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Hyperon-Nucleus Scattering in Dirac Phenomenology

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Abstract

Optical potentials for Λ and Σ scattering off nuclei are developed based on a global nucleon-nucleus Dirac optical potential and SU(3) symmetry. The differential cross section and analyzing power are calculated for a few energies and nuclei. The tensor coupling has a large effect on the predictions for the analyzing power.

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1. Introduction

The Dirac mean field approach[1] has proved valuable in describing nuclear shell and optical model potentials for nucleons. The optical potential can either be derived using a microscopic approach based on the nucleon-nucleon t-matrix[2-5] or determined by fitting[6-9] nucleon-nucleus scattering data over a wide range of energies and nuclei.

The Dirac mean field approximation appears to be a successful approach to the Λ -nucleus shell model potential[10-14]. Starting with parameters obtained from a nucleon shell model and using SU(3) symmetry one gets a qualitative picture of the Λ hypernuclear levels. After a slight adjustment of the parameters even a quantitative description is possible. The small spin orbit splittings can naturally be accounted for by including a Lorentz tensor potential with the strength predicted by SU(3). It thus makes sense to extend these ideas to higher energies and apply Dirac phenomenology to the description of cross sections and analyzing powers for Λ and Σ scattering off nuclei.

We start with a global optical model for nucleon-nucleus scattering[9]. This gives us strengths and shapes for the real and imaginary parts of the nucleon-nucleus scalar and vector potentials. Following the work on Λ hypernuclei we assume that the real parts of the optical potentials can either be determined by the use of SU(3) Clebsch-Gordon coefficients or deduced from hypernuclear data. We also assume that the imaginary strengths can be obtained by the squares of these coefficients. For a Σ hyperon an additional contribution to the imaginary part should be expected due to $\Sigma N \rightarrow \Lambda N$ conversion.

Currently there is no data on hyperon-nucleus scattering. However, this may change in the near future when an experiment at KEK may be able to provide data on Σ^+ -nucleus[15,16] scattering. The description of quasi-free hyperon production ($\gamma, K^+ \Lambda$), an approved proposal at CEBAF[17], also requires knowledge of the hyperon-nucleus optical potential. The present calculation is a first attempt to obtain estimates of the hyperon-nucleus scattering observables in anticipation of these results and as a guide to experimentalists planning future experiments.

In the following section we present the model and parametrization used in our calculations. The detailed description of the underlying nucleon-nucleus optical potential can be found in ref. [9]. The results are given in sect. 3. The conclusions of the study are drawn in sect. 4.

2. Parametrization of the optical model

We start with the proton-nucleus optical potential fits of Cooper *et al.*[9]. These fits are valid over a wide range of energies and nuclei. We then use SU(3) to extrapolate to hyperon-nucleus scattering. There are two consequences of SU(3). The first is that for the real parts of the optical potential the strengths scale like the YY_m ($Y = \Lambda, \Sigma, m=\sigma, \omega$) couplings. Thus for both the Λ and Σ we reduce the scalar and (time-like) vector potentials by the same factor $\alpha_Y = \alpha_V = 2/3$. The second SU(3) consequence is that we also include an anomalous coupling for the vector field with $f = -g$ and $f = +g$ for Λ and Σ , respectively. Here f is the strength of the tensor coupling of the hyperon to the ω meson and g is the corresponding vector coupling.

Thus we solve the Dirac equation:

$$[-i\alpha \cdot \nabla + V_0(\mathbf{r}) + \beta M + \beta S(\mathbf{r}) - \frac{i(f/g)\beta\alpha \cdot \nabla V_0(\mathbf{r})}{2M} + V_{\text{Coulomb}}(\mathbf{r})]\psi(\mathbf{r}) = E\psi(\mathbf{r}), \quad (1)$$

where $V_0(\mathbf{r})$ and $S(\mathbf{r})$ are the vector and scalar potentials felt by the hyperon. The tensor coupling term directly affects the strength of the hyperon spin-orbit interaction and therefore influences the analyzing power A_y . As we will see this is especially true for the Λ . On the other hand, we do not include the isovector ρ meson which can contribute to the Σ optical potential. This may be important particularly in systems with an excess of neutrons[14].

Since the imaginary part of the optical potential arises predominantly from processes where the projectile interacts twice with the nucleus we use for the imaginary part of the optical potential the square of the factor for the real part. This is admittedly crude but should serve as a first estimate. For pure SU(3) symmetry the imaginary part of the Y -nucleus optical potential is thus obtained by multiplying the nucleon-nucleus potential by $\alpha_{Y\gamma}^2 = \alpha_{3Y}^2 = (2/3)^2 = 4/9$.

When applied to bound hypernuclear systems the SU(3) values of the hyperon couplings give only a qualitative description of the experimental data. Therefore we also tried other pairs of scaling factors α_{iY} ($i = S, V$) adjusted to give the correct binding of hyperons in Λ (Σ) hypernuclei. In addition, this gives us an opportunity to test the sensitivity of the predictions of our model to its input. The scaling factors α_{iY} used in our calculations are listed in table 1. The values denoted by MF are from the mean field calculation of ref. [14]. The values denoted by OP were determined for each nucleus ^{12}C , ^{40}Ca and projectile Λ , Σ by searching for α_{iY} consistent with existing data on hyperon binding and simultaneously close to the SU(3) values. The fits of the α_{iY} factors for real parts of the optical potentials were done using the geometry obtained from the global optical potential at 30 MeV. This is as low as the optical potential of ref. [9] goes and we do not expect much change in extrapolating to zero energy.

There are a number of hypernuclear mean field calculations[18-23] in which the strength of Λ couplings is much smaller than the SU(3) predictions. The typical $\alpha_{i\Lambda}$ values used in these works lie between 1/3 and around 0.4. Therefore, for the sake of comparison we have made calculations of the Λ -nucleus scattering observables for values of $\alpha_{i\Lambda}$ close to 1/3. In all cases the imaginary optical potentials are obtained by using the squares of the factors for the real potential.

When comparing the α_{iY} values for potentials with optical model geometry with those obtained in Dirac mean field calculations[14] we see that they are close (0.621 vs 0.618 as seen in the table entry corresponding to Fig. 1). It should be noted that this is not only the case for the targets listed in table 1 but also for the other nuclei for which we obtained an almost identical parametrization of the optical potential. This suggests that the r -dependence of the optical potential[9] is similar to that of the mean field model[14]. Moreover, this confirms the validity of our approach since in this case we are not far from where the couplings in ref. [14] have been determined. The slightly larger difference between MF and OP values in the case of ^{12}C reflects the fact that relativistic mean field model gives for ^{13}C overbinding by about 1 MeV[14]. For the Σ hyperon we use the parametrization close to that for the Λ . This

choice is consistent with existing information from Σ^- atoms and from ΣN scattering [23-27]. As noted above we set the ρ coupling to zero.

For Σ scattering there are additional processes that affect the imaginary part of the optical potential, namely the $\Sigma N \rightarrow \Sigma N$ charge exchange and the $\Sigma N \rightarrow \Lambda N$ conversion in the nuclear medium. This introduces additional absorption that is not contained in the SU(3) estimates. We have investigated this effect as well and show the results in the next section.

3. Results

Calculations for the differential cross sections and analyzing powers were carried out using a modification of the program RUNT[28] for a selection of nuclei and energies. The choice of different parametrizations, energies, projectiles and targets enabled us to investigate various features of hyperon-nucleus scattering. Here we present only results for Λ and Σ hyperon scattering off ^{12}C and ^{40}Ca at two different energies, 30 and 300 MeV. The sensitivity to different aspects of the calculations are demonstrated in the five figures shown. The corresponding parametrizations for each particular figure are listed in table 1.

Figure 1 shows the cross section and analyzing power for the scattering of Λ 's on ^{40}Ca at 30 MeV for different scaling factors $\alpha_{i\Lambda}$ from table 1. While the MF and OP parametrizations give very close predictions of σ and A_y in the whole region under investigation, the SU(3) parametrization deviates significantly from them for the larger angles $\Theta_{\text{cm}} > 30^\circ$. The analyzing power A_y is almost 0 for each parametrization. As will be shown later this is mainly a result of tensor coupling.

The comparison of predictions for ^{40}Ca and different types of projectiles at 300 MeV is made in Fig. 2. The cross sections are qualitatively similar, small deviations are caused by the different contribution of the Coulomb interaction and tensor coupling for each type of hyperon. The predictions of A_y differ considerably between Σ and Λ scattering. The difference between Σ^+ and Σ^- is not so pronounced which signals that A_y is affected far more by the tensor coupling than by the Coulomb interaction. We should point out that in other calculations we have carried out with smaller values of α_{iY} , the Coulomb potential started to play a more significant role. For the α 's close to SU(3) values, the dominant effect of the tensor coupling is confirmed in Fig. 3 where we present the results for Λ - ^{40}Ca at 300 MeV for various strengths of tensor coupling $f/g = -1, 0, +1$. (It is to be noted that the unrealistic value $f/g = +1$ is used just for comparison.) Again, cross sections are qualitatively similar for different values of f/g with maxima and minima at roughly the same angles. More significant differences for larger angles are probably experimentally inaccessible due to a decrease of the magnitude by more than a factor of 100. However, the situation changes for A_y , where the predictions are strongly sensitive to the tensor coupling. Particularly for $f/g = -1$ we obtained quite a different result. For $f/g = 0$ and 1, the A_y predictions differ significantly at small angles ($\Theta < 12^\circ$) while for larger angles they become almost identical. The $f/g = -1$ (value suggested by SU(3)) leads to considerably smaller values of analyzing powers - A_y is close to zero for forward angles. This result suggests that measurements of A_y would give information on the tensor coupling of the vector meson to a hyperon.

Figure 4 illustrates how the predictions of scattering observables change when

we use different strengths of the hyperon couplings. The calculations were done for $\alpha_Y \approx 1/3$ which is close to values frequently used in the literature [18-23]. The angular dependence of the cross section is more or less similar to that of Fig. 3 – the differences start to appear at larger angles where the cross section is more than 2 orders of magnitude lower than for forward angles. For $f/g = -1$ we obtained again very small A_Y . For the other values of tensor coupling the A_Y differs significantly from the predictions of Fig. 3, even for small angles. This result suggests that the measurement of the analyzing power for Σ -nucleus scattering might bring some information about the strength of the YN interaction. On the other hand in the case of Λ -nucleus scattering the small spin-orbit force due to $f = -g$ means that we can not extract from A_Y separate information about the scalar and vector potentials.

In order to get closer to an experimental situation [15,16] we have calculated scattering of Σ^+ on ^{12}C at 300 MeV for different scaling factors. The results are presented in Fig. 5. We again obtained similar predictions for both $SU(3)$ and OP parametrizations. The large values of analyzing power indicate that it is reasonable to expect that significant deviations of A_Y from zero would be detected in experiment.

Finally, in Fig. 6 we show the effect of including increased absorption for the Σ . This arises from coupling to the Σ channel. Taking an estimate of the size from ref. [24,25] we have added a 20 MeV absorptive term to the scalar potential. When the quadratic terms are taken into account this leads to approximately 15 MeV of absorption in the Schrödinger equivalent potential. Since this estimate is rather crude we have also done the calculation with half and twice this absorption. In addition, we have checked whether the results change when the absorptive term is added to the vector potential instead of the scalar potential. In this case the effect is somewhat larger due to the E/M factor in the Schrödinger equivalent potential. Consequently, the two approaches have different energy dependences. The additional absorption shifts the diffractive minima to lower angles. It increases the cross-section in the Coulomb nuclear interference region and makes the diffractive minima somewhat deeper. The analyzing power is decreased at the first maxima but still remains sizeable.

4. Conclusion

We have calculated the differential cross sections and analyzing powers for Λ and Σ scattering off nuclei in the Dirac approach. The results tend to be sensitive to our choice of input parameters. However they are sufficiently similar that we can draw qualitative conclusions. The differential cross section show the typical diffractive shape. The different parameter sets predict relatively similar angular dependence – the magnitudes can differ by more than a factor of two particularly at large angles.

We observed strong sensitivity of A_Y to the tensor coupling. The analyzing powers are small for the Λ but substantial for the Σ 's at energies around 300 MeV, which is a region where experimental data could be expected. The predictions of A_Y are quite sensitive to the overall strengths of the ΣN couplings. This effect is masked to some extent by uncertainties in the absorption. Nevertheless the measurement of A_Y for Σ -nucleus scattering thus might become a source of information on the YN interaction. Moreover, the sensitivity of the predicted scattering observables to the absorption is probably large enough to allow the extraction of information about

$\Sigma N \rightarrow \Lambda N$ conversion.

It is to be stressed again that the presented calculations should be regarded as the first qualitative estimate for hyperon nucleus scattering. There is still a lot of theoretical as well as experimental work to be done in this field.

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References

- [1] B.D. Serot, J.D. Walecka, *Adv. Nucl. Phys.* **16** (1986).
- [2] B.C. Clark, S. Hama, R.L. Mercer, L. Ray and B.D. Serot, *Phys. Rev. Lett.* **50** (1983) 1644.
- [3] B.C. Clark, S. Hama, R.L. Mercer, L. Ray, G.W. Hoffmann and B.D. Serot, *Phys. Rev. C* **28** (1983) 1421.
- [4] J.A. McNeil, J.R. Shepard and S.J. Wallace, *Phys. Rev. Lett.* **50** (1983) 1439.
- [5] J.R. Shepard, J.A. McNeil, and S.J. Wallace, *Phys. Rev. Lett.* **50** (1983) 1443.
- [6] E.D. Cooper, B.C. Clark, R. Kozack, S. Shim, S. Hama, J.I. Johansson, H.S. Sherif, R.L. Mercer and B.D. Serot, *Phys. Rev. C* **36** (1987) 2170.
- [7] E.D. Cooper, B.C. Clark, S. Hama, and R.L. Mercer, *Phys. Lett.* **206B** (1988) 588, **220B** (1989) 658(E).
- [8] S. Hama, B.C. Clark, E.D. Cooper, H.S. Sherif, and R.L. Mercer, *Phys. Rev. C* **41** (1990) 2737.
- [9] E.D. Cooper, S. Hama, B.C. Clark, and R.L. Mercer, *Phys. Rev. C* **47** (1993) 297.
- [10] B.K. Jennings, *Phys. Lett.* **246B** (1990) 325.
- [11] M. Chiapparini, A.O. Gattone, and B.K. Jennings, *Nucl. Phys. A* **529** (1991) 589.
- [12] J. Cohen, H.J. Weber, *Phys. Rev. C* **44** (1991) 1181.
- [13] A. Ramos, E. Van Meirgaard, C. Bennhold, B.K. Jennings, *Nucl. Phys. A* **544** (1992) 703.
- [14] J. Mares and B.K. Jennings, submitted *Phys. Rev. C*.
- [15] M. Leiri, private communication.
- [16] D. R. Gill, private communication.
- [17] C.E. Hyde-Wright (spokesperson), "Quasi-Free Strangeness Production in Nuclear", CEBAF experiment 91-014.

Table 1 The scaling factors α_{iY} ($i = S, V$ and $Y = \Lambda, \Sigma$) used in this work.

Particle	Line Type		α_v	f/g	α_s
Fig. 1. ^{40}Ca 30 MeV					
Λ	solid	SU(3)	0.667	-1	0.667
Λ	dashed	MF	0.667	-1	0.621
Λ	dash-dotted	OP	0.667	-1	0.618
Λ	dotted	OP	0.727	-1	0.667
Fig. 2. ^{40}Ca 300 MeV					
Λ	dashed	OP	0.667	-1	0.618
Σ^+	solid	OP	0.667	+1	0.616
Σ^-	dash-dotted	OP	0.667	+1	0.616
Fig. 3. ^{40}Ca 300 MeV					
Λ	dashed	OP	0.667	-1	0.618
Λ	solid	OP	0.667	+1	0.618
Λ	dotted	OP	0.667	0	0.618
Fig. 4. ^{40}Ca 300 MeV					
Λ	dashed	OP	0.333	-1	0.345
Λ	solid	OP	0.333	+1	0.345
Λ	dotted	OP	0.333	0	0.345
Fig. 5. ^{12}C 300 MeV					
Σ^+	solid	SU(3)	0.667	+1	0.667
Σ^+	dashed	OP	0.667	+1	0.606
Σ^+	dash-dotted	OP	0.743	+1	0.667

- [18] R. Brockmann and W. Weise, Phys. Lett. **69B** (1977) 167.
[19] J. Boguta and S. Bohrman, Phys. Lett. **102B** (1981) 93.
[20] J. Cohen and R.J. Furnstahl, Phys. Rev. **C35** (1987) 2231.
[21] M. Rufe, J. Schaffner, J. Maruhn, H. Stöcker, W. Greiner and P.-G. Reinhard, Phys. Rev. **C42** (1990) 2469.
[22] J. Schaffner, C. Greiner and H. Stöcker, Phys. Rev. **C46** (1992) 322.
[23] N.K. Glendenning, D. Von-Eiff, M. Haft, H. Lenske and M.K. Weigel, Phys. Rev. **C48** (1993) 889.
[24] C.J. Batty, Nucl. Phys. **A372** (1981) 433.
[25] C.J. Batty, A. Gal and G. Toker, Nuc. Phys. **A402** (1983) 349.
[26] J. Schaffner, C.B. Dover, A. Gal, C. Greiner, D.J. Millener and H. Stöcker, preprint BNL-49062, in press.
[27] C.B. Dover, D.J. Millener and A. Gal, Phys. Rep. **184** (1989) 1.
[28] E.D. Cooper, PhD Thesis, Alberta, 1981 (unpublished).

Figure captions

1. The observables predicted for 30 MeV Λ 's elastically scattered from ^{40}Ca using the parametrization from table 1.
2. The observables predicted for 300 MeV Λ (dashed line), Σ^+ (solid line) and Σ^- (dash-dotted line) elastically scattered from ^{40}Ca . The parametrization used is given in table 1.
3. The effect of the tensor coupling on the observables for 300 MeV Λ 's elastically scattered from ^{40}Ca . The predictions for $f/g = -1$ (dashed line), $f/g = 0$ (dotted line) and $f/g = +1$ (solid line) are compared. The scaling factors used are from table 1.
4. The observables predicted for 300 MeV Λ 's elastically scattered from ^{40}Ca using weaker Λ coupling, $\alpha_{\Lambda} \approx 1/3$. The parametrization used is presented in table 1.
5. The observables predicted for 300 MeV Σ^+ 's elastically scattered from ^{12}C . The parametrization used is given in table 1.
6. The effect of the additional absorption due to the $\Sigma N \rightarrow \Lambda N$ conversion on the observables for 300 MeV Σ^+ 's elastically scattered from ^{12}C . The parametrization used is given in table 1.

Fig. 1

Fig. 2

Fig. 4

Fig. 3

Fig. 6

Fig. 5