modes with a statistical significance of several tens of events, classifying them, and measuring relevant angles. Emulsions ensure a record spatial resolution of 0.5 μm, which makes it possible to separate the traces of charged particles in the three-dimensional image of an event within the thickness of a single layer (600 μm) and to attain a high accuracy in measuring angles. The traces of relativistic nuclei of H and He are separated visually. As a rule, the charge of a light nucleus undergoing peripheral fragmentation can be determined as the sum of the charges of relativistic fragments. The isotopes of H and He can be separated via measurements of multiple scattering on the tracks of light fragments. An analysis of products originating from the relativistic fragmentation of neutron-deficient isotopes has additional advantages owing to a greater fraction of observed nucleons and the smallest degree of Coulomb distortions. For details of our irradiation procedure and for a description of special features of our analysis of interactions in the emulsion used, the interested reader is referred to [5,6]. Presented immediately below are the first results obtained by studying the fragmentation of ^{8}B nuclei at an energy of 1.2 GeV. These include the distribution with respect to final charge states and angular spectra of fragments. Also, we perform a comparison with data on ^{10}B nuclei from [3, 6] and data on ^{7}Be nuclei from [7].

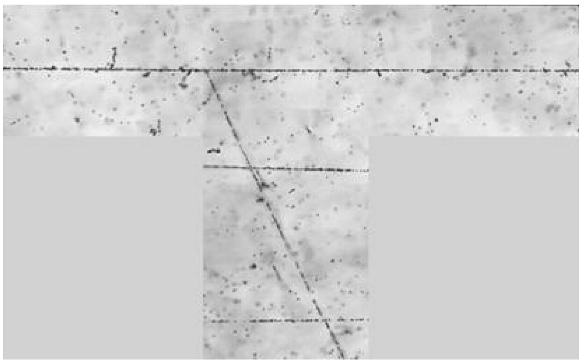

Fig. 1. Microphotograph of the fragmentation of a ^{10}B nucleus on an ^{1}H nucleus in emulsion at an energy of 1.2 GeV per nucleon at the PAVIKOM facility (Lebedev Institute of Physics, Russian Academy of Sciences, Moscow). The track of the primary nucleus ^{10}B undergoes virtually no change in direction after the interaction vertex. The track of the recoil proton exhibits a large scattering angle. The process was identified as $^{10}\mathrm{B} + p \to {}^8\mathrm{Be} + 2n + p$.

IRRADIATION OF EMULSIONS WITH A BEAM OF ^{8}B

In investigations that employ an emulsion irradiated with secondary beams, it is necessary to ensure that nuclei under study be readily identifiable. In order to form a beam of ^{8}B nuclei at the JINR nuclotron, we therefore used the process in which the primary ^{10}B beam of energy 1.2 GeV per nucleon underwent fragmentation on a polyethylene target. Such processes were observed in studying the interactions of ^{10}B in an emulsion [6]. By way of example, a microphotograph of an event in which a primary nucleus ^{10}B fragments into a quintuply charged nucleus accompanied by the track of the recoil proton is shown in Fig. 1. Since the nucleus of the isotope ^{9}B does not exist in a bound state, on one hand, and since it is necessary to compensate for the transverse momentum of the recoil proton, on the other hand, the most probable interpretation of such an event implies the emission of two neutrons from ^{10}B and the formation of ^{8}B. The fact that there is no isotope ^{9}B among relativistic fragments can be used in separating the ^{8}B beam from ^{10}B by the magnetic rigidity (the difference is about 20%). The nuclotron beam channel used in the irradiation has an appropriate momentum acceptance, about 2 to 3%. The assumption that two nucleons are emitted was confirmed in tuning the channel

Table 1. Charge-topology distribution of the number $N_{\rm pf}$ of peripheral interactions observed in an emulsion irradiated with a secondary beam of ^{8}B nuclei

Q	N_Z					$N_{\rm pf}$	
	$Z=5$	$Z=4$	$Z=3$	$Z=2$	$Z=1$	$N_{\rm tf}$	$N_{\rm ws}$
7	–	–	–	2	3	–	1
7	–	–	–	1	5	1	–
6	–	–	–	2	2	8	2
6	–	–	–	1	4	6	4
6	–	–	–	–	6	1	–
5	–	–	–	1	3	61	14
5	–	–	–	2	1	44	12
5	–	–	1	–	2	8	–
5	–	–	1	1	–	1	–
5	–	1	–	–	1	17	24
5	1	–	–	–	–	17	1
5	–	–	–	–	5	21	4
4	–	–	–	–	4	5	1
4	–	–	–	2	–	24	1
4	–	–	–	1	2	42	–

Note: We denote by Q the total charge of relativistic fragments within a cone of opening angle 8° in an event, by N_Z the number of fragments of charge Z in an event, by $N_{\rm ws}$ the number of white stars, by $N_{\rm tf}$ the number of events involving target fragments.

to the separation of ^{9}B, in which case boron nuclei virtually disappeared in the channel, but they appeared in tuning to ^{10}B and ^{8}B. In an analysis of irradiated emulsions, the absence of white stars having topology of H + He and He + Li relativistic fragments from the possible admixture of ^{6}Li and ^{10}B nuclei was an additional confirmation of the aforesaid. The fraction of ^{7}Be nuclei, which are close in magnetic rigidity (the difference is about 10%), in the ^{8}B beam formed was estimated a value below 10% by using a scintillation monitor and was excluded by charge topology. The most intense background to beam tracks was due to ^{3}He nuclei and was eliminated upon visually scanning the emulsion.

CHARGE TOPOLOGY of ^{8}B DISSOCIATION

In scanning emulsion layers along tracks of beam nuclei, we found 929 inelastic interactions over the total length of 123 m. This leads the mean-free-path value of $\lambda = 13.3 \pm 0.4$ cm, which corresponds to the inelastic cross section for the ^{8}B nucleus with

Table 2. Distribution of white stars associated with ^{7}Be and ^{8}B nuclei with respect to charge dissociation modes [for a comparison to be more convenient, one nucleus of H (proton) was excluded from the charge mode for the ^{8}B nucleus]

Charge mode	^{7}Be	Channel fraction, %	^{8}B (+H)	Channel fraction, %
2He	41	43	12	40
He + 2H	42	45	14	47
4H	2	2	4	13
Li + H	9	10	0	0

a normal density. If, in searches for interactions in an emulsion, use is made of the method of scanning along the track of a primary particle, the probabilities of various dissociation channels are determined by the frequency of appearance of events characterized by a given charge topology.

Among events found in the way outlined above, there are 320 stars in which the total charge Q of relativistic fragments within the fragmentation cone of opening angle 8° satisfies the condition $Q > 3$. Such stars were associated with events of peripheral dissociation, $N_{\rm pf}$. The distribution of $N_{\rm pf}$ with respect to the number N_Z of relativistic fragments whose charge number is Z is given in Table 1, where data are displayed for 256 events involving target fragments, $N_{\rm tf}$, as well as for 64 events not involving target fragments (white stars), $N_{\rm ws}$. For stars associated with $N_{\rm tf}$, channels where the multiplicity of relativistic fragments is in excess of two, $N_Z > 2$, are dominant. Among peripheral events, white stars ($N_{\rm ws}$) are of particular interest (see Table 1). Since tracks of target fragments do not accompany them, white stars provide the possibility of revealing the role of various cluster degrees of freedom under conditions of a minimum distortion of the nuclear structure.

Two white stars of $Q = 4$ can be attributed to the contribution of background nuclei ^{7}Be (see Table 1). In analyzing an emulsion exposed to a ^{7}Be beam, it was found in [7] that the probability of peripheral interactions of ^{7}Be that lead to the formation of target fragments is approximately one-half as high as the probability of analogous interactions not leading to the formation of target fragments. Therefore, the main contribution to the number $N_{\rm tf}$ for $Q = 4$ must come from ^{8}B interactions accompanied by a decrease of unit in the charge within the fragmentation cone.

Events in which $Q = 5$ are the main branch of dissociation. For this group of events, the main distinction between $N_{\rm tf}$ and $N_{\rm ws}$ manifests itself in the $Z = 4 + 1$ two-particle mode. Because of a neutron deficit, this mode is unambiguously interpreted as $^8\mathrm{B} \to {}^7\mathrm{Be} + p$. Upon selecting white stars, its fraction increases sharply—from 10% in the presence of target fragments to 44% for white stars. This mode has the lowest threshold, and this is the reason why it is dominant among the most peripheral events.

The probability distribution for white-star formation by ^{8}B nuclei can be compared with analogous data for ^{10}B nuclei of energy 1 GeV per nucleon [3, 6]. The fraction of the three-prong mode $^{10}\mathrm{B} \to 2\mathrm{He} + {}^{1,2}\mathrm{H}$ was 73%, the deuteron contribution being 40%. The probability of the $^{10}\mathrm{B} \to {}^9\mathrm{Be} + {}^1\mathrm{H}$ vee proved to be as small as 2%. The distinction is explained by a lower binding energy of the deuteron in the ^{10}B nucleus in relation to the proton binding energy. For the isotope ^{8}B, on the contrary, the yield of the $^8\mathrm{B} \to {}^7\mathrm{Be} + p$ vee is higher because of a low binding energy of the outer proton. Thus, the ^{8}B nucleus manifests its structure in the enhanced production of $N_Z = 2$ white stars. Among $Q = 5$, $N_Z = 2$ events, one of N_{tf} (Li + He) cannot be associated with the interactions of ^{8}B.

For the ^{8}B nucleus, the probabilities of white stars fragmenting into the 2He + H and He + 3H channels are 22 and 25%, respectively, while, for the ^{10}B nucleus, the probabilities of these modes are 73 and 12 %. So large a distinction is explained by the presence in the ^{8}B nucleus of the cluster ^{3}He, which has a much lower dissociation threshold than ^{4}He.

The presence of white stars featuring more than two fragments, $N_Z > 2$, may be due to the dissociation of the ^{7}Be core. In order to verify this assumption, the distribution with respect to the charges of relativistic fragments in white stars is presented in Table 2 for ^{7}Be [7] and ^{8}B nuclei. For ^{8}B, one singly charged relativistic fragment (presumed halo proton) is excluded from the displayed events. Identical fractions of the 2He and He + 2H modes, which are two main dissociation channels, are observed for ^{7}Be and ^{8}B nuclei. This indicates that the excitation of the ^{7}Be core is independent of the presence of the additional proton loosely bound in the ^{8}B nucleus.

The observation of four unusual $Q = 5$ white stars corresponding to the complete-disintegration process $^8\mathrm{B} \to 5\mathrm{H}$ is noteworthy (Table 1). This process involves the breakup of two clusters He and has a high energy threshold. Previously, events of this type were observed for ^{7}Be and ^{10}B [6] nuclei ($^7\mathrm{Be} \to 4\mathrm{H}$ and $^{10}\mathrm{B} \to 5\mathrm{H}$, respectively). Because of the neutron deficit in the ^{8}B nucleus, it is easier to observe nucleonsin this case. Moreover, this enhances Coulomb repulsion in the system of fragments. The formation

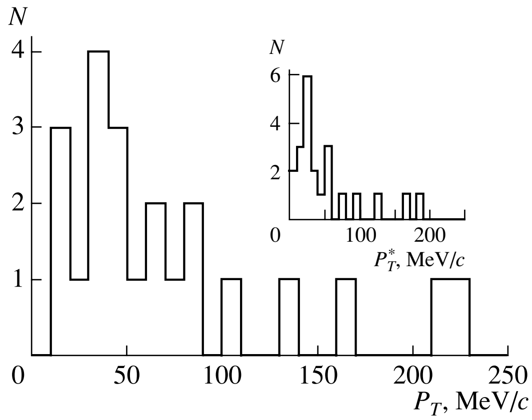

Fig. 2. Transverse-momentum (P_T) distribution of protons produced in $^8\mathrm{B} \to {}^7\mathrm{Be} + p$ white stars. The inset shows the analogous distribution with respect to P_T^* in the $^7\mathrm{Be} + p$ c.m. frame.

of such ensembles of H nuclei may underlie the multiparticle fragmentation of heavier nuclei into a greater number of fragments.

The formation of $Q = 6$ white stars (see Table 1) may be associated with the admixture of ^{10}C nuclei in the composition of the beam used. Nuclei of this species may be produced via the $^{10}\mathrm{B} \to {}^{10}\mathrm{C}$ charge-exchange process in the target intended for the generation of ^{8}B nuclei and be entrained by the secondary beam because of a small difference in magnetic rigidity between them and ^{8}B (about 4%) and because of a momentum spread intrinsic in them. White stars for which $Q = 6$ do not contain $Z > 2$ fragments. Their topology is compatible with the assumption that this carbon isotope breaks up into the ^{8}Be core and two protons ($^{10}\mathrm{C} \to {}^8\mathrm{Be} + 2p$) or with the assumption that one of the clusters He undergoes breakup ($^{10}\mathrm{C} \to {}^4\mathrm{He} + 2\mathrm{H} + 2p$). This circumstance is indicative of the possible formation of a ^{10}C beam ($^{10}\mathrm{B} \to {}^{10}\mathrm{C}$) under conditions convenient for investigations in emulsions. A white star for which $Q = 7$ may be attributed to the double production of charged mesons.

ANGULAR FEATURES OF THE ^{7}Be + ^{1}H CHANNEL

White stars associated with the $^8\mathrm{B} \to {}^7\mathrm{Be} + p$ channel (Table 1) yield a pair of observed tracks within a small angular cone about the track of the primary nucleus. According to our measurements, the average polar emission angle is $\langle\theta_p\rangle \approx 2.0°$ for protons and $\langle\theta_{\mathrm{Be}}\rangle \approx 0.4°$ for ^{7}Be nuclei.

The measurements of the angles make it possible to reconstruct to a high precision the transverse-momentum (P_T) spectra by using the formula $P_T =$

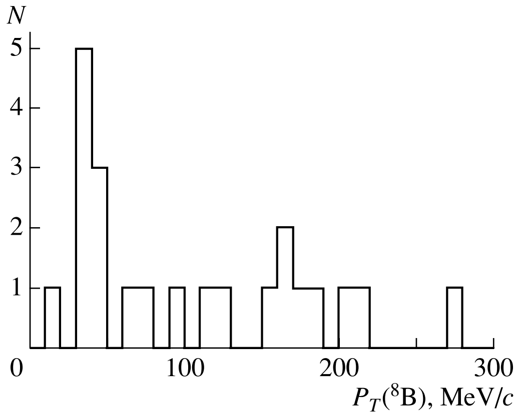

Fig. 3. Total-transverse-momentum [$P_T(^8\mathrm{B})$] distribution of $^7\mathrm{Be}+p$ pairs produced in $^8\mathrm{B}\to{}^7\mathrm{Be}+p$ white stars.

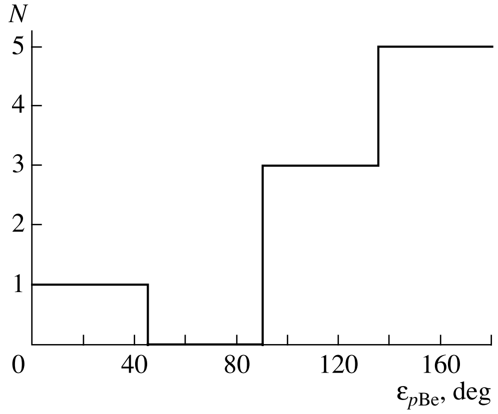

Fig. 4. Distribution with respect to the azimuthal angle $\varepsilon_{p\mathrm{Be}}$ between the $^7\mathrm{Be}$ and p momenta in $^8\mathrm{B}\to{}^7\mathrm{Be}+p$ white stars for $P_T(^8\mathrm{B}) < 60$ MeV/c.

$AP_0 \sin\theta$, where A is the fragment mass number, θ is the fragment emission angle, and P_0 is the ^{8}B momentum per nucleon ($P_0 = 2.0$ A GeV/c). Figure 2 displays the P_T distribution for protons, the respective mean value being $\langle P_T\rangle = 73 \pm 7$ MeV/c. A transition to the $^7\mathrm{Be}+p$ c.m. frame compensates for the transverse-momentum transfer to the ^{8}B nucleus involved, this leading to a much narrower P_T^* distribution (inset in Fig. 2), the respective mean value being $\langle P_T^*\rangle = 52 \pm 5$ MeV/c. So low a value of $\langle P_T^*\rangle$ complies with data reported in [1, 2], where an FWHM value of 46 ± 3 MeV/c was obtained for the longitudinal-momentum distribution of fragments originating from the $^8\mathrm{B}\to{}^7\mathrm{Be}$ stripping reaction. Thus, a weak binding of the outer proton and the nuclear core manifests itself under very clear conditions of the observation of fragmentation.

Figure 3 shows the distribution with respect to the total transverse momentum $P_T(^8\mathrm{B})$ that the ^{8}B nuclei received in the formation of $^7\mathrm{Be}+p$ white stars; its mean value is about 100 MeV/c. The distribution peaks at $P_\mathrm{T}(^8\mathrm{B}) \approx 50$ MeV/c. This asymmetry of the $P_T(^8\mathrm{B})$ distribution may be due either to neutron emission by target nuclei or to the contribution of the process $^8\mathrm{B}\to{}^7\mathrm{Be}^*+p\to{}^7\mathrm{Be}+\gamma+p$ [8], which involves the excitation of the nuclear core (^{7}Be).

We can estimate the role of azimuthal-angle ($\varepsilon_{p\mathrm{Be}}$) correlations between ^{7}Be and p. This distribution has the meaning of asymmetry with respect to an angle of $\pi/2$; it is approximately equal to 0.3, which is indicative of a sizable contribution of pair dissociation processes. Figure 4 displays the $\varepsilon_{p\mathrm{Be}}$ distribution of events selected by imposing the cut $P_T(^8\mathrm{B}) < 60$ MeV/c. The asymmetry is seen to increase sharply to about 0.7, which is indicative of the binary character of ^{8}B breakup at low transverse-momentum transfers.

CONCLUSIONS

For the first time, nuclear emulsions have been irradiated with a beam of relativistic nuclei ^{8}B. Data on the branching ratios for channels of ^{8}B fragmentation in peripheral interactions have been obtained. Fifty-five events involving the peripheral dissociation of ^{8}B nuclei have been selected among events that do feature final-state target fragments or mesons (white stars). On their basis, it has been revealed that a leading contribution comes from the $^8\mathrm{B}\to{}^7\mathrm{Be}+p$ mode, which has the lowest energy threshold. Information about the branching ratios for dissociation modes featuring a high multiplicity has been obtained. The dissociation of the ^{7}Be core in the ^{8}B nucleus bears resemblance to the dissociation of a free nucleus ^{7}B. A further analysis of fragmentation topology makes it possible to identify the isotopes of H and He.

The transverse-momentum distributions of fragments originating from the $^8\mathrm{B}\to{}^7\mathrm{Be}+p$ dissociation mode have been deduced. A rather small mean value of $\langle P_T^*\rangle = 52 \pm 5$ MeV/c for these distributions in the c.m. frame reflect a low binding energy of the outer proton in the ^{8}B nucleus. A strong azimuthal-angle correlation between ^{7}Be and p manifests itself in selecting events where the transverse-momentum transfer to the ^{8}B nucleus is less than 60 MeV/c.

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