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MASTER

Hypernuclear Physics Research at Brookhaven*

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ABSTRACT

This paper describes the results of a recently completed study of the hypernucleus ${}^{12}_{\Lambda}C$. The observed formation of hypernuclear states at large momentum is compared with theoretical expectations. Future directions of the research program at Brookhaven are outlined.

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INTRODUCTION

Hypernuclear physics research at Brookhaven today centers around the hypernuclear spectrometer at the AGS which began operation a little over a year ago. The major result of the program which has recently been completed is a detailed study of the hypernucleus ${}^{12}_{\Lambda}C$. Hypernucleus formation has been observed out to quite high momentum transfer--280 MeV/c.

There are several classes of hypernuclear states which require large momentum transfer for their formation. Our experiments provide evidence for the formation of some of these states at a level in good agreement with distorted wave impulse approximation calculations; however, other states which should have been amply produced according to the best current theoretical calculations are not observed. We have measured angular distributions for the formation cross sections of the observed states from 0 to 19°. The large range of these distributions (compared to previous measurements) permits a straightforward identification of the spins and composition of the states.

${}^{12}_{\Lambda}C$, PAST EXPERIMENTS

The hypernucleus ${}^{12}_{\Lambda}C$ has been an object of great interest during the past decade. It was first observed in 1970 by Bohm et al.[1] in an experiment using the emulsion technique. Surprisingly, the first observation of this hypernucleus was not of the ground state, but of a state at 11 MeV excitation energy decaying by proton emission. This was the first example of a highly excited, particle unstable state of any hypernucleus. At the Zvenigorod conference (1977), Pniewski and Zieminska[2] reported an observation in emulsion of the ground state of ${}^{12}_{\Lambda}C$ by the Warsaw group.

Several counter experiments[3,4,5] have used the (K^-,π^-) reaction in flight to study $^{12}_{\Lambda}C$, in each case with small momentum transfer to the nucleus. Hypernucleus formation by stopped kaons proceeds with 250 MeV/c momentum transfer to the nucleus. However in this technique, used by Faessler et al.[6], the momentum transfer is not variable.

EXPERIMENTAL METHOD

We[7] used the reaction $K^- + {}^{12}C \rightarrow {}^{12}_{\Lambda}C + \pi^-$ with kaon momentum 800 MeV/c to form $^{12}_{\Lambda}C$. The kaon and pion momenta were measured to one part in 10^3. The missing mass was evaluated to give the spectrum of hypernuclear states. At zero degrees, the reaction takes place with 70 MeV/c momentum transfer. Small momentum transfer suppresses the background of quasi-free lambda formation and gives a high probability of hypernucleus production. However, small momentum transfer corresponds to small angular momentum transfer and thus a limited class of states are preferentially excited. It is advantageous to vary the momentum transfer over as large a range as possible, so that other hypernuclear states may be observed. This was done by detecting the pion at angles up to 19 degrees with respect to the kaon direction. The experiment uses the Low Energy Separated Beam I at the Brookhaven Alternate Gradient Synchrotron. The beam contains $2\ 10^5$ kaons per AGS pulse (of one second duration) accompanied by 12 times as many other particles (mainly pions). A Cerenkov counter identifies kaons in the beam. The counter CK (Fig. 1) has a lucite radiator which discards light from pions by total internal reflection while transmitting light from kaons to six symmetrically mounted photomultiplier tubes.

One dipole and four quadrupole magnets (D1, Q1-Q4 in Fig. 1) bring the beam to a dispersed focus on the target. The target for the study of ${}^{12}_{\Lambda}C$ was a scintillation counter, ST. In seventy percent of hypernuclear decays, the deposition of energy in the target scintillator is large enough to distinguish the event. This signature, though not essential, greatly simplified the analysis of the data.

Multiwire proportional chambers P1-P3 define the trajectory of the kaon for momentum determination. The chambers have three planes of wires, each with one millimeter wire spacing. The pion from hypernuclear formation is detected in a second, similarly constructed spectrometer mounted on a platform that can rotate up to 35 degrees with respect to the beam direction. A liquid hydrogen Cerenkov counter (CH) was used during part of the data taking to detect pions immediately after the target. Time of flight between the scintillation counters S1, ST and S2 provided additional particle identification.

The pion detecting spectrometer has a solid angle of 12 msr. The energy resolution of the experiment was 2.5 MeV FWHM, primarily limited by the use of a thick target. Kaon flux at the target was typically 2.4 10^4 per AGS pulse.

RECENT RESULTS FROM BROOKHAVEN CONCERNING ${}^{12}C$

An angular distribution of the states of ${}^{12}_{\Lambda}C$ excited in the reaction ${}^{12}C(K^-,\pi^-){}^{12}_{\Lambda}C$ was measured[7] with kaon momentum 800 MeV/c. Figure 2 shows a spectrum taken at $\theta_{K\pi}=15°$ corresponding to a momentum transfer to the nucleus of 210 MeV/c. The lower mass peak corresponds to a binding energy of the lambda of 10.79 ± .11 MeV. Experiments using the emulsion technique report[2] a binding energy of 10.76 ± .19 MeV for the ground state of ${}^{12}_{\Lambda}C$. This agreement, leads us to identify the lower peak as the ground state.

The higher mass peak has 11 MeV excitation energy and an analysis of its angular distribution leads us to conclude that it corresponds to more than one state.

Dover et al.[8] have calculated the angular distributions of the ground state and simple particle hole excited states of ${}^{12}_{\Lambda}C$. The results of that calculation (with kinematic conditions appropriate to this experiment) are shown in Fig. 3 along with our data points. The important features of their calculation are as follows:

a) The distorted waves for the incident kaon and outgoing pion are generated from an optical potential derived from the Fermi averaged $\bar{K}N \rightarrow \bar{K}N$ and $\pi N \rightarrow \pi N$ free space amplitudes.

b) On shell transition amplitudes for the elementary process $K^- n \rightarrow \pi^- \Lambda$ are used.

c) The wave functions for n and Λ states are calculated from a Woods-Saxon nuclear potential shape with depth chosen to fit the binding energy appropriate to the orbital under consideration.

The ground state angular distribution is well reproduced by the calculation apart from an overall normalization factor. The shape of the angular distribution of the 11 MeV peak is also well described, assuming particle hole configurations $(\Lambda p_{3/2}, np_{3/2}{}^{-1})$ and $(\Lambda p_{1/2}, np_{3/2}{}^{-1})$; the former configuration gives rise to a 0^+ and a 2^+ state, the latter to a 2^+ state. (Unnatural parity states are not expected to be excited with significant strength in our kinematic range.)

Figure 3 shows the relative contributions of the 0^+ and 2^+ components to the 11 MeV peak as a function of angle according to Dover et al. At small angles, the angular distribution shows the sharp rise characteristic of the coherently produced 0^+ state. The shoulder at large angles is explained in terms of the excitation of the 2^+ states. Making the assumption that at 0° we are exciting 0^+ only and at 15° we are exciting 2^+ only we can set limits on the spacing of these states although they are not resolved by our experiment. Assuming that at 15° only one 2^+ state contributes, the 0^+-2^+ spacing is less than 420 keV. Assuming that at 15° the two 2^+ components contribute equal strength, the 2^+-2^+ spacing is less than 800 keV. These limits will constrain the spin dependent parts of the lambda nucleus residual interaction and are consistent with a weak spin dependence.

A fundamental question should be posed: are the states excited in the (K^-,π^-) reaction pure particle hole states? For example, the coherent $(\Lambda p_{3/2},np_{3/2}^{-1})\ 0^+$ state can mix with the coherent $(\Lambda s_{1/2},ns_{1/2}^{-1})\ 0^+$ state resulting in the much discussed strangeness analog state, or an anti-analog state depending on the sign of the mixing angle. The wave function of the coherent excitation then has the form

$$\psi = \cos\alpha(\Lambda p_{3/2},np_{3/2}^{-1})\ 0^+ + \sin\alpha(\Lambda s_{1/2},ns_{1/2}^{-1})\ 0^+.$$

Dover et al. have assumed a mixing angle α=-10 and added the mixed 0^+ cross section to the net 2^+ excitation. The resulting angular distribution is shown in Fig. 4 along with our data points for the 11 MeV peak. This calculation is in much poorer agreement with our data than the calculation of Fig. 3 which assumes no mixing. Thus mixing effects are not of major importance.

The existence of core excited hypernuclear states has been predicted.[9] These states would consist of a lambda in an s orbit coupled to the excited states of the ^{11}C core. A search was made in the region above the ground state for an event excess using our 15° data. We see no evidence for such states. The total event excess in the region 2 to 7 MeV excitation is 6% ± 5% of the ground state strength. This is to be compared with an expectation of two states, one at 3.29 and one at 5.11 MeV excitation with summed strength 33% of the ground state strength. The disagreement between experiment and theory should motivate additional experiments to search for core excited states predicted in other hypernuclei. An experiment detecting gamma rays from the deexcitation of the core in coincidence with a (K^-,π^-) energy difference measurement would be particularly effective in observing these particle stable states. The absence of core excited states at the expected strength may be attributable to uncertainties in the knowledge of the ^{11}C and ^{12}C wave functions or it may signal some more fundamental problem in the theoretical understanding of hypernuclei.

FUTURE PLANS FOR HYPERNUCLEAR RESEARCH AT BROOKHAVEN

In early 1980 we will extend our experiments to several, as yet unexplored hypernuclei (^{13}C, ^{18}O, ^{10}B and ^{14}N). We feel that the comparison of adjacent hypernuclei, ones that differ by a single neutron, by a single proton, or by two neutrons will be a valuable tool in pinning down the nature of the states excited in the (K,π) reaction. Targets used to study hypernuclei in the in-flight strangeness exchange reaction have thus far been primarily even-even nuclei with equal numbers of neutrons and protons. In selecting targets we have departed from this regularity.

An important issue in hypernuclear physics is the strength of the Λ-nucleus spin orbit coupling. Recent data[5] on $^{16}_{\Lambda}O$ has been interpreted as demonstrating that the Λ-nucleus spin-orbit coupling is at least one order of magnitude smaller than the nucleon-nucleus coupling. This conclusion comes from a comparison of the energy of hypernuclear states resulting from the substitution of a Λ for either a $p_{1/2}$ neutron or a $p_{3/2}$ neutron.

It should be emphasized that the two body Λ-nucleon spin orbit interaction gives rise to several terms[11] in the Λ nucleus potential. In addition to the usual

$s_\Lambda \cdot l_\Lambda$ term, splittings can arise from the interaction of the spin of the Λ with the angular momentum of unpaired nucleons. This $s_\Lambda \cdot l_N$ interaction is effective even in the case of a lambda particle in an s orbital. A phenomenological analysis of the ground states of p shell hypernuclei shows this term to be large. In the case of ${}^{16}_{\Lambda}O$ described above, both terms are certainly present and the possibility of a fortuitous cancellation cannot be eliminated. In the case of ${}^{13}_{\Lambda}C$ we can observe a lambda particle in a $p_{1/2}$ orbit interacting with a $\sim 0^+$ ${}^{12}C$ core.

Late in 1980 we plan to modify our experiment to increase the hypernuclear event rate by almost a factor of 10. This will be accomplished by using the last stage of the beam line for kaon momentum analysis, thereby decreasing the flight path for kaons. With the increased flux, experiments observing hypernuclear gamma rays in coincidence with the (K,π) data will be feasible.

FIGURE CAPTIONS

Fig. 1 The hypernuclear spectrometer at Brookhaven.

Fig. 2: The mass spectrum of ${}^{12}_{\Lambda}C$ as recorded at 15° with a resolution of 2.5 MeV, FWHM. The solid curve represents a parabolic fit to the quasi-free continuum, while the dashed curve is a linear extrapolation, used to determine the continuum background under the peak.

Fig. 3 Angular distributions (lab) calculated for the reactions ${}^{12}C(K^-,\pi^-){}^{12}_{\Lambda}C$ at incident laboratory momentum 800 MeV/c are compared with the Brookhaven data. The upper curve is for the state $({}_{\Lambda}s_{1/2}, {}_{n}p_{3/2}^{-1})_{1^-}$, after renormalization of the calculated cross section by a factor 0.48. The lower curves are for the $({}_{\Lambda}p_{3/2}, {}_{n}p_{3/2}^{-1})_{0^+}$ excitation and for the sum of the $({}_{\Lambda}p_{3/2}, {}_{n}p_{3/2}^{-1})_{2^+}$ and $({}_{\Lambda}p_{1/2}, {}_{n}p_{3/2}^{-1})_{2^+}$ excitations, using Woods-Saxon wave functions and adopting B_{Λ} = 0.1 MeV for these three states. The net $(0^+, 2^+, 2^+)$ excitation cross section is plotted and then compared with the data after renormalization by a factor 0.39. For comparison, the 0^+ angular distribution calculated for oscillator wavefunctions is also plotted.

Fig. 4 The calculated angular distribution for the $({}_{\Lambda}s_{1/2}, {}_{n}s_{1/2}^{-1})_{0^+}$ excitation, with B_{Λ} = 10.8 MeV and Woods-Saxon wavefunctions. Its amplitude is mixed with that for the $({}_{\Lambda}p_{3/2}, {}_{n}p_{3/2}^{-1})_{0^+}$ excitation, with mixing angle $\alpha = -10°$. This mixed 0^+ cross section is added to that for the net 2^+ excitation, the latter being unaffected by this mixing, and the result (TOTAL CALC.) is then compared with the Brookhaven data, after renormalizing it by a factor 0.55 (dashed curve).

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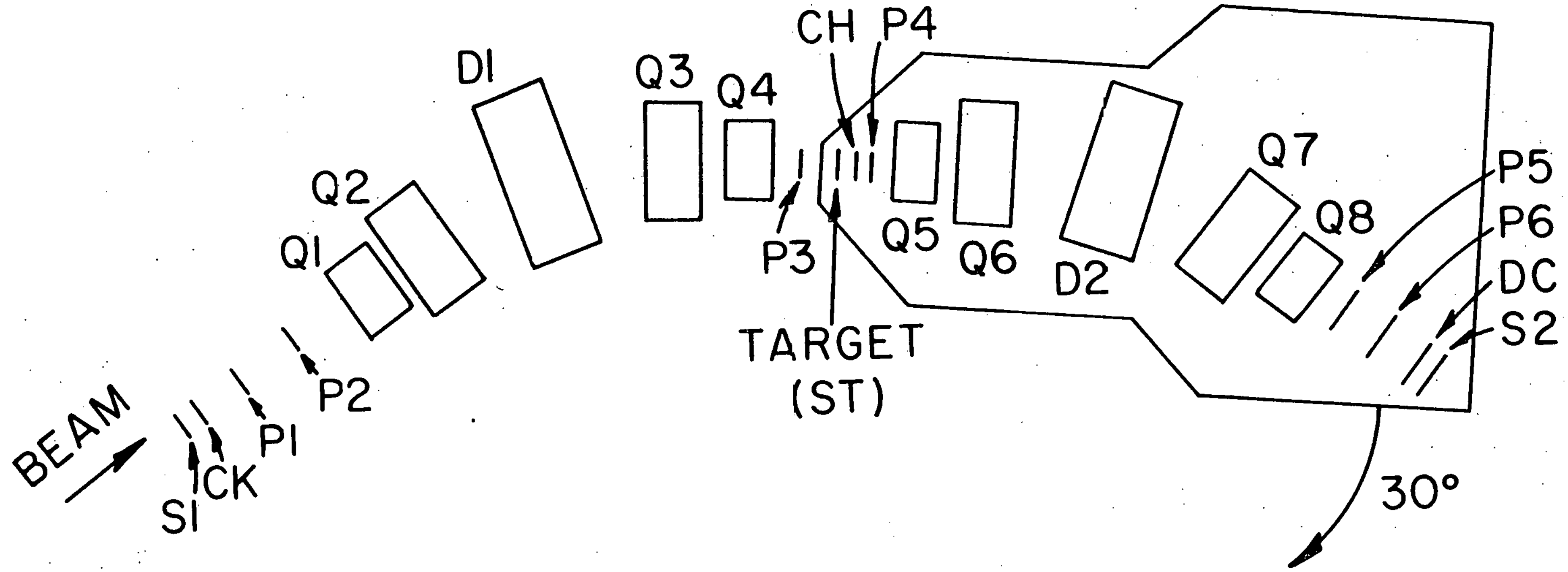

BEAM
S1
CK
P1
P2
Q1
Q2
D1
Q3
Q4
P3
CH
P4
TARGET
(ST)
Q5
Q6
D2
Q7
Q8
P5
P6
DC
S2
30°

Fig. 1

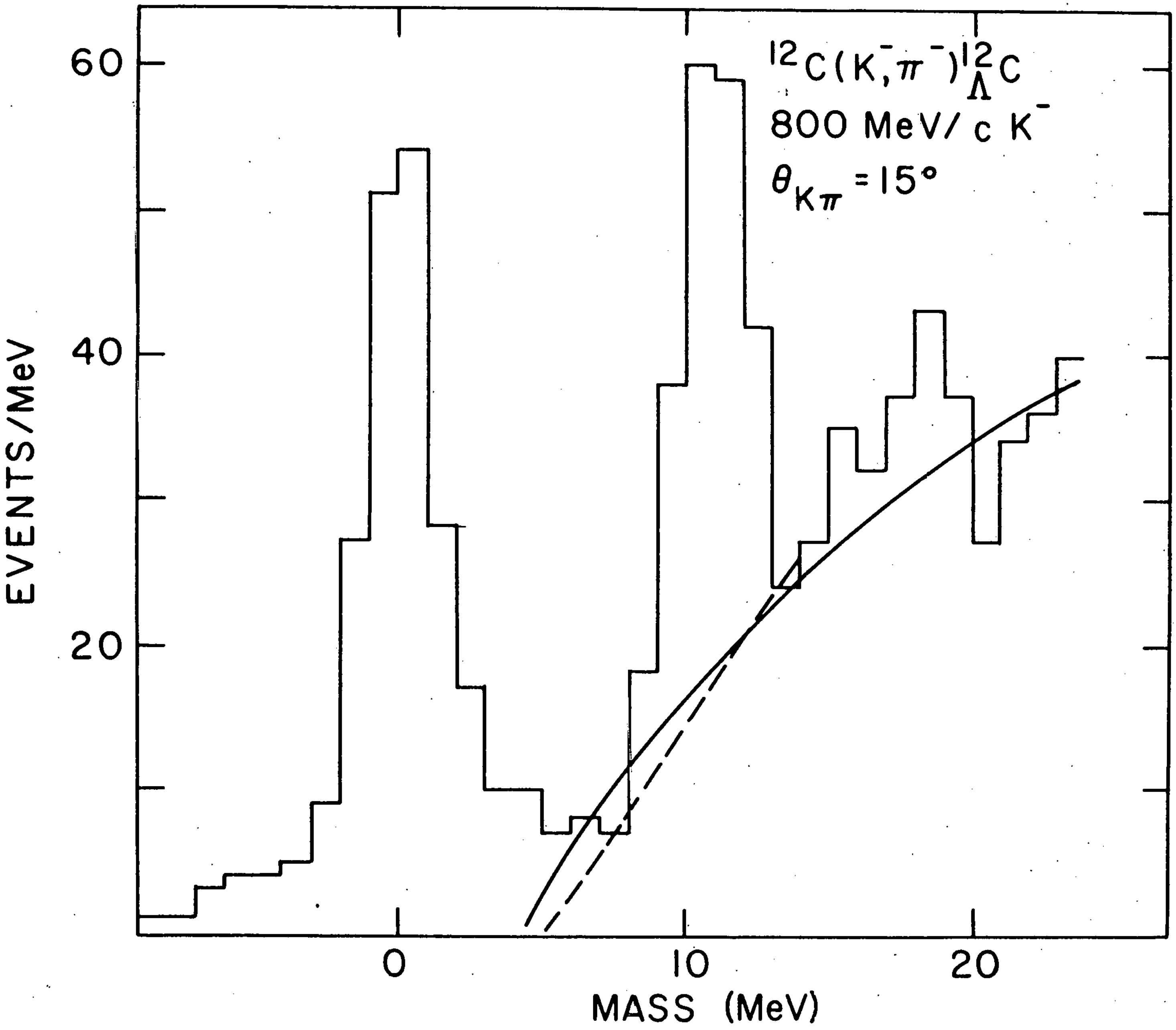
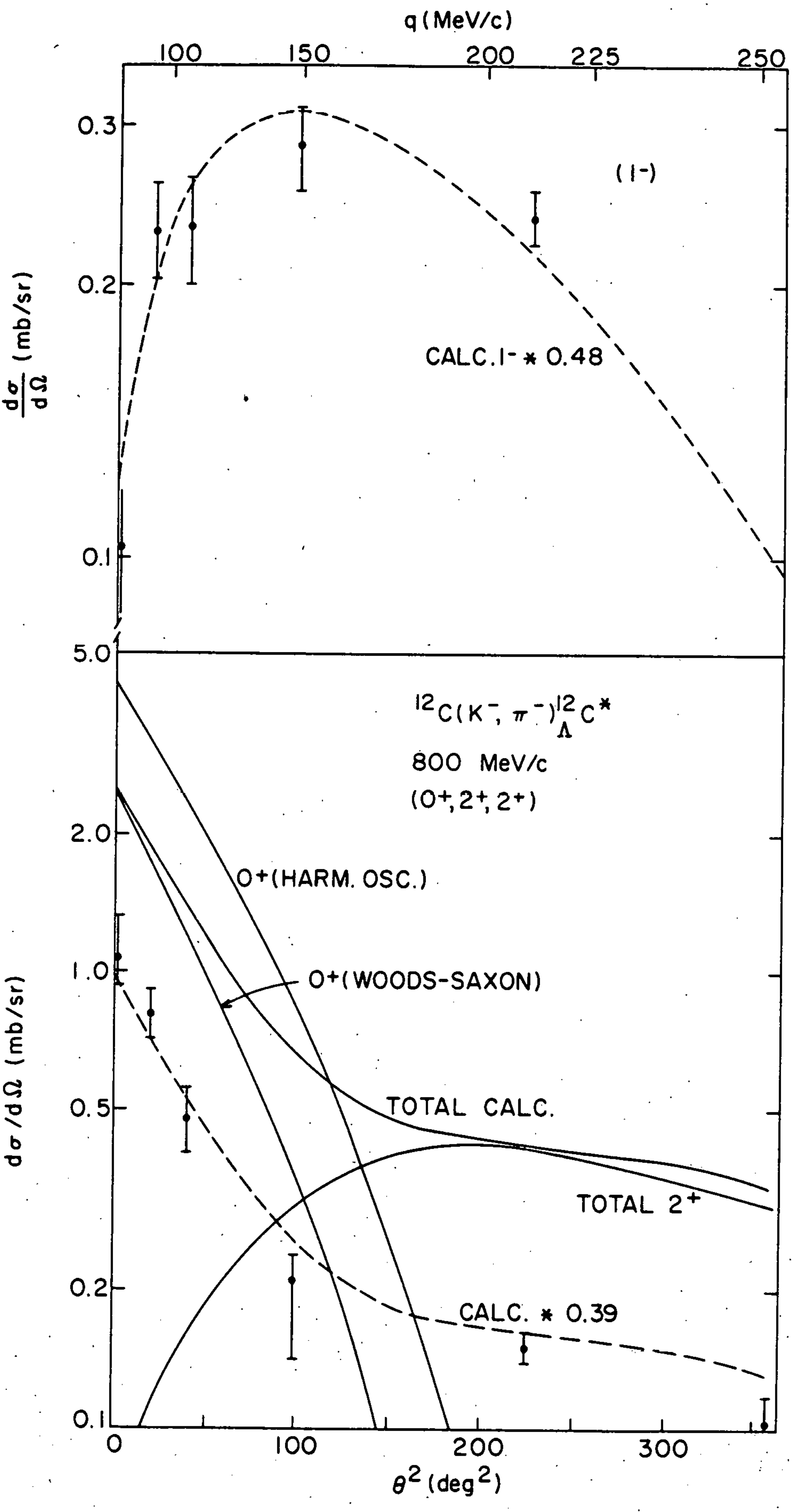

$^{12}C(K^-,\pi^-)^{12}_{\Lambda}C$
800 MeV/c K⁻
$\theta_{K\pi}=15°$
EVENTS/MeV
60
40
20
0
10
20
MASS (MeV)

Fig. 2



q (MeV/c)
100
150
200
225
250
0.3
0.2
0.1
$\frac{d\sigma}{d\Omega}$ (mb/sr)
(1-)
CALC. 1- * 0.48
5.0
2.0
1.0
0.5
0.2
0.1
$^{12}C(K^-,\pi^-)^{12}_{\Lambda}C^*$
800 MeV/c
(0+, 2+, 2+)
0+(HARM. OSC.)
0+(WOODS-SAXON)
TOTAL CALC.
TOTAL 2+
CALC. * 0.39
$d\sigma/d\Omega$ (mb/sr)
0
100
200
300
θ^2 (deg^2)

Fig. 3

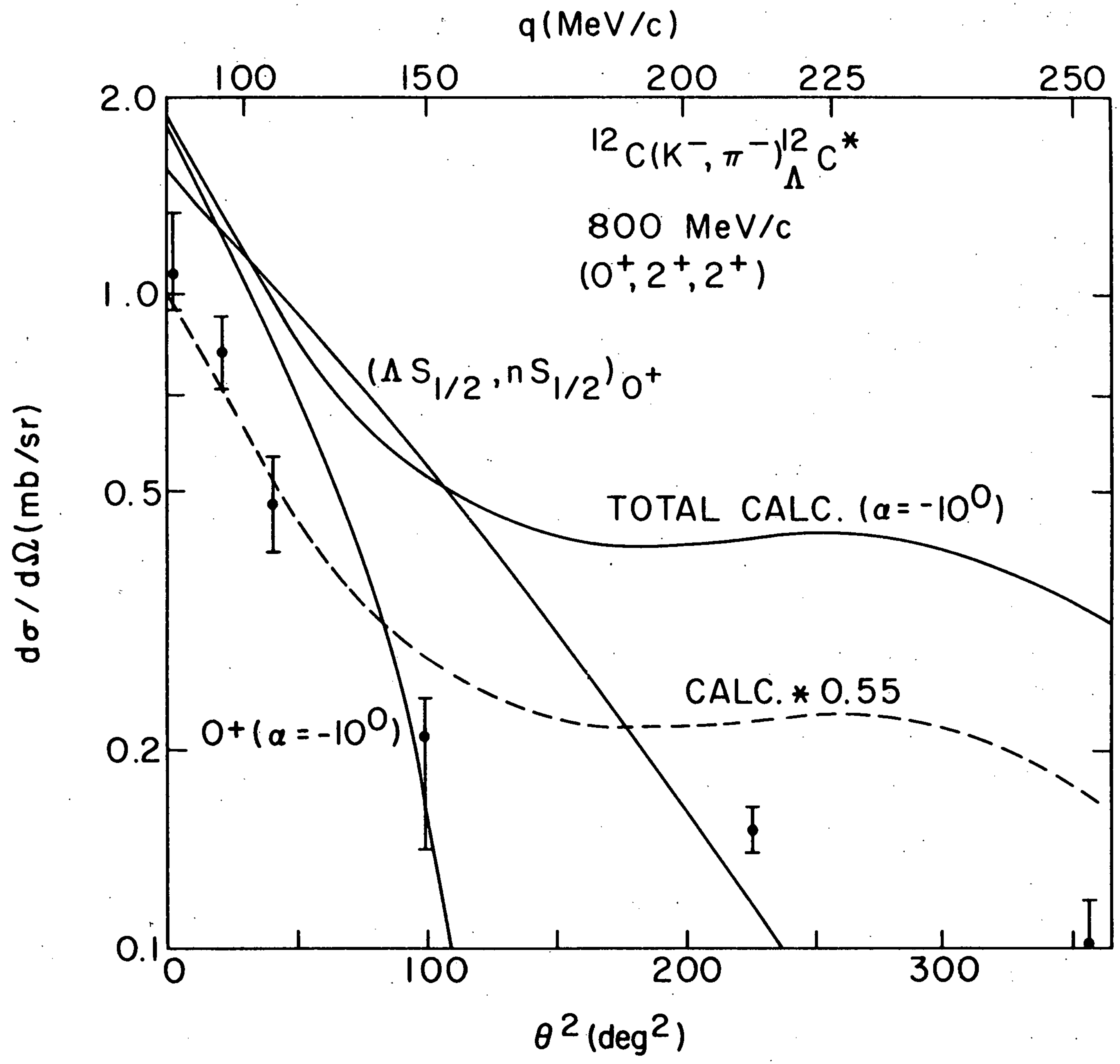

q(MeV/c)
100
150
200
225
250
2.0
1.0
0.5
0.2
0.1
0
100
200
300
$^{12}C(K^-,\pi^-)^{12}_{\Lambda}C^*$
800 MeV/c
$(0^+,2^+,2^+)$
$(\Lambda S_{1/2},nS_{1/2})0^+$
TOTAL CALC. (α=-10^0)
CALC. * 0.55
0+ (α=-10^0)
$d\sigma/d\Omega$(mb/sr)
θ^2(deg^2)

Fig.4