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Study of low-energy physics with high-energy muon interactions in nuclear emulsion

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Our previous results on the production of "giant dipole" resonance in nuclear emulsion are confirmed by an independent technique. Arguments used by Shivpuri *et al.* with their meager statistics at low energy, as compared with ours, do not refute our final results.

Ever since we performed our first experiment[1] on high-energy muon-nucleon interaction in nuclear emulsion, we have been able to use the muon beam in a variety of different experiments[2-8] in our laboratory and to compare them with other experimental work on electromagnetic and hadronic interactions. The muon's heavier mass makes the energy loss by radiation negligible, and in the experiments where photons or electrons are generally used, one could use the muon beam perhaps more profitably. For the study of the giant-dipole resonance (GDR) in a nucleus, it has been a common practice to use bremsstrahlung spectra at low energy. Experiments studying nuclear radiation generally require resolution of the order of 1 MeV, and among the many detectors nuclear emulsion would be better for higher-resolution work. Thus, for the primary beam we used muons and for the detector we used a nuclear emulsion for studying the giant-dipole resonance (GDR) in the heavy and the light nuclei of the emulsion at high momenta of 10.1-GeV/c positive and 15.8-GeV/c negative muons, which had not been studied previously. Here the main objective was to see if the emulsion technique at high energies with the muon beam would give any reasonable answer for heavy and light elements; if it did, one could study the giant-dipole resonance in different elements which could be impregnated into the nuclear emulsion. This practice of impregnation of different elements in nuclear emulsion has been very fruitful during the past 10–15 years in the studies of hypernuclear physics. The details of our experiment were given in our preliminary report,[9] where we emphasized that one has to be very careful to avoid personal biases in the selection of events of type $(1+1)$ with "clear vertices." We shall not accept an event as having a clear vertex if it has (i) any Auger electron, (ii) any heavy blob or stem, or (iii) even a single extra grain attached at the vertex which can be taken very easily by mistake as a background grain (in which case the event would be assumed to have a clear vertex). Regarding the identity of the secondary particles produced at the vertex, we may point out that only the thickness of the track was used in separating the tracks from different Z (charge) values; however, for tracks belonging to the same Z values, i.e., $Z=1$ (p, d, and t), it was mentioned earlier[9] that we used the well-known "constant sagitta" method.[10] The percentages of different particles produced by these two methods were mentioned previously.[9]

Recently some objections[11] have been raised to our experimental results in nuclear emulsion. As stated previously,[9] the emulsion is composed of heavy elements (Ag and Br) and light elements (C, N, and O) with about 82% of the nucleons in the heavy elements. In order to confirm our previous results,[9] we further used an independent technique based on the range of the shortest prong to separate the light from the heavy elements in the nuclear emulsion. We assumed that the Coulomb barrier prevented the emission of low-energy protons and α's from Ag and Br. Thus, the "shortest-range prong" method of separation would give those events having a prong of length less than 50 μ lower limit for the light element involved in the reaction. With this method we find that about 30–35% of the interactions occurred with light elements and 65–70% occurred with heavy elements. These results are not far from our previous results. They also agree with the results of Peterson *et al.*[12] and Miller,[13] who found that 45–47% and 45%, respectively, of their photostars took place in light elements. We may point out that such events, where the mesons are produced and are reabsorbed, will increase the relative contribution of the stars produced in the heavy elements.

In our previous work,[9] we have not claimed to know the structure of the individual nuclei. Figures 1(b) and 1(c) of Ref. 9 show clearly the proton energy distribution for events belonging to *light* and *heavy* elements at 10.1 GeV/c and 15.8 GeV/c muon beam momenta. Our work, previously presented,[9] represents the largest statistics in the study of the giant-dipole resonance with muon beams at two high energies. Kirk *et al.*[14] used low-energy muon beams at 2.5 GeV/c and 5.6

GeV/c with statistics less than 13% of ours. Shivpuri *et al.*[11] also used low-energy muons with statistics less than 10% of our data. In these cases, though the authors[15] *assumed* (and did not prove) that the majority of the events of type $(1+1)$ belong to GDR, in neither case was any effort made to separate these events belonging to light and heavy elements. Ours is the only experimental attempt to separate them by two independent methods. They agree not only among themselves but also with other photoproduction experiments.[12,13] The authors in Ref. 15 *assumed* that the majority of the events of type $(1+1)$ produced by muons belonged to GDR. The only way one could say this would be by observing the details mentioned in our previous work. One has to look at the energy and angular distribution of the ejected protons.

Most of the proton tracks are very short and the ranges of all these low-energy tracks must be corrected for their straggling effect. Fractional errors in the range, arising from the uncertainty in the emulsion density, can be very large. We made use of all these corrections for the energy spectrum of the low-energy protons which were shown[9] in Figs. 1(b) and 1(c) of Ref. 9. Thus we see that (i) there is no long tail present in the energy spectrum shown[9] in Figs. 1(b) and 1(c); (ii) the spectrum of heavier elements is peaked at lower values than the spectrum of lighter elements; (iii) the resonance energy varies approximately as $A^{-1/3}$; and (iv) in Fig. 2 one can see[9] that the angular distribution of the ejected protons is nonisotropic with a peak at 90° for GDR, while for the evaporation process the distribution is isotropic. The angular distributions in Fig. 2 are fitted by a function of the type $f(\theta)=a+b\sin^2\theta$, which is evidence for the dipole nature of γ-ray absorption in the process we investigated. About 90% of the one-pronged events, i.e., the $(1+1)$ type, which were selected under very stringent selection criteria, fell under the category of GDR. These results agree very well with those of George,[16] Peterson *et al.*,[12] and Castagnoli *et al.*[17] in photonuclear stars produced by bremsstrahlung radiation.

The total number of $(1+1)$-type events observed in Ref. 11 is 46. As we stated earlier, 90% of these, i.e., 41 events, could belong to the giant resonance. We also know[4-8,18] that the number of events of the type $(2+1)$ should be about 50% of the $(1+1)$ type, i.e., ~20 events. We feel that with such poor statistics (~20 events) one cannot make any convincing statements about their energy spectrum[11] in a topic such as the one under discussion.

In conclusion, we may say that our previous results on the study of giant-dipole resonance in nuclear emulsion, with the largest statistics for the two high-energy muon beams, are confirmed by an independent technique and will be useful in some future investigations.

Note added in proof. In the following note by McNulty *et al.* we do not find anything new from their previous note[11] which will disprove the conclusions drawn by us by two independent techniques, and our results check very well with the other authors.[11-17,19] In their 46 $(1+1)$ events the authors did not even separate protons from the other produced particles (d, t, and α), which are at least 20%, and this will reduce their total number to 35 $(1+1)$ events, which is too small a number to allow any comparative analysis by dividing them further into light and heavy elements.

(1) The angular distribution given by the function $f(\theta)$, where θ is the angle with respect to the beam direction (z axis), has a smaller χ^2 value than the $\sin\theta$ function.

(2) In the energy spectrum there is a much larger statistical weight for heavy elements, and it is not 50 and 36 heavy events as quoted by McNulty *et al.* The 10% difference is quite in agreement with the statement of Miller[13] that his findings (45–47)% are approximate.

(3) 104 $(2+1)$ events (from separate experiments) do not belong to the note[11] under discussion, where a total of only 46 $(1+1)$ events were discussed, and as we pointed out above there should be fewer than 20 $(2+1)$ events, which are too few to allow us to conclude anything.

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Reply to "Study of low-energy physics with high-energy muon interactions in nuclear emulsion"*

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None of the discrepancies which led us originally to conclude that the method proposed by Jain and Stern was not reliable have been resolved in the preceding paper. We restrict our comments here only to those points raised by Jain that have not already been discussed adequately in our earlier article.

In our laboratory we have been involved in a long-range study of a variety of muon-induced interactions in nuclear emulsions. Recently[1] we described a number of discrepancies between our results[2] and those of Jain and Stern.[3] These discrepancies led us to conclude that the method proposed by Jain and Stern for distinguishing between interactions involving light nuclei and those involving heavy nuclei was not reliable. Arguments based in part on these discrepancies were presented in Ref. 1 to show that when nuclear emulsion was used in the manner proposed in Ref. 3 it falls far short of being the "ideal target-detector system" for studying nuclear structure.[3] In the preceding paper,[4] hereafter referred to as A, Jain discusses some of these arguments and reports on a second analysis of the data using the "shortest-range-prong" technique. We feel that most of the objections raised in A have already been answered and we refer the reader to Ref. 1. We restrict ourselves in what follows to comments on those remaining objections which concern points that we have not previously discussed.

(1) Although our data on $(1+1)$ events[1,2] are consistent with dominance by giant-dipole-resonance (GDR) events, we have neither assumed this in our analysis nor presented our data as proof of such a hypothesis, as is suggested in A. Moreover, we are not convinced that the arguments enumerated in A are sufficient to show that 90% of their $(1+1)$ events are GDR events. Their arguments involve the angular distributions and the kinetic energy spectra of the ejected protons. The angular distributions given in Fig. 2 of Ref. 3 do not appear, as claimed in A, to be greatly different from the $\sin\theta$ distribution predicted for an isotropic distribution. Certainly Fig. 2 of Ref. 3 does not show 90% of the data to be in disagreement with the assumption of isotropy. Similarly, the energy spectrum presented in Figs. 1(a) and 1(b) of Ref. 3 is substantially the same as the well-known energy spectrum[5] of evaporation prongs. The difference in the tail of the two distributions would involve only a few events. The shift in peaks and resonance energy between the distributions labeled "light" and "heavy" do not have the required statistical weight to be significant. There were only 50 and 36 heavy events in the 10.1- and 15.8-GeV/c distributions, respectively.[3]

(2) In A, Jain claims that by applying the independent "shortest-range-prong" technique he obtains a separation into light and heavy events which is not far different from that obtained by the method we objected to.[1] What is important is whether the two techniques make the same identification for individual events. The total separations obtained with the two techniques differ by at least 10%. Yet reliable separation is essential to the